The Fourth Dimension of Color & the Dual Color Wheel: New Theories Relevant to Artists

by Stephen Knudsen

If you've ever attempted to mix some envisioned color but were unable to do it, you know what I'm talking about when I say that something has been missing from established color theory literature. For many of us this may have first occurred when an educator had us paint a color wheel with three primary colors. In theory, these three colors, when mixed, were to produce all other colors on the wheel. Often it did not quite work out. More importantly we may have settled for some inferior color quality in a work of art because we could not achieve the colors we imagined.

Understanding Translucency and Opacity in Pigments

The problem starts at the very beginning. Day one in a color theory course we learn that there are three dimensions of color. *Hue* is the name of the color, like cadmium red. *Value* is the lightness or darkness of the color. *Saturation* (or *intensity*) is the dullness or brightness of the color. But for anyone who appreciates access to the full power of color it probably should not stop with three.

Let us propose a fourth dimension of color: *translucency/opacity.* For those of us involved in subtractive color (*pigment*), the degree of translucency or opacity of color depends in large part on the refractive index (RI) of the pigment. Knowing this just might make all the difference the next time you are at the palette.

The refractive index (RI) of a pigment is a number usually ranging from 1.4 to 2.8. The higher the number the more a light speed of 186,000 miles/second is slowed down as it passes into the pigment molecule. Change in speed causes light to bend (refract) and when extreme enough it renders the pigment opaque. Conversely, the lower the RI, the less light is refracted and the more translucent the pigment will be when it is made into paint. One of the most translucent pigments is Indian yellow with a refractive index approximately 1.5. One of the most opaque pigments is the rutile form of titanium white with a refractive index of approximately 2.7. See the simple division calculation for the refractive index of titanium white below:

Refractive Index (RI) of Titanium White (TiO_2) =
Speed of light through a vacuum (186,000 miles per second) ÷
Speed of light through TiO_2 (68,888 miles per second) = **2.7**

Here is a simple, practical application of the fourth dimension of color. Imagine the following color problem: You are trying to replicate the vivid green that occurs when light passes through a leaf from behind. This would certainly be a very translucent, light and highly saturated green. The color would glow. Since the color quality is translucent, the place to start is with a green that has a low refractive index. Phthalo green has the very low refractive index of approximately 1.4 and thus is a good choice. Out of the tube, phthalo green is very dark so we must lighten it. See **Figure 1**.

We have a choice between two very different tinting methods here. First, we could simply physically mix titanium white into the green. See the left side of **Figure 1**. However, this creates a mixture with a higher refractive index — an opaque tint. In addition, mixing in titanium white significantly dulls the green. We could not be

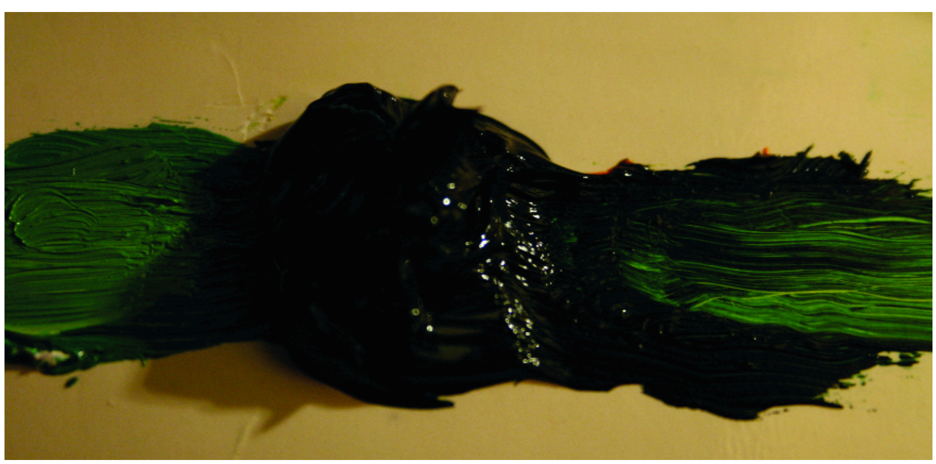

Photo courtesy of Stephen Knudsen.

Figure 1: Two Tinting Methods. The middle section is the organic pigment, phthalo green. The left side has been mixed with titanium white, an inorganic pigment. The right side is the translucent tint thinly stained over a white ground. Notice how the translucent tinting method has retained more saturation. Note: A small amount the Indian yellow was added to the original green to adjust temperature.

further from the glowing green that we are after. Instead of a bright and translucent green, we now have a dull and opaque green.

Let's try something else. This time we'll preserve the low refractive index. Take the phthalo green and simply rub (stain) it over a white surface, or add a glazing medium and glaze it over a white surface. (See the right side of **Figure 1**). This thin layer of phthalo green, superimposed over white, will become lighter as the white shows through the green. We made this tint without losing translucency or saturation. Titanium white still played a part here, but the white was never physically mixed with our green. We kept the refractive index of our green low. We achieved the desired glowing color sensation that we would see in backlighted leaves or colored glass. (Of course in different color problems the opaque tinting method has its place, as do hybrids of the opaque/translucent methods.)

Choosing Between Organic and Inorganic Pigments

An understanding of the fourth dimension of color helps us to make appropriate pigment choices. Available pigments fall into two categories — either organic or inorganic. Organic pigment molecules have carbon chains and/or rings as their core molecular structure. Phthalo green is an example of an organic pigment. Its molecular structure is shown in **Figure 2**. The pigment version of phthalo green has the low refractive index of approximately 1.4. It therefore exhibits astonishing translucency when suspended in a binding medium, such as linseed oil.

Inorganic pigment molecules do not have carbon as their basic structure. An example of an inorganic pigment would be chromium green oxide. A molecule of chromium green contains just two metal atoms of chromium (Cr) and three oxygen (O) atoms. Its molecular formula is Cr_2O_3. No carbon (C) is part of this molecule. Chromium green has the high refractive index of 2.5 and is very opaque, whether in powder form or suspended in a painting medium such as linseed oil. See the sidebar (right), which lists the usual characteristics of each pigment category.

There are *three primary organic pigments* well worth memorizing. These primary pigments should approximate those used in the CMYK (cyan, magenta, yellow, black) printing process. They are phthalo blue-green shade, quinacridone rose and yellow azo. These are pigments with a low refractive index and are translucent leaning, which is the rule for organic pigments. The *three primary inorganic pigments* worth memorizing are cerulean blue, cadmium red and cadmium yellow. These are pigments with a high refractive index and opaque-leaning, which is the nature of many inorganics.

To have full power at the palette, at a bare minimum it is suggested to have all six primaries listed above. Having only opaque inorganic primaries limits one to having only opaque primaries,

Image courtesy of Stephen Knudsen.

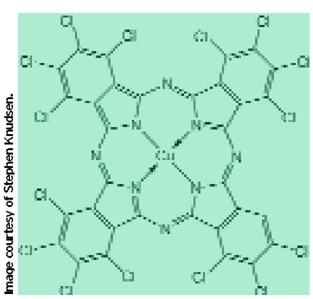

Figure 2: The molecular structure of phthalo green. This is an example of an organic pigment. The bulk of this organic molecule is made up of 32 carbon atoms, located at the empty corners of all hexagons and pentagons. Often carbon (C) is not written into the structure, but is assumed to exist at each corner.

For painters it is helpful to organize paints into these two categories: inorganic and organic pigments.

Inorganic Pigments

- All true cadmiums, cerulean, whites, etc.
- Higher refractive indexes: Many are 2.0 or more
- Many of the commonly used inorganics are opaque or semi-opaque; some of the blues are exceptions to this rule *
- Out of the tube of oil paint these are often of higher stiffness and are more matte
- Very well suited in under painting in indirect technique and very well suited for direct technique. Most are not suited for glazing other than in very small amounts to chalk up an organic glaze — common in flesh glazes
- Lower tinting strength **

Organic Pigments

- Quinacridones, azos, phthalos, Indian yellow, etc.
- Lower refractive indexed: Most organic pigments are 2.0 or less
- Most are translucent or semi-translucent
- Out of the tube of oil paint these are of lower stiffness and more glossy
- Very well suited to glazing in indirect painting technique. Also very well suited, in small quantities, for adjusting color of a mixture of inorganic pigments in direct technique and in under painting in indirect techniques
- Higher tinting strength **

* There are notable exceptions to the rule of inorganics leaning toward the opaque. For example, the inorganic ultramarine blue is a very translucent pigment. Also, the inorganic iron oxides (earth pigments) become semi-translucent when chemically hydrated. They also become semi-translucent when favorable natural impurities such as silicates are present in certain significant amounts.

** Pigments with high tinting strengths are not easily diffused in mixtures due to greater pigment particle surface area. For example, one would need very little organic quinacridone rose to make a pink when mixing into white. A lower tinting strength inorganic such as cadmium red would have to be used in much greater quantity to get a value of pink the same as the quinacridone pink.

Gamblin Artist Colors Co. clearly articulates similar category attributes in their sales literature. Most major paint manufactures will provide information on translucency/opacity. Molecular make-up, refractive indexes, production protocols, and history of pigments can be found on Web sites such as "Pigment Through The Ages," http://www.webexhibits.org/pigments/indiv/technical/indianyellow.html.

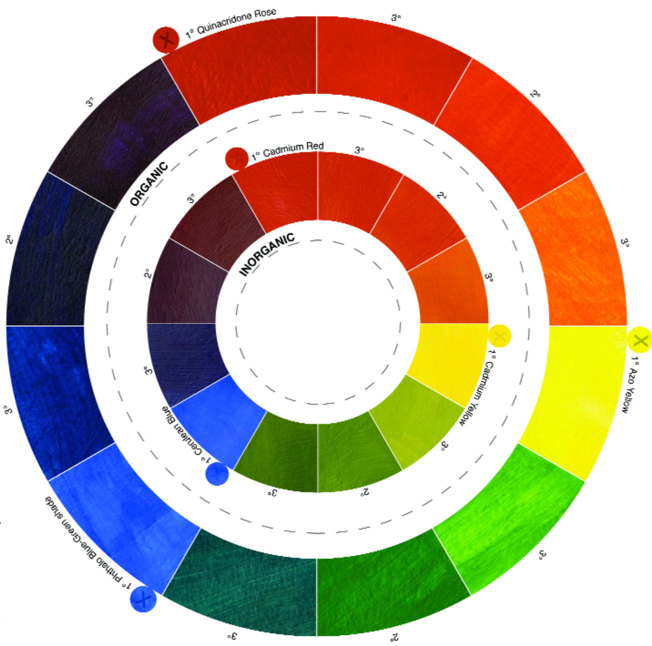

Image courtesy of Stephen Knudsen.

Figure 3: The Knudsen Dual Color Wheel. This system uses six primary pigments, three translucent on the outer wheel and three opaque on the inner wheel. This incorporation of the fourth dimension of color increases mixing power. Graphic provided by Ashley Gaffney.

secondaries and tertiaries. Conversely having only organic primaries limits one to having just translucent primary, secondary and tertiary colors (at full saturation).

It is helpful to turn the traditional subtractive color wheel into a dual wheel with three organic primaries on the outside wheel and three inorganic primaries on the inside wheel. See **Figure 3**: Knudsen Dual Color Wheel. With this system, rather than the traditional subtractive wheel, one should be able to come closer to creating any desired color. Being open to both organic and inorganic options as well as a mix of the two categories gives more power to get the job done.

Choosing the Right Medium

There is another important factor having to do with the translucency/opacity that artists can control. The refractive index (RI) of the chosen medium (*binder*) should be considered. The greater the disparity of refractive indexes (pigment molecule to its binder) the greater the push toward opacity. All powdered pigment (without a binder) is surrounded by air. Air has a very low refractive index of 1.0. Therefore in powder form, Indian yellow, even with its low RI of 1.52, is opaque in air because of the large **(.52)** difference in refractive indexes. But when the Indian yellow molecule is surrounded by linseed oil, the pigment is rendered translucent. This is because the RI of linseed oil is 1.47 and thus the disparity between oil and Indian yellow is a negligible **.05 (1.52-1.47)**. In short, one's choice of binder affects opacity/translucency. For instance egg yolk, with an RI of 1.42 is less than the RI of linseed oil at 1.47. Looking at these two numbers we can see that the RI of oil is closer to the 1.52 RI of Indian yellow. Therefore, Indian yellow in linseed oil is more translucent than the same Indian yellow as egg tempera.

Create Your Own Dual Color Wheel

It is best to see the dual wheel constructed with all six of the actual primary pigments as noted in the system above, rather than seeing it in a CMYK color plate. Try making it in paint. The advantages of this dual system over the single subtractive color wheel will then become even more evident. The traditional single wheel is either too translucent-biased or opaque-biased depending on the three primaries chosen. In the dual wheel system, three low-refractive index primaries and three high-refractive index primaries open up color nuance options and take one much closer to creating any desired color.

Of course in any system, the chosen pigments will not fit perfectly at any theoretical primary position. These pigment imperfections, though often slight, give reason to add pure (not mixed) secondaries to the palette, such as green, violet and orange. To get full power, add two greens: one opaque (high RI) and one translucent (low RI). Do the same for the violet and the orange. Many artists have noticed the futility in trying to make a CMYK plate perfectly replicate the true color fullness of a painting. Though better, even in the high-end printing process — Pantone's Hexachrome (CMYKOG) system — complete replication is impossible.

Using Color Theory in Practice

Let us look at some practical applications of painting with pigments from a system with a fuller range of refractive indexes as in the Dual Wheel (**Figure 3**). Imagine painting an ear with the light raking across the surface of the ear. Imagine a second example with the light passing through the ear from behind, causing parts of the ear to glow red. With the raking light, one can use primarily the opaque inorganics and capture the observed color — rendering the backlighted ear would benefit from a very different method. The glowing light in the thin areas of the ear could be captured with an organic glaze or stain mixed with a small amount of white. The thicker areas of the ear, where light penetration wanes, could then be captured primarily with inorganic pigments such as umbers, siennas, cerulean blue, cadmiums, etc.

Take a look at the painting, *Mortality* (see **Figure 4**). This was a work where technical issues were better solved using the dual wheel theory. The six dual wheel primaries, plus titanium white, made up the bulk of the palette. Pure secondary pigments (both organic and inorganic) were also added to the palette. Flesh areas were worked indirectly, moving from early layers with a greater proportion of inorganic pigments to later layers with a greater proportion of organic pigments. This decrease in pigment refractive index from layer to layer helps to simulate the complexity found in real flesh. It gives a quality of subsurface nuance and light scattering found in real flesh.

A caustic network created by complex light and water interactions can be another challenging color problem. A *caustic net-*

Figure 4: *Mortality* by Stephen Knudsen. Oil on canvas, 72" x 72". All the formal painting decisions, especially concerning color, were used to accentuate this woman's athletic, intellectual and spiritual strength. Questions concerning all four dimensions of color were carefully considered working toward this end.

work is the pattern created on a surface such as a riverbed when the surface waves act as positive and negative lenses focusing and defocusing light. In areas where light is focused, the color can be extremely light and saturated. In the painting, *Mortality* (**Figure 4**), such glowing areas were created solely with organic pigments such as Indian yellow and quinacridone rose glazed or stained over the light ground. The glowing orange areas in the water are an example. Other light areas in the water that were surface reflections, but not caustic networks, such as the stone and flesh reflections, had greater reliance on opaque inorganic pigment mixes including titanium white. These lights therefore became chalkier and duller.

In short, painting certain subjects may often require the solving of complex color problems — be it the desire to emulate a color sensation in nature or anything the mind can conjure. Using a pragmatic color theory that takes into account issues of translucency/opacity is well worth consideration. **AC**

Stephen Knudsen is a color theorist and has taught introductory and advanced color theory, design, and painting for the past 19 years at the Savannah College of Art and Design. He also taught high school biology and chemistry for four years. He is a painter with an international exhibition record. E-mail: sknudsen@scad.edu, website: www.steveknudsen.com