handprint : modern color theory (applications)

handprint.com (http://www.handprint.com/HP/WCL/color18b.html)

modern color theory (applications)

The previous page focused on the conceptual framework of color theory, including the three colormaking attributes, basic color naming, misconceptions in the color explanations offered by tradtional color theory, the basics of additive and subtractive color mixing, substance uncertainty, and the geometrical form of visual color relationships lightness, hue, chroma, lightness and chroma, and hue and chroma.

This page describes the important applications of that theoretical knowledge: the difference between conceptual, schematic and physical gamuts, the behavior of paint mixtures, basic paint naming, the six important pigment attributes, the six important paint attributes and palette designs. The page concludes with an overview of the principles of color contrast, a review of color symbolism, and a summary of all the principles identified in this and the previous page.

As the focus here is putting knowledge to work, there is considerable information about paints and color mixing that is not in the traditional scope of color theory. This signifies one of my major criticisms of old school "color theory": that it treats "color" in the abstract, as ideas or essences, rather than in the material substance of paints and inks that actually must be manipulated to make a work of art.

material color relationships

In an earlier section (http://www.handprint.com/HP/WCL/color18a.html#spacedifferences), I pointed out the difference between a true *color space,* which represents all visual colors (the colors it is possible to see), and a *gamut,* which represents all the colors it is possible to produce by means of a color production technology.

Here I use the concept of a **gamut** to clarify the three common ways that artists think about color. I first contrast a schematic painter's gamut with an idealized color geometry such as the traditional artist's color wheel (http://www.handprint.com/HP/WCL/color13.html#secondary). Then I will illustrate how a schematic gamut compares to an actual material gamut, and finally describe the *working gamut* that a painter develops through experience with mixing paints. The working gamut provides the framework for some basic to help you manage color as you paint.

The Material Gamut. A gamut is defined by measuring with a spectrophotometer the material color (http://www.handprint.com/HP/WCL/color18a.html#threecolors) (the reflectance curve (http://www.handprint.com/HP/WCL/color18a.html#reflectancecurve) for paints, inks, printers or photographic emulsions, emittance curve for video displays) of the individual colorants ("primary colors") in a color production technology, and the material color of a large number of different mixtures of two or more primary colorants; then using colorimetry (http://www.handprint.com/HP/WCL/color6.html#colorimetry) to represent these color measurements as specific points within a three dimensional color space, such as the $\mathbf{L^*u^*v^*}$ dimensions of

CIELUV (http://www.handprint.com/HP/WCL/color7.html#CIELUV), the **L*a*b*** dimensions of CIELAB (http://www.handprint.com/HP/WCL/color7.html#CIELAB) or the **Jab** or **Qab** dimensions of CIECAM (http://www.handprint.com/HP/WCL/color7.html#CIECAM). The gamut is then the *smallest three dimensional solid* within the color space that includes all these color samples.

A gamut can describe any kind of color reproduction technology. The collection of all unique colors that can be produced by your computer screen is your computer's *monitor gamut,* and the collection of all unique colors that can be produced by your inkjet printer is your *printer gamut*. The collection of all unique colors that can be mixed with your selection of watercolor paints is your **palette gamut**.

To define a palette gamut, watercolor paints (or the raw pigment in the paints) are dispersed in a transparent vehicle such as water or acrylic resin and applied to white paper. Their reflectance curves are measured with a spectrophotometer, and into the three colormaking attributes (http://www.handprint.com/HP/WCL/color18a.html#colormakingattributes). These attributes can then be represented as a diagram:

color theory

modern color theory (concepts) (http://www.handprint.com/HP/WCL/color18a.html)

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

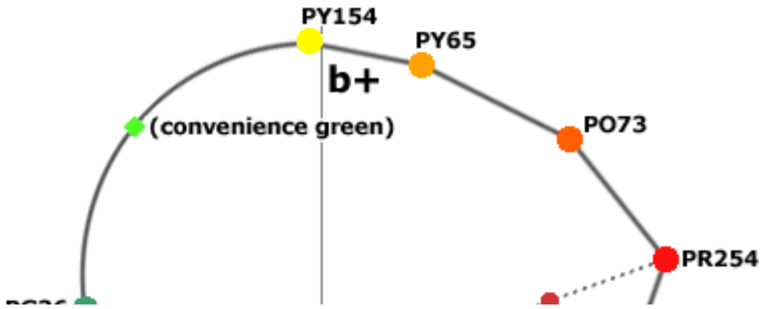
(http://www.handprint.com/HP/WCL/wcolor.html)

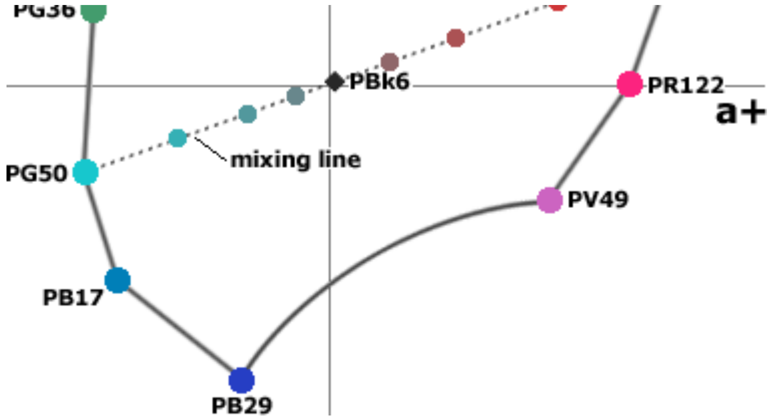
Hue is defined as the **hue angle** of the color around the gray or neutral center of the gamut (diagram, right). This is the circular angle (from 0° to 360°) measured counterclockwise between two lines originating at the neutral center of the color space, from one line through the hue violet red (**a**+) to the other line through the hue to be specified. In this scheme *yellow* (**b**+) is approximately at 12 o'clock and has a hue angle of 90°, *violet red* (**a**+) is at 3 with a hue angle of 0°, *blue violet* (**b**) is at 6 with a hue angle of 270°, and *blue green* (**a**) is at 9 with a hue angle of 180°.

Chroma is represented by the distance from the achromatic center toward the edge of the gamut, in units that represent an average perceptual change (http://www.handprint.com/HP/WCL/color3.html#purechroma) equal to the average perceptual change in units of lightness. (A color change of 10 units in chroma should appear to be as large as a color change of 10 units in lightness.) Paints at the center of the gamut are very dull or gray; paints far from the center are the most intense (saturated).

Instead of using hue angle and chroma, the color's position can be stated as a distance on the two perpendicular dimensions, **a** and **b**.

If we apply these methods to a selection across a range of hues from the most saturated pigments used in commercial watercolor paints, we get the picture of a typical watercolor gamut (diagram, below).



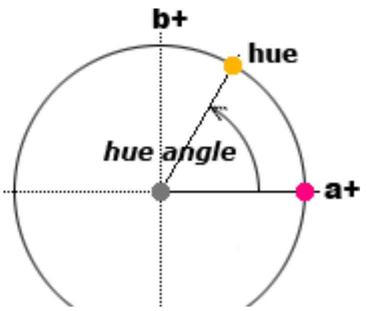


a typical watercolor gamut

paint chromaticities on the CIECAM $\mathbf{a_C b_C}$ plane, with a mixing line and the location of mixable and unmixable colors

The two most important features of a gamut are its *size* the larger the gamut, the more unique color mixtures it can contain and its *color distribution* a gamut that contains every hue to similar chroma or lightness limits is more versatile than a gamut that contains only dull versions of some hues, or contains all hues within a more restricted lightness or chroma range. In short, the optimal gamut should allow the **maximum color contrasts** in visual color.

The unique color mixtures between any two pigments can be represented in a gamut diagram by measuring them spectrophotometrically, converting the measurements into the **ab** coordinates, and locating them in the diagram. Connecting these mixtures defines the **mixing line** between the two paints. Every color it is possible to mix with the two paints (without adding water or a third paint) will be located on this line.

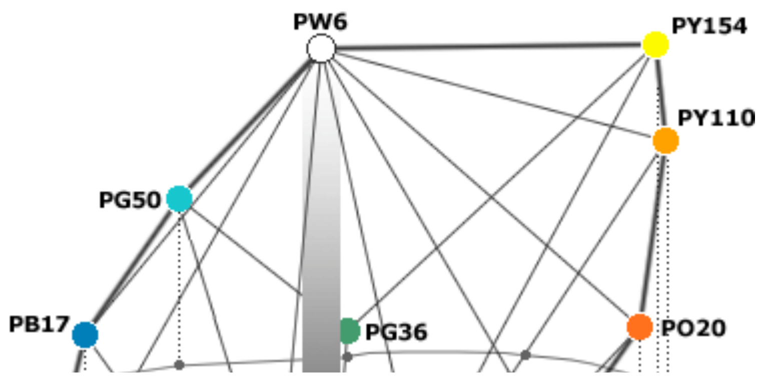


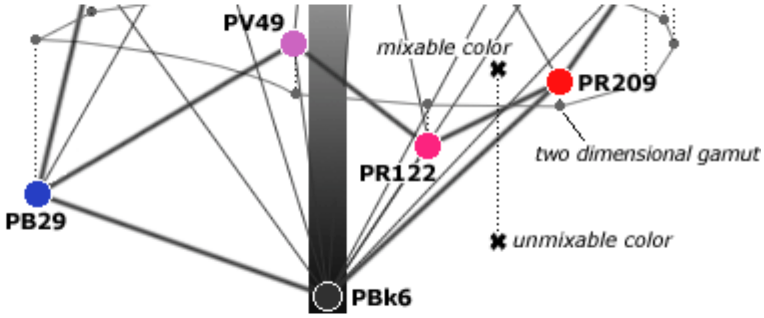
hue angle and chroma as
measured on the CIECAM ab plane

We are usually more interested in the **gamut limit** that encloses all the colors it is possible to mix with any combination of pigments in the palette (including, implicitly, white and/or black along the missing lightness dimension). The gamut limit is enclosure created by mixing lines between pairs of the most saturated paints in the palette. For convenience we define these as straight lines between the most saturated paints of similar hue, and by measured mixing lines between paints whose hues are far apart as shown between PV49 and PB29, and between PG36 and PY154. These lines are often curved, especially in green mixtures.

Now the gamut contains the chromaticity of all **mixable colors**, or **ab** color values it is possible to match by some mixture of the paints around the gamut limit. It also defines the **unmixable colors** that are *out of gamut* and cannot be matched by the chosen paints.

We cannot be sure a color is actually mixable unless we include the lightness dimension, because the gamut tapers to a point at white and black: as mixtures become lighter or darker (http://www.handprint.com/HP/WCL/color18a.html#chromainhue), the width of the gamut contracts and the number of mixable colors grows smaller. Adding lightness creates a three dimensional gamut image (diagram, below).





a three dimensional watercolor gamut

in the CIECAM $\mathbf{Ja_Cb_C}$ color space

Now let's define two terms relevant to painting practice:

A palette primary (http://www.handprint.com/HP/WCL/intstud.html#step5) is any paint located on the gamut limit. Palette primaries define the *corners* of the gamut "box". Mixture lines between two neighbor palette primaries, including mixtures with white and black, define the *limits* or edges of the gamut enclosure.

A palette gamut (http://www.handprint.com/HP/WCL/intstud.html#step7) is the collection of *all unique colors* that two or more of the palette primary paints can make if they are mixed in any combination, in any proportions including any proportion of water (white paper) or dark achromatic (black) paint in the mixture. All these *mixable colors* are inside the three dimensional gamut enclosure.

What are the two essential differences between a color space and a gamut?

1. A gamut is **always smaller than the visual color space**. There are always some colors you can see in the real world that cannot be recreated by the colors produced by a computer monitor or the inks available in a printer or the paints available on a painting palette.

Gamut limits arise from the two fundamental ways that physical imaging media fall short of the response capabilities of our visual system. The first shortcoming is due to the overlap among the **L**, **M** and **S** photoreceptor response curves (http://www.handprint.com/HP/WCL/color6.html#twoparadoxes), which creates curved chroma limits that cannot be matched by the straight line mixtures of palette primaries. The second shortcoming arises from the *limited dynamic range* of imaging media compared to the dynamic range of human vision.

The dynamic range can be expressed as the contrast ratio (http://www.handprint.com/HP/WCL/color4.html#charcurve) between the lightest and darkest luminance values in an image. A photograph or painting, which is a single reflecting surface viewed under a single average illumination, creates a contrast ratio of about 20:1. This is the same contrast ratio as most environmental surfaces under natural light. But these surfaces also appear in sunlight or in shadow (skylight), and in varying depths of shadow, along with reflections and highlights, so that the overall luminance range is much larger. Images that represent surfaces in both light and shadow, or transmitting materials such as stained glass and plant leaves, or images that contain emitting lights or reflections of sunlight on water, must represent a dynamic range of 4 log units (10,000:1) or more.

Gamut limitations must be apparent any time colorants in a medium with a 20:1 contrast ratio (such as painting) are used to represent a visual environment with a much greater contrast ratio. The principal limitation is in *luminance contrast* or brightness contrast of the image, but this also directly affects the amount of *chromatic contrast* or saturation in the image. Artistic media always appear either darker (less luminous) or grayer (less contrasty) than our visual experience.

2. A gamut is **always distorted by colorant mixtures**. It is always possible to match any isolated visual color by a mixture of just two lights a monochromatic light of the same hue, and a white light and by adjusting the surround luminance to create the luminance contrast necessary for the perception of blackness.

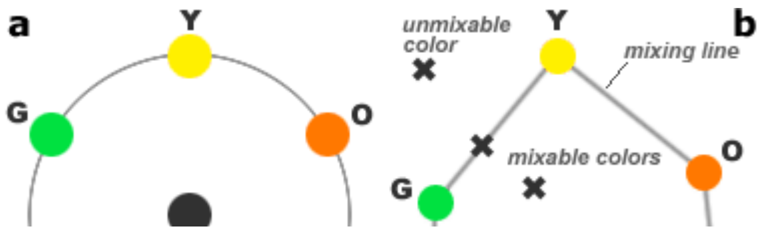
Color reproduction mixtures of material pigments or dyes are more troublesome. Mixing lines are typically curved, three dimensional gamut limits may be unexpectedly concave or convex, some "mixable colors" may be difficult to match exactly.

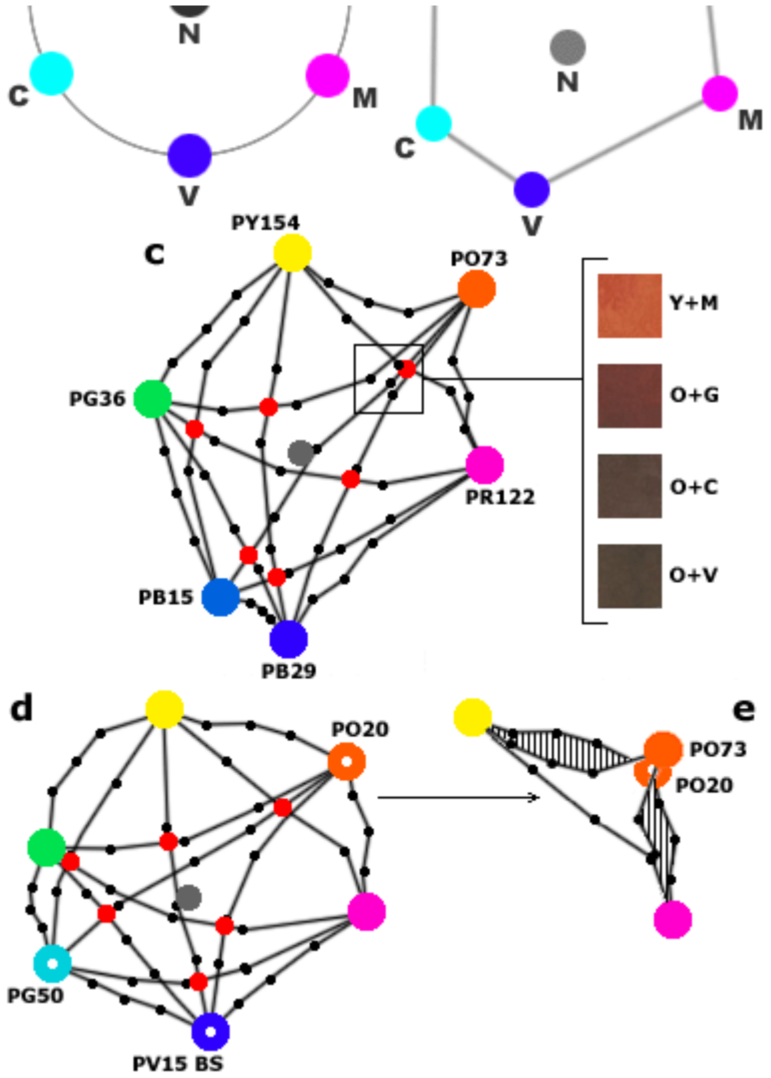
A watercolor palette gamut is also affected by the attributes of the paper (http://www.handprint.com/HP/WCL/paper2.html) that the paints are applied to. To see this, apply and compare the same paint mixtures on high quality watercolor paper and on newsprint sketch paper or gray construction paper.

The most important paper attributes are the *lightness* or total reflectivity of the paper, the *whiteness* or color tint of the paper, the *surface finish* (texture and sizing) of the paper, and the paper's *absorbency* or tendency to soak paint into its inner fibers rather than hold paint on its surface. The largest gamut is produced by very reflective, white papers with a smooth, well sized finish and nonabsorbent surface.

Conceptual, Schematic and Physical Gamuts. The gamut diagram allows a useful comparison among the three kinds of color (http://www.handprint.com/HP/WCL/color18a.html#threecolors): *conceptual color* (colors we think about or talk about, abstract colors such as "primary" colors, colormaking attributes such as lightness or chroma, all the colors that we describe as "red", colors labels such as sky blue, grass green, etc.), *visual color* (how colors appear in experience), and *material color* (actual paints and the mixtures possible with those paints).

The diagram (below) highlights the differences between these three kinds of color.





schematic and actual color relationships

(a) color relationships in an idealized color wheel; **(b)** color relationships in a schematic gamut, showing mixable and unmixable colors; **(c)** actual chromaticity gamut defined by six specific watercolor paints, with mixing scales identified by black dots; **(d)** actual gamut produced by replacing three paints in previous palette, showing (inset left) four different colors at the same gamut location; **(e)** change in saturation of yellow to magenta mixtures when PO20 is replaced by a more saturated orange paint (PO73)

The idealized artist's color wheel (**a**) arranges color icons systematically inside a simple geometric figure (circle, triangle, cube, double cone, etc.). It is useful only to anchor the most basic subtractive color mixing rules (*"yellow and blue make green"*) or to indicate the location of specific hues (*"turquoise is between blue and green"*).

A schematic gamut (**b**) discards the simple geometric figure and ideal color locations, and reproduces the relative color locations approximately; but the gamut boundaries are simplified. This kind of diagram is useful to illustrate basic technical facts, such as the location of unmixable colors or the difference between the gamuts in different media.

An actual gamut (**c**) is based on measurements of all color locations in a color space, including the mixing lines along gamut limits. This shows the hue and chroma differences among paints and the curvature in many mixing lines.

The actual gamut seems to match fairly well both the idealized color wheel and the schematic gamut, but this depends very much on the specific choice of pigments. If we replace three of the six palette primaries, the overall shape of the gamut changes dramatically (**d**). Gamuts are always dependent on the choice of palette primaries; we cannot simply substitute one "color" of paint for another and expect to get similar mixing effects.

And visual color cannot always help us decide which paint will perform better in mixtures, due to substance uncertainty (http://www.handprint.com/HP/WCL/color18a.html#subprobs). For example, replacing one saturated "orange" paint (PO20 (http://www.handprint.com/HP/WCL/watero.html#PO20)) with another (PO73 (http://www.handprint.com/HP/WCL/watero.html#PO73)) significantly changes the gamut limit and the mixtures possible with the yellow and magenta primaries (**e**). Surprisingly, the *lower chroma* paint produces mixtures with yellow and magenta that are *more saturated*. This illustrates that mixtures with other paints (http://www.handprint.com/HP/WCL/color18a.html#colorinmixture) are the only sure way to understand the material color and the actual usefulness of the paint in the palette gamut.

Finally, the inset to (**d**) illustrates the variety of colors that can be located at the same chromaticity (**a,b**) location in a two dimensional gamut diagram. Note the large differences in lightness and the corresponding differences in saturation.

The Painter's Working Gamut. Experienced painters develop a **working gamut** through trial and error with color mixtures using different paints. The working palette identifies each paint with a *conceptual color* or color idea that relates the palette paints to each other, and to important mixture colors, through familiar mixing lines (diagram, below).

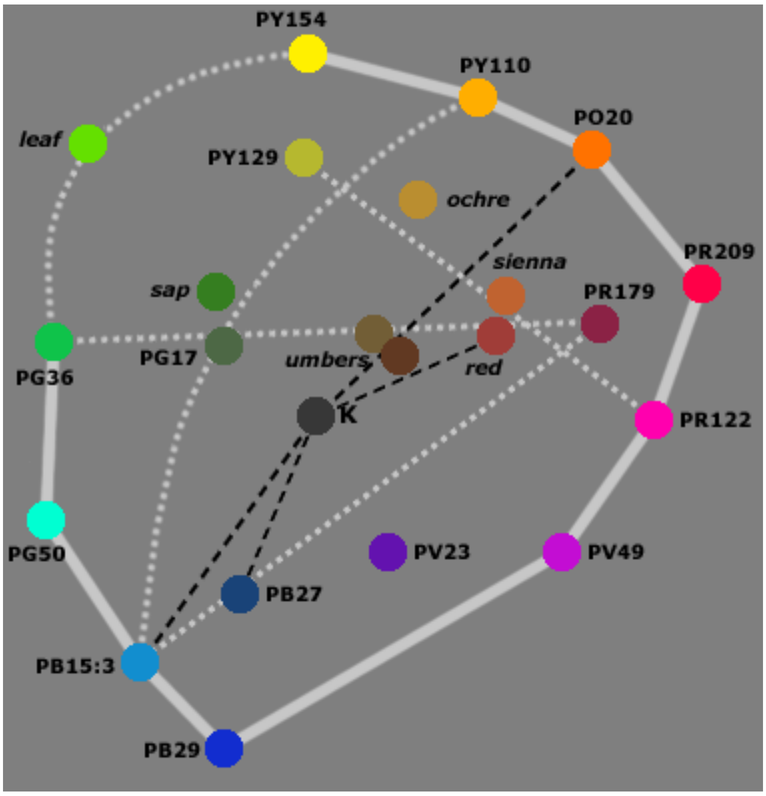


diagram of a painter's "working gamut"

The working gamut is organized around four kinds of knowledge.

relative color locations (colored dots). The conceptual colors associated with paints are (1) arranged around the neutral or achromatic point, and (2) spaced in relation to each other according to their visual color and the variety of mixtures they make with other paints. Two paints that mix few or similar colors seem closer together than paints with a large color mixing range.

mixtures along gamut limits (white solid lines). Each pair of paints is associated with a mixing line that defines a small section of the gamut limit and creates the most saturated possible color mixtures between two hues.

key mixing lines (white dotted lines). These are mixing lines within the gamut defined by several characteristic or familiar mixture values of dull, dark or pastel color mixtures. For example, the mixture of quinacridone magenta (PR122 (http://www.handprint.com/HP/WCL/waterc.html#PR122)) and copper azomethine (*green gold,* PY129 (http://www.handprint.com/HP/WCL/watery.html#PY129)) is thought of as a series that includes an ochre color, a sienna color, and a dull red color (like perylene maroon, PR179 (http://www.handprint.com/HP/WCL/waterr.html#PR179)). Perylene maroon and phthalo green YS (PG36 (http://www.handprint.com/HP/WCL/waterg.html#PG36)), in different proportions, produce a series that includes an iron red, a raw umber, and a chromium oxide green (PG17 (http://www.handprint.com/HP/WCL/waterg.html#PG17)).

mixing complements (black dashed lines). Finally, a few paints are paired as true mixing complements (http://www.handprint.com/HP/WCL/mixtable.html), or the paints that most conveniently mix a gray or black color. Sometimes these lines are hese lines can be quite bent or curved in comparison to the paints relative color locations. Thus, the mixing complements iron blue (prussian blue, PB27 (http://www.handprint.com/HP/WCL/waterb.html#PB27)) and iron oxide red (venetian red, PR101 (http://www.handprint.com/HP/WCL/watere.html#PR101)) were Winslow Homer's favorite gray mixture for stormy skies.

Painters plan or analyze color mixtures, from a desired color or *target color* back to the palette paints, through a series of steps. The basic hue of the color is identified along the gamut limits, and the best color match in terms of color series possible along each of the characteristic mixing lines.

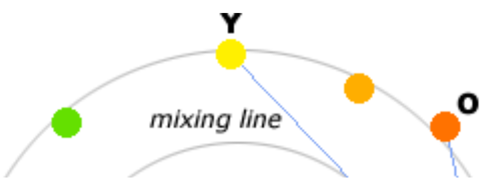
The working gamut usually suggests several different paint combinations (http://www.handprint.com/HP/WCL/mix.html#step3) to mix a target color. The painter uses the paint (staining, granulation, transparency, etc.) to decide which combination of paints is most suitable for a specific color context.

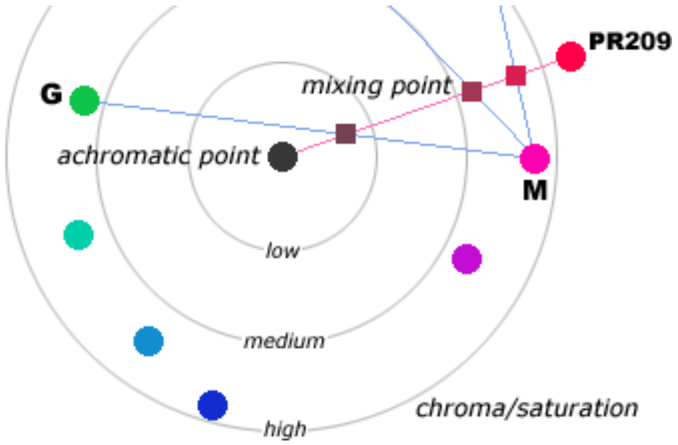
Many painters are reductive in their color mixing choices, using familiar mixtures of the same paints for the same purposes, or using only pure paint colors from a fixed palette selection. This gives their work a signature quality, and imparts a particular visual style.

The Behavior of Paint Mixtures. All working paint gamuts are shaped by the same underlying behavior of subtractive color mixture and substance uncertainty. So it is

The Rule of Saturation Costs. If we first set aside lightness and focus only on the hue difference between two paints and the chroma of their average mixture, the working palette expresses a general and very important paint mixing concept.

The diagram (below) illustrates a working palette of a dozen paints (including black), visualized now as a surface of possible color mixtures between the paints. All achromatic colors (grays) will be at the center of the circle, and the most saturated color mixtures will be around the circumference, between two neighbor palette primaries.





saturation costs on the hue circle

Assume that we want to mix a color that will match the hue of quinacridone red (PR209 (http://www.handprint.com/HP/WCL/waterr.html#PR209)). If we mix a saturated magenta paint (**M**) with a saturated orange paint (**O**), the mixing line between them must lie close to the circumference of the hue circle, so the mixture will be very saturated. If we mix magental and yellow (**Y**), the mixing line is now farther from the circle and closer to the center, so the mixture will be duller. If we mix magenta and green (**G**), the mixing line passes close to the achromatic center of the hue circle and the mixture will be very dull and, if more green is added to make the hue approximately yellow, the paint mixture may be indistinguishable from gray.

If you choose a different paint as the hue you want to match, and compare the mixing lines created by paints that are close to or far from that target hue, you will find the same relationships apply. We can state this as a general rule, the *rule of saturation costs:*

38. The farther apart two paint colors are on the hue circle, the duller their mixture will be.

A specific application of this rule is the *rule of complementary mixtures:*

39. Two paint colors on opposite sides of the hue circle will mix an achromatic or near neutral color.

Both rules are dependent on the *rule of chroma and lightness* between the two paints:

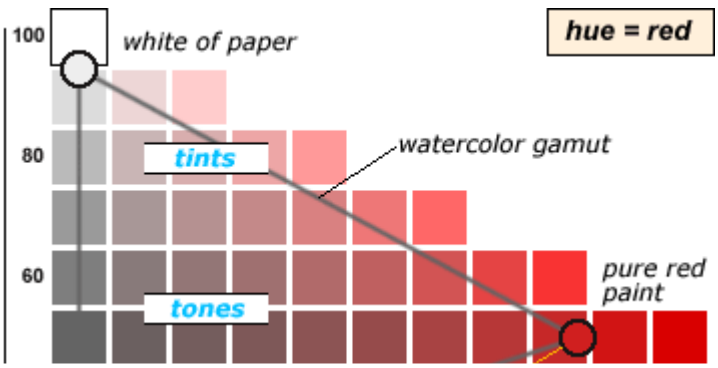
40. The mixture of two paints will always be duller than the more saturated paint and darker than the lighter valued paint.

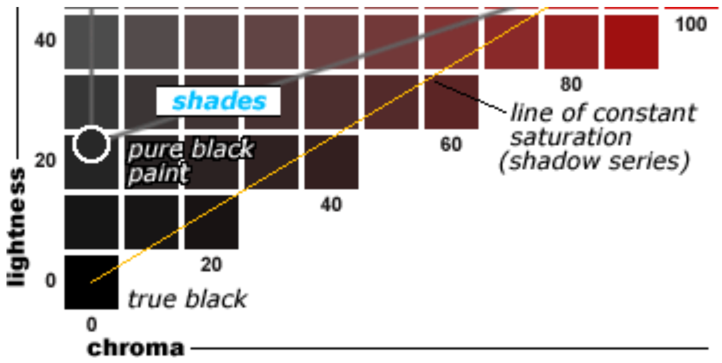
Note that the comparison is only in relation to the lighter valued and more saturated paint. Because of the strongly neutralizing effect of near complementary paint mixtures, it is possible for a mixture to be duller than the duller of the two paints, or darker than the darker paint.

Manipulating Lightness & Chroma. It is a much simpler paint mixing operation to change the lightness and/or chroma of a color without altering its fundamental hue.

In the European painting tradition, these *desaturating* mixtures of a pure pigment with another color, or with white and/or black, were called **broken colors**, and *breaking a color* was synonymous with dulling or whitening it.

In the common modern terminology these mixtures are called **shades, tones or tints** of the color, depending on whether the paint is mixed with black, gray or white. An example is shown in the figure below for a middle red.





shades, tones and tints of a middle red

The pure pigment color, as raw paint from the tube, is best displayed in paint that has been properly diluted (http://www.handprint.com/HP/WCL/tech16.html#notblack) in most commercial watercolors, by a paint to water ratio (by volume) of between 1:4 to 1:6 so that the paint does not appear bronzed or blackened when applied to paper, but also does not appear to be whitened or diluted by the color of white paper showing through the paint. Paint applied in this way displays the paint color at a lightness that allows its maximum chroma to appear.

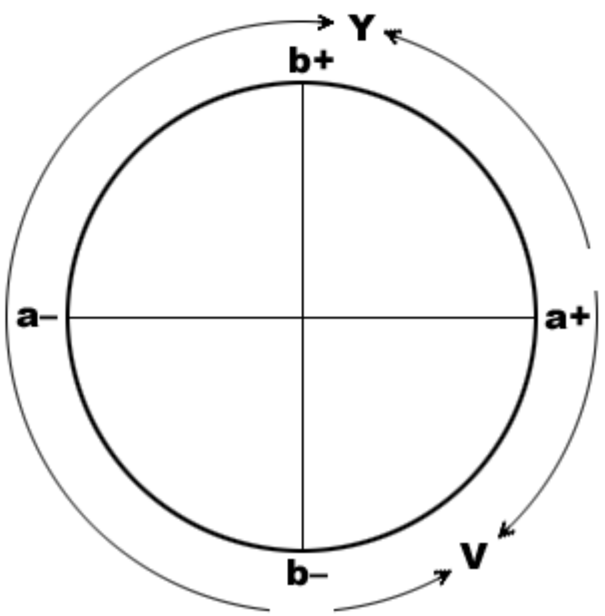
Starting with this "peak chroma" preparation, the paint color can be modified by:

reducing both the chroma and lightness of the color (**LC**) by mixing with a black or dark near neutral paint, which can reduce the lightness to the darkest value possible in watercolors (around step 2 on a value scale), to produce **shades** of the hue

reducing the chroma of the color without significantly changing the lightness (**C**), by mixing with either (1) a gray mixture of black and white of approximately the same lightness as the pure color, or (2) another paint of similar lightness that is a mixing complementary color (http://www.handprint.com/HP/WCL/color18a.html#visvsmix), which brings the mixture color closer to gray; these are **tones** of the hue reducing the chroma and increasing the lightness of the color up to the "white" lightness of the paper or canvas (+**LC**), by mixing with pure water (in watercolors or acrylics) or a white paint or colorless medium (in acrylics and oils), to produce **tints** of the hue.

There are two quirks in color mixing that should be recognized when manipulating hues across the different paths of reduced chroma:

1. hue shifts. Lightening most paints by diluting with water or mixing with a white pigment causes a *hue shift* in the color of the mixture. In particular, as paints are lightened most spectrum red, orange and yellow paints shift toward yellow, blue red and violet red paints shift toward violet, blue and blue violet paints shift toward violet, and blue green paints shift toward green. However there can be paradoxical effects depending on the actual reflectance profile of the paint: cadmium red orange (PO20 (http://www.handprint.com/HP/WCL/watero.html#PO20)) shifts toward orange as it is lightened, but pyrrol orange (PO73 (http://www.handprint.com/HP/WCL/watero.html#PO73)) shifts toward violet.



hue shifts with lightness increase

hues from green blue to red shift toward yellow as they lighten; hues from blue violet to violet red shift toward violet as they lighten

The diagram (above) indicates the overall pattern of the shifts: toward *yellow* for "spectrum" hues, and toward *violet* for "extraspectral" hues. There are several specific exceptions in red paints (http://www.handprint.com/HP/WCL/IMG/RC/red.html), for example, the direction of the shift depends on whether the color is a spectrum red or a blue red. The shifts are generally larger for saturated than for unsaturated paints, and greater in paints that are yellow green, yellow orange, blue or red violet than in paints that are blue green, green, red, or violet.

2. complementary lightness reduction. The mixing lines with an achromatic white, gray or black paint are always linear or nearly so: in mixtures of a red paint and a gray paint of the same lightness, the middle shades are not darker or lighter than the red and gray paints. However, the mixing lines between *orange/blue* or *red/green* mixing complements (http://www.handprint.com/HP/WCL/color18a.html#mixcomps) can be strongly bowed downwards, toward darker values, around the neutral mixtures. A spectacular example is the mixture of pyrrol scarlet (PR255 (http://www.handprint.com/HP/WCL/waterr.html#PR255), lightness 48) and phthalo green (PG7 (http://www.handprint.com/HP/WCL/waterg.html#PG7), lightness 50), which does not make a middle gray (around lightness 48 or 50) but a very impressive dark gray (http://www.handprint.com/HP/WCL/mixtable.html#PG7) (lightness 22).

Shadows & Shadow Series. The main reason colors are dulled and darkened is to represent surface shadows, so it will be useful to consider how that is typically done by painters.

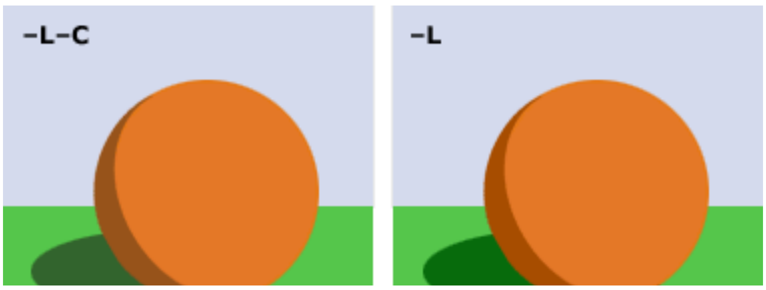
In all light environments, shadows are rich with information. Their cast represents the relative direction of light, the sharpness of their edges the angular size of the light, and the contrast between dark and light the luminance of the light.

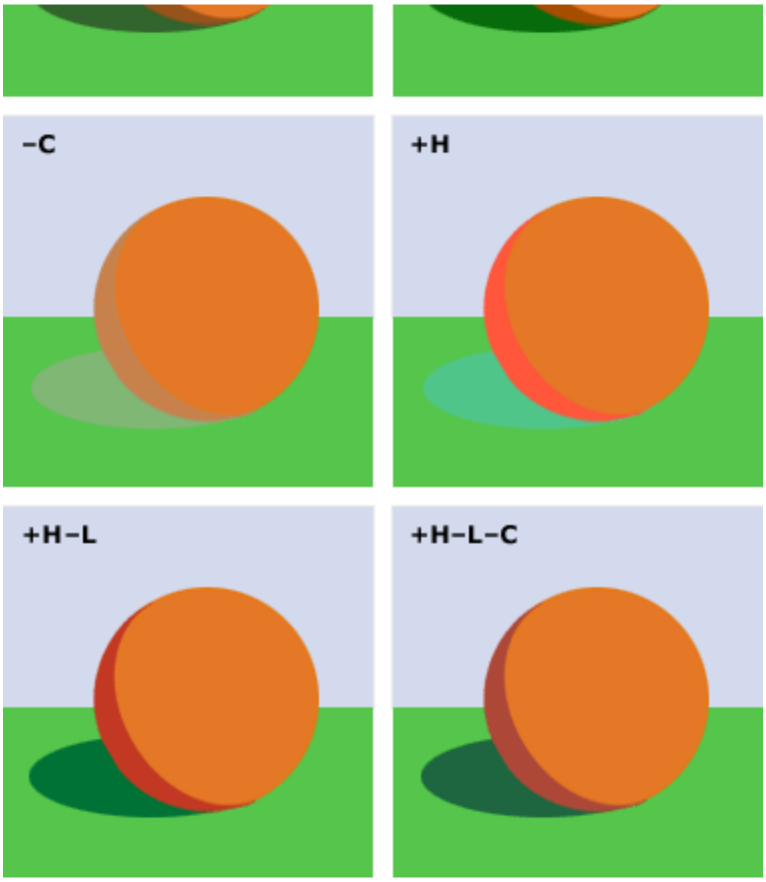
When measured instrumentally, shadows retain exactly the same saturation (chroma relative to lightness) as fully lighted surfaces. No matter how dimly lit the surface is, the proportion of chroma to lightness is always the same. This proportion is defined by a *line of constant saturation* from the pure black value to the pure (fully illuminated) surface color.

A "true" black is not available in any painting or printing medium, since all materials scatter some light (http://www.handprint.com/HP/WCL/color18a.html#WCK) at the surface; this scattering is more acute in watercolor paints, which do not form a paint layer (http://www.handprint.com/HP/WCL/color18a.html#cterror10). Therefore mixtures with a black paint are actually mixtures with a *gray* paint, and so always reduce the saturation of the pure paint in a way that mixtures with *darkness* (shadow, decreased illumination) do not. This causes the "blackening" (actually, graying) of the darkest values.

In addition, traditional color theory teaches that the chromaticity of *red*, *yellow*, *green* or *blue green* lights induces our visual system to tint the shadow cast by the light with the of the light. (Lights tinted *blue* and *blue violet* would produce a *yellow* complement, but yellow cannot appear as a tint of darkness.)

The easiest way to sort through these complications is with visual examples, such as the orange ball on a green surface in the diagram (below).





painting strategies for rendering object shadows

LC: constant saturation (proportional reduction in lightness and chroma); **L**: reduced lightness only; **C**: reduced chroma only; +**H**: "darker" hue shift only; +**HLC**: "darker" hue shift with reduced lightness only; +**HLC**: "darker" hue shift with constant saturation (proportional reduction in lightness and chroma)

The "objective" shadow rendering is the one with constant saturation (lightness and chroma reduced in equal proportion, **LC**, top left), which is appropriate in photorealist painting but will appear too dry or lifeless according to contemporary visual tastes. Breaking down the shadow changes into separate components shows that a lightness reduction by itself (**L**, top right) is adequate, and that a chroma reduction or a hue shift (**C** and +**H**, middle row) by themselves are unsuccessful.

Most painters would use a constant saturation color reduction, with a "darkening" hue shift (toward blue for greens, toward red for oranges). This is often equivalent to adding blue violet or violet paint, either as a foundation tint layer or as paint added to the shadow color mixture.

Note that, comparing **LC** with **+HLC**, the **LC** shadow appears relatively too dull and light valued: shifting the hue toward red (or blue, for the shadowed surface) has the effect of darkening the color. In general, if a shadow area appears either too luminous or too dark, it is often not the lightness but either the hue or the chromatic intensity of the shadow color that needs to be adjusted. Attempting to darken or lighten the shadow often makes the problem worse.

The Relative Effects of Color Mixtures. Finally, we can generalize about the changes in lightness, chroma and hue that appear in mixtures of two paints at different locations around the hue circle.

Chroma/saturation is in principle always the easiest attribute to adjust: to reduce chroma, we simply mix the paint color with a gray paint of matching lightness; to increase chroma, we simply mix the paint color with a more saturated paint of the same hue and equal lightness.

Difficulties arise because of the limited available selection of pigments, because it is cumbersome to mix a matching gray before using it to desaturate a color, and because the resulting grayed paint mixtures are generally less attractive than paints desaturated with a mixing complement.

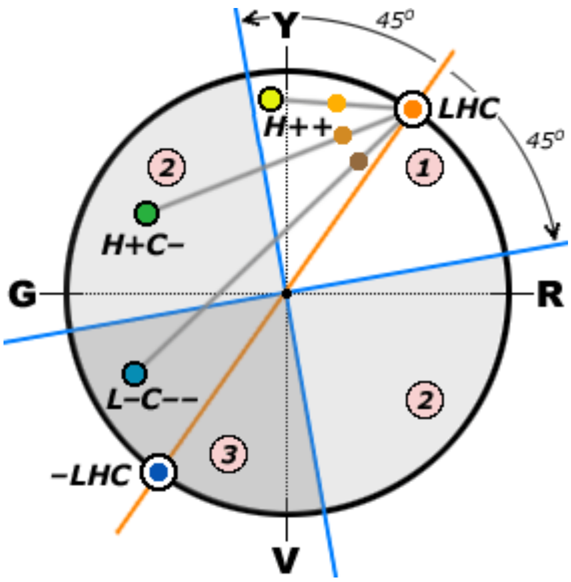
In addition, we have already seen that our freedom to increase or decrease the lightness of a hue depends on its hue and chroma (http://www.handprint.com/HP/WCL/color18a.html#chromainhue): saturated colors cannot be lightened or darkened without also reducing their chroma, and some hues are "inherently" dark (violet) or light (yellow) at even moderately high chroma, and must be made less saturated to move them into a larger lightness range.

In watercolors, any color change is implemented in one of two ways:

by **mixing** the two paint colors together, either by *physically mixing* the paints (completely dispersing them as a single liquid mixture); or by *mingling* the color, for example by picking up separate dissolved paint colors with the same brush and applying them without mixing to the paper; or by applying first one paint color to the area to be covered, then *dropping in* or adding the second paint color to it, before the first paint application has dried.

by **glazing** one paint color over another, after the first (underlying) paint layer has *completely* dried. In general, the glazed or overlaid paint layer produces a larger or more satisfying color shift when the darker paint is applied over the lighter paint, the cooler paint over the warmer paint, the more saturated paint over the less saturated paint, the transparent paint over the opaque paint, and the finely divided paint over the granulating or sedimentary paint.

As the painter usually only has a dozen or so paints to work with, the combined changes in hue, chroma and lightness have to be judged in any mixture. The diagram below shows the basic pattern of these combined changes.



simultaneous color changes across hue circle mixing distances

For any specific color we want to change (the **change color**, shown as **LHC**) above, the mixing complement of that color (**LHC**) is approximately opposite it on the hue circle.

If we then define a quadrant centered on the change color and extending 45° of the hue circle on either side, then we can divide the hue circle into quarters: the *analogous quadrant* (**1**), the *complementary quadrant* (**3**), and the *bridge quadrants* (**2**). Then:

Mixing the change color with any other saturated paint in its analogous quadrant (**1**) generally shifts the hue with little effect on the chroma (**H++**). The direction and amount of lightness change is determined by the lightness of the second paint and how much of it is added to the change color.

Mixing the change color with any saturated paint in either of the two bridging quadrants of the hue circle (**2**) will moderately shift its hue and reduce its chroma (**H+C**).

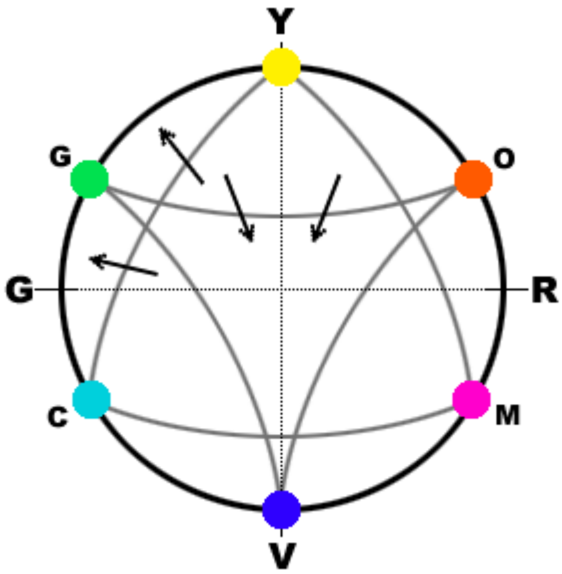
Mixing the change color with any paint in the complementary quadrant of the hue circle (**3**) will have little effect on the hue but will have a dramatic effect on the chroma (**C**) and also disproportionately reduce the lightness (**L**) as well, after taking into account the shift that would occur based only on the lightness of the second paint.

Mixing the change color with a significatly *less saturated* paint has the same effect as mixing it with a saturated paint in a farther quadrant. Mixing the change color with an unsaturated paint in the analogous quadrant has a similar effect to mixing the change color with a saturated paint in a bridging quadrant; mixing the change color with an unsaturated paint in a bridging quadrant has a similar effect to mixing it with a saturated paint in the complementary quadrant.

In general, a dark valued and/or unsaturated paint will have mixing complements across a wider range of hues than a light valued or saturated paint.

These guidelines apply to any change color, regardless of its hue or whether it is a "primary" color or not. The orange complementary line can be rotated like a compass needle, and blue quadrant lines with it, and the same relationships apply.

The diagram (above) shows the mixing lines from **LHC** as straight lines, but we have already found that this is not generally true of a gamut space. The mixing space quirks that produce curved mixing lines (http://www.handprint.com/HP/WCL/color15.html#mixlines) need to be taken into account when anticipating the effect of color mixtures on adjusted color.



curved mixing lines around a subtractive gamut

As a rule of thumb, mixing lines between the **subtractive primaries** (*magenta, yellow* or *cyan*) tend to bow outward: they produce a *smaller chroma loss* than would be expected by the distance between them on the hue circle. This is because subtractive cyan and yellow colorants have high lightness and a broad area (http://www.handprint.com/HP/WCL/color5.html#idealsub) of overlapping "green" reflectance, which sustain the chroma of their mixtures and produce a very large outward bowing in green mixtures (http://www.handprint.com/HP/WCL/color15.html#mixlines). The outward bowing of magenta and yellow mixtures is illusory (the mixing lines are approximately straight in a color space), and occurs because most artists think of *magenta* or *red* as farther from *yellow* than is the case.

Mixing lines between the **additive primaries** (*orange, green* or *violet*) tend to bow inward: they produce a *larger chroma and lightness decrease* than would be expected by the distance between them on the hue circle. This is because most subtractive colorants in these hues have a **narrow area** of high reflectance and, in both orange and violet pigments, are highly saturated. This means the areas of high reflectance do not overlap when the paints are mixed, which subdues the chroma of their mixtures. In addition, the inward bowing of mixing lines between *yellow green* and *yellow orange* occurs because unsaturated yellows appear excessively darkened or dull.

41. Saturation costs are not equal across equal spans of a visual hue circle; they vary because of quirks in human color vision and in the material attributes of different paint colors.

The "Color" Is in the Mixtures. Experienced painters work with this intuitive rule: **the *material* color of paints appears in their mixtures**. This puts the value of a paint predominantly on the **mixture colors** that a paint produces with all other paints on the palette, and not on the color appearance of the paint in its pure form. In particular, artists pay attention to the *chroma and lightness* of paints, not just their hues whether they are intense or dull, light or dark. They learn, by trial and error, how the paints behave when they are diluted, and mixed with every other paint on the palette, and they prefer paints that are versatile, rather than pretty by themselves.

42. The usefulness of a palette primary lies in the complete range of mixture colors it can make with all other paints on the palette.

So we now have to consider the material qualities of paints, and how painters evaluate them in their work. This requires a clear and reliable way to *talk about color* in paints.

talking about paints

There is an astonishing culture of imprecision and metaphor in the way artists are taught to speak and commonly do speak about their paints and inks. This culture of vagueness means that painters do not really understand how their paints are made, and what kind of materials create them.

Traditional color theory ignored the distinctions between material, visual and conceptual colors because color was discussed in the abstract: material colors were subordinated to visual color, and visual color was used as an example or token for conceptual color. So cadmium yellow paint would be just one choice among many paints to provide a yellow color, but (because all paint colors are "impure" (http://www.handprint.com/HP/WCL/color18a.html#cterror07)) every paint was only an approximation or substitute for *yellow,* the conceptually pure "primary" yellow.

There were defensible justifications for spurning the material for the conceptual. Most 18th and early 19th century pigments really were "impure" or relatively dull, or would quickly become dull through sunlight exposure; but these problems have been solved by modern saturated, lightfast pigments. The focus on design rules, and the involuntary phenomena of *complementary color contrast,* turned attention toward abstract or perceptual rules of color that had little to do with materials: *yellow* produces a strong contrast with *violet* whether the colors are in oils, watercolors, pastels, colored papers or digital media.

But an unintended effect of this focus was an ignorance of materials, which ultimately limits a painter's ability to choose the right art materials and skillfully control their use. The painter becomes a creature of habit, confused by marketing gimmicks and dependent on lucky discovery to understand how materials behave. There is a better way.

Pigments, Paints & Colors. The first point to clarify is the difference between pigments, paints and "colors" (http://www.handprint.com/HP/WCL/pigmt6.html#colors):

Pigments are either mineral or chemical compounds that do not dissolve in water, or dyes chemically bonded to transparent crystals that do not dissolve in water, as used in art materials (paints, chalks, pencils and inks). (*Dyes* are colorants that dissolve (break down into individual identical molecules) in water and are mixed into or chemically bound to a material to give it color, as used in textiles, leather goods, foods and cosmetics.)

Paints are the gooey substances made by mixing a pigment with a viscous *binder* (such as liquid acrylic resin or gum arabic) and a *solvent* (such as water) that is packaged in a tube and squeezed out for a painting.

"Colors" are either visual sensations (http://www.handprint.com/HP/WCL/color18a.html#threecolors) or the often poetic **marketing names** chosen by the paint manufacturing company to distinguish one tube of paint from all the others in their retail display rack and catalogs.

The situation is complicated by the fact that paints (as well as most inks, pastels and pencils) come in three different types:

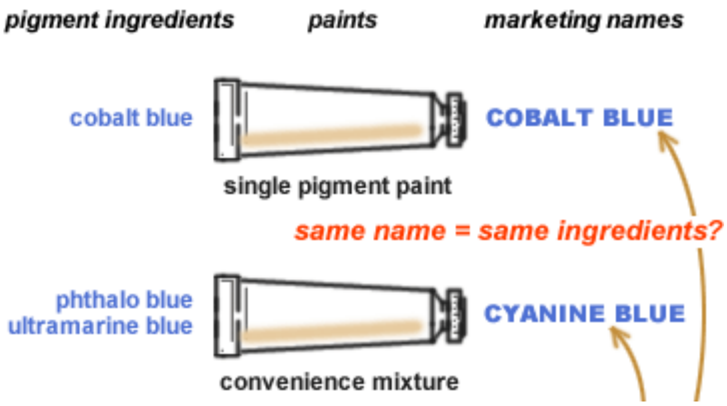
a **single pigment paint** contains only one kind of pigment, mixed with the . The visual color of the paint is entirely due to the visual color of the pigment: you can see the quality of the pigment in the paint color, and all the paint attributes are due to the material qualities of that single pigment, so the behavior of the paint is very predictable.

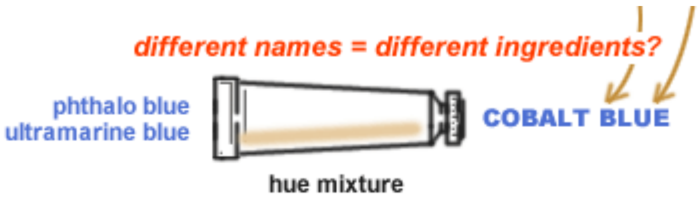
a **convenience mixture** is a paint formulated with two or more different pigments, combined to achieve a specific useful color. The majority of *green, violet* and "earth" (iron oxide) paints are in fact convenience mixtures. These paints are very useful to save the painter the trouble of mixing the color herself; the only drawback is that all the ingredient pigments must be of high quality or the paint color or lightfastness will suffer.

a **hue paint** or hue mixture is a paint containing one or more pigments, formulated to imitate the color of a pigment that is not used because it is impermanent (*alizarin crimson hue*), expensive (*cadmium red hue*), or no longer manufactured (*manganese blue hue*).

As if things were not complicated enough, paint manufacturers have a disorienting preference for historical paint names that describe obsolete pigments.

The diagram (below) illustrates why it is important to clearly distinguish between the pigment, paint and "color" across these three kinds of paints.





the problem with paint marketing names

In this example, two different paints with the same marketing name ("cobalt blue") are made with different ingredients, and only one is made with genuine cobalt blue pigment. In contrast, two paints that are made with exactly the same pigment ingredients have different marketing names, because one is formulated to match a specific visual color ("cyanine blue") while the other is formulated to substitute for an expensive pigment ("cobalt blue").

Color Index Name. The common name for most pigments is often a technical chemical name ... something about benzimidazolone, or quinacridone, or quinophthalone, or thioindigoid ... and a broad term like "arylide yellow" can apply to many different formulations of pigment. We're no longer in that warm and fuzzy realm of poetic paint marketing names.

Painters however can rely on the color index naming system that is standardized, regulated and disseminated by the **Society of Dyers and Colourists**, London (UK), in collaboration with the American Association of Textile Chemists and Colorists (USA).

The **color index name lets you identify pigments** without chemist's jargon. It's a simple code, that consists of:

The letter **P** to denote a pigment (rather than a dye, **D**, or a basic dye, **B**); you will occasionally see **N** to refer to natural pigments such as cochineal, rose madder, gamboge or lapis lazuli

A letter to denote one of ten basic color categories: **R** for red, **O** for orange, **Y** for yellow, **G** for green, **B** for blue, **V** for violet, **Br** for brown, **W** for white, **Bk** for black and **M** for metallic

A number referring to a standard list of pigments within each color category. This number is assigned as a pigment is introduced for commercial use, and may be withdrawn or deleted if the pigment is no longer manufactured.

So PY40 (http://www.handprint.com/HP/WCL/watery.html#PY40) refers to the 40th entry in the list of yellow pigments (aureolin), PO20 (http://www.handprint.com/HP/WCL/watero.html#PO20) to the 20th pigment in the list of oranges (cadmium orange), NR4 (http://www.handprint.com/HP/WCL/waterc.html#NR4) refers to the fourth red listed in the natural pigment list (cochineal).

The color index name and/or constitution number is the **most reliable way to identify paint ingredients**. To help you learn this color naming system which is very easy to use once you get familiar with it all paints in the guide to watercolor pigments (http://www.handprint.com/HP/WCL/waterfs.html), in the complete palette (http://www.handprint.com/HP/WCL/palette1.html), and all pigments mentioned in the text are identified by color index name.

The color index name does not identify a consistent *visual color,* because some chemically equivalent pigments can exist in several forms that create a different color. Some important examples: **cadmium yellow** (PY35 (http://www.handprint.com/HP/WCL/watery.html#PY35)) can be anything from a lemon yellow to a near orange, **cadmium red** (PR108 (http://www.handprint.com/HP/WCL/waterr.html#PR108)) can range from a scarlet red to a dark maroon, **natural iron oxide** (PBr7 (http://www.handprint.com/HP/WCL/watere.html#PBr7)) can be anything from a dull yellow or orange to a brownish black, **quinacridone violet** (PV19 (http://www.handprint.com/HP/WCL/waterc.html#PV19R)) can be a bright red, dull carmine, bright rose, or dark reddish violet, **cobalt turquoise** (PB36 (http://www.handprint.com/HP/WCL/waterb.html#PB36)) can be a cerulean blue or a dull turquoise green, and **cobalt titanate green** (PG50 (http://www.handprint.com/HP/WCL/waterg.html#PG50)) can range from a pale bright turquoise to a dull yellowish green. These variations within the same CI name are produced through adustments in the manufacturing methods (especially in the amount of time the pigment is calcinated and in the extent or method of grinding into fine particles) or through variations in the the proportions of pigment ingredients or in the structure of the pigment crystal.

Even with these exceptions, the color index naming system is very useful. A look at some commercially available green paints (http://www.handprint.com/HP/WCL/waterg.html#convenience) will show you immediately how the color index names are much superior to the manufacturers' **marketing names** if you want to find out the actual ingredients and **paint colors** involved in your paint selection:

what's in a paint name? *marketer's paint nameingredients (color index names)paint color* bamboo greenPG36 (http://www.handprint.com/HP/WCL/waterg.html#PG36) cupric green lightPG36 (http://www.handprint.com/HP/WCL/waterg.html#PG36) winsor green YSPG36 (http://www.handprint.com/HP/WCL/waterg.html#PG36) bright greenPG36 (http://www.handprint.com/HP/WCL/waterg.html#PG36) sap greenPG7+PY150 (http://www.handprint.com/HP/WCL/waterg.html#PG7) sap greenPG36+PO49 (http://www.handprint.com/HP/WCL/waterg.html#PG36) hooker's greenPG36+PO49 (http://www.handprint.com/HP/WCL/waterg.html#PG36) emerald greenPG7+PY175+PW4 (http://www.handprint.com/HP/WCL/waterg.html#PG7) emerald greenPG18 (http://www.handprint.com/HP/WCL/waterg.html#PG18)

The first four greens are made of exactly the same pigment, and will look almost identical on the paper, even though they have completely different marketing names. None of these manufacturer labels refers to the pigment's common name (phthalocyanine green).

The next three greens are mixtures of two pigments: the first two paints have different ingredients even though the marketing names and visual paint colors are the same; the last two paints have the same ingredients (in different proportions), but the marketing names (and paint colors) are different. Without the color index names you couldn't sort this out.

The last two examples show two paints with the same name: the CI name shows that one is made of three ingredients (and is a *hue mixture*) and the other is a single pigment that most paint manufacturer call by its common name, *viridian*. (*Vert émeraude* is the common name for viridian in France.) You also can verify that neither paint contains a speck of the historical pigment *emerald green*, PG21, the poisonous copper acetoarsenite.

Labeling standards formulated by ASTM International (http://www.astm.org/) require the paint label or wrapper to list the CI name and common name of the pigment ingredients, as well as the pigment's ASTM or manufacturer . Paint marketing names are unregulated and completely untrustworthy, so **always use the color index name** on the packaging to see what you are buying.

All reputable paint manufacturers provide the ASTM standard information. If you encounter a paint brand that does not provide this industry standard information on the paint packaging and in the brochure, you have a simple remedy **don't buy the paint!**

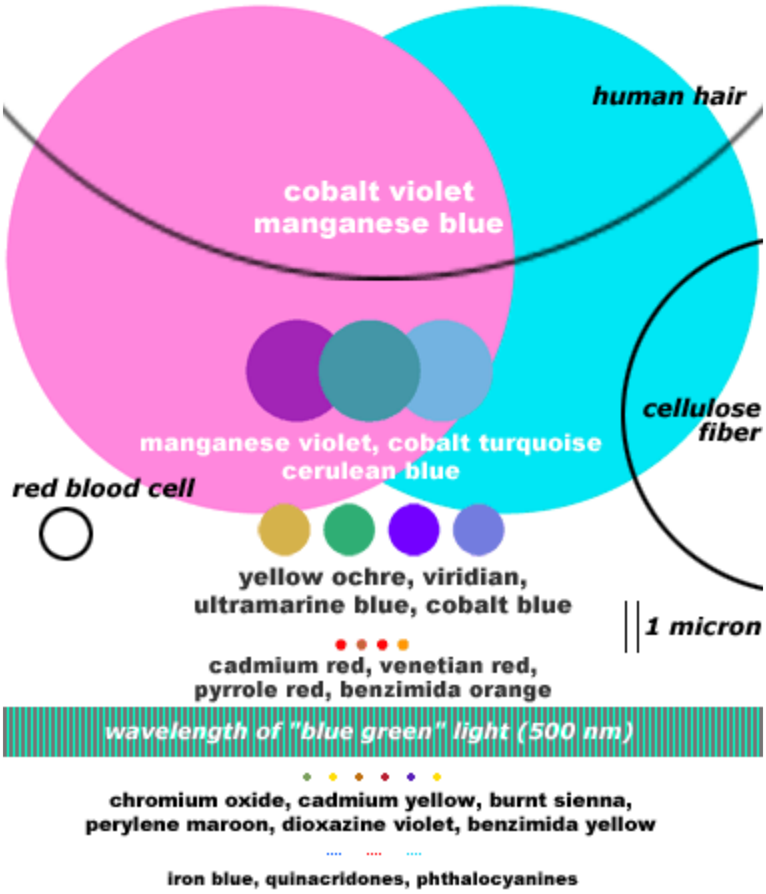
The Six Pigment Attributes. The following six physical characteristics of watercolor pigments color appearance, particle size, tinting strength, transparency/hiding, specific gravity, lightfastness are the most important for painters to understand. They are discussed on the page on the material attributes of paints (http://www.handprint.com/HP/WCL/pigmt3.html).

1. Color Appearance. Obviously, the most important pigment attribute is its color its lightness, hue and chroma (http://www.handprint.com/HP/WCL/color18a.html#colormakingattributes) when displayed in a standard preparation. Usually the pigment is *dispersed* in a clear vehicle or medium, then *mechnically applied* to a support such as filter paper, watercolor paper, board or canvas.

The color attributes of all pigments currently offered by the major brands of watercolor paint are listed in the guide to watercolor pigments (http://www.handprint.com/HP/WCL/waterfs.html). All the pigments are listed within the 18 major hue categories (http://www.handprint.com/HP/WCL/color18a.html#huecategories), plus four *earth color* categories and the achromatic categories *white, gray, dark shade* and *black,* in the page the complete palette (http://www.handprint.com/HP/WCL/palette1.html).

2. Pigment Particle Size. The single pigment attribute that has the greatest impact on all the pigment attributes that matter to a painter is particle size (http://www.handprint.com/HP/WCL/pigmt3.html#particlesize). This means the *average* size across all pigment particles, since pigments (like beach sand or river rocks) are not all exactly the same size although most synthetic inorganic (http://www.handprint.com/HP/WCL/pigmt1b.html) and synthetic organic (http://www.handprint.com/HP/WCL/pigmt1d.html) pigments can (for a price) be manufactured to very limited size tolerances.

Traditional watercolor painters prized *granulation,* or the visible grainy texture of the paint, in certain mineral pigments used in large particle sizes, especially the cobalt (http://www.handprint.com/HP/WCL/pigmt1b.html#cobalt) and some iron oxide (http://www.handprint.com/HP/WCL/pigmt1b.html#iron) pigments. The visually similar attribute of *flocculation,* or the appearance of clumping or mottling in dried paint such as ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)) or magnetic black (PBk11 (http://www.handprint.com/HP/WCL/waterw.html#PBk11)), is due to a slight electrostatic or magnetic attraction among large pigment particles applied as a juicy brushstroke of diluted paint. But these effects characterize pigments at the very large end of the particle size range (pigments manufactured as ceramic or cement colorants), as shown in the schematic (below).



comparative particle sizes of common watercolor pigments

1µm (micron) = 1,000th of a millimeter; diameter of human hair, cellulose fiber and red blood cell, and width of 1 micron and 500 nm, inserted for scale. **Note:** most pigments clump into agglomerations or aggregates that can be many times larger than individual particles

Mineral pigments often shatter into a large range of particle sizes, especially in coarse grades; and synthetic pigment particles may clump into *agglomerations* or *aggregates* that are larger than the individual particle sizes shown here (images, below). And pigment manufacturers must serve many different end user requirements, so paint manufacturers can choose pigments in a variety of particle sizes, crystal forms or laking substrates. Nevertheless, most pigments used in modern watercolor paints are now at or below 1 micron in average diameter.

Painters will recognize that many of the "opaque", nonstaining, dull, weakly tinting and inert pigments will have large particle sizes, and many of the "transparent", staining, highly saturated, strongly tinting, and actively diffusing pigments have small particle sizes.

This is because making pigment particles smaller increases the surface area (http://www.handprint.com/HP/WCL/pigmt3.html#surfacearea) in the same volume or weight of pigment material, and this increased surface area increases the surface scattering (http://www.handprint.com/HP/WCL/color18a.html#WCK) of the pigment. This increased surface scattering is why ice appears transparent and colorless, but snow appears opaque and white. So if the pigment is too dull, dividing it into smaller particles will make it whiter, and scattering will overwhelm the pigment color. Dull pigments must be used in coarser grades.

Dividing the pigment into smaller particle sizes also increases the surface area of pigment that can absorb light, so in general pigments with smaller particle sizes have a higher *tinting strength* that offsets the increased scattering; they are often more *transparent;* and because they are more exposed to light, they may also be less *lightfast*.

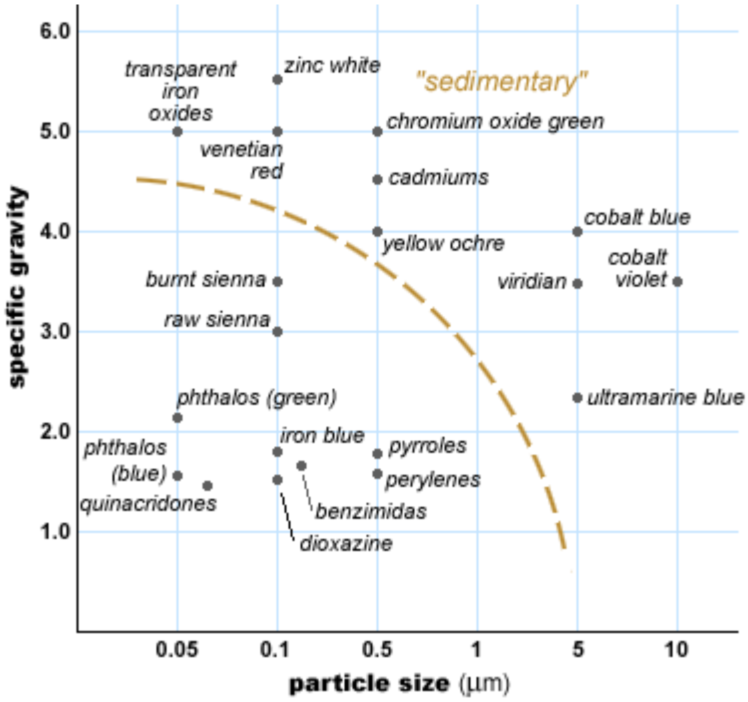
3. Tinting Strength. The depth or intensity of color imparted to a standard quantity of colorless medium either a standard quantity of white paint or a standard volume of water by a standard quantity of pure pigment is the tinting strength (http://www.handprint.com/HP/WCL/pigmt3.html#tinting) of the pigment. The higher the tinting strength, the darker or more saturated will be the color of the tinted medium.

Strongly tinting pigments generally have small particle sizes, and this characterizes most modern synthetic pigments used by watercolor paint manufacturers, as pigment manufacterers make smaller particle sizes that can be used across a wider range of manufacturing applications.

Pigment tinting strength is a very desirable pigment attribute. Watercolor painters are aware of tinting strength as differences in the quantity of paint required in paint mixtures. Cerulean blue has a low tinting strength, ultramarine blue or cobalt blue a moderate tinting strength, and phthalo blue or iron blue a high tinting strength. However, painters can only assess , as paint manufacturers vary the quantity of pigment in a paint to minimize the differences in the tinting strength of the pigments.

4. Specific Gravity. Specific gravity is the weight of a solid material in comparison to the weight of an equal volume of water. Watercolorists become aware of specific gravity when they discover that dilute solutions of some pigments in particular the cobalts, chromiums and cadmiums need to be stirred each time the brush is charged with more paint. Many watercolorists categorize these paints as **sedimentary**, which seems to mean that the pigment is very dense or very heavy, or both.

The smallest particles of heavy pigments can remain suspended in solution, like motes of dust in the air, because of the continuous jostling of water molecules. So the "sedimentary" pigment attribute depends on the combined effects of specific gravity and particle size, as shown in the diagram.



the variety in "sedimentary" paints

The mostly synthetic organic pigments (but including iron blue and carbon black) that have *both* small particle size and low specific gravity are close to the weight of water; they also are very small, which means the movement of water molecules can jostle them afloat longer.

The "sedimentary" pigments are *either* very heavy (high specific gravity) or very large, or both. Many of these pigments have a relatively low , so the (pigment density) must be increased to produce a satisfactory color concentration.

Note that some generic "earth" pigments (yellow ochre, venetian red) are "sedimentary" while others (raw sienna) are not. Burnt sienna and raw umber in particular can be either "sedimentary" or "transparent" depending on brand; the "sedimentary" paints contain pigments with larger particle size or lower tinting strength.

These differences in combined specific gravity and particle size appear in a sedimentation test (http://www.handprint.com/HP/WCL/pigmt3.html#sedtest). But watercolor painters encounter them in paint mixtures. A mixture of venetian red and iron blue, or phthalo green and yellow ochre, must be stirred each time the mixture is taken up by the brush, because the two pigments quickly separate in solution.

5. Transparency / Hiding. Traditionalist watercolor painters prize the *transparency* of pigments, which is their term for paints with very low hiding power. Transparency is actually a different paint attribute, one that is also useful for painters to evaluate.

For watercolorists, transparency or low hiding is the "show through" of a color or pattern that is underneath the paint. As all pigments in dry form are opaque powders, low hiding is caused by small pigment particle size and high tinting strength, which means there are fewer and smaller pigment particles on the paper. The "transparency" occurs *between* the pigment particles, not *through* them.

Most color theory tutorials recommend that watercolorists evaluate paint hiding power by painting overlapping stripes in a plaid sequence, so that each paint is painted over itself and both under and over all other paints. In this test the more opaque paint will (1) change color less when painted over itself, and (2) dominate any color it is painted over. In the example at right, the magenta and yellow stripes are painted in numerical order, and the yellow paint is less transparent (more opaque) than the magenta.

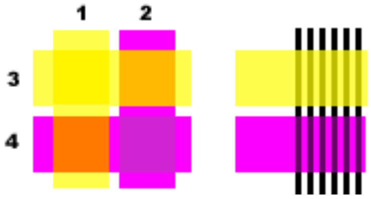
In fact, watercolorists are actually describing the **hiding power** of a pigment, or the thickness of a paint film required to completely mask a black and white pattern on a painted surface. n alternative and more accurate test of hiding power is the degree to which the paint will mask an underlying pattern of black and white lines, such as closely spaced lines drawn on the paper with a black Sharpie indelible marker. Paint hiding will obscure this pattern in comparison to the pattern viewed on unpainted paper, or in comparison to other paints.

The **transparency** of a pigment is degree to which the paint layer disappears when applied over a black surface. This test is especially useful to reveal "white" brighteners (http://www.handprint.com/HP/WCL/pigmt1.html#brightener) or extenders (http://www.handprint.com/HP/WCL/pigmt1.html#fillers) in paints.

black paper comparison of eleven brands of quinacridone paint

(top, left to right): M. Graham quinacridone rose (PV19), Winsor & Newton quinacridone magenta (PR122), Daniel Smith quinacridone magenta (PR202), Holbein rose violet (PR122), Schmincke purple magenta (PR122); (center): Da Vinci alizarin crimson hue, Da Vinci quinacridone carmine; (bottom, left to right): Old Holland magenta (PR122), Rowney Artists quinacridone magenta (PR122), MaimeriBlu verzino violet (PR122), Sennelier quinacridone purple (PR122)

The illustration shows black field samples for common quinacridone paints on a heavy black bristol (matt board). The "white" additives in the Rowney Artists and Sennelier paints are glaringly obvious brilliant when viewed in sunlight. On acrylic, the Sennelier ingredients were grainy, like superfine sugar crystals, and rubbed off when touched. The Daniel Smith, Old Holland, Schmincke and MaimeriBlu paints showed the least opaque discoloration and had the darkest dried color, and hence are the most transparent of the group.



evaluation of paint hiding power

applying one paint over another is less accurate than applying a single paint over a black/white pattern

evaluation of paint transparency

a completely transparent paint will seem to disappear on a black ground

For all pigments, the "transparency" of a paint is increased by *diluting with water:* the greater the proportion of water to paint in a mixture, the more transparent the finished color will be. This is why the watercolorist's transparency is usually greater for pigments with higher tinting strength: the paint produces a powerful color at a higher dilution.

6. Lightfastness. The ability of a paint under prolonged light exposure to retain its color appearance without fading or darkening is its **lightfastness**. (*Colorfastness* is the resistance of a fabric dye to fading or bleeding when exposed to water, bleach or detergents.)

Pigment lightfastness is critical in the choice of watercolor paints, because watercolor paints applied to paper do not form a paint layer, as acrylic or oil paints do, that can block fading ultraviolet light from degrading the pigments. All watercolor painters should know the basic logic and methods of a paint lightfastness test (http://www.handprint.com/HP/WCL/pigmt9.html), and test their choice of paints for *impermanent* or *fugitive* pigments.

Using impermanent materials erodes the market reputation and value of watercolor paintings for all painters, and betrays a cynical indifference to the good will of your buyers.

examples of common watercolor lightfastness issues

(top row) alizarin crimson (PR83), rose madder genuine (NR9), naphthol red (PR170), naples yellow hue (+PW4), rhodamine violet (PV1); *(bottom row)* potassium cobaltinitrite (PY40), convenience green mixture, bismuth yellow

(PY184), quinacridone magenta (PR122), dioxazine violet (PV23)

The samples (above) illustrate the undesirable pigments that watercolor painters will most often find recommended in art tutorials and offered by commercial watercolor brands:

premodern pigments that are widely known to be fugitive (alizarin crimson, PR83 (http://www.handprint.com/HP/WCL/waterr.html#PR83) and rose madder genuine, NR9 (http://www.handprint.com/HP/WCL/waterc.html#NR9))

naphthol pigments, many of which are fugitive (permanent red, PR170 (http://www.handprint.com/HP/WCL/waterr.html#PR170))

whitened paints that are formulated with a white pigment, such as most naples yellow (http://www.handprint.com/HP/WCL/watery.html#naples) hue mixtures

"brilliant" paints or fluorescent paints containing dyes, such as rhodamine violet (PV1 (http://www.handprint.com/HP/WCL/waterv.html#PV1)) or holbein's "opera"

aureolin, the pigment potassium cobaltinitrite (PY40 (http://www.handprint.com/HP/WCL/watery.html#PY40))

green convenience mixtures made with an unreliable yellow pigment (such as this sap green, PG7 (http://www.handprint.com/HP/WCL/waterg.html#convenience)) or with yellow and green pigments that fade unevenly.

The illustration includes three examples of the unreliability of published paint lightfastness ratings, including paint manufacturer and ASTM lightfastness ratings, as an assurance of paint lightfastness.

The first example shows a watercolor made with **bismuth yellow** (PY184 (http://www.handprint.com/HP/WCL/watery.html#PY184)), which is very permanent in lightfastness tests but here has discolored for some reason, possibly contamination with impurities during manufacture.

The last two examples show pigments routinely condemned as impermanent in published paint guides, but which in my lightfastness tests have either proved to be consistently lightfast (**quinacridone magenta**, PR122 (http://www.handprint.com/HP/WCL/waterc.html#PR122)) or have turned out lightfast in the paints from some paint manufacturers but not others (**dioxazine violet**, PV23 (http://www.handprint.com/HP/WCL/waterv.html#PV23)).

Lightfast watercolor paints on archival papers are as durable as paintings in oil or acrylic. Contemporary watercolor artists are increasingly careful to **avoid fugitive or impermanent paints** which includes all 19th century organic pigments (alizarin crimson, rose madder, carmine lake) and many convenience (premixed) greens and purples. Mindful of the problems described above, they test their own paints, inks or colored pencils to confirm manufacturer quality standards.

The Six Paint Attributes. Painters do not deal directly with pigments, however, but with the pigments as they are compounded into paints. The following physical characteristics of watercolor paints are discussed on the page how watercolor paints are made (http://www.handprint.com/HP/WCL/pigmt1.html).

1. Backbone Composition. The basic manufacturing template of a watercolor paint is its **backbone composition** the choice of ingredients and their proportions in the paint. The backbone composition is the foundation of the manufacturer's brand style (http://www.handprint.com/HP/WCL/pigmt2.html) and quality standards. It usually consists of most or all of the following ingredients:

One or more **pigments**, in proportions that vary with the particle size, specific gravity and tinting strength of the pigment (larger, heavier and weakly tinting pigments are used in a higher concentration or).

A **brightener**, transparent or "white" crystals that lighten the value and increase the chroma of the dried paint (as clearly visible in the transparency test).

The colorant ingredients are dispersed in a **vehicle** or medium consisting of:

binder, traditionally (since the 17th century) and still today *gum arabic* but, in some brands, a *synthetic glycol;* paints high in binder have a "gummy" or taffylike texture and dry to a rock hard crystal

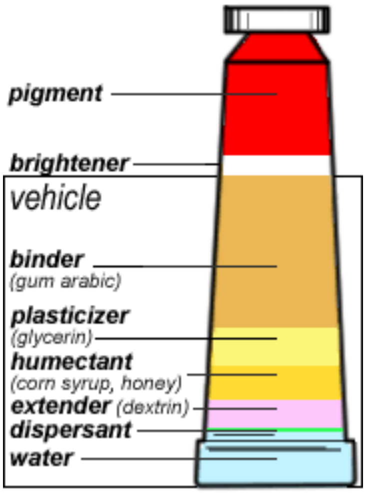
plasticizer, usually *glycerin,* that prevents the dried gum arabic binder from completely crystallizing, and (especially in pan paints) helps the binder dissolve when wetted; paints low in plasticizer will dry to a glassy, hard surface and are slow to dissolve in water; paints high in plasticizer will bleed or lift more easily when rewetted

humectant, traditionally simple syrup or honey but now often *corn syrup,* to help the paint retain mosture (especially in pan paints); paints high in humectant remain "sticky" in pans or paint wells and never seem to dry completely

extender or filler, such as *dextrin,* used to bulk out and thicken the paint without noticeably affecting the color; paints low in extender have a liquid texture; paints high in extender have a dry, "short" or stiff texture, like clay or ointment

manufacturing additives, in particular *dispersants* (to prevent clumping of the raw pigment after manufacture and to speed up the milling of the pigment and vehicle ingredients) and a *fungicide* or preservative to suppress the growth of mold or bacteria; paints milled with dispersants are very active or "shooting" wet in wet, and tend to be more staining

water, which dissolves or suspends all the ingredients, carries them onto the paper, and evaporates when its work is done.



schematic backbone composition of a modern watercolor paint

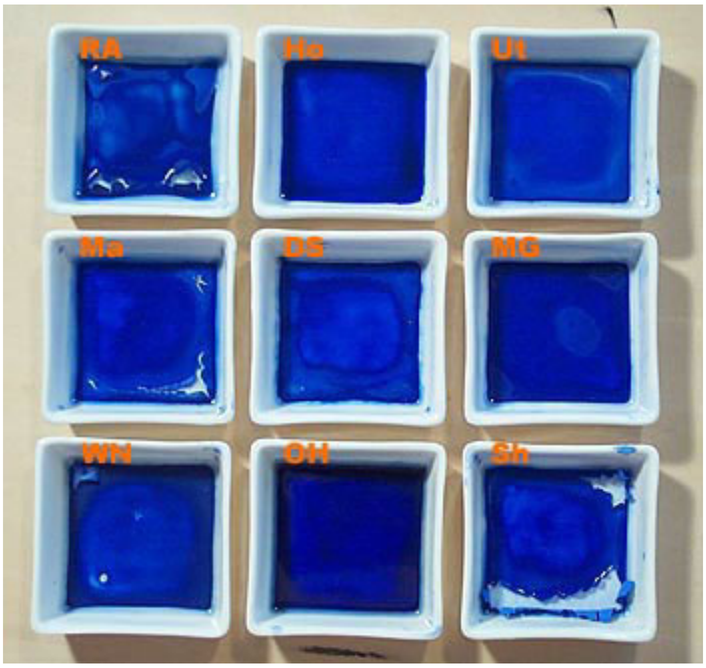
some ingredients will be absent in some brands or "colors", and all ingredients are mixed in different proportions depending on brand style and pigment attributes

These ingredients, and the proportions among them, have different effects on watercolor paints. The best way to understand these effects and evaluate them in commercial paints is to make your own handmade watercolor paints (http://www.handprint.com/HP/WCL/pigmt1.html#handmade).

The only way to identify the ingredients actually used in a paint is a chemical **deformulation analysis**, which can run upwards of $1000 for a single sample.

However I find a very simple and compelling exercise is to run the same pigment color in different brands through this simple sequence:

(1) Measure out an equal quantity of paint (e.g., a level 1/4 teaspoon) into a large, flat bottom mixing cup or large mixing well, and *dissolve completely* in about 2 teaspoons of water. Cover the sample with cloth or wax paper and set aside *undisturbed* to dry completely depending on heat and humidity, this may take 4 to 10 days.



drying comparison of nine brands of cobalt blue

left to right: (top) Rowney Artists, Holbein, Utrecht; (middle), MaimeriBlu, Daniel Smith, M. Graham, (bottom) Winsor & Newton, Old Holland (cobalt blue deep), Schmincke

This gives you some insight into the *paint vehicle*. The photo shows some obvious differences among nine brands of cobalt blue: (1) some (Rowney, MaimeriBlu, Winsor & Newton, Schmincke) show slight to considerable cracking and peeling of the dried paint layer, while others (M. Graham, Old Holland) show the shiny, flat, solid surface of a vehicle high in gum content; (2) some show obvious discoloration or blotching, which implies fillers, brighteners or pigment particles with a wide size variation (smaller particles generally appear duller or whiter, and will also sink out of solution last, forming the top layer).

(2) Next, **rewet the dried samples** with 1 teaspoon clear water, and thoroughly dissolve the pigment in the saucers by mixing for a minute or two with a wet acrylic brush. Some paints redissolve quickly and evenly, while others will break up into coarse particles or flakes, which only slowly dissolve.

(3) Premoisten and blot an area 2" to 3" square on heavy (600GSM or higher) cold pressed, absorbent watercolor paper (not bristol board), and gently pour (do not paint) about half the redissolved paint mixture into the square. The paper should rest on a perfectly level surface where it can be left disturbed to dry completely, which may take 2 or 3 days.

rewetting comparison of nine brands of cobalt blue

left to right: (top) Rowney Artists, Holbein, Utrecht; (middle), MaimeriBlu, Daniel Smith, M. Graham, (bottom) Winsor & Newton, Old Holland (cobalt blue deep), Schmincke. (Image contrast increased and saturation reduced by 10% to enhance surface variations.)

This procedure separates the "dry" contents of the paint, including pigment particles of different sizes, brighteners, and filler. The dried paints have settled out in layers, with the lightest particles on the surface of the paper, while the vehicle has been absorbed into the paper itself. The paint layer is much thicker than you can usually obtain with a brush, so the binding strength of the vehicle is put to a severe test. The paints will display much larger color variations in chroma and lightness, which in the example (above) are much more noticeable in the original samples than in the photograph.

(4) Finally, rub each sample several times with a cotton swab or a finger wrapped in a paper towel. Some of the paints show some pigment rub off this way, while others will yield almost none.

The optimal paints will show the least ruboff, discoloration, splotching, bronzing, flaking or cracking across all tests, and will rewet quickly and smoothly. Paints that do well are most likely to serve your needs across all professional painting techniques and archival standards.

2. Staining. Watercolors characteristically provide the painter with a unique quality of impermanence: most paints can be redissolved by wetting and gently brushing with a stiff bristle synthetic fiber brush, then lifted by blotting the dissolved paint mixture with a paper towel. Staining is a watercolor paint's resistance to removal after it has been applied to paper.

As defined, staining is not an inherent property of a pigment but arises through the combined effects of several pigment, paint and paper attributes:

Pigments with a small average more easily sink or creep into the tiny spaces between paper fibers (http://www.handprint.com/HP/WCL/paper1.html#furnish), where they "stain" because they are embedded too deeply to swab away.

These small or *finely divided* pigments are often milled with a dispersant (http://www.handprint.com/HP/WCL/pigmt1.html#additives) that increases the capillary movement of pigment particles into the paper fibers. Paints made with a high proportion of humectant (http://www.handprint.com/HP/WCL/pigmt1.html#humectants) also tend to penetrate the paper more deeply.

Paints made with a high proportion of gum arabic binder (http://www.handprint.com/HP/WCL/pigmt1.html#binder) tend to hold the paint on the surface of the paper and to surround both pigment particles and paper fibers in a gummy coating that completely redissolves, which makes the pigment easier to remove.

A paper pulp (http://www.handprint.com/HP/WCL/paper1.html#furnish) that has been lightly macerated (http://www.handprint.com/HP/WCL/paper1.html#machinery), or pulp that is made with wood fiber or asian grasses, is far more absorbent than paper pulp made with heavily macerated cotton or linen cellulose, and will stain more.

A heavier surface and/or internal sizing (http://www.handprint.com/HP/WCL/paper1.html#sizing) seals the cellulose fibers from contact with the pigment and closes off more of the spaces between fibers, keeping the pigment particles on the surface.

A smoother paper finish (http://www.handprint.com/HP/WCL/paper1.html#finish) (hot pressed rather than rough) is produced by *calendering* the paper, or pressing it between iron rollers; this compresses the spaces between the paper fibers and reduces the channels along which pigment particles can penetrate deep into the paper. But this also makes hot pressed papers less absorbent, so they often receive a lighter coat of surface sizing, and hot pressed papers still have a surface texture that is many times larger than finely divided pigment particles, so aggressive staining can occur and scraping to remove staining paints can be more obtrusive on the smooth finish.

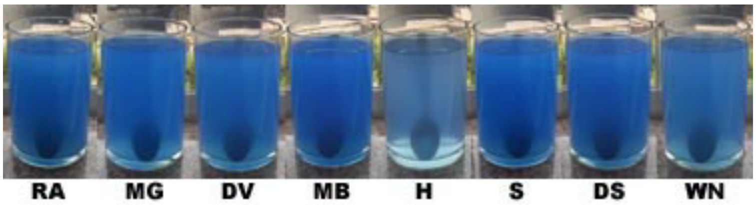
Some watercolor paints stain even more aggressively than typical due to an *electrostatic attraction* between the pigment particles and common painting implements, such as brush hairs, plastic palettes or ceramic mixing dishes. They form a stain that is highly resistant to removal and in extreme cases can only be cleaned from brushes or palettes with a detergent or aromatic solvent. This is typical of several synthetic organic pigments, including dioxazine violet, the phthalocyanines (blue, turquoise or green), many quinacridones, and some pyrrole reds or oranges.

Pigments with no electrostatic charge and large pigment particle sizes lift easily under almost all conditions; these include most cobalt pigments, and most "natural" iron oxide pigments classified as PBr7 (http://www.handprint.com/HP/WCL/watere.html#PBr7) or PY43 (http://www.handprint.com/HP/WCL/watere.html#PY43) (marketed as *yellow ochre, raw sienna, burnt sienna, raw umber* or *burnt umber*).

3. Pigment Load (Tinting Strength). Pigment load is simply the volume or weight of pigment as a proportion of the total volume or weight of the paint.

From a quality perspective, paints with a higher pigment load are almost always more desirable than paints with a low pigment load, up to the point where the pigment density detracts from other paint attributes (especially color, hiding, transparency or diffusion). Thus, most paint manufacturers use less phthalo green than possible, not because the pigment is expensive, but because it is very powerfully tinting and becomes almost unmanageable (and intensely staining of paper and brushes) if used at high concentration. However, most "student" grade paints have a lower pigment load than "professional" paints, so the paints are cheaper to produce but also more difficult to work into very rich color.

Pigment load cannot be assessed by weighing a tube of paint that has been squeezed out in a dish and left to completely dry, since the paint also contains carbohydrates, fillers and the laking substrate used to turn dyes into pigments. Instead pigment load is evaluated with a paint tinting test (http://www.handprint.com/HP/WCL/pigmt3.html#tinttest), by completely dissolving 1/2 teaspoon of paint in a quart of water, as shown below for different brands of cobalt blue.



tinting test solutions of eight brands of cobalt blue

left to right: Rowney Artists, M. Graham, DaVinci, MaimeriBlu, Holbein, Schmincke, Daniel Smith, Winsor & Newton

Cobalt blue is a moderately expensive pigment, especially in art quality grades, so it is often used sparingly or goosed with an unacknowledged phthalo blue. This test shows clear differences across the various paint brands: paints with the highest load of the highest quality pigment will have a rich but transparent color; paints with additives will appear murky, and paints with low quality pigment or low pigment load will appear diluted or weakly colored.

4. Dispersability. A subtle but important pigment attribute is its **dispersability**, or how easily the paint dissolves in water. Highly dispersible paints tend to have a liquid or viscous consistency and disappear almost immediately when mixed with water. Difficult to disperse paints have a gooey or stringy consistency and form a sticky sludge in the paint well that takes a patient brushing to dissolve.

Highly dispersible paints tend to be **active wet in wet**, in part because the paints often contain a dispersant (http://www.handprint.com/HP/WCL/pigmt1.html#additives), which acts exactly like dishwashing soap to loosen, break apart and dissolve the individual pigment particles when the paint is manufactured; and a high proportion of plasticizer and humectant, which prevent the gum arabic from crystallizing and hold water in the paint, even when it is dry.

In watercolors, pigments with tiny particle sizes the phthalos, carbon blacks, iron blue, many earth pigments, alizarin crimson, and many of the semitransparent synthetic organics and larger soft pigments, such as ultramarine blue or the cadmiums, which will cake together under milling pressure, tend to be manufactured with more dispersants. Cheaper paint brands try to save money by rushing the milling process, so the dispersant content tends to be higher and to be used across a wider range of pigments.

Old Holland paints generally, and paints with very large particle sizes and high specific gravity, have a high gum content; in the latter case, because the pigment particles will otherwise sink to the bottom of the tube when paints are hung in retail display racks. This is why tubes of viridian, cobalt violet, ceruleuan blue and similar paints exude a bead of pure gum when they are first opened.

5. Diffusion. *Diffusion,* or the tendency of the paint to expand rapidly when applied to wet paper, is due to very small particle size in paints with low specific gravity, and/or dispersant in the paint.

The tendency of the paint to form a *backrun* when rewetted after it has partially dried, is enhanced by small particle size in paints that have low specific gravity, and therefore are easily moved by capillary action when water or paint are added to paper that has dried to a satin wetness (http://www.handprint.com/HP/WCL/wet1.html#3).

6. Gloss. Gloss is the geometrical diffusion in the surface reflectivity of the paint. Matte paints will reflect incident light equally in all directions; gloss paints will reflect incident light primarily in a single direction, like a mirror.

Gloss is only a feature of watercolor paints when (1) the paint vehicle contains a large proportion of binder, and (2) the paint has been applied thickly, or in successive layers, so that the paper pulp is completely saturated with binder and the excess is deposited as a puddle or scum on the surface. This produces a blotching or blackening of the color called **bronzing**, and is undesirable.

many painter's palettes

Painters who have reached this stage of color comprehension often crystallize their understanding of color and paint mixture as a *personal palette,* which in fact comprises four different judgments: (1) choice of a physical implement, typically plastic or metal, for displaying the paints to the brush; (2) a specific choice of paints, by brand, pigment or "color"; (3) a specific arrangement of the paints on the palette (for example, in color wheel order, or with transparent and saturated paints on one side and opaque or "earth" paints on the other); and (4) an overall color style or color space (muted or colorful) which usually implies a color mixing strategy (using many pure paints, or a few "primary" paints).

(The *Grammar Police* have asked me to explain that a **pallet** is a shipping platform or a humble bed; a **palate** is the roof of a mouth; a **palette** is the flat implement used to hold and mix paints and the selection of paint colors or the color scheme used by the painter.)

Palette Gimcrackery. Welcome dear friends to the wonderful world of expensively priced and cheaply manufactured artists' painting implements (http://www.handprint.com/HP/WCL/tech14.html#palettes)! We have plastic palettes and metal palettes, sturdy palettes and flimsy palettes, round palettes, square palettes, tray palettes, dish palettes, deep palettes, shallow palettes, palettes with snap on lids that do or do not prevent paint evaporation, palettes with individual snap on caps over each paint well, palettes with wide paint wells, shallow paint wells, palettes that fit into your pocket or overstuff your backpack ... palettes, yes we have palettes!

All these implements are generally white (to allow accurate judgment of mixture colors) and are made of plastic or enameled metal. They consist of some combination of three features:

paint wells, separate enclosures, usually arranged in a row or a circle, designed to hold a single color of paint

mixing wells, shallow depressions several inches across in which dilute paint solutions (wash mixtures) can be blended

mixing areas, flat surfaces on which paint can be squeezed, puddled, stirred and blended.

There is a great variety in the dimensions, layout, geometry, capacity, sturdiness, resistance to staining and working convenience of these implements. It's clarifying to evaluate the three features separately, in terms of the number of paints you normally use, the size of your brushes, the volume and types of color mixtures you like to develop, and your painting area and working practices. (Are you more likely to confuse paint colors, or spill paint mixtures?)

There is a lot to be said for consistency and order and neatness, but I don't find a lot to like in most retail offerings. My guidance is to be patient about adopting new products, and do so only after you are clear about the features you value the most. Otherwise you will soon have a collection of a dozen or more different palettes, all filled with dried out paint, that encumber your studio shelves and painting momentum.

As I explain in the section life without a palette (http://www.handprint.com/HP/WCL/tech14.html#nopalette), I can enthusiastically recommend that you forego any palette commitment and instead store and mix tube paints in separate porcelain containers, commonly sold as condiment dishes (image, right).

I currently store and use about 50 separate paints in this way, have done so for 10 years, and have had no problems with paints deteriorating or molding in any way. In general the higher the quality of paint, the more happily it adapts to this "pan" storage; and they eliminate all the color searching, cap sticking, paint thickening and tube wringing inconvenience of tube paints.

The major advantage is that I am not locked into a specific palette implement or paint selection. I choose paints as I need them for a specific painting, and mix them in empty condiment dishes or cups. A dozen or so paints are more useful than the rest, but I am not restricted to a single palette selection and bypass the chore of "refreshing" the paints from the tube. The freedom and convenience are most welcome.

Paint Arrangement. If an orderly arrangement of paints in a series of paint wells is helpful to you, you will quickly discover the arrangement most suitable to the number of paints and palette that you use. Just arrange the *tubes* of paint in various ways until you find the happiest solution. Then squeeze the paints into the paint wells.

The Four Palette Limitations. Finally there is the color selection, the number of paints the painter will have on his or her palette, and the choice of colors within that limited number.

Four Palette Limitations. Your confidence in color selection will be greatly enhanced if you first understand the **four fundamental palette limitations** that a painter encounters in almost any limited selection of paints:

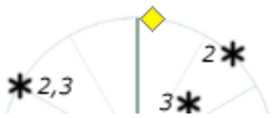
limited value range the palette primaries may not be able to produce a neutral mixture that is visually indistinguishable from black, so that all other color mixtures can achieve deep, dark shades.

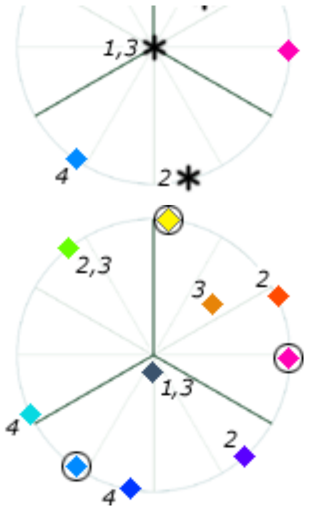
limited chroma the palette primaries may not be able to reproduce all hues at a relatively high or equally balanced chroma; typically the hues between two palette primaries will have a significantly restricted chroma range, due to saturation costs.

color mixing inconvenience it may be necessary to mix two or more palette primaries in order to obtain a color that is used frequently or in large quantities in an image (such as green, in landscape or botanical work).

pigment monotony the pigments of the palette primaries may all be too similar on their physical attributes, in particular on particle size, diffusion and transparency; this is a drawback if pigment texture or semitransparent color mixtures are important to the image.

A comparison of the relatively limited primary triad palette (three paints in colors yellow, magenta, blue) with the palette of 10 paints used by painter Chuck Long (http://www.handprint.com/HP/WCL/palette4f.html) illustrates the common solutions that artists find for these four limitations.





solving the four fundamental palette limitations in
the "primary" triad palette

1. limited value range. At the neutral center of the color space, the primary triad palette will mix what is not always an adequate dark gray [**1**], and at considerable inconvenience [**3**]. In most printing applications, the triad is supplemented by a carbon black ink; the extra printing plate and press run is justified by the significantly improved value range and chromatic balance of the image.

Long adds a cool, dark neutral paint (the convenience mixture *payne's gray*) which is one of a group of paints (including *indigo*, *sepia* and *neutral tint*) that are made with **carbon black** (PBk6 (http://www.handprint.com/HP/WCL/waterw.html#PBk6) or PBk7 (http://www.handprint.com/HP/WCL/waterw.html#PBk7)) tinted with a green, blue, violet or brown paint. All these paints provide a near black; but the cool, violet or blue tinted paints are also useful as a shadow color; strongly diluted, they can render cool, veiled skies or water. (Oil and acrylic painters additionally have to add a white paint to their palette, to complete the value range at the high end.)

2. limited chroma. The primary triad palette does not mix all hues with comparable saturation; mixed orange, violet and green hues are always much duller than the primary triad paints, often objectionably so [**2**].

To remedy this, Long adds a green convenience mixture, a violet, and an intense scarlet paint. Now the dullest mixtures are approximately halfway between these six palette primaries, and saturation costs are much reduced.

3. mixing convenience. Even though an expanded gamut is the basic goal, it is tedious to mix daily or in large quantities colors that must be used frequently. This is especially an issue with muted yellows and browns, with foliage greens, and with dark neutral mixtures [**3**]. Paints labeled *sap green* (and similar convenience greens (http://www.handprint.com/HP/WCL/waterg.html#convenience) such as *hooker's green, permanent green* or *olive green*) provides a generic dark, dull green that is easily modified by the addition of *any other paint* on the palette to conveniently produce a large and convincing variety of green colors. The many "earth" pigments (http://www.handprint.com/HP/WCL/earthp.html) (iron oxides) provide muted yellows, oranges and reds. The *dark shade* paints mixed with carbon black (marketed as *sepia, indigo, payne's gray, neutral tint, lamp black* or *ivory black*) provide a ready black.

4. pigment monotony. Although pigment variety has been intentionally suppressed in most contemporary watercolor brands, many painters rely on coarsely divided pigments for wet in wet granulation or flocculation. The traditional reserve of these effects has been "cool" pigments, including cobalts (cobalt violet PV14 (http://www.handprint.com/HP/WCL/waterv.html#PV14), cobalt blue PB28 (http://www.handprint.com/HP/WCL/waterb.html#PB28), cerulean blue PB35 (http://www.handprint.com/HP/WCL/waterb.html#PB35) or cobalt turquoise PB36 (http://www.handprint.com/HP/WCL/waterb.html#PB36)), ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)), iron blue (PB27 (http://www.handprint.com/HP/WCL/waterb.html#PB27)), viridian (PG18 (http://www.handprint.com/HP/WCL/waterg.html#PG18)), but also including many synthetic or "transparent" iron oxides (PR101 (http://www.handprint.com/HP/WCL/watere.html#PR101)); diffusion effects are enhanced through the use of highly reactive paints. These add fleecy or grainy textures, and wet in wet effects of diffusion and backruns, that emerge in wash areas and diluted color mixtures.

Other pigment attributes transparency, staining, tinting strength and lightfastness in particular are also important to many painters, and most professional palettes include some paints chosen for their specific pigment attributes separate from their inherent color or impact on the mixing gamut.

Common Palette Designs. Painters are quite specific about their choices of paints. These choices represent their preferences for the pigment characteristics found in specific colors of specific brands of paint.

I review the major commercial watercolor brands (http://www.handprint.com/HP/WCL/pigmt2.html) on another page. In this section I will briefly describe the major considerations behind the palette design (http://www.handprint.com/HP/WCL/paletfs.html) expressed in the paint selection from the use of a single paint color to palettes of two dozen or more paints.

tube paints stored as "pan paints" in porcelain condiment dishes

Monochrome Palettes. The most common of these is the value design palette (http://www.handprint.com/HP/WCL/palette4a.html) consisting of a single black or dark neutral paint (palette scheme, right).

A monochrome palette is limited only to the achromatic series black, grays and white produced by vine, ivory or lamp black diluted with water and applied to pale or white paper. (India ink can be used in the same way as black watercolor.) By eliminating color, and using a dark paint with little or no pigment texture, the artist must focus on two key design elements: value structure and brushwork (brushed texture). For this reason it is typically called a **value design palette** by artists, because it puts the focus on the value composition (http://www.handprint.com/HP/WCL/tech12.html#valuesketch) of a painting, and emphasizes the reproduction of light and atmosphere through value contrasts alone. And without color to distinguish among objects, brush technique becomes much more important. Precise edges, perfectly graded shadows, diverse brush marks (including drybrush), and the texturing effects of blooms, blotting, washes and resists are all displayed more dramatically.

An important variation on the monochrome palette is black paint with a chromatic paint, which produces a broad contrast in the chroma of color mixtures within a very narrow hue range (palette scheme, right). This is the *harmony of scale* that the 19th century color theorist Michel-Eugène Chevreul (http://www.handprint.com/HP/WCL/book3.html#chevreulharmonies) included among his six color harmonies.

The most popular strategy is to combine either a lamp or ivory black, or the convenience dark shade *sepia*, with one or more red or orange "earth" pigments, such as **burnt umber** (PBr7 (http://www.handprint.com/HP/WCL/watere.html#BU)), **burnt sienna** (PBr7 (http://www.handprint.com/HP/WCL/watere.html#BS) or PR101 (http://www.handprint.com/HP/WCL/watere.html#PR101)) or **venetian red** (PR101 (http://www.handprint.com/HP/WCL/watere.html#PR101)), or any iron oxide paint labeled *transparent brown, red, or orange*. If these paints are used on tinted or colored papers, then a white paint such as **titanium white** (PW6 (http://www.handprint.com/HP/WCL/waterw.html#PW6)) can be added as well (palette diagram, left). This selection of paints mimics the basic color world of *sanguine chalk* drawings (popular since the Renaissance) and the color variation found in Conté crayons (http://en.wikipedia.org/wiki/Cont%C3%A9). This palette is very effective in portrait work, and dramatic when used with a harmonizing or contrasting tint of paper. (In lieu of tinted paper, a white paper can be prepared with a wash of very diluted paint.) The hue range can be expanded by adding a yellow orange iron oxide (**gold ochre**, PY42 (http://www.handprint.com/HP/WCL/watere.html#PY42)), but in general a distinct yellow hue detracts from the effect.

two monochrome palettes

(top) value design palette; (bottom) sepia tone palette

"Primary" Color Palettes. These palettes consist of three paints corresponding to the three subtractive "primary" colors: *violet red* (magenta), *yellow* and *green blue* (cyan). The common recommendations (palette scheme, right) are:

violet red (http://www.handprint.com/HP/WCL/palette1.html#violetred): quinacridone magenta (PR122 (http://www.handprint.com/HP/WCL/waterc.html#PR122)) or quinacridone rose (PV19 (http://www.handprint.com/HP/WCL/waterc.html#PV19R)).

yellow (http://www.handprint.com/HP/WCL/palette1.html#yellow): benzimida yellow (PY154 (http://www.handprint.com/HP/WCL/watery.html#PY154)) or hansa yellow (PY97 (http://www.handprint.com/HP/WCL/watery.html#PY97)).

green blue (http://www.handprint.com/HP/WCL/palette1.html#greenblue): phthalo blue GS (PB15 (http://www.handprint.com/HP/WCL/waterb.html#PB15)) or cerulean blue (PB35 (http://www.handprint.com/HP/WCL/waterb.html#PB35)).

As shown by the arrows, a great variety of three paint choices are possible with this palette, simply by shifting the hue and/or reducing the chroma of one or more of the primary paints. Each modification will produce a different and often distinctive range of color mixtures. (Daniel Smith has turned this simple fact into a new category of marketing romance, built around a line of prepackaged primary paint combinations.)

As one contrasting example, the Velázquez palette (http://www.handprint.com/HP/WCL/palette4b.html) (palette scheme, right) reduces the chroma of the yellow and red primaries, shifts the yellow and red closer together, and shifts the green blue toward violet blue:

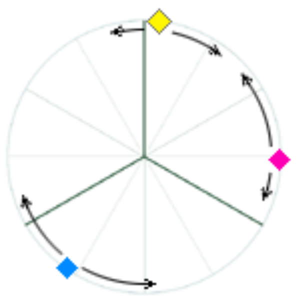
earth yellow (http://www.handprint.com/HP/WCL/palette1.html#earthyellow): yellow ochre (PY43 (http://www.handprint.com/HP/WCL/watere.html#PY43)) or raw sienna (PBr7 (http://www.handprint.com/HP/WCL/watere.html#RS)).

earth orange/red (http://www.handprint.com/HP/WCL/palette1.html#earthorange): burnt sienna (PBr7 (http://www.handprint.com/HP/WCL/watere.html#BS)) or venetian red (PR101 (http://www.handprint.com/HP/WCL/watere.html#PR101)).

violet blue (http://www.handprint.com/HP/WCL/palette1.html#violetblue): ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)) or indanthrone blue (PB60 (http://www.handprint.com/HP/WCL/waterb.html#PB60)).

This palette produces very muted greens and violets, and moderately dull warm hues. The desaturated color gamut allows for many interesting painting effects.

It is even possible to use a "primary" triad palette that consists of the *additive* primaries (*red orange, green* and *blue violet*), which in subtractive mixtures have such a potent darkening effect that I have recommended them as one way to mix a synthetic black (http://www.handprint.com/HP/WCL/waterb.html#indigo). Slightly changing the proportion of each pigment in the mixture allows the painter to shift the hue bias (http://www.handprint.com/HP/WCL/paint17.html), but as three paints are involved and none of them are "primary" colors, this method can also be considered a variation on the painting strategy that underlies the Velázquez palette (http://www.handprint.com/HP/WCL/palette4b.html).



two triad palettes

(top) "primary" triad palette, with arrows showing the range of hue choices for each primary; (bottom) velàzquez palette

Six Color Palettes. Careful examination of the color reproduction limitations (http://www.handprint.com/HP/WCL/color18a.html#cterror08) that arise from the "primary" triad palette, and study of the gamut that is possible if we allow an , indicates that almost the entire color mixing potential possible in watercolor paints can be achieved with a minimum of six colors of paint.

This creates the six paint palette (http://www.handprint.com/HP/WCL/intstud.html#step4) or secondary palette (http://www.handprint.com/HP/WCL/palette4e.html) (palette scheme, right), a simple and practical palette for learning color mixing with paints:

violet red (http://www.handprint.com/HP/WCL/palette1.html#violetred): quinacridone magenta (PR122 (http://www.handprint.com/HP/WCL/waterc.html#PR122)) or quinacridone rose (PV19 (http://www.handprint.com/HP/WCL/waterc.html#PV19R))

red orange (http://www.handprint.com/HP/WCL/palette1.html#redorange): cadmium orange (PO20 (http://www.handprint.com/HP/WCL/watero.html#PO20)) or cadmium scarlet (PR108 (http://www.handprint.com/HP/WCL/waterr.html#PR108)) yellow (http://www.handprint.com/HP/WCL/palette1.html#yellow): benzimidazolone yellow (PY151 (http://www.handprint.com/HP/WCL/watery.html#PY151) or PY154 (http://www.handprint.com/HP/WCL/watery.html#PY154)) or cadmium lemon (PY35 (http://www.handprint.com/HP/WCL/watery.html#PY35))

green (http://www.handprint.com/HP/WCL/palette1.html#green): phthalo green YS (PG36 (http://www.handprint.com/HP/WCL/waterg.html#PG36)) or phthalo green BS (PG7 (http://www.handprint.com/HP/WCL/waterg.html#PG7))

green blue (http://www.handprint.com/HP/WCL/palette1.html#greenblue): phthalo blue GS (PB15:3 (http://www.handprint.com/HP/WCL/waterb.html#PB15)) or phthalo cyan (PB17 (http://www.handprint.com/HP/WCL/waterb.html#PB17))

violet blue (http://www.handprint.com/HP/WCL/palette1.html#violetblue): ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)) or cobalt blue deep (PB72 (http://www.handprint.com/HP/WCL/waterb.html#PB72))

Many artists choose a seventh paint as a convenient source for the darkest values:

dark neutral (http://www.handprint.com/HP/WCL/palette1.html#dkshade): either carbon black (usually **lamp black**, PBk6 (http://www.handprint.com/HP/WCL/waterw.html#PBk6)), or a convenience mixture of carbon black with a tinting pigment that creates a bias toward brown (*sepia*), violet (*neutral tint*), blue (*indigo*) or green (*payne's gray*). Perylene black (PBk31 (http://www.handprint.com/HP/WCL/waterw.html#PBk31)) or indanthrone blue (PB60 (http://www.handprint.com/HP/WCL/waterb.html#PB60)) also make a useful dark neutral.

Other artists prefer instead to mix dark neutrals from two complementary palette primaries. In watercolors, the **darkest neutrals** are mixed with phthalocyanine (http://www.handprint.com/HP/WCL/pigmt1d.html#phthalocyanine) pigments usually a red and blue green paint (phthalo green BS, PG7 (http://www.handprint.com/HP/WCL/mixtable.html#PG7)); or a scarlet and blue paint (phthalo blue, PB15 (http://www.handprint.com/HP/WCL /mixtable.html#PB15)). In the six paint palette, either the orange and cyan or magenta and green mixtures can be used to make the dark neutral.

In watercolor paints, the eighth palette "primary" white is provided by water, which dilutes any paint mixture toward the white of the watercolor paper. White watercolor paints are not commonly used because they lack the transparency of other colors, and produce less lightfast mixtures.

The more commonly recommended six paint palette, characteristic of traditionalist "workshop" artists, is the split "primary" palette (http://www.handprint.com/HP/WCL/palette4r.html) (palette scheme, right). As I explained earlier (http://www.handprint.com/HP/WCL /color18a.html#cterror08), this is simply a 19th century attempt to expand the "primary" triad gamut while preserving the 18th century theory of primary colors. It results in a smaller gamut that is strongly biased along the warm/cool dimension, and it requires more inconvenient color mixing than the hexachrome palette.

two six paint palettes

(top) hexachrome palette; (bottom) split "primary" palette

Basic Palettes. As we have been steadily adding paints to the palette, the obvious next step in palette design is to adopt as many paints as necessary to minimize, as far as practicable, the negative effects of the . The result is a selection of about a dozen (10 to 14) paints that I call the basic palette (http://www.handprint.com/HP/WCL/palette5.html).

Starting with the hexachrome palettes described above, the basic palette additions typically include:

a "warm" (orange yellow (http://www.handprint.com/HP/WCL/palette1.html#orangeyellow) to red (http://www.handprint.com/HP/WCL/palette1.html#orangered)) paint, to enhance the saturated warm hue mixtures between yellow and magenta.

one or more "earth" pigments (http://www.handprint.com/HP/WCL/palette1.html#earthyellow), especially from the traditional and highly useful "earth quartet" (http://www.handprint.com/HP/WCL/earthp.html) (raw sienna (http://www.handprint.com/HP/WCL/watere.html#RS), burnt sienna (http://www.handprint.com/HP/WCL/watere.html#BS), raw umber (http://www.handprint.com/HP/WCL/watere.html#RU) and burnt umber (http://www.handprint.com/HP/WCL/watere.html#BU)), substituted or supplemented with the less commonly used yellow ochre (http://www.handprint.com/HP/WCL/watere.html#PY43) and/or venetian red (http://www.handprint.com/HP/WCL/watere.html#PR101), to increase the convenience of making dull warm mixtures.

a violet paint (http://www.handprint.com/HP/WCL/palette1.html#redviolet) or violet convenience mixture (including a *red violet* such as cobalt violet).

a larger selection from among the limited choice of blue pigments (http://www.handprint.com/HP/WCL/palette1.html#violetblue), to expand the variety of pigment textures, the hue range from violet blue to green blue, the lightness range (from very dark to moderately dark), the saturation range from intense (ultramarine blue, manganese blue , cobalt teal blue) to dull (cerulean blue, iron blue), or the saturation of mixtures with yellow to make green.

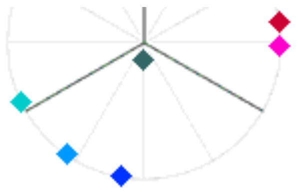
a green paint (http://www.handprint.com/HP/WCL/palette1.html#bluegreen) or green convenience mixture (http://www.handprint.com/HP/WCL/waterg.html#convenience) (commonly a phthalo green mixed with a yellow or orange yellow pigment and marketed under traditional color names such as *hooker's green, permanent green, cadmium green, sap green, leaf green* and *olive green*).

and finally, a dark neutral (http://www.handprint.com/HP/WCL/palette1.html#dkshade) either carbon black (usually **lamp black**, PBk6 (http://www.handprint.com/HP/WCL/waterw.html#PBk6)), or one of the dark shade convenience mixtures of carbon black with a tinting pigment (*payne's gray, indigo, neutral tint* or *sepia*).

The palette schemes (right) illustrate my recommendations for a basic palette (http://www.handprint.com/HP/WCL/palette5.html), and the basic palette choices of two professional painters, Chuck Long (http://www.handprint.com/HP/WCL/palette4f.html) and Charles LeClair (http://www.handprint.com

/HP/WCL/palette4v.html). (The question mark "**?**" indicates a questionable paint recommendation; in both cases this is the fugitive pigment alizarin crimson (http://www.handprint.com/HP/WCL/waterr.html#PR83) that is still favored by artists who learned to paint in the middle 20th century.) It will be useful for you to stop here and examine each palette scheme: try to understand how the painter has addressed the four palette limitations.

It's no coincidence that the most popular formats for the *plein air* painter's metal paint box (http://www.artsupplies.co.uk/item-lightweight-metal-tin-watercolour-boxes.htm) are designed to hold either 12 half pan or 12 whole pan paints. The basic palette is the keystone of most painter's palettes and the core of most painting tutorials a generous but not excessive selection of colors that is adaptable to almost any painting set up, pictorial genre or artistic style.



three basic palettes

(top) chuck long palette of 10 paints; (middle) charles leclair palette of 12 paints; (bottom) handprint basic palette of 12 paints

Colorist/Realist Palettes. Adding more paints to the basic palette usually indicates that the painter seeks to eliminate color mixing entirely, and/or expand further on the range of pigment textures. There is no lightness increase, and at best a small chroma increase in specific hues, over what can be attained with six carefully chosen paints.

The palette schemes (right) illustrate the range of paint selections by three colorist painters the 17 paint palette used by Carol Carter (http://www.handprint.com/HP/WCL/palette4m.html); the 21 paint palette I use in my plein air paint kit (http://www.handprint.com/HP/WCL/tech33.html#paints); and the 30 paint palette once recommended by Jim Kosvanec (http://www.handprint.com/HP/WCL/palette4t.html). Other examples are discussed in the pages on palette paintings (http://www.handprint.com/HP/WCL/paletfs.html). One of my favorite illustrations is the variety of paint tubes, painting specific plastic palettes, and paint mixtures that appear in the online video *Painting Spirit* about colorist painter Joseph Raffael (http://www.josephraffael.com/video/spirit.php). For these painters, the main attraction is that single pigments produce the most saturated color for any specific hue with the exception of violet, blue and green hues, where the limited pigment selection must be augmented by mixtures.

The other reason to adopt a larger paint selection is that a selection two dozen or more paints makes it possible to mix just about any color with just two paints. Although most painters resort to more complex mixtures, and correct an initial color mixture with glazes, the basic point still holds: it is easier to match a photographic color range with a larger number of paints. Despite the fact that all photographic colors are produced by mixtures of just three dyes, it is very difficult to find the exact primary triad mixture of paints to match dull or dark colors. So "realist" palette designs typically include an ample selection of "earth" and dark paints. Painters using large palettes in a realist painting style include Liz Donovan (http://www.handprint.com/HP/WCL/palette4o.html) and Michael Rocco (http://www.handprint.com/HP/WCL/palette4k.html).

Working With Paints. The step by step procedures for working with paints and preparing paint mixtures are outside the usual topic coverage in color theory. But it is essential that the painter who wants to control color learn how to control color mixing with paints.

Color mixing involves the "conceptual" process of analyzing a specific color into a range of different possible combinations and proportions of the paints available on the palette, then choosing the specific recipe that yields the best result; and the "mechanical" process of squeezing out paint, adding water, combining paints and so on.

An overview of the conceptual color mixing approach that I recommend is presented in the section basic mixing method (http://www.handprint.com/HP/WCL/color14.html#mixmethod) and in the section on "improvising color" in the page learning color through paints (http://www.handprint.com/HP/WCL/intstud.html#step15). The method is explained step by step on the page basic mixing method (http://www.handprint.com/HP/WCL/mix.html).

The mechanical procedures for mixing paints are described on the page working with paints (http://www.handprint.com/HP/WCL/tech14.html) separately for mixtures with tube paints (http://www.handprint.com/HP/WCL/tech14.html#tubepaints) and for pan paints (http://www.handprint.com/HP/WCL/tech14.html#panpaints).

Fusing the conceptual with the mechanical and using both effectively in painting is simply a matter of practice that is, making many paintings and along the way using many tubes or pans of paint.

a digression on color contexts

We've seen that the gamuts of all art media, with the exception of hybrid HDR video displays, generate a range of colors that is than the range of colors that appears in the physical world.

Traditional color theory tried to get around this limitation by exploring the subjective or perceptual dimensions of color (for example, in simultaneous color contrast), and to extend the nonrepresentational or "expressive" uses of color in color harmony, color impact, and color symbolism. The goal was to use these subjective and symbolic color effects to increase the visual impact of a painting, print or photograph.

However, color is always dependent on context and on the content of an image, which means we need to take an **ecological approach** to color effects we have to look at the natural situations in which those effects occur, or are useful to the broader goals of visual perception.

three colorist palettes

(top) carol carter palette of 17 paints; (middle) bruce macevoy field palette of 21 paints; (bottom) jim kosvanec palette of 28 paints

The Four Perceptual Anchors. In keeping with this distinction between the perceptual and cognitive aspects of color vision, there are four image attributes which the visual system uses for continuous self regulation. These aspects of the image are both fundamental to image quality, and have no symbolic or complex cognitive content. For example, they can all be incorporated into modern electronic cameras and security systems.

The first perceptual anchor is **average luminance**. This determines the luminance adaptation (http://www.handprint.com/HP/WCL

/color4.html#sensitivity) of the eye (when luminances are widely distributed across the image and similar in value), the lightness contrast and the chromatic intensity of hues. Vision sees light before it sees anything else. Luminance is the fundamental attribute of every visual image: sight is continuously embroidered in light.

The second is **luminance contrast**. Contrast perceptually defines two luminance regimes: *reflectance* or surface contrast, which under the same illumination varies in luminance by no more than 20:1; and *emittance* or light source contrast, which is luminance that is much brighter than surfaces and at least double the adaptation "white" luminance (which can be dark gray surface (http://www.handprint.com/HP/WCL/color4.html#gelbstaircase)). Increasing luminance adaptation causes a visible increase in both chroma contrast and lightness contrast, in the visual quality of "white" surfaces, in discernable spatial frequencies and in textures. Luminance contrast is the primary basis for image quality.

Bias 4. Reflecting surfaces have a limited luminance ratio of about 20:1, so most visual contrast arises from illuminance changes.

The darkest surfaces reflect about 5% of the light incident on them, and a pure white reflects about 97% or 98% of the incident light, which is a luminance ratio of less than 20:1. However, human vision has a luminance response range, when fully adapted to a stable level of illumination, of about 5 orders of magnitude, or a response ratio of 100,000:1. Clearly, we have way more visual response capability than necessary to see the difference between black and white surfaces.

The visual challenges arise from changes in illuminance, for example when we go in and out of a house having a garden party, or enter a deep forest from a sunlit meadow, or when the sun goes behind dark clouds, or when light fails rapidly after sunset. So long as the illumination changes are not as stark as the transition from noon summer sunlight to a darkened movie theater, we move from handle light variation without difficulty.

34. Small luminance contrast ratios are produced by the diffuse reflectance of light from surfaces; the most extreme luminance contrasts arise from the emittance and transmittance of light sources.

Bias 5. Color vision identifies as a light any luminance source several times brighter than the surround.

Exit.

Bias 6. Color vision treats luminance contrast and chroma contrast as two aspects of the same visual property of luminance intensity.

Oh yeah.

34. Color vision assumes color lies in the relation of surfaces to shadows.

We commonly experience a significant change in colors as the illumination changes from noon sunlight to twilight. As light intensity increases, *lightness contrast* increases as well: blacks become darker and whites brighter. This change, called the Stevens effect (http://www.handprint.com/HP/WCL/color4.html#stevenseffect), means that painters must use the maximum possible value contrasts to depict sunlit scenes, and restrict values to darker shades of gray to render twilight or dark motifs. However, as lightness contrast increases with higher illuminance, so does *chroma contrast:* brightly lit surfaces show a broader range of chroma and more colorful maximum intensity. This Hunt effect (http://www.handprint.com/HP/WCL/color4.html#hunteffect) means that brightly lit subjects require a larger chroma contrast between dull and intense colors.

At extremely low illuminance levels colors are radically diminished and finally disappear altogether, with the exception of colored light sources. This transition from mesopic to scotopic (http://www.handprint.com/HP/WCL/color4.html#mesopiccolor) vision first eliminates perceptible differences between saturated and unsaturated yellows, then between greens and blues, then between reds and browns, and finally all color differences other than lightness. Most painters render night scenes using dark blues and grays and reduced spatial details.

The third perceptual anchor is **temporal contrast** within the whole or part of the image. This covers a wide range of image attributes, but in all cases appears as *change* within the apparent physical space comprised by the image and/or the three dimensional color space of the image. Temporal contrast can be *movement,* as when a shape, pattern or texture area shifts from one spatial location to another; or *color change,* as when the ground darkens under a cloud; or *shape change,* as when a cloud billows or a vase shatters; or *gradient flow,* as when looking forward in a moving car or downward into a waterfall.

Temporal contrast represents change in the physical world or in the viewer's spatial relation to the world. We respond to it even in peripheral vision and across all luminance adaptation levels, and it has the consistent effect of defining an event in time and altering immediately our environmental concept, for example from light to dark or security to danger. It can also be any object change, and here shape, color and movement are most important.

The fourth and last anchor comprises various **focus/parallax cues**. These are the quality of the visual field as a two dimensional optical image (peak edge and texture clarity) and as a three dimensional spatial image, produced by **parallax** or *binocular imaging* between the images from each eye. Focus and parallax are the essential cues, visible within the image itself, of spatial depth and focus accommodation by a stationary observer.

These four visual attributes are anchors of color vision in the specific sense that vision typically suffers severe image degradation unless it has appropriately accommodated or adapted itself to them.

34. The four anchors of color vision are luminance level, luminance contrast, temporal contrast and focus/parallax.

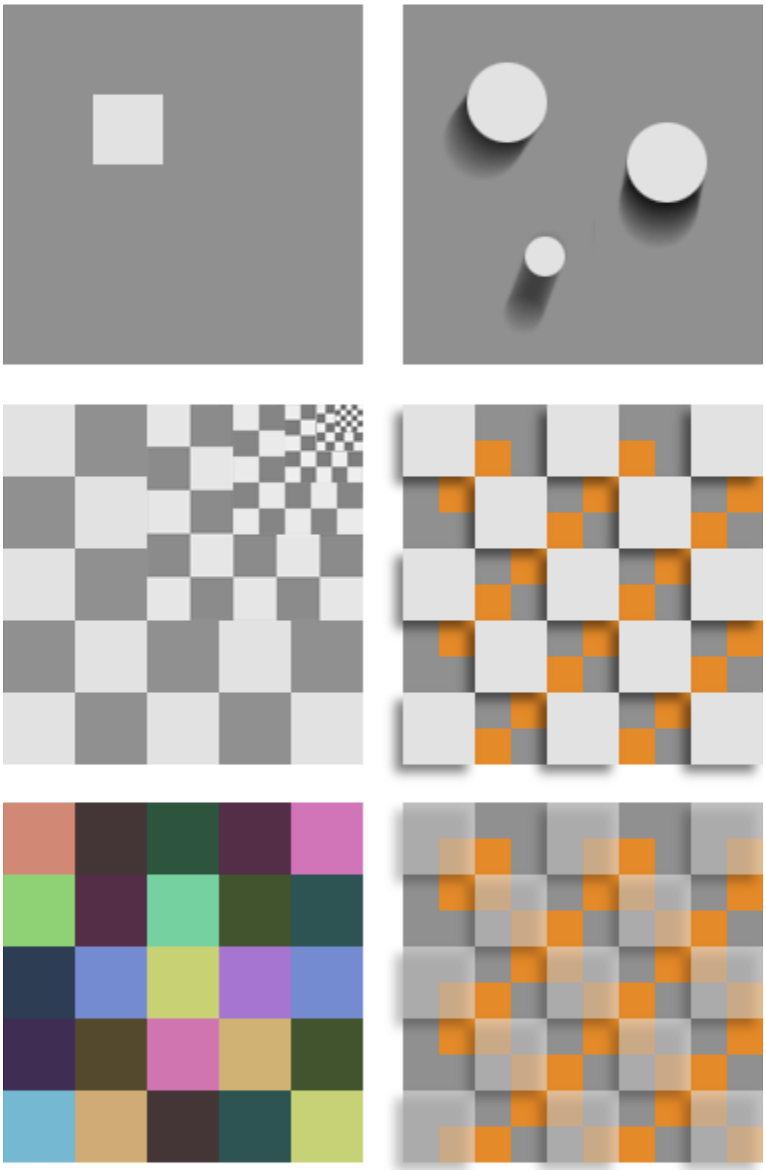
The Six Dominant Interpretations of Image Content. A visual stimulus must be radically impoverished (http://www.handprint.com/HP/WCL/color4a.html#unrelatedview) before the experience of color as the color *of something* can be completely suppressed. This is a negative demonstration of the fact that vision operates under the strong imperative to *see something*. This imperative evolved out of an immutable existential fact: we are surrounded by a physical world, so as long as we are conscious with functional eyes, there must always *be something* there to see.

Quite a lot of recent research in vision science has focused on the issue of how vision identifies a relatively complex "something" (such as a teapot or a face) from simpler, more primitive "somethings" (such as edges, areas and surfaces), which themselves must be extracted from the in focus luminance and temporal contrasts found in the light adapted images from our two eyes.

Much of this work proceeds on the practical assumption that visual capabilities can be simulated by a computer. Much of this work is technical, and involves a "bottom up" approach that starts with the image and ends with the recognition of an object. This means it is opposite to the "top down" artistic strategy, which starts with the visual unity and, by a process of simplification, impoverishment or transformation, extracts from the unity a less complex artistic image.

However, the academic research has clarified the dynamic and interpretive behavior of vision, which can be summarized as a variety of specific effects that appear most clearly in simplified color arrangements. It is helpful to remember that in all circumstances vision will attempt to "find" or construct one of these visual elements out of any visual image.

These preferred or frequent patterns or parsings found in visual images are the **six dominant interpretations** of image content (diagram, below). They represent strong "attractors" that draw the content of every visual image toward a specific interpretation. As such, they resemble visual forces or powers which the artist must wield, balance, and guide to a particular purpose.



the six dominant interpretations of

image content

(top left) variety or aggregation; **(top right)** pattern, texture and gradient; **(middle left)** shape, object or form/background; **(middle right)** light and shadow (direction and intensity of illumination); **(bottom left)** spatial depth and occlusion; **(bottom right)** transmittance (translucency or transparency)

Before proceeding, it will be useful to define some terms (as used here).

34. A *texture* is repetition of visual qualities within a limited subset of spatial frequencies. A *gradient* is a continuous change across spatial distance from one distinct visual quality to another. A *texture gradient* is a texture whose color and/or spatial frequencies continuously change across spatial depth or visual width. A *visual area* is any visual quality that joins no other visual area through a gradient. An *object* is a visual area identified as a physical form. A *pattern* is a texture of repeating areas, forms or objects. A *grouping* is an aggregation of forms or objects in a pattern of visual precedence or order; a *clutter* is an aggregation of many forms or objects without apparent precedence or order.

Color vision first of all reports variety or aggregation, differences, variance; we easily perceive jumbles, tangles, piles, screes, scatters, sparklings and spangles. It's always fun to go into an antique store, glance quickly down a shelf of small items, then walk past the shelf noticing all the specific items that were invisible in the clutter. When we see sunlight reflected from distant waves, we see a field of glittering, uncountable unique lights.

If scatters have pattern or rhythm, specifically rhythm in one or more spatial frequencies (http://www.handprint.com/HP/WCL/color8.html#spatialfreq), then we perceive pattern if the spatial frequency is low, and texture if the frequency is high: wood grain, rug pile, sand jumble, water ripples, hair curls, grasses, wovens; or we perceive the absence of texture, as in polished metal, still water, the blue sky, printed color.

texture and pattern in an image

The image illustrates the importance of spatial plane to texture: the same material (construction scaffolding) appears incoherent or orderly depending on whether or not the pattern or texture adheres to a visible spatial plane. This shows that pattern and texture occupy a middle place between aggregation and objects in space. The influence of *gradient* to define a receding surface or depth through obstructions is also apparent.

Pattern/texture and the absence of pattern/texture form visual areas, which abut each other to define edges and outlines. These separate forms from each other and foreground forms from their backgrounds. We see recognizable things, physically separate objects of chemically different composition. Variety and pattern are pushed into the background, and objects acquire surfaces that have texture and color. Forms can transition into patterns, especially across a spatial extent (as the trunk of a tree turns into branches and twigs) or into space (as cobblestones at our feet become a vague pattern in the distance).

Objects are separated from each other in space, and have three dimensional contours, so they identify the intensity and direction of illumination by the shadows created on their unlighted sides and cast onto other objects or surfaces. Objects cast shadows on farther objects, or shadows run sideways across horizontal or vertical surfaces.

Next color defines space, as objects or areas that overlap one another visually (occlusion) or vary in size or brightness with distance, occlusion and size being the principal cues to spatial recession. Space is separate from illumination, in the sense that objects can be placed anywhere and have the same relation to solar light.

Finally, color can communicate the transmittance qualities of semiopaque or translucent media such as fogs, mists, rains, murky water, filters, tinted or steamed windows, fabrics. Texture disappears, the edges of forms become less distinct, color desaturates and may take on an all over tint yellow for a smoky day, gray for a winter mist, green for deeper water.

transmittance cues in sky and water

These are the six dominant forms of color.

34. The six dominant interpretations of surface color contrast are: (1) variety or aggregation, (2) pattern, texture or gradient, (3) shape, form or object/background, (4) illumination, (5) occlusion and spatial depth, and (6) transmittance.

The Line Symbol. An important orphan in the dominant constructions is *line,* which is (in drawing) any single continuous mark whose width is very small compared to its length. Line also appears as one of the essential primitives in visual processing, and it is extracted from any qualitative discontinuity between adjacent visual areas.

The key point is that **lines are symbols for edges**, with the trivial exception of lines that represent visually matching objects (wires, hairs, cracks etc.) The art school cliché that *"straight lines do not exist in nature"* misses the point that lines are symbols, not things.

As an edge symbol, the line is a drawing sign for *demarcation, separation or alignment*. To understand this function, it is helpful to look at representations made exclusively of lines of constant width and color (black), as shown in the figure (below).

line versions of the six dominant constructions

(compare to); see text for explanation

Comparison of this figure with the matching color version (above) shows clearly where the line version falls short. Line performs exceedingly well as *form or object outline,* essentially symbolizing a surface without any information as to texture or color. Line also does very well at representing certain textures.

However it has the least talent for indicating aggregation, illumination, complex occlusion and translucency all constructions that rely heavily on *texture and color differences* to appear clearly.

To compensate, artists developed a variety of techniques for **shading**, the process of modulating the lightness or color of an image area through the width, spatial frequency and direction of repeated lines. Darkness is controlled by the width and spacing of the lines; spatial frequencies are smoothed out by overlapping lines in different directions; light areas are modulated by breaking lines into dots or dashes. In charcoal or chalk drawings the original lines can be partially or completely effaced by smudging or stumping, by modeling with an eraser, or by completely covering all lines by other lines of a different color, blending chalk on the page.

34. Line is a drawing symbol of edge (demarcation, separation or alignment); line is most effective as form or object outline, or in representing certain textures; it is weakest at representing light and shadow, complex occlusion and transparency.

34. To represent gradients in texture, value or color, the width, spatial frequency and direction of repeated lines are manipulated in various techniques of shading.

principles of color contrast

The previous section outlined some of the basic facts of color in context how color looks in the world of physical objects and light sources, and how visual images tend to settle or clarify into a handful of basic interpretations.

Now we can turn to the more traditional aspects of color, which are the effects of one color on another, either when one color is viewed after another (*successive color contrast*) or when two colors are viewed together, either side by side or against the same background or within the same pattern (*simultaneous color contrast*).

Hue Opponency in Color Vision. After Newton's discovery (http://www.handprint.com/HP/WCL/color18a.html#newtonhuegeometry) of the hue circle and the additive mixture of light, naturalists focused on the *hue contrasts* induced in color vision. We will look briefly at three of these: afterimages, shadow contrasts, and simultaneous color contrasts.

These three visual effects all demonstrate the fundamental color vision principle of **complementary colors**. It is hard to overstate the importance of complementary colors as a guiding star of traditional color theory. They affirmed the circular symmetry of color relationships that was announced in Newton's geometrical mixing method (http://www.handprint.com/HP/WCL/color2.html#mixingcircle), and they demonstrated the dynamic contribution of our perception to color experience, marking color as a fundamentally subjective quality of our world.

Afterimages. Afterimages come in two forms. Positive afterimages (http://www.handprint.com/HP/WCL/color4.html#posafter) result when the eye is exposed for some period to a light stimulus that is at the upper limit of the current luminance adaptation, or briefly to a light stimulus that is far above the adaptation limit.

This produces a lingering phantom image that is at first the same color as the stimulus, but then oscillates across a range of hues. Thus, most people will see a lovely yellow green afterimage if they look briefly and directly at the reflection of the sun in a car windshield. A digital camera flash viewed in a dim room produces an immediate yellow green, which rapidly alters through yellow and magenta to a violet and darkening blue green.

positive afterimages of a bright light

the positive afterimage of a camera flash viewed in a dim room is immediately a yellow green (left), which oscillates through yellow/magenta to a violet/blue green

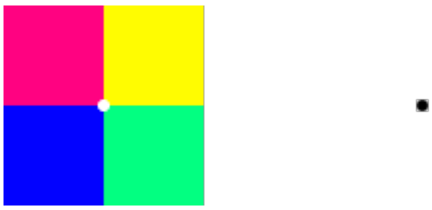
The intense light exposure strongly bleaches the rods and cones, and the oscillations result as the stunned photoreceptors recover at different rates and at a lag with the chromatic adaptation mechanisms in the visual cortex. These phantom colors gradually lose clarity and chromatic intensity; when viewed against a bright background (such as the sky, or the white of a computer monitor) the afterimage area appears to be a dark neutral blotch.

In my experience, these positive afterimages do not produce clear yellow, orange or red colors or their complementary blue hues. Warm hues are dependent on to appear clearly, and as there is no contrasting background to a negative afterimage, warm colors do not appear even when the afterimage light stimulus has a yellow or red hue.

Negative afterimages (http://www.handprint.com/HP/WCL /color4.html#negafter) result when the eye is first exposed continuously to a moderately bright color stimulus, then turned to view a blank, dimly lit neutral surface. The image colors are normally stable, and can be refreshed by blinking.

Negative afterimages demonstrate a local chromatic adaptation (http://www.handprint.com/HP/WCL/color4.html#chromaadapt), which is a general visual response that attempts to restore a "white" balance or chromatic neutrality to visual experience. In the 18th century this was interpreted as the eye's tendency to "seek balance", for example in J.W. von Goethe's (http://www.handprint.com/HP/WCL/book3.html#goethe) claim that complementary color afterimages arise because the eye seeks "to experience completeness, to satisfy itself." This encouraged the 19th century concept of "color harmony" as an arrangement of colors that, as a whole, produce a neutral balance among antagonistic hues. It was even suggested that all the colors in a perfectly harmonious *painting*, if spun rapidly like a color top, would produce a gray blur.

As simple demonstration: stare for 20 seconds at the white dot in the colored square on the left, then look away to the black dot on the right. After a moment (it helps to blink your eyes), a faint afterimage of the colored squares will swim into view but the colors will be different. What colors do you see?



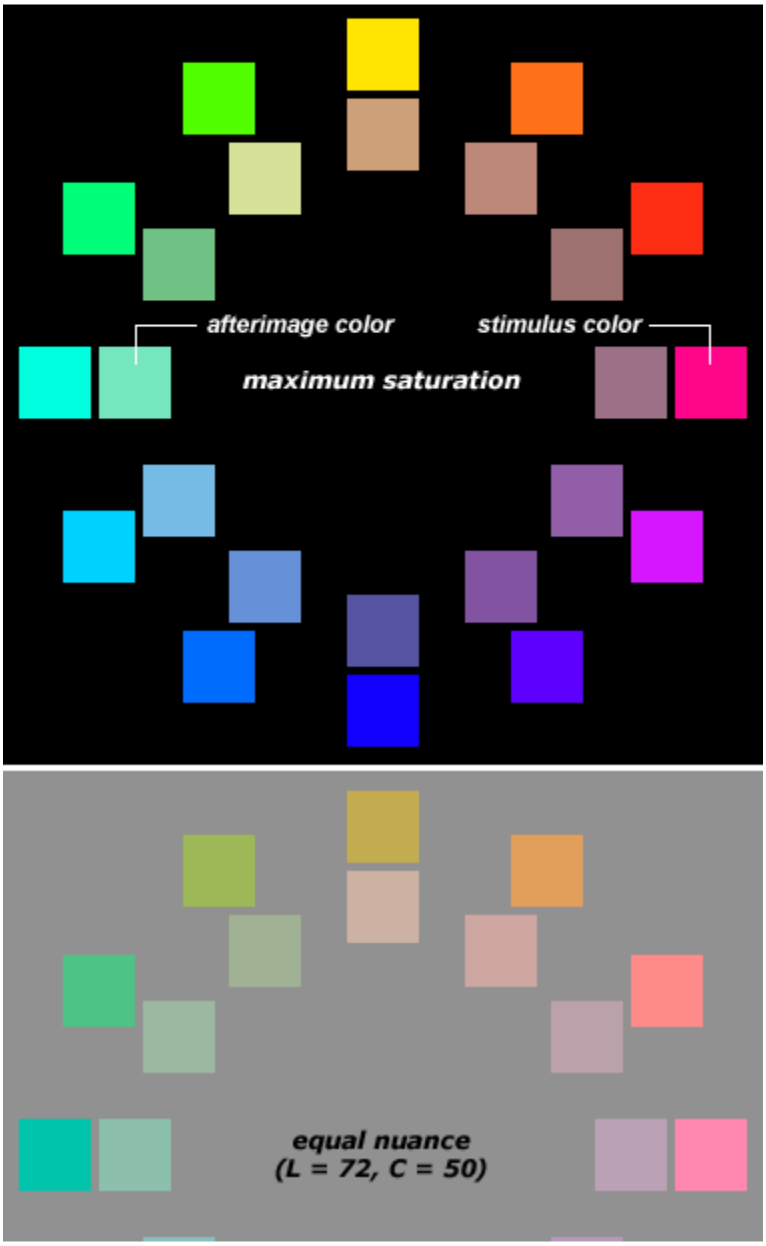
demonstration of negative afterimages

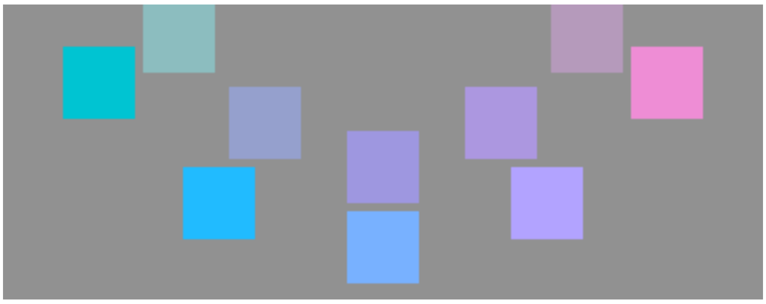
Stare at the center of the colored square for 20 seconds, then look at the black dot on the right.

For most people, the colors in the afterimage are almost exactly reversed: the green turns magenta, the blue turns yellow, the magenta turns green, and the yellow turns blue. These illusory colors are the **visual complements** to the hues in the original image. This **complementary afterimage** also works for most other colors: an orange square will produce a blue afterimage, yellow green will produce violet, and so on, all the way around Newton's color circle.

range of dominant hues in positive afterimages

However, the overall chromatic contrast plays a significant role in the afterimage appearance. I fixated for 20 seconds on each of 12 colored squares from around the hue circle, then viewed the afterimage on a gray background, while matching the afterimage color by adjusting the color of an adjacent square in Photoshop. The complete procedure is described here (http://www.handprint.com/HP/WCL/color4.html#negafter). The results I observed are shown below, with the afterimage color located opposite its stimulus color (next to the complementary color it should match).





colormatching of isolated afterimage colors

Afterimages are not equivalent around the hue circle: a saturated blue does not make an intense yellow afterimage (viewed in isolation), but a dull yellow can make a relatively saturated violet; a saturated blue green makes a relatively dull red, but a saturated red makes an intense blue green. In fact, all the "warm" hues from *yellow green* through *violet red* appear in their unsaturated form as browns or ochres, because saturated warm hues require luminance contrast.

And there is very little hue contrast from yellow to red, compared to the hue contrast from green to blue or from blue to violet, when the afterimages are generated by a single color in isolation. When different colors are presented together, as in the square demonstration image (above), they exert a mutual influence that sharpens the hue contrasts. This reveals the powerful effect that context has on color appearance, even in afterimages.

Increasing field luminance (from black to gray) causes a slight decrease in chroma and in the lightness variation across the afterimages; luminance contrast increases the afterimage intensity. The stimuli at equal nuance (matching chroma and lightness) show less hue contrast around the hue circle. In fact, only three hues appear: the additive primaries *red, green* and *blue violet*.

Contrasting Shadow Colors. A quaint preoccupation of 18th century naturalists was the apparent tint induced in shadows cast by differently colored lights. As Martin Kemp (http://www.handprint.com/HP/WCL

/book3.html#kemp) points out, the methods for producing the effect, usually attributed to J.W von Goethe (http://www.handprint.com/HP/WCL /book3.html#goethe), were actually described several times in the 18th century: the French naturalist Comte de Buffon described complementary colored shadows and complementary afterimages to the French Academy of Sciences in 1742.

The classical set up placed an object so that it cast two shadows on a white surface behind it, one shadow from dim skylight, the second shadow from a candle. The original description by Benjamin Thompson (Count Rumford), describes both the set up and the spontaneous response:

"While I was employed in the prosecution of my experiments on the intensities of light, I was struck with a very beautiful and what I then considered as a new appearance. Desirous of comparing the intensity of the light of a clear sky, by day, with that of a common wax candle, I darkened my room, and letting the daylight from the north (coming through a hole near the top of the window shutter) fall at an angle of about 70° upon a sheet of very fine white paper, I placed a burning wax candle in such a position that its rays fell upon the same paper, and, as nearly as I could guess, in the line of reflection of the rays of daylight from without; when, interposing a cylinder of wood, about half an inch in diameter, before the centre of the paper, and at the distance of about two inches from its surface, I was much surprised to find that the two shadows projected by the cylinder upon the paper, instead of being merely shades, without colour as I expected to find them, the one of them that which, corresponding with the beam of daylight, was illuminated by the candle was yellow; while the other, corresponding to the light of the candle and consequently illuminated by the light of the heavens was of the most beautiful blue that it is possible to imagine." ("An Account of Some Experiments On Coloured Shadows", 1793)

With the contemporary selection of colored lights, the full range of color contrasts can be explored.

To produce the effect, place a vertically elongated shadow casting object near a neutral or white wall, then at a distance place a low wattage white light and a colored light so that the two lights cast separate shadows. Finally, move the colored light toward or away from the object until its shadow is as dark as the shadow from the white light. In the example (image, right), the white light casts a shadow that is illuminated by the red light, and therefore appears red. The red light casts a shadow that is illuminated by the white light, but appears clearly tinted by green, the visual complement of red. The effect is quite pretty and worth seeing for yourself.

In the same way, a green light will produce a vivid red shadow color, and a yellow light will produce a very pretty violet (mimicking the classical set up with a candle). However a violet and white light will only produce identical dark neutral shadows. Yellow cannot be a shadow color: a desaturated or very dark yellow appears very similar to black.

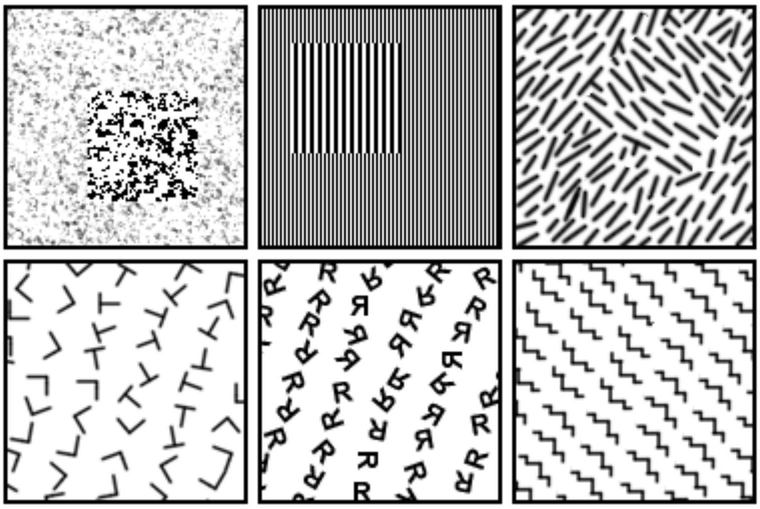
Note that this "illusion" can be photographed, so it is replicated by the trichromatic CCD chip and color balancing algorithms available in a modern digital camera.

the appearance of a red/white shadow contrast experiment

The afterimage and shadow demonstrations both illustrate the opponent structure (http://www.handprint.com/HP/WCL/color18a.html#modernhuegeometry) of complementary hues though only with relatively poor hue contrast within hue categories, and with some contrast hues (yellow) appearing only weakly if at all.

Edge Enhancement & Area Continuity. Before we approach the topic of contrast between different color areas, it is useful to understand how color areas are defined in the first place: by establishing boundaries or edges between areas, and by minimizing contrast between areas.

Let's start with texture. We can create a very large number of monochromatic textural contrasts using a variety of repeated shapes or patterns.



texture as an edge definer

mouseover to see the contrasting texture area

Shows that texture is relatively poor as an edge definer, so the emphasis shifts to color, in particular lightness and hue contrast.

Visual Fusion. At one extreme the eye is bounded by limits in its optical resolution. Even though these are, in the fovea, at the theoretical (physical) limits of an optical system, the resolving power of the eye is much lower in peripheral vision: you cannot read this text by fixing you gaze in the margins. *Visual fusion* refers to how the visual system averages or blends details into the impression of a continuous surface.

Of course visual fusion is important as the perceptual mechanism that produces the continuously graded appearance of all half tone or screen printing technologies, which have produced nearly every press printed illustration, photograph and color image over the past century (and television or monitor images of the last few decades).

But its real significance is as an illustration of the profound importance of **spatial frequency** in a variety of visual effects. The demonstration that two distinct colors actually appear to mix is actually a demonstration that the eye is actively combining, weighting and adjusting different aspects of the visual image, and in this process the twin attributes of contrast and visual size are among the most important.

Spatial frequency is typically stated as **cycles per degree** of visual angle; examples are shown in the diagram (right). Fusion is indicated by the appearance of a yellow color, which becomes pronounced above 6 cycles per degree; texture disappears at around 20 cycles per degree, or a spatial frequency of about 3 minutes of an arc.

Computer media provide a clean example of visual fusion, because the colors are generated by visually and physically discrete lights. (In print media, the additive mixture is confounded with subtractive mixture, produced when the printed ink dots partially or completely overlap.) The example (diagram, below) confirms the pure additive mixture with .

additive mixture in visual fusion

blue and yellow make gray; orange and green make yellow; red and blue make red violet

Surprisingly, visual fusion is not consistent across different hue contrasts or color mixtures. The diagram (below) shows visual fusion when contrast in lightness or chroma has been eliminated to clarify the effects of hue contrast and visual size alone.

spatial frequency, hue contrast and visual fusion

patterns of pixel widths 6 to 1 (vertical columns), in hues alternating on the **r/g** dimension (top three rows) or **y/b** dimension (bottom three rows) at lightness 70, or in grays alternating in lightness 75 and 65 (middle three rows); chroma of hues adjusted to produce achromatic fusion

The diagram (above), should be viewed at increasing distance, to observe how visual fusion affects the same physical pattern at different distances. (Each pixel is about 0.025cm or 0.01 inch wide, so you can determine the visual angle from the distance viewed and the pixel width of the lines.)

The diagram demonstrates three basic features of visual fusion: (1) dots fuse more easily than lines, (2) vertical lines fuse more easily than horizontal lines, and (3) **y/b** hue contrasts fuse more easily than **r/g** hue contrasts.

Crispening. At the same time, the eye must parse the entire visual environment: the main imperative is to identify surfaces and objects rather than the texture or fine pattern of those surfaces.

spatial frequency

at normal reading distance (24"), the two squares are 1° wide; the examples show spatial frequencies of 1 to 20 cycles per degree

Crispening is the increased color contrast that appears between two color areas that differ only slightly in lightness but that "bracket" or stand on either side of the value of the background.

Thus, if the background is a middle gray, crispening will enhance the apparent difference between one gray that is slightly lighter and a second gray that is slightly darker than the background. If the same grays are placed against a background gray that is very much lighter or darker than both of them, they appear more similar or are indistinguishable.

color shifts due to crispening

(top) crispening based on lightness differences only; (center) crispening based on chroma differences only; (bottom) crispening based on hue differences only

As the illustrations show, crispening is (again) strongest in very small lightness differences.

The surprise is that the crispening effect is reversed in both chroma and hue contrasts. When the lightness and hue of all three colors (the two test colors and the background) are the same, the apparent difference between the two test colors is minimized when the background has a chroma that is between them; in fact, the colors seem to merge with the background. But the contrast is enhanced when the background chroma is either much higher or lower than the test colors: when the background is dull, the higher chroma test color appears much brighter, and when the background is saturated, the lower chroma color appears much darker. A similar effect appears in the hue contrasts among colors of the same lightness and chroma (diagram above, bottom).

The implication is that color vision enhances lightness differences in all situations, but suppresses chroma or hue differences when these are relatively small. If the differences are larger, then the standard effects of simulataneous contrast are exerted more strongly as the differences in hue or chroma become greater.

34. Spatial surface perception suppresses contrast, spatial edge perception enhances contrast; texture is a type of contrast suppression, form is a type of edge enhancement.

Edge Enhancement & Surface Continuity. Other contrast effects appear to operate under two complementary imperatives: to enhance the visual contrast of edges, and to minimize the color variation in color areas. Together these effects produce **form contrast**, as the purpose seems to be to isolate forms from other forms and/or from the background.

Edge contrast is commonly illustrated with the phenomenon of **Mach bands**, which causes the edge contrast between two similar color areas to be enhanced. If the areas are similar in lightness, then the contrast causes the edge of the lighter area to appear lighter, and the edge of the darker area to appear darker. When the color areas are a series of bars in a gray scale, this produces a distinct scalloping or fluting of the color contours, much like the fluting in a Dorian column (image, below)

mach bands

contiguous gray bars differing in lightness by **L** = +3

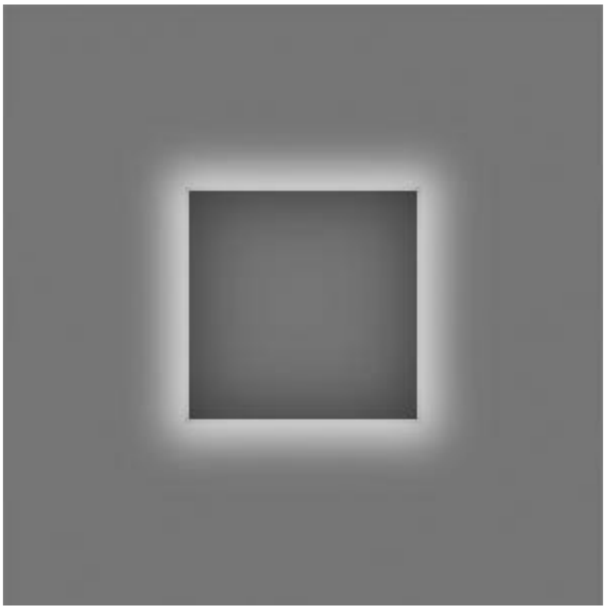
This fluting appears because the competing edges are relatively close together and the lightening on one side of each bar competes with the darkening on the opposite side.

mach bands

contiguous gray bars (top) of width 5 pixels and lightness difference **L** = +1; (middle) of width 20 pixels and lightness difference **L** = +4; (bottom) of width 80 pixels and lightness difference **L** = +16

This fluting appears because the competing edges are relatively close together and the lightening on one side of each bar competes with the darkening on the opposite side.

When edges are placed farther apart, surface continuity can be illustrated with the **Cornsweet illusion**, which is effectively the edge contrast propagating inward to lighten or darken the color area.



the cornsweet illusion

mouseover to confirm that the lightness of the gray central square and the gray background are the same

Thus, the lightness of the gray central square and the gray background are the same, but they appear different due to the propagating effect of the edge contrast.

All these contrast effects illustrate the interrelated vision imperatives.

34. Color vision primarily attempts to find and clarify edges, to use edges as the border of color areas, to consolidate areas by reducing color variation within them, and to enhance area definition by increasing the contrast between them.

Color Induction. One of the most characteristic topics in traditional color theory is the change in the appearance of a standard color that is caused by a contrasting background or surround color. These effects emerge both when the colors are presented as visually large and contiguous color areas (*simultaneous color contrast*) or as colors woven into higher frequency visual patterns (*color assimilation* or *color spreading*).

In modern color research these effects are subsumed under the general headings **chromatic induction** (when the shifts involve the hue or chroma of a color) and **lightness induction** or **brightness induction** (when the shifts involve lightness or luminance).

Before proceeding, it's worth emphasizing that color induction can appear either strong or negligible for different viewers or in different contrast presentations: as with most aspects of color vision, color induction reveals large individual differences in color vision. I describe the examples below as they appear to me, but your mileage may vary.

Color induction has been studied using a variety of patterns and formats. A useful one is the display of a relatively narrow ring of test color within concentric rings of two complementary colors, which define a specific axis of chromatic contrast and also provides a wide field (http://www.handprint.com/HP/WCL/color6.html#fieldsize) color contrast that minimizes the contribution of foveal vision. The width of the circular lines can be varied to assess the effect of either contrast or spreading.

As shown below (diagram, top), a red orange test ring (left) is contrasted with rings of yellow and blue violet (middle) or of green and violet (right).

chromatic induction (as simultaneous contrast)

In these types of contrasts the largest chromatic shifts tend to be observed in warm hues (especially orange) viewed against a complementary contrast that varies the amount of **S** cone stimulation, although the hue shift in a green test color, against the same complementary contrasts but with the contrast colors in reverse position (diagram, bottom), is also pronounced.

An alternate format is to present the test color as a large area with the induction color as a superimposed grid of narrow colored lines. This produces a color shift that has traditionally gone by the name **spreading** but is now called **assimilation**: the background color seems to assimilate or blend with the grid color. Note that the grid spacing is too large for the effect to be produced by visual fusion: blurring by the cornea and lens, interconnections among retinal neurons, and a low spatial frequency averaging of the large color area play a role.

achromatic and chromatic induction (as assimilation or spreading)

In the first example (diagram, top), the middle gray background is shifted lighter or darker by a superimposed grid of lighter or darker lines. In the second (middle) example, the background yellow green is shifted toward yellow or blue by the contrasting orange or blue grids; in the third pattern (bottom), the red background is shifted toward blue or yellow by the contrasting blue violet or yellow grids.

Simultaneous color contrast had been recognized by painters at least as early as Leonardo, and the changes in textile patterns caused by weaving different colored yarns together had been mentioned by Aristotle. But color induction began to be studied systematically in the late 17th century as part of a growing interest in visual effects that seemed to originate in the eye.

It was ushered in color theory by the publication of Michel-Eugène Chevreul's The Law of Simultaneous Color Contrast (http://www.handprint.com/HP/WCL/chevreul.html) in 1839, a study of color based on years of observation, experimental manipulation, and color demonstrations practiced on his coworkers and textile customers. From this long exploration, Chevreul identified a consistent pattern in the appearance of two colors viewed together:

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

Given Chevreul's practical interests, his examples include many patterns based on alternating color areas or large area textile patterns. The later tradition, after the Bauhaus, has been to simplify the contrasts as a visually extended (at least 1° wide) square within a surrounding square at least 3 times as wide.

A variation of this classic (and now standard) color theory format was raised to the status of an iconic series of "squares within squares" paintings by Josef Albers (http://www.handprint.com/HP/WCL/book3.html#albers) (image, right).

The diagram (below) shows the chromatic induction examples () in this format. Note that the apparent shift is weaker in this format, as the larger color areas are able to stand on their own.

chromatic induction in the chevreul format

fixate on the black dot to see the contrast more clearly homage to the square

by josef albers

In fact, Chevreul's generalization requires interpretation of the color contrast in context. A lot depends on the visual size and patterning of the color areas being compared, on our interpretation of the colors as surfaces under lighting in three dimensional space, and finally on our judgment of the illuminance and chromaticity of the light.

To assess the generality of chromatic induction, I painted out physical examples of the color contrasts that appeared to produce the largest effects. As one might expect, I found that the effects are not at all the same in different media (diagram, right). In general, chromatic induction exerts a larger effect when:

spatial frequency is higher (the visual size of contrasting color areas is smaller)

luminance is lower (the colors are viewed in dim rather than bright light)

contrasts involve red vs. green (red/green, green/yellow or yellow/red contrasts) rather than green vs. violet or violet vs. red.

In the example comparison (right), the green/red mixture produces a very similar color shift, whereas the green/violet mixture appears quite different in the two images. (This matches the visual comparison between the watercolor and electronic stimuli.) Nevertheless, electronic images appear to be a useful way to study these effects; in fact, they seem to produce the effects at around their maximum.

As part of my study of these phenomena I have prepared a library of color induction & color harmony (http://www.handprint.com/HP/WCL/IMG/CICH

/cich.html), which can help you assess the variations in chromatic induction effects.

Lightness Induction. The main effect is luminance, or lightness. Luminance contrast is visually very powerful and typically provides more than 90% of the information in a visual image. When luminance variation is removed from an image, the image is drastically degraded (http://www.handprint.com/HP/WCL/color11.html#dominance); but when hue and chroma variations are removed, the image is still highly interpretable.

Simultaneous lightness contrast produces a characteristic shift in the lightness of colors just as Chevreul predicted (image, below).

color shift in a simultaneous lightness contrast

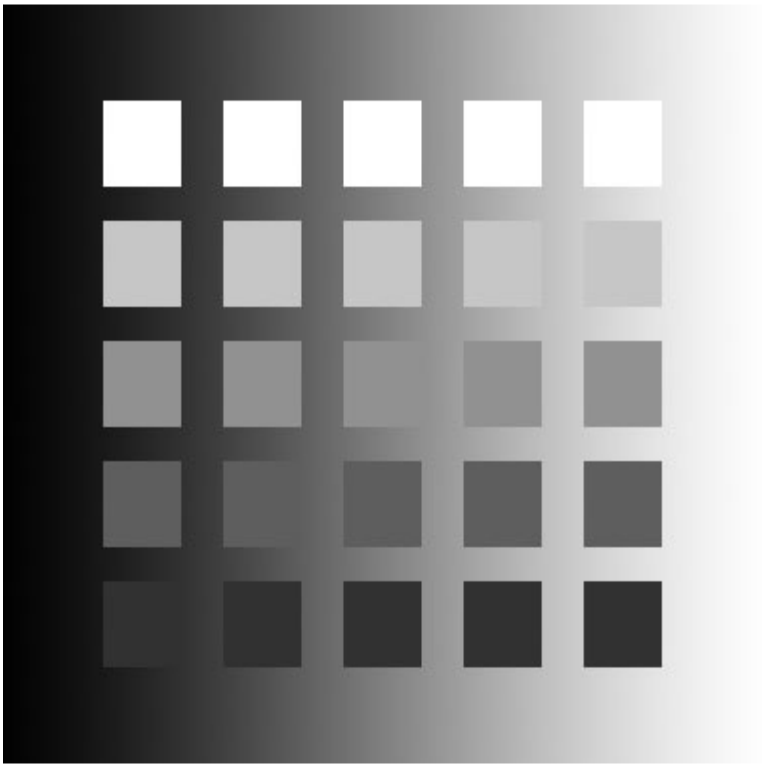
all squares have the same hue and chroma; fixate on the black dot to see the contrast more clearly

The effect spills over from lightness into chroma, so that placing colors on dark backgrounds appears to make them both lighter and more saturated (image, below).

color shift due to lightness contrast

fixate on the black dot to see the contrast more clearly

When these relative color effects are compounded across a range of lightness values, a dark valued background produces a upward compression in the lightness gradations, and a light valued background produces a downward expansion in the lightness gradations. This is known as the BartlesonBreneman effect (http://www.handprint.com/HP/WCL/color4.html#bartbren) (diagram, below).



the effect of background lightness on a gray scale

gray values in each row are identical; a dark background makes white appear brighter, compresses lightnesses toward white and reduces the apparent contrast across gray scale steps

This single diagram is worth careful study. Note that the darker background (far left) has the effect of "illuminating" all the gray values, as if a light were shining on them from the upper left. Since the "white" lightness has relatively little room to become brighter and still appear as a surface color rather than a light, the grays are compressed into it. The near white background (far right) forces the darkest gray to appear black or nearly so, without reducing the apparent purity of the white.

variations in chromatic assimilation

(top) stimulus created in Photoshop; (bottom) stimulus created with watercolor on paper

As the dynamic range of most print media suffers primarily from an inadequacy in the darkest values, black and white photographic prints and watercolor paintings are usually mounted against a white matte background if the maximum lightness contrasts are desired, and on a light gray background if balanced or perceptually equal lightness contrasts are preferred.

In fact, is possible to induce the perception of white (http://www.handprint.com/HP/WCL/color4.html#gelbstaircase) in an isolated and strongly illuminated surface that is covered with a matte, pure *black* paint!

Chromatic Induction. As a form of luminance perception, or chromatic luminance (http://www.handprint.com/HP/WCL/color3.html#colormakingchroma), a strong chromatic contrast also has a significant effect on color appearance (image, below).

color shift due to chroma contrast

all squares have the same lightness and hue; fixate on the black dot to see the contrast more clearly

As the example shows, high color chroma has the same effect as high lightness (luminance), dulling and darkening the central color; dull chroma has the effect of lightening and brightening the central color.

This effect is somewhat hue dependent. In computer monitor images it is very pronounced in violet red to violet blue hues, but is more muted in other hues (image, below top). This may be an artifact of the inequalities in saturation computed for different hues within the gamut of a computer monitor.

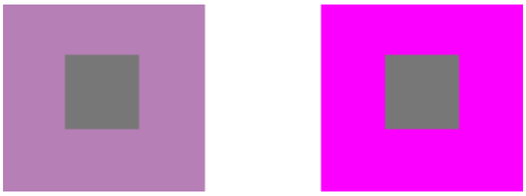
color shift due to chroma contrast

(top) all squares have the same lightness and hue; (bottom) central squares and background squares of different hues; fixate on the black dot to see the contrast more clearly

Note that the effect of chroma contrast is strongest when all colors are the same hue. When the central square is a different hue from the background (image, above bottom), the apparent magnitude of the chromatic effect is reduced.

This leads to a secondary principle of simultaneous contrast: the more similar the color areas appear, the greater the color shift necessary to produce visible contrast. We will return to this in the guise of .

Traditional color theory routinely makes the claim that these effects are most visible when the central color is gray: the color contrast is projected onto this neutral background (image, below).

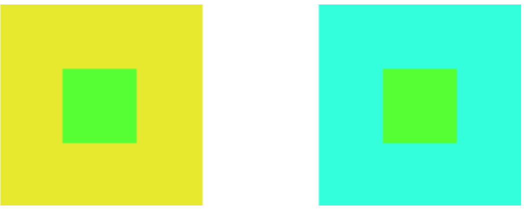


chromatic induction in an achromatic color

produced by contrast in chroma with lightness and hue constant (top), or by contrast in hue with lightness and chroma constant (bottom)

Although I see a small value shift in the central square, a change in the luminance contrast caused by the chromatic contrast, I don't see a significant sensation of hue (presumably, a green hue) in either square.

Hue Contrast. Despite the long testimony of traditional color theory, I find that simultaneous hue contrast produces the weakest contrast effects.



color shifts due to hue contrast

all squares in each row have the same lightness and chroma

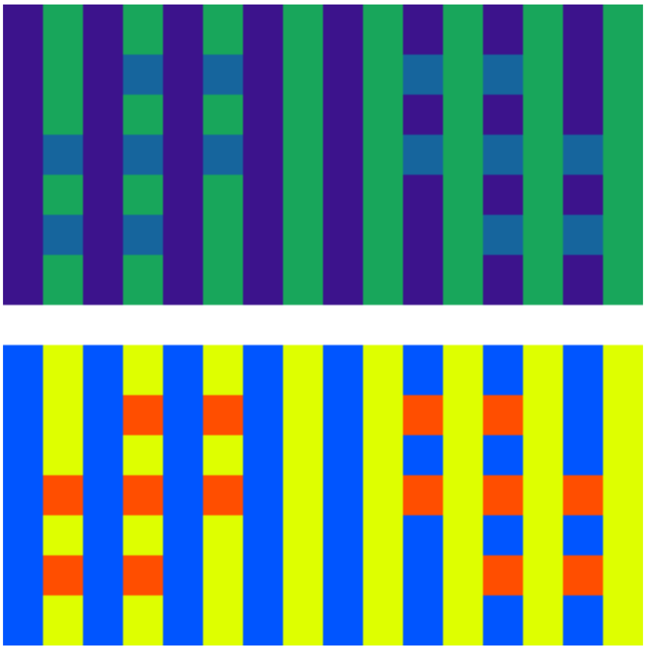
To my eye the primary color shift is (still) on either lightness or chroma, or both: the central squares do not appear to be significantly different hues so much as different values or intensities of the same hue. (The biggest shift appears in the violet, but this may be because blue violets in particular seem to shift hue as their lightness increases. This is the Abney effect.)

the abney effect

hue shifts due to changes in hue purity or lightness

In general, then, the opponency and contrast effects Chevreul described do not operate mechanically or consistently in color vision. They are subordinated to the larger goal of perceiving the environment clearly, depending on the context of the color, and operate much more forcefully in lightness and chroma contrasts than in hue contrasts at least, as these appear in electronic media images.

Spatial Effects In Color Induction. As part of this representation, different color shifts can be induced by the large area structure of the color areas of a complex pattern (known as *White's effect*), as clearly demonstrated in the example (diagram, below).



color shifts in a simple pattern

The two clusters of identical dull blue squares (top) or red orange squares (bottom) are placed against a regular pattern of alternating stripes. The edge contrasts for all the blue squares are identical two sides of each square border on green, and two on violet. The only difference is in the overall pattern: the blue squares interrupt either the green or violet stripes, which causes the other color to appear as continuous stripes.

The effect is enhanced if the space between the stripes is narrowed (right). The spreading effect begins to take over and the squares shift toward the color of the stripes on either side rather than the stripes that form the "background".

The astonishing result is that **hue shifts emerge from the pattern alone**: the squares that interrupt the violet stripes appear lighter and less saturated than the squares that interrupt the green stripes. Visual completion (http://www.handprint.com/HP/WCL/color8.html#completion) causes the squares to appear as horizontal blue bands, which means the eye interprets the pattern as blue stripes *behind* the uninterrupted colored bands and *in front of* the interrupted color, which acts as a . The squares that interrupt (are "in front of") the green background (left) shift toward a violet hue and a darker value, while the squares that interrupt the purple stripes (right) shift toward a green hue and a lighter value.

A very simple example is the **DeValois checkerboard** (image, below). We start with a simple pattern of alternating light and dark middle gray bands, arranged as a horizontal strip. When this strip is superimposed on a cyclic pattern of lighter and darker bands (image, mouseover), the alternating strip adopts the same cyclic pattern, but in complementary contrast.

induced pattern contrast in the DeValois checkerboard illusion

mouseover to see pattern contrast

The DeValois illusion can be made stronger or weaker by decreasing or increasing the width of the central band of alternating color; the band must be as wide as the cyclic background before the effect disappears. This is an important clue that visual area affects the strength of color appearance, and more generally that edge enhancement, visual fusion and simultaneous contrast are different aspects of an integrated visual system.

lightness shifts induced by visual completion

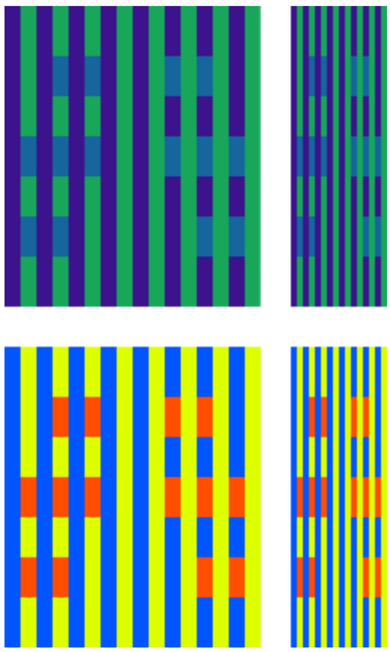
mouseover to see pattern contrast

You may suspect that somehow these shifts are related to the center/surround contrasts of edge and region detection (http://www.handprint.com/HP/WCL/color8.html#edgeregion), but this is not the case. In the above example, visual completion causes us to perceive the gray cross in the center as a circle, which induces the perception that the circle is "behind" the four squares and "in front" of the contrasting background. Even though the edges around the circle are almost entirely with the four squares, the lightness shift is *toward* the value of the squares and *away from* the contrasting background.

An achromatic spatial illusion (below) demonstrates how **spatial color can strongly alter surface color** to match or consolidate a three dimensional perception.

a spatial illusion alters lightness appearance

In both figures the basic pattern is a 5 x 5 matrix of identically shaded achromatic "tiles", with the shape of some tiles changed in shape or orientation to create the illusion of a surface folded vertically (left) or horizontally (right). This is sufficient to produce contrasting spatial illusions and color changes: (1) each column appears as a flat surface crossed by alternating bands of color (left) or as a band of continuous color at different angles to the light (right); and (2) the apparent lightness of any single facet changes depending on the spatial interpretation: compare between figures the second and fourth facets of the middle column. These discrepancies are not noticed as conflicts or changes in *color:* they disappear into the spatial illusion. The *modeling* of the folded surface, the idea of its geometrical form in space, acts as a **scission template** functioning across its entire surface.



enhancement of chromatic induction at higher spatial frequencies

Translucency Effects. Color shifts can also be induced by a pattern or "foreground vs. background" interpretation of the geometrical areas or color shapes in an image (White's effect). The following example shows this clearly, as it does not rely on color gradation and therefore is quite effective as a web browser image.

The eye seems adapted to segregate image regions using transparency or occlusion as a guiding principle. The illustration at right presents an especially startling example.

(a) To begin, we arrange two rows of identical gray bars so that they slightly overlap in their spaces. Note that they appear to be exactly the same lightness because they are.

(b) Light and dark squares can be added to the ends of these bars, but the apparent lightness of the bars remains largely unchanged. (I see a very slight shift to make the upper bars appear darker than the lower, corresponding to the Craik-O'Brian effect.)

(c) Or, a lighter gray field can be added around the lower bars, but this again does not alter the apparent uniform value of the bars.

(d) However, when the two elements are combined, the mind interprets the continuous horizontal edge created by the small squares and the large gray field to mean there is a **coherent spatial relationship** among *all* the color areas: the overall pattern resembles two rows of bars partially obscured at the bottom by a shadow or a translucent filter. This spatial interpretation causes the mind to infer color appearances that can "explain" the value contrasts in the apparent lightness relationships the upper bars appear much darker than the lower ones.

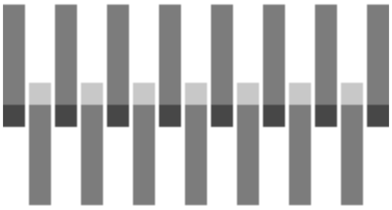
These effects are not limited to value (lightness) alone. The section on saturation and value (http://www.handprint.com/HP/WCL/color11.html#satvsval) demonstrates similar and large shifts in apparent chroma and hue, simply by changing the location of the colors within an apparently three dimensional figure.

We can conclude from these and many other specific demonstrations that the mind is continually adjusting our visual experience to **clarify the world's spatial structure** specifically, the effects of illumination on three dimensional surfaces. That is, color shifts do not arise "bottom up" through the local contrasts of different color areas, as "color theory" assumes. They are *imposed* "top down" by the mind, which first generates a three dimensional model of the world and the illumination within it using lightness information (http://www.handprint.com /HP/WCL/color11.html#dominance) alone, then adjusts or "paints over" this three dimensional framework with color appearances appropriate to show the inferred forms and contours.

The contrast effects described in this section can only suggest the important effects of edge, pattern and spatial relationships on apparent color. They confirm that (1) edge contrast, (2) the visual frequency or spacing of a pattern, (3) the unity of colors in the representation of a single object or surface, (4) the spatial illusion created by a design, (5) simultaneous color contrast, and (6) visual contrast around a visual "average" are all significant factors in modifying or enhancing the apparent colors in a painting or image.

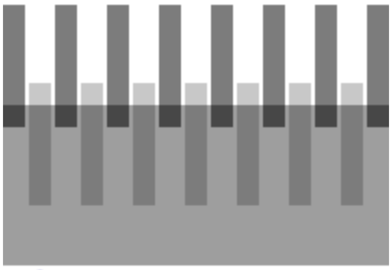
The significance a viewer assigns to local color information is dependent on his or her interpretation of the entire visual context in which the color appears: the artist must build the unified effect of a design in the choice of all its parts.

a



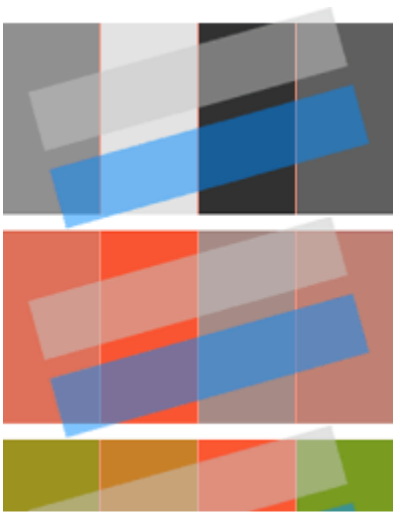
b

c



d

lightness shifts in a transparency illusion



translucency effects on patterns of different lightness, saturation and hue

This index page (http://www.handprint.com/HP/WCL/parttot.html) of color patterns.

Color Harmony. Various color combinations are modeled in the pages on color schemes (http://www.handprint.com/HP/WCL/parttot1.html).

34. Pattern disappears into texture at a spatial frequency of about 6 cycles per degree (a US quarter at 100 yards).

A recent paper by Dale Purves concludes that "a wide range of information is taken into account in determining the perception of luminances (2-D contours, 3-D shape, binocular disparity, object orientation, object color, the presence of penumbras, and presumably much else that remains to be studied)". The fundamental conclusion, illustrated here as well, is that color vision is a remarkably synthetic process.

Simulating Transparency. Simulate transparency by contrast; Albers examples.

surface color & illumination

Everything that has been said so far about color contrasts assumes that the colors are displayed under a "white" light. For the painter especially, it is important to consider both the color of light and the effect of this color on the appearance of colored surfaces.

How Is Light Color Defined? The optimal display of any color is under incident light (illuminance) that is spectrally *broadband,* visually *white,* and adequately *bright*.

broadband means that most or all visible wavelengths are present in the light; it is not "spiky" or "gappy" composed of a few separate wavelengths or missing large bands of the visible spectrum.

white means that the light has no visual chromaticity or tint; the light stimulates the **L**, **M** and **S** cones equally at the given illuminance or light intensity; the intensity or energy of light at all wavelengths is roughly the same (at the extreme, as an equal energy illuminant (http://www.handprint.com/HP/WCL/color6.html#equalenergy)).

bright means that the illuminance produces at least a mid mesopic luminance adaptation (http://www.handprint.com/HP/WCL/color4.html#sensitivity); this means the source illuminance is at least 100 lux, or generates a luminance of at least 100 cd/m^2 on an achromatic, diffusely reflecting surface.

34. Color vision accepts as "white" any light source that provides illuminance at approximately equal energies across the visible spectrum and at mesopic or photopic illuminance levels.

A conceptually simple approach was devised to combine all these features in a single illuminance property: the color rendering index (http://www.handprint.com/HP/WCL/color12.html#colorrendering) (CRI) of a light. This measures how closely a variegated group of surface color samples, viewed under the light source we want to evaluate, are perceived to match their appearance when viewed under a benchmark or reference light source. In the present context, a color rendering index of 100 means that all hues are perceived just as they appear under a reference ideal "white" light source.

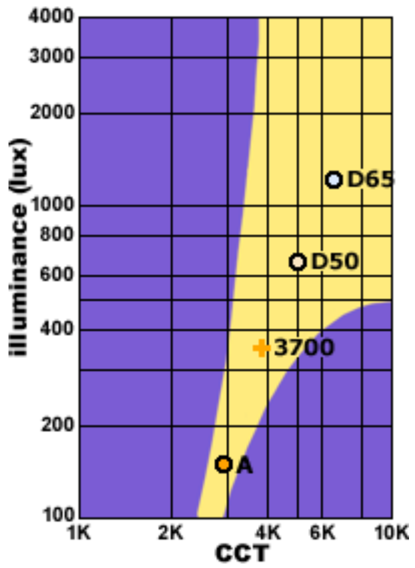
These differences represent the **color rendering** quality of a light. The *color rendering index* (CRI) is a numerical rating of how closely the color appearance of surfaces viewed under the light matches the color appearance of the same surfaces viewed under a blackbody light of the same CCT. It is calculated by averaging the colorimetric differences (if any) between the reflectance of 8 to 14 standard colors as illuminated by the test light and a correlated light source of equal luminance and a flat, smooth emission profile, after chromatic adaptation to each light.

Experience shows that lights with a CRI of 100 (http://en.wikipedia.org/wiki/Color_rendering_index) are natural light sources (http://www.handprint.com/HP/WCL/color1.html#solarlight) (the noon sun, the sky, or the daylight mixture of sun and sky), incandescent light sources (tungsten or halogen bulbs, carbon arcs, propane lanterns) and certain combustion sources (multiple wax candles, burning magnesium). In contrast, nearly all fluorescent lights have a CRI between 50 to 90, and sodium or mercury vapor lights have a CRI below 50.

The implementation of CRI measurement does not take into account the illuminance produced by the light source whether the light appears bright or dim although illuminance has a significant effect (http://www.handprint.com/HP/WCL/color12.html#kruithof) on color appearance and indeed on a viewer's mood as well. Dim lights in general have a much lower color rendering effectiveness than bright lights, and dim bluish lights a much lower color rendering effectiveness than dim warm lights (diagram, right).

So lights with a high or perfect color rendering index must also be adequately bright. The diagram suggests a simple rule of thumb for the illuminance that produces the best color rendering: the illuminance in lux should be roughly 1/10th the CCT of the light. For example, illuminant **A**, with a CCT of 2860°K, should be used at around 280 lux.

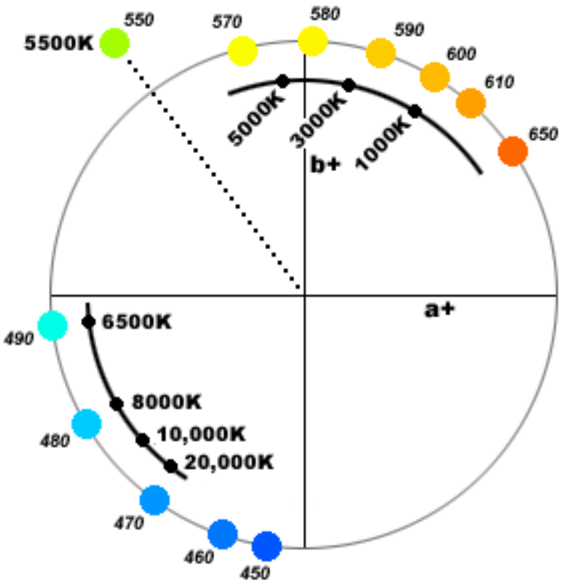
High CRI lights are indistinguishable from broadband lights, though such lights may have a weak but distinct chromaticity. So we also must describe the color or chromaticity of the light. This is done by means of the *correlated color temperature* or **CCT**. This approach relies on the fact that the spectral power distribution (http://www.handprint.com/HP/WCL/color3.html#solarspd) of natural light sources can be simulated very closely by a theoretical spectral power distribution called a **black body** that radiates light because it is hot, just as metals begin to glow as they are heated. The range of blackbody colors (http://www.handprint.com/HP/WCL/color12.html#CCT) varies from a deep red at blackbody temperatures below 1000°K, through orange, yellow and near white, into a blue at extremely high temperatures (above 10,000°K; diagram, right).



"preferred" light intensity for different illuminants

yellow shows zone of preferred intensities for each CCT; adapted from Kruithof (1941), Weintraub (2004)

In the , the arrow indicating the direction of "yellow" wavelengths (around 575 nm) shows that the y/b opponent function can easily compensate for the daylight shifts in chromaticity down to about 5000°K. But under extreme "blue" or "red" (late afternoon) daylight phases **the r/g function is also involved**. This is easier to see if the chromaticities of daylight CCTs (disregarding their typically low saturation and huge differences in luminance) are shown as hue angles on the CIECAM chromaticity plane.



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)

This diagram allows comparison of the color shifts in natural light with the traditionally defined : the match is quite good.

The y/b function makes the major adjustments around the average solar "white", while the r/g function tracks hue changes at lower temperatures. In video production, there are analogous Y/B and R/Y controls to adjust the image *white balance;* digital artists use green/magenta, red/cyan and yellow/blue controls that change the balance between the three complementary contrasts that define the secondary color wheel (http://www.handprint.com/HP/WCL

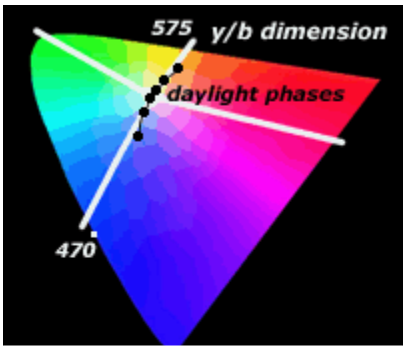
/color13.html#secondary).

Warm hues (matched by CCTs below 5000°K) are smeared across the hue range from yellow to red; cadmium pigments (http://www.handprint.com/HP/WCL/pigmt1b.html#cadmium) represent this range very well. The daylight CCTs above 6500°K start at a teal blue and shift to a middle blue at 10,000°K, the CCT of skylight; this range is represented by cobalt pigments (http://www.handprint.com/HP/WCL/pigmt1b.html#cobalt). The best paint matches to the typical blue sky color are a dulled cobalt blue (PB28 (http://www.handprint.com/HP/WCL/waterb.html#PB28)) or iron blue (PB27 (http://www.handprint.com/HP/WCL/waterb.html#PB27)), both visual complements of orange yellow. The sky typically appears relatively dark, with a luminance near the zenith that approximately matches a middle gray (reflectance 30%). Again, moderately diluted cobalt paints reproduce these values well.

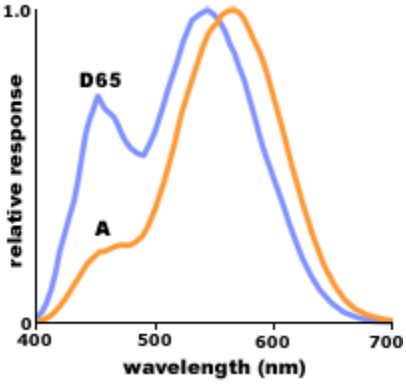
Effect of Illuminant On Visual Color & Color Rendering. If the illuminant is tinted then color vision attempts to remove the apparent color through chromatic adaptation and discounting the illuminant.

The generalization that explains the essential effect of light on surface color is: **light mixes subtractively with surface color**. A blue light on a yellow surface has the same effect as a glaze of blue paint over a layer of yellow paint, or a yellow surface viewed through a blue filter.

34. Light mixes subtractively with surface colors.



the blackbody locus in the CIELUV chromaticity plane



relative visual response to two standard illuminants

A (CCT = 2860°K) and **D65** (CCT = 6500°K)

We can simulate this effect in Photoshop by creating a color circle, for example of nuance colors of identical chroma and lightness (diagram, right top), then adding a layer of solid color over this color circle, and adjusting the transparency of the layer until the desired filtering effect is produced (diagram, right middle).

If we then measure these "filtered" colors and plot their changed location in the color space (diagram, right bottom), we will find that they have all (1) become darker due to the filtering, (2) shifted in the direction of the hue of the filter layer, and (3) have shifted in proportion to the difference between the hue of the color and the hue of the filter layer.

Visual colors produced by the same material color under different types of light are called **corresponding colors**. Thus, a near gray is the corresponding color under reddish light for a blue violet viewed under "white" light.

In all cases, the direction of the hue shift depends on the relative location of the surface and filter colors: hues that are complementary to the filter layer hue lose chroma as they shift toward gray, hues that are the same as or analogous to the filter layer hue increase in chroma and become more saturated. Typically the achromatic (white or gray) color has shifted along the hue angle of the filter hue.

These effects can be predicted in modern color models (such as CIELAB (http://www.handprint.com/HP/WCL/color7.html#LABMunsell)) by applying the emittance profile of a standard illuminant to the reflectance profile of a material, although in practice this is done using only the stimulus trichromatic values (XYZ values (http://www.handprint.com/HP/WCL/color6.html#tristimulus)) for both the material and the light.

The critical exception to these general principles is that all surface and light mixtures, because they are subtractive mixtures, display the same substance uncertainty (http://www.handprint.com/HP/WCL/color18a.html#subprobs) that we find in the mixture of two paints. That is, materials display metamerism (http://www.handprint.com/HP/WCL/color18a.html#metamerism): materials of the same visual color do not always produce the same subtractive mixtures.

This means we cannot predict the direction or size of the hue shift produced by the surface and light mixture based on the visual color alone. Surface materials with the same visual color may actually have very different material colors (reflectance profiles), and these will mix differently with the emittance profiles of different lights. This can be observed in the interior materials of cars or trucks, which will appear to match in noon daylight but can appear to differ when viewed under mercury vapor street lights or neon commercial lights at night.

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

illuminant and color rendering

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

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

Study of these different color patterns shows the extremes to which light color can shift surface color, and also how specific hues respond to different colors of light. Three illuminants are important in the blackbody series:

D65 is the "daylight" standard illuminant, matching the average CCT of noon daylight (http://www.handprint.com/HP/WCL/color1.html#dayphases) (sun + sky). D65 is often chosen as the "white" illuminant in color vision research, because it appears to be a "true" white across most mesopic and photopic levels of illuminance (although it appears as a feeble bluish gray light at low illuminances).

D50 (not shown above) is the standard illuminant (http://www.handprint.com/HP/WCL/color12.html#CCT) matching "warm" (late morning or early afternoon) daylight; it is more common in graphic arts applications and recommended for the display of color samples in the Munsell Color System (http://www.handprint.com/HP/WCL/color7.html#Munsell) and the Swedish

NCS (http://www.handprint.com/HP/WCL/color7.html#NCS).

A is the standard illuminant at 2860°K, matching a 120W incandescent light bulb; it can proxy for any of the CCTs in incandescent tungsten or halogen light sources (which vary from 2750°K to 3400°K). (The tinted spotlights cannot be assigned a meaningful CCT, as their intense color takes them very far off the blackbody locus.)

The effect on all colors shows that, compared to the **D65** appearance, the "warm" **A** illuminant slightly dulls the greens, blues and violets (visible especially in the green blue and blue green), but does not affect very much the appearance of yellows and reds (though note the visible shifts in green yellow and red violet).

The colored spots illustrate that the emittance profile of the light is visible in the paint colors: the red (**R**) light emits no green or violet light, so all paints reflecting those wavelengths primarily appear as black. The same effect appears in the green (**G**) light, which emits no violet or deep red light. However it is clear that there is some blue and violet light in the yellow (**Y**) spotlight, and some red and yellow light in the blue (**B**) spotlight, as the complementary colors are not completely blackened. Obviously, the **Y** spot provides reduced color rendering, while the other colored spots have very low color rendering: the **R** and **G** spots have a CRI near zero.

Representing Illuminant Changes. These preliminaries allow a simple, summary statement of the color changes a painter must observe when representing light changes.

34. As light changes, surface colors shift in the direction of the chromaticity of the light source, more strongly in complementary hues than in analogous hues, but with variations in the direction and size of the color shift that reflect substance uncertainty in the combination of

emittance and reflectance profiles.

simulation of corresponding colors

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

We can assess this rule by looking first at the corresponding colors in the **D65** and **A** illuminants illustrated above. These define color shifts that should resemble our Photoshop simulation. In fact (diagram, right top), we do find very large shifts in the complementary hues and smaller shifts in the analogous hues. But the shifts in blues and violets seem to be directly toward yellow, while the shifts in greens, yellows and reds are toward red orange.

It is unclear how much these irregularities are due to substance uncertainty in the paints, to inaccuracies in the camera or image color balancing, gamut limitations in the camera CCD or computer monitor, or distortions in the Photoshop LAB measurements that were used to create the diagram.

An alternative test is to examine the color shifts used in a modern videogame to represent the change in daylight illumination from noon to near sunset (images, below). (Many videogames now simulate illuminant changes across both day and night, and these effects are likely produced by algorithmic, global changes in the color space, calculated separately for surface or sky colors.) When these changes are mapped in the CIELAB **ab** plane (diagram, right bottom) they conform more closely to the shifts expected in theory. Even so, the shifts are not exactly toward the same hue, or of the same size, and this variation seems necessary to create the effect of different surfaces changing in different ways under the same light transition.

videogame rendering of illuminant changes

color shifts used to model noon and near dusk daylight

What is clear in both cases is the variety in the direction and size of the color shifts. In fact, shifting all hues according to a single effect has the effect of making the image appear submerged in a colored liquid or placed behind a tinted glass. Variety in the shifts, including the relative darkening and changes in chroma, signal the effects of light on natural surfaces.

These images do not accurately represent the luminance changes in the video display; the "noon" color palette has a much higher contrast ratio than the dusky palette, which increases the apparent saturation of many of the colors. Any color shifts intended to represent specific illuminants must also track the chroma limits and lightness contrasts that occur at different adaptation levels (http://www.handprint.com/HP/WCL/color18a.html#geometry).

This brings us to the point of simulating color in very dim light, dusk or nighttime lighting conditions. A recent paper (http://graphics.ucsd.edu/~henrik/papers/night/) by Henrik Jensen and colleagues provides the following guidance for representing scenes under low mesopic or photopic illumination:

subjectively the full moon appears large in the sky, though it is only 1/2° (the width of a US quarter at about one yard); its color is slightly redder than sunlight, but much dimmer.

rods and cones probably both contribute to a short wave or "blue" channel in low mesopic and scotopic light, overweighting the **y/b** contrast toward blue, and a sampling of night paintings showed the average color balance was shifted in the direction of violet blue at low chroma.

there is considerable loss of detail; spatial discrimination decreases to about 1/4° visual angle, or half the diameter of the full moon. But edges are not blurred as much, especially if they border luminance contrasts.

stars exhibit *stellation*, a disk of refraction pattern caused by diffraction patterns at the outer border of the lens, enhanced by the enlarged pupil aperture.

the **gamma** and dynamic range both decrease

Light & Color in Space. Light diffusion, shadow clarity, detail contrast.

Spatial depth + detail contrast = edge

Edge separators: lightness, chroma?, hue?

Hue separators: 5 basic hues, plus orange (2 stages of yellow transition).

illustrative color shifts

on the CIELAB **ab** plane; (top) between illuminants **D65** and **A** in the color circle; (bottom) between noon and sunset in the videogame

Mixture Changes.

Much information about computer simulation of lighting environments can be found in Advanced Renderman: Creating CGI for Motion Pictures (http://www.amazon.com/Advanced-RenderMan-Creating-Pictures-Kaufmann /dp/1558606181/) by Anthony Apodaca & Larry Gritz (San Francisco: Morgan

Kaufmann, 1999). A less technical, equally insightful and more graphically pragmatic resource is Jeremy Birn's Digital Lighting and Rendering (2nd Edition) (http://www.amazon.com/Digital-Lighting-Rendering-Jeremy-Birn/dp/0321316312/) (San Francisco: New Riders Press, 2006).

color symbolism

In fact, rigor in the color theory literature consists of stating simplistic rules decisively, then refusing to concede that the rules are arbitrary. **color theory is attractive not because it is true, but because it replaces complex experience with simple rules**.

Constructive Color Associations. Although there are as many as 15 different causes of color (http://www.handprint.com/HP/WCL/color10.html#colorcauses), there is a *perceptual* connection between color sensations and major types of physical materials or aspects of light.

These associations occur between *constructive categories* of the world and *nuance clusters* of colors a limited range of hues within a limiting range of lightness, chroma and gloss. These form the basis of a natural color harmony (http://www.handprint.com/HP/WCL/color17.html#lighteffects). Since these constructive categories are not manufactured by culture, they define the deepest and most consistent layer of color experience.

A clue to the selection of these categories can be found in the primitive structure (http://www.handprint.com/HP/WCL/color2.html#language) of Western languages, the Indo-European word roots. Besides privileging the bronze age menagerie of horse, steer, cow, goat, sheep, pig, dog, wolf, fox, mouse and bird, these point to the physical categories, and the handful of color categories bright (*bhel*-), dark (*nebh*-), white (*albho*-), pale (*pel*-), gray (*kas*-), black (*neg*-), red (*rendh*-), gold (*ghel*-), brown (*bher*-), green (*ghre*-), bluish (*sleia*-) used to negotiate the world in a prehistoric and prescientific era.

Consider first light sources and natural illuminance levels (http://www.handprint.com/HP/WCL/color4.html#illuminancespan). These are anchored in the sun (130,000 lux) at one extreme and night (less than 0.1 lux) at the other, with the sky (at around 3,000 lux) appearing as a blue surface of medium lightness.

Within this luminance framework, the lightness of surface materials is judged as light or dark, with the added attributes of hue and chroma. Lightness and chroma interact to create the separate visual sensations of *whiteness* or surface scattering, *darkness* or lack of reflectance, and *blackness* or nonchromatic reflectance (grayness). Colors are rarely perceived as very dark or very chromatic without a reduction in whiteness, perceived as gloss, translucency or wetness.

Culture Specific Symbol Systems. In some cases these rules create a **predefined symbolic code**. They provide a way for an artist to say something that has already been said to an audience that expects to hear it. As such color theory is purely conventional, and coercive in the mild sense that it restricts the range of an artist's expression and limits the audience that can interpret it. That is often its goal, because that is the only way to endow color with communicative significance.

The select audience is a particular consumer market segment, social group or social class, and **the class dimension of color theory comes through clearly in the emphasis on character terms** or "color personalities" ascribed to individual colors and color combinations: red is male, green is peaceful, blue is mystical, pastels are modern, taupe is trendy, and so on. The artist first conceives a design goal as a "moral" state for example, "this will be a *serene* room" or "I wish to paint a *serious* picture" then uses the theory to identify the appropriate colors or color harmony, and from there proceeds to the selection of colored fabrics or paints. (Colors have even been linked to male or female essences, to times of the day, to geometrical forms [yellow is a triangle], to musical intervals, and so on.) But what about "playful," or "nurturing," or "days of the week," or any other attribute not in the color symbol vocabulary? Those represent design issues that were irrelevant to the viewpoint of the male, technophilic, overintellectualized, mystical, humorless and misguided group of artists who invented the color codes in the first place.

Of course, if the viewer does not recognize this culturally dependent color symbol code, believes in a different code or comes from a different culture, or simply approaches color experientially rather than intellectually, then the symbolic aspects of color theory become irrelevant and impotent.

To refute the charge that their color codes might be arbitrary, "color theorists" argued that there are **universal physical or psychological reactions to different colors**. Colors must have a universal significance because they arouse our physiology or psychology in consistent ways: green calms and red excites, yellow makes cheerful and blue makes introspective. These hypotheses have been extensively tested by academic color research from around 1890 up to the present day; Bauhaus designers even sent out survey questionnaires to measure the collective emotional associations assigned to colors. The net result of this research? Just hundreds of publications to show that **consistent physiological effects of color don't exist**. (One well established finding: there are beneficial effects from *white light* exposure in the treatment of SAD or seasonal affective disorder.)

Lacking consistent proof for the physiological or psychological power of color, "color theorists" fell back on the idea that embody transcendental qualities of light or nature or spiritual being. (The tactic here is an old one: lacking empirical proof, fall back on religion.) Some "color theorists" of the 19th and early 20th centuries linked the "primary" triad to the Holy Trinity. On those imaginary cornerstones rigid geometrical or symbolic models could be rebuilt; and within those models, the "primary" triad acquired a stupefying magical or pseudoreligious symbolism. Once humans get rolling on an allegorical or symbolic system, free of any concern for the facts, there is no end to their ingenuity.

The real problem? color theory then becomes **detached completely from the materials of color making or the facts of color vision**. Color is an experience, a perceptual phenomenon, yet color theory talks about "blue" or "yellow" detached from any material circumstances, as abstractions or absolutes. There is an implicit appeal to the scientific premises of our technological culture, the 19th century expectation that all aspects of human existence could be (ought to be) reduced to simple universal principles: color obeys "laws." In fact, color is not like gravity, for the simple reason that living things are not the same as inanimate objects and neurobiology is completely different from physics. As I've shown elsewhere, "primary" colors are either imaginary or imperfect (http://www.handprint.com/HP/WCL/color6.html#imaginary), they are either "colors" that are invisible (and arbitrary), or they are represented by physical colorants that, in the case of paints, can behave in surprising and erratic ways. It seems to me evident that most of the great painters, the painters I most admire, anyway Titian, Caravaggio, Velàzquez, Vermeer, J.M.W. Turner, Monet, Degas, J.S. Sargent, John Marin, Fairfield Porter there is an incredible sensitivity to and masterful handling of the *color materials,* the paints themselves, and the many amazing effects they can produce on the eye.

Linguistic Color Associations. Culture sticks its own symbolic or ritual associations onto these categories: as in earth = fertility or meat = energy.

word / color associations

mouseover to see colors

As John Gage (http://www.handprint.com/HP/WCL/book3.html) points out, the surest antidote to a dogmatic color theory is art history. There simply are **no consistent color meanings in world art**, no consistent methods for handling color materials, no universal optical effects embodied in painting techniques. Several movements in modern painting for example the Pre-Raphaelites, Cubists and Fauves used "shocking" or "forbidden" or "wild" color schemes to break out of conventional color codes and use color to say new things. After a brief period of argumentative turmoil, these practices became the new color norms, the new color codes, and color dogma rolled on as complacently as before.

A related problem is that **color theory is careless about controlling hue, lightness and chroma** as separate sources of color effects: violet against yellow, or orange against blue, differ significantly in lightness and chroma as well as hue. When each colormaking attribute is tested separately, the same contrast demonstrations (http://www.handprint.com/HP/WCL/color12.html#complementary) show that **lightness and chroma have a much stronger contrast impact than hue**, which by itself has a weak effect.

An article in the *New York Times* (http://www.nytimes.com/2009/02/06/science/06color.html) (February 5, 2009) summarizes recent scientific studies, which still grapple with these issues:

Trying to improve your performance at work or write that novel? Maybe it's time to consider the color of your walls or your computer screen.

If a new study is any guide, the color red can make people's work more accurate, and blue can make people more creative.

In the study, published Thursday on the Web site of the journal Science, researchers at the University of British Columbia conducted tests with 600 people to determine whether cognitive performance varied when people saw red or blue. Participants performed tasks with words or images displayed against red, blue or neutral backgrounds on computer screens.

Red groups did better on tests of recall and attention to detail, like remembering words or checking spelling and punctuation. Blue groups did better on tests requiring imagination, like inventing creative uses for a brick or creating toys from shapes.

"If you're talking about wanting enhanced memory for something like proofreading skills, then a red color should be used," said Juliet Zhu, an assistant professor of marketing at the business school at the University of British Columbia, who conducted the study with Ravi Mehta, a doctoral student.

But for "a brainstorming session for a new product or coming up with a new solution to fight child obesity or teenage smoking," Dr. Zhu said, "then you should get people into a blue room."

The question of whether color can color performance or emotions has fascinated scientists, not to mention advertisers, sports teams and restaurateurs.

In a study on Olympic uniforms, anthropologists at Durham University in England found that evenly matched athletes in the 2004 Games who wore red in boxing, tae kwon do, Greco-Roman wrestling and freestyle wrestling defeated those wearing blue 60 percent of the time. The researchers suggested that red, for athletes as for animals, subconsciously symbolizes dominance.

Effects that were perhaps similarly primal were revealed in a 2008 study led by Andrew Elliot of the University of Rochester. Men considered women shown in photographs with red backgrounds or wearing red shirts more attractive than women with other colors, although not necessarily more likeable or intelligent.

Then there was the cocktail party study, in which a group of interior designers, architects and corporate color scientists built model rooms decorated as bars in red, blue or yellow. They found that more people chose the yellow and red rooms, but that partygoers in the blue room stayed longer. Red and yellow guests were more social and active. And while red guests reported feeling hungrier and thirstier than others, yellow guests ate twice as much.

Experts say colors may affect cognitive performance because of the moods they engender.

"When you feel that the situation you are in is problematic," said Norbert Schwarz, a psychology professor at the University of Michigan, "you are more likely to pay attention to detail, which helps you with processing tasks but interferes with creative types of things."

By contrast, Dr. Schwarz said, "people in a happy mood are more creative and less analytic."

Many people link red to problematic things, like emergencies or X's on failing tests, experts say. Such "associations to red stop, fire, alarm, warning can be activated without a person's awareness, and then influence what they are thinking about or doing," said John A. Bargh, a psychology professor at Yale University. "Blue seems a weaker effect than red, but blue skies, blue water are calm and positive, and so that effect makes sense too."

Still, Dr. Schwarz cautioned, color effects may be unreliable or inconsequential. "In some contexts red is a dangerous thing, and in some contexts red is a nice thing," he said. "If you're walking across a frozen river, blue is a dangerous thing."

Indeed, Dr. Elliot of the University of Rochester said blue's positive emotional associations were considered less consistent than red's negative ones.

It might also matter whether the color dominates someone's view, as on a computer screen, or is only part of what is seen. Dr. Elliot said that in the Science study, brightness or intensity of color not just the color itself might have had an effect.

Some previous cognitive studies found no effect from color, although some used mostly pastels or less distinctive tasks. One found that students taking tests did better on blue paper than on red, but Dr. Schwarz said the study used depressing blue and upbeat red.

The Science study's conclusion that red makes people more cautious and detail oriented coincides with Dr. Elliot's finding that people shown red test covers before I.Q. tests did worse than those shown green or neutral colors. And on a different test, people with red covers also chose easier questions. I.Q. tests require more problem solving than Dr. Zhu's memory and proofreading questions.

When Dr. Zhu's subjects were asked what red or blue made them think of, most said that red represented caution, danger or mistakes, and that blue symbolized peace and openness. Subjects were quicker to unscramble anagrams of "avoidance related" words like "danger" when the anagrams were on red backgrounds, and quicker with anagrams of positive, "approach related" words like "adventure" when they were on blue backgrounds.

The study also tested responses to advertising, finding that advertisements listing product details or emphasizing "avoidance" actions like cavity prevention held greater appeal on red backgrounds, while ones using creative designs or emphasizing positive actions like "tooth whitening" held more appeal on blue.

When the participants were asked if they believed red or blue would improve performance, most said blue for both detail-oriented and creative tasks. Maybe, Dr. Zhu said, that is because more people prefer blue.

The study did not involve different cultures, like China, where red symbolizes prosperity and luck. And it said nothing about mixing red and blue to make purple.

Colors cannot be assigned objective meanings because **cultural expectations and experience play a large role in a viewer's response**. This is a *good thing:* it means **the symbolic power of color is continually renewing itself**, adapting to the range of color experience in a culture at any historical moment. "Color theorists" perversely want to fix this symbolic power once and for all as a universal language of color, a kind of chromatic Esperanto. Their theories (and Esperanto) haven't gained wide support because people much prefer to use the color codes (and color terms) that grow from their culture and social situation. Case in point: most German and French color symbolists claimed that red is a "sensual" or "earthy" color. The Russian Wassily Kandinsky used red as the "spiritual" color. Why? Well, in rural Russia, the "red corner" of devout peasant homes that is, a corner actually painted bright red is where religious icons were displayed.

color theory describes color as an *external fact with consistent properties,* when all the available evidence about color suggests exactly the opposite: **color experience is completely dependent on the physical, visual, artistic and cultural context**. Color is not an essence that inspires us directly, like a holy ghost or a jolt of electricity. Abstract color ideas divert attention from the material presence and power of a work of art. Artists paint with paints, not with colors:

paint is on the paper or canvas, color is in a viewer's mind.

conclusion

This survey of modern color theory has covered a lot of ground, so to facilitate reference the color theory principles have been been collected together on the page summary of modern color theory (http://www.handprint.com/HP/WCL/princsum.html), with links to the section in the modern color theory where each the principle is explained.

My critique of traditional color theory has focused on three key themes:

traditional color theory treats color perception as a fixed or mechanical process, generalizing from limited color demonstrations to the entirety of visual experience. This is the **limited validity** of traditional color theory it inhabits only a very small part of visual experience.

traditional color theory treats color perception in the abstract, in terms of "red" or "green" as color concepts or color ideas, which omits attention to the specific quality of a color (a light valued, desaturated red orange; a mid valued, intense blue green), and to the material basis of the color as light, surface or paint. This is the **abstract description** in color theory.

traditional color theory simply has not kept up with the enormous advances in color science in the 20th century. Artists are today taught the same rules, formalisms and color concepts that were developed in the 18th and 19th centuries. This is the **antiquarian emphasis** in color theory.

Put simply: color theory developed through contrasting colored squares may, in the end, only help you to understand ... colored squares.

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