The Polar Color System

This paper proposes a Polar Color System (PCS) model to explain human color perception. The PCS model represents mentally perceived colors as points residing on the three-dimensional surface of a four-dimensional hyper-sphere. The advantages of PCS over other color systems is that PCS reveals the full spherical symmetry of mental color perception, and remarkably, it also gives us the opportunity to potentially answer the age-old question of how it is that we perceive the subjective experience (i.e. "qualia") of colors within our minds (e.g. how we see "red" in our "mind's eye").

PCS is a modification of the Munsell Color System (MCS) and the Natural Color System (NCS), both of which are based on Ewald Hering's opponent process hypothesis of color vision. MCS and PCS represent colors as objects in a three-dimensional space (Figures 1 and 2). They both start with a central column of neutral gray colors with White at the top and Black at the bottom. MCS refers to this set of colors in terms of "value" that can range from 0=Black to 5=Neutral Gray to 10=White. NCS refers to this as "degree of blackness" (or "degree of "svartness" where "Svart" is Swedish for Black), whose values range from 0=White (W) through 50=Neutral Gray (N) to 99/100=Svart (S). Surrounding the central column is a ring of two sets of "opponent" colors (Yellow-Blue and Red-Green), along with intermediate colors, which both systems refer to as "hues".

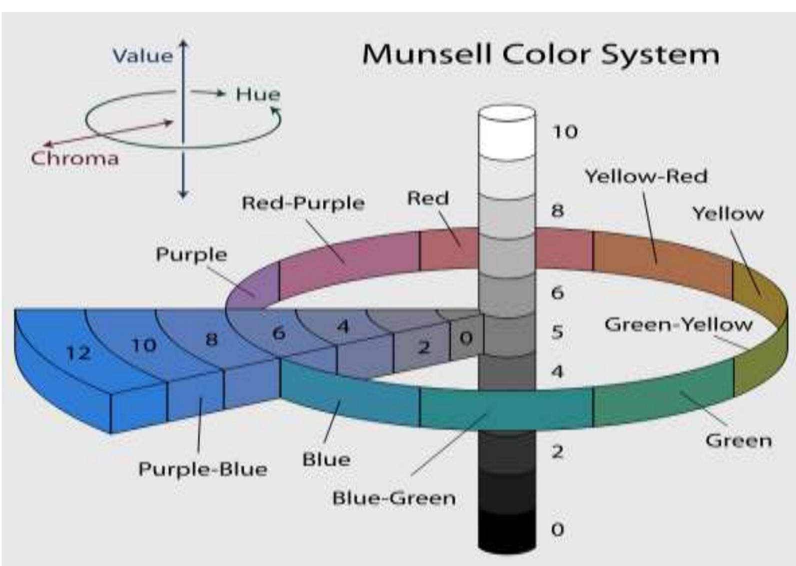

Figure 1 - Munsell Color System, collected from Wikipedia, https://en.wikipedia.org/wiki/Munsell_color_system

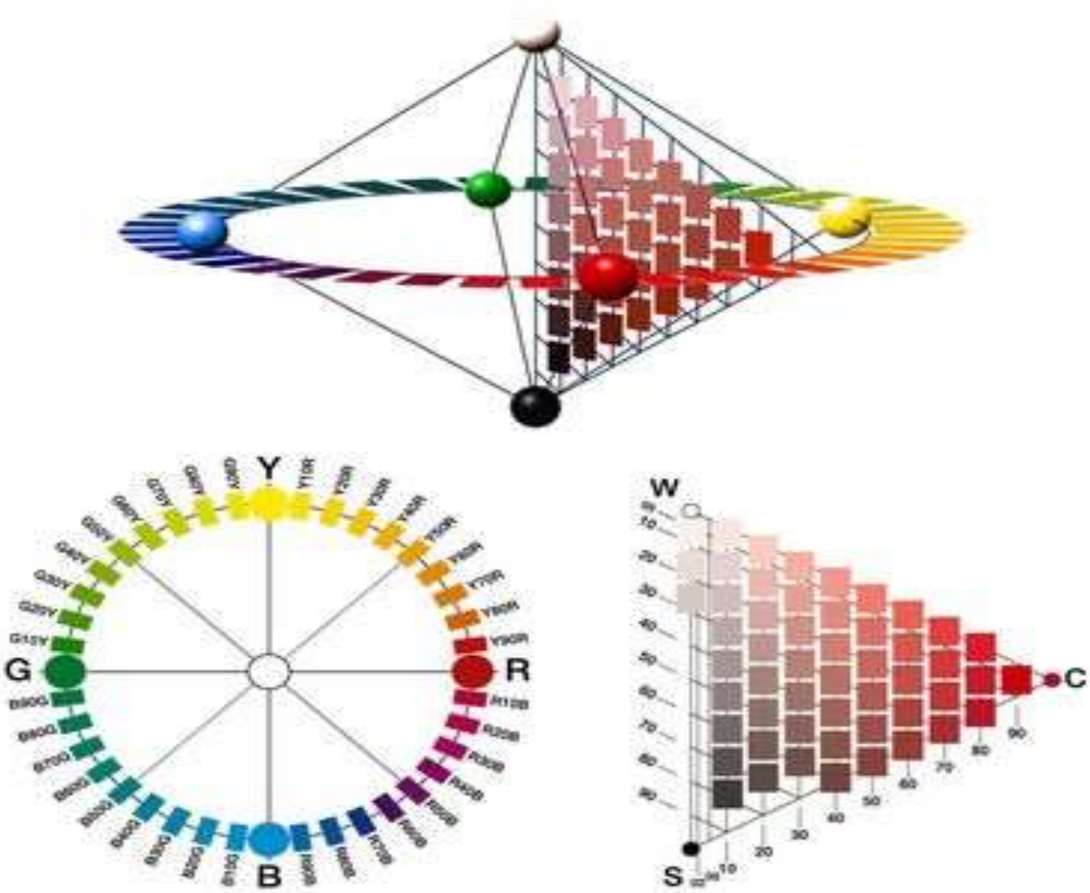

Figure 2- NCS Color System, collected from
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PCS modifies MCS and NCS by moving the central column of neutral gray colors onto the surface of a hemisphere, as shown in Figure 3. The location of each gray color point is then defined in PCS by the polar coordinate angles φ_1 and φ_2.

PCS angle φ_1 is defined as the angular distance of each color point from 0^o at Neutral Gray (N) to 90^o at the edge of the hemisphere, either at pure White (W) or pure Black (S). This is similar to longitude on a world map with N at the North Pole, except that N in PCS is defined at 0^o. (Note that the Neutral Gray (N) color in PCS corresponds to MCS Value=5 on the Munsell neutral color column, and NCS=50 on the NCS neutral color column.)

PCS angle φ_2 is defined as the angular distance from White (W) along the great circle that intersects White (W) and Black (S), and that is perpendicular to the half-circle defined by White-N-Black. This is similar to latitude on a world map with White (W) on the Prime Meridian.

So on the PCS hemisphere, pure White (W) is located at $(\varphi_1, \varphi_2) = (90^\circ, 0^\circ)$ which corresponds to MCS Value=10 and NCS=0. Pure Black is located at $(90^\circ, 180^\circ)$ or $(90^\circ, -180^\circ)$, which corresponds to MCS Value=0 and NCS=99/100. φ_2 for Neutral Gray (N) is arbitrary, so it is denoted with *. Intermediate light gray colors between Neutral (N) and White (W) are located at $(\varphi_1, 0^\circ)$, where φ_1 ranges from 0° at N to 90° at W. Intermediate dark gray colors between Neutral (N) and Black (S) are located at $(\varphi_1, 180^\circ)$, where φ_1 ranges from 0° at N to 90° at S. For example, light-gray with lightness half-way between Neutral and White is located at $(45^\circ, 0^\circ)$ (MCS=7.5, NCS=25).

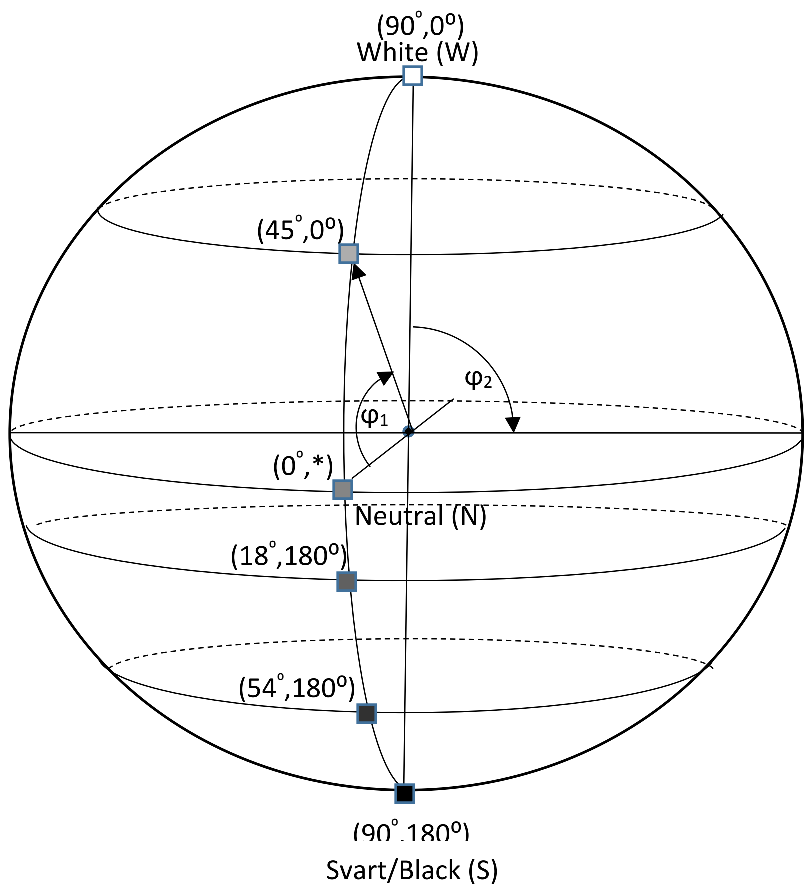

Figure 3 - PCS Neutral Colors

Colors other than White-Neutral-Black (or "hues") are added to PCS by mapping opponent colors on the PCS hemisphere orthogonal to the White-Neutral-Black half-circle arc and centered at N. The first set of opponent colors to be mapped is Blue-Yellow, as shown in Figure 4.

The Blue-Yellow color locations on the PCS hemisphere are also defined by the polar coordinates φ_1 and φ_2. φ_1 is the same angle that defined the Black-Neutral-White colors in Figure 3. But when the Blue and Yellow hues are added, φ_1 now defines the degrees of separation of the hue from Neutral, which corresponds to the "chroma" (or "chromaticness") of MCS and NCS. Negative φ_1 corresponds to the Blue hue, from pure Blue at φ_1=-90^o to pure Neutral at φ_1=0^o. Positive φ_1 corresponds to the Yellow hue, from pure Neutral at φ_1=0^o to pure Yellow at φ_1=+90^o.

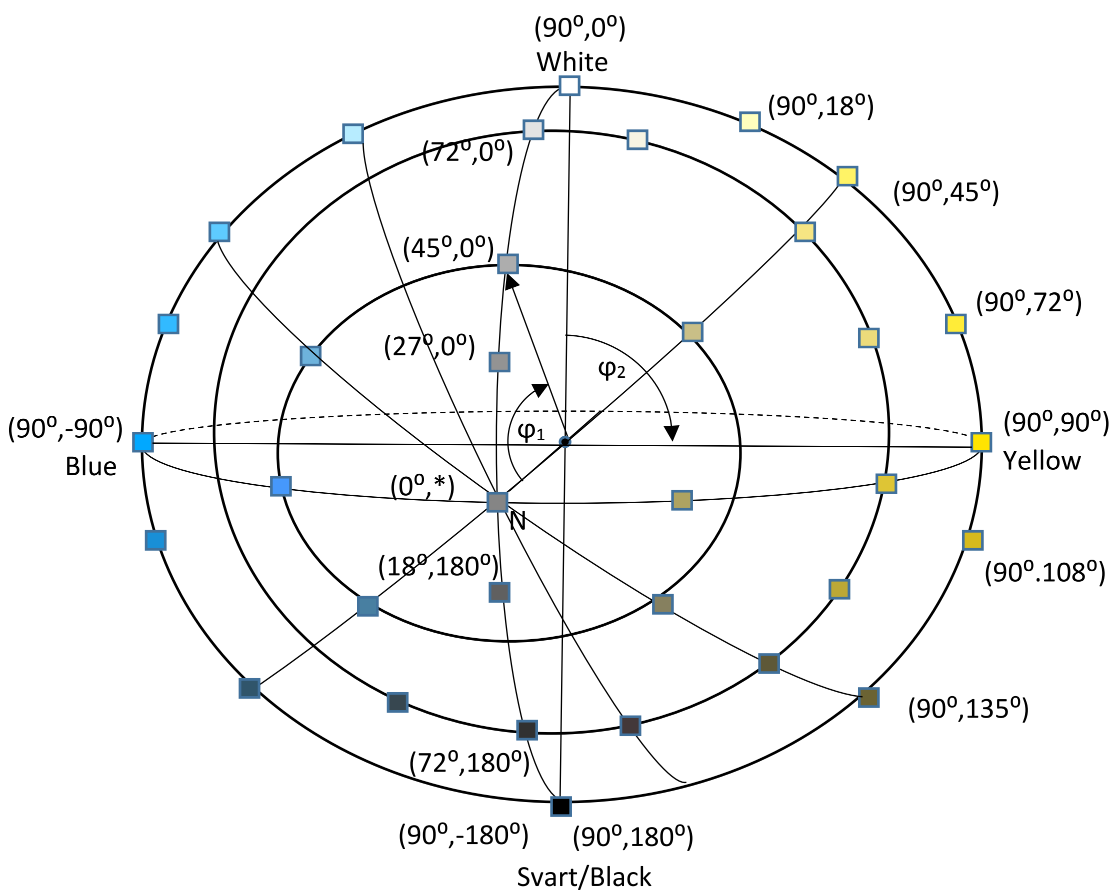

Figure 4 - PCS Blue-Yellow Hemisphere

Values of φ_2 define the degree of lightness or darkness of the hue. Lightness refers to the amount of White that mixes with the hue. Darkness refers to the amount of Svart/Black that mixes with the hue. For the Yellow hue, the lightness varies from $\varphi_2=0^o$ at pure White to $\varphi_2=90^o$ at pure Yellow, and darkness varies from $\varphi_2=90^o$ at pure Yellow to $\varphi_2=180^o$ at pure Black. For the Blue hue, the lightness varies from $\varphi_2=0^o$ at pure White to $\varphi_2=-90^o$ at pure Blue, and darkness varies from $\varphi_2=-90^o$ at pure Blue to $\varphi_2=-180^o$ at pure Black.

The PCS Blue-Yellow hemisphere of colors can be mapped to the NCS system by projecting the PCS Blue half-hemisphere onto a two-dimensional NCS Blue color triangle, and the PCS Yellow half-hemisphere onto an NCS Yellow color triangle. Figure 5 shows the PCS Blue-Yellow hemisphere colors with their corresponding NCS color notations. For example, pure light yellow half-way between White and Yellow, i.e. PCS $(\varphi_1, \varphi_2) = (90^o,45^o)$, corresponds to NCS 0050-Y.

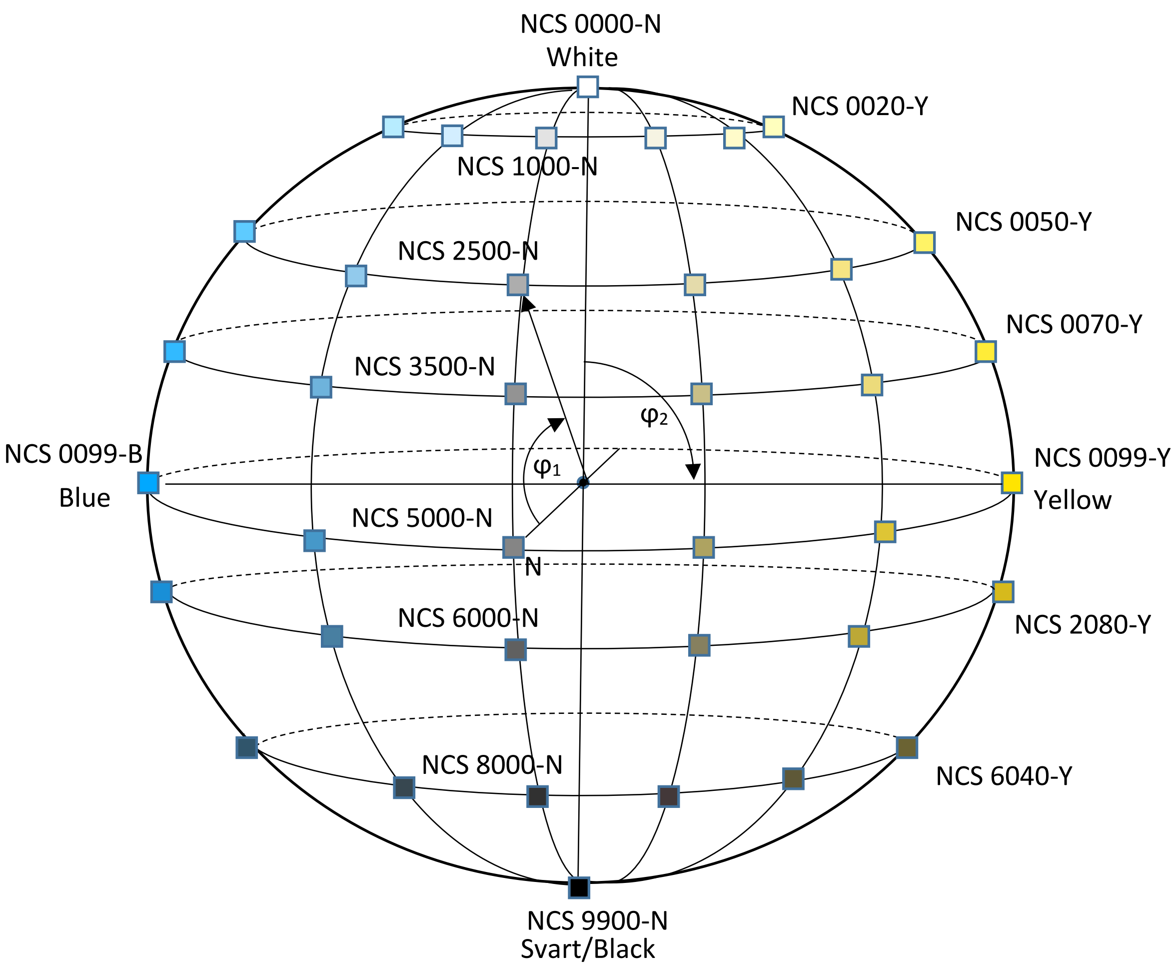

Figure 5 - PCS Blue-Yellow Hemisphere with NCS Notation

The Red-Green opponent colors are added to the PCS hemisphere by adding a third dimension that is orthogonal to both the White-N-Black and Yellow-N-Blue half-circles and centered at N. Values for Red-Green hues are defined by adding a third polar coordinate φ_3 that is defined as the degrees of separation from Yellow. So $\varphi_3=0^o$ at Yellow, $\varphi_3=90^o$ at Red, $\varphi_3=180^o$ at Blue, and $\varphi_3=-90^o$ at Green.

Unfortunately, when a third dimension is added to the PCS hemisphere surface, the surface extends into four dimensions, so it can't be shown in totality directly on the page. However, different portions of the hemisphere can be shown successively in multiple figures, in order to help visualize the full surface. For example, Figure 6 shows a portion of the surface without White and Black, and without angle φ_2.

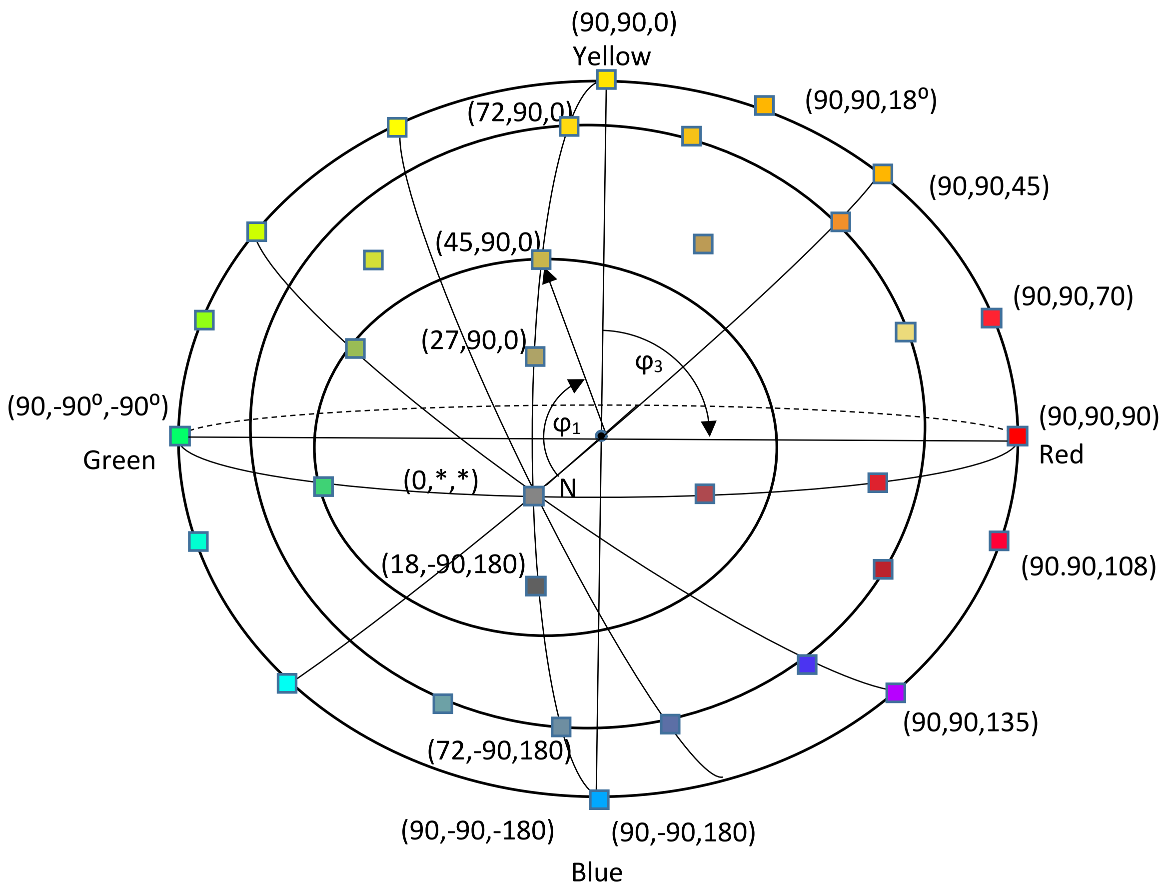

Figure 6 - PCS Yellow-Red-Blue-Green Hemisphere (w/o White-Black)

In Figure 6, the three dimension coordinates (90,90,90) given for Red indicate that it is located 90^o from Neutral (N) along angle φ_1, then 90^o from White (W) along angle φ_2 (not shown) , and then 90^o from Yellow (Y) along angle φ_3. Other dimension coordinates are similar. The hues in Figure 6 represent different levels of mixing between Yellow, Red, Blue, Green and Neutral Gray. In the Munsell MCS system, this corresponds to a disk of hues with varying chroma at Neutral Value = 5. In NCS, it corresponds to the horizontal intersection of all the color triangles at a degree of blackness (svartness) = 50. So the PCS ring of pure hues at φ_1=90^o corresponds to the MCS color ring at Value=5, and to the NCS color ring at blackness=50.

Figure 7 below shows a different portion of the hemisphere, with the pure Red-Green hues mixing with White-Black, and without Yellow-Blue. The mixing of Red-Green with White-Black is analogous to the mixing of Yellow-Blue with White-Black as shown previously in Figure 4.

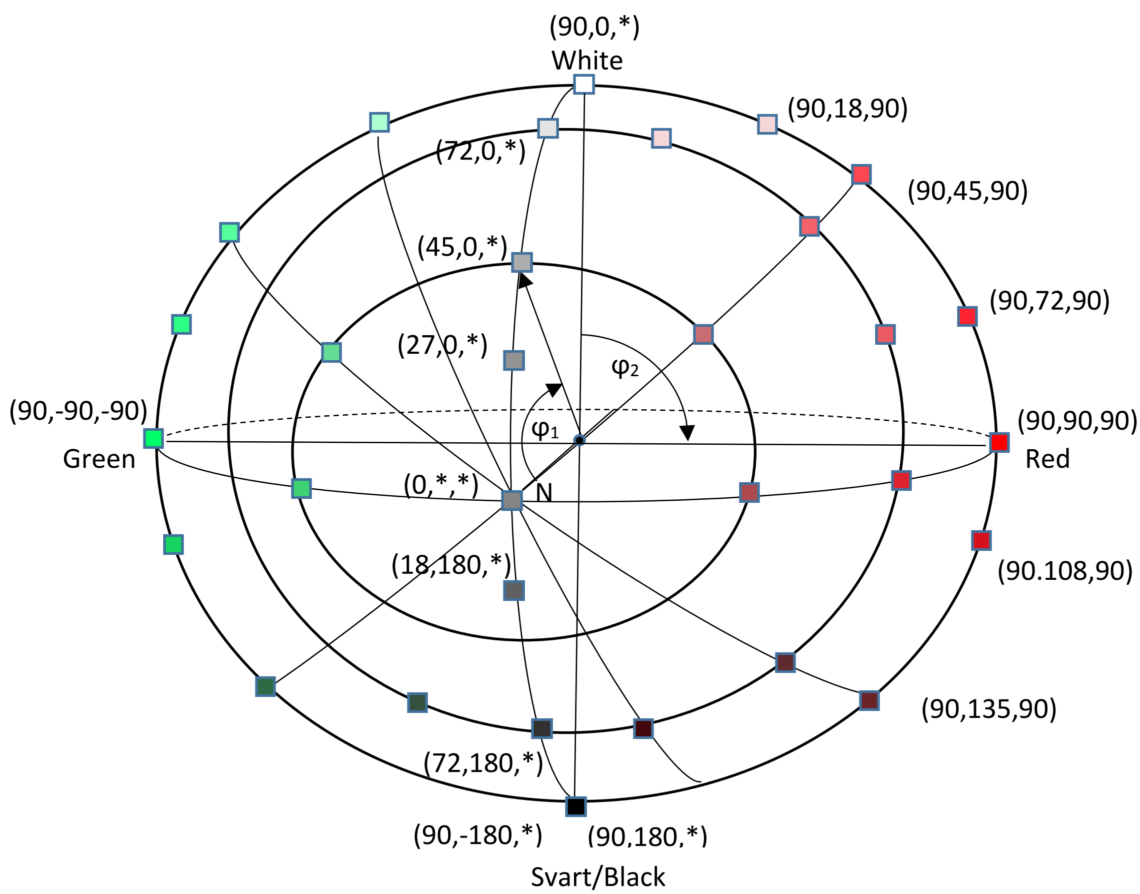

Figure 7 - PCS Red-Green Hemisphere with White and Black

In a manner similar to the mapping of Yellow-Blue hues to the NCS system discussed above, the Green half-hemisphere of Figure 7 can be mapped to the NCS Green color triangle, and the Red half-hemisphere can be mapped to the NCS Red color triangle.

The mixing of White-Black with color hues intermediate to the primary Yellow-Red-Blue-Green hues can be shown on PCS hemispheres with φ_3 angles other than -180⁰, -90⁰, 0⁰, +90⁰ and +180⁰. For example, the Orange hue half-way between Yellow and Red has a φ_3 angle of 45⁰. (This corresponds to Y50R on the NCS color ring.) The opponent color to Orange is Blue/Green, which is half-way between Blue and Green, and has a φ_3 angle of -135⁰ (B50G in NCS).

Figure 8 shows the PCS hemisphere portion for Orange and Blue/Green mixtures with White-Black.

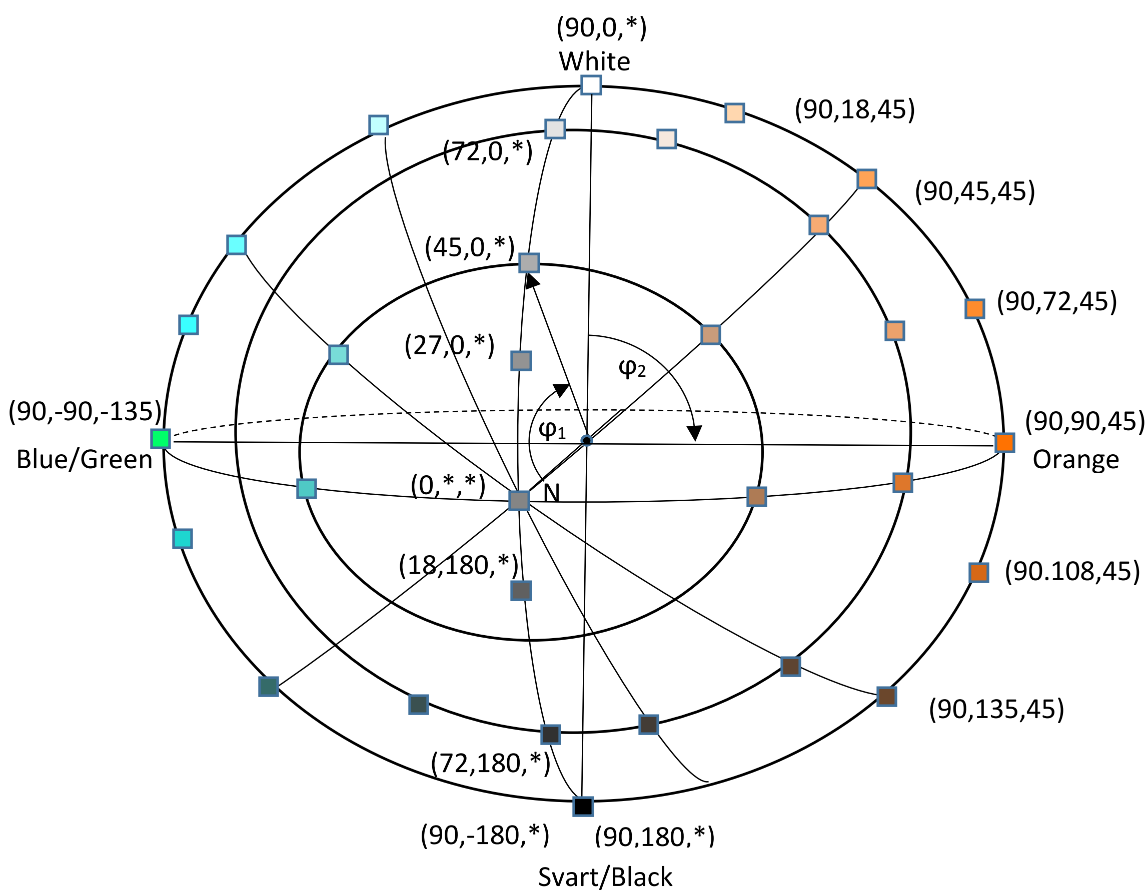

Figure 8 - PCS Orange - Blue/Green Hemisphere with White and Black

Projection of 4D PCS Hemisphere into 3D

There are other ways to visualize the full three-dimensional PCS surface. For example, the portion of the hemisphere defined by only the φ_1 angle with N at the peak can be "projected" or "flattened" onto a lower dimension. To see this, consider first how projection might work in lower dimensions, e.g. for the two-dimensional surface of one of the hemispheres of a three-dimensional sphere. For example, consider the two-dimensional hemisphere surface shown in Figure 7 for the mixing of Red-Green and White-Black with N at the peak. That surface can be projected onto a two-dimensional solid circle (or "disc") with N at the center by flattening the φ_1 angle onto a line, as shown in Figure 9.

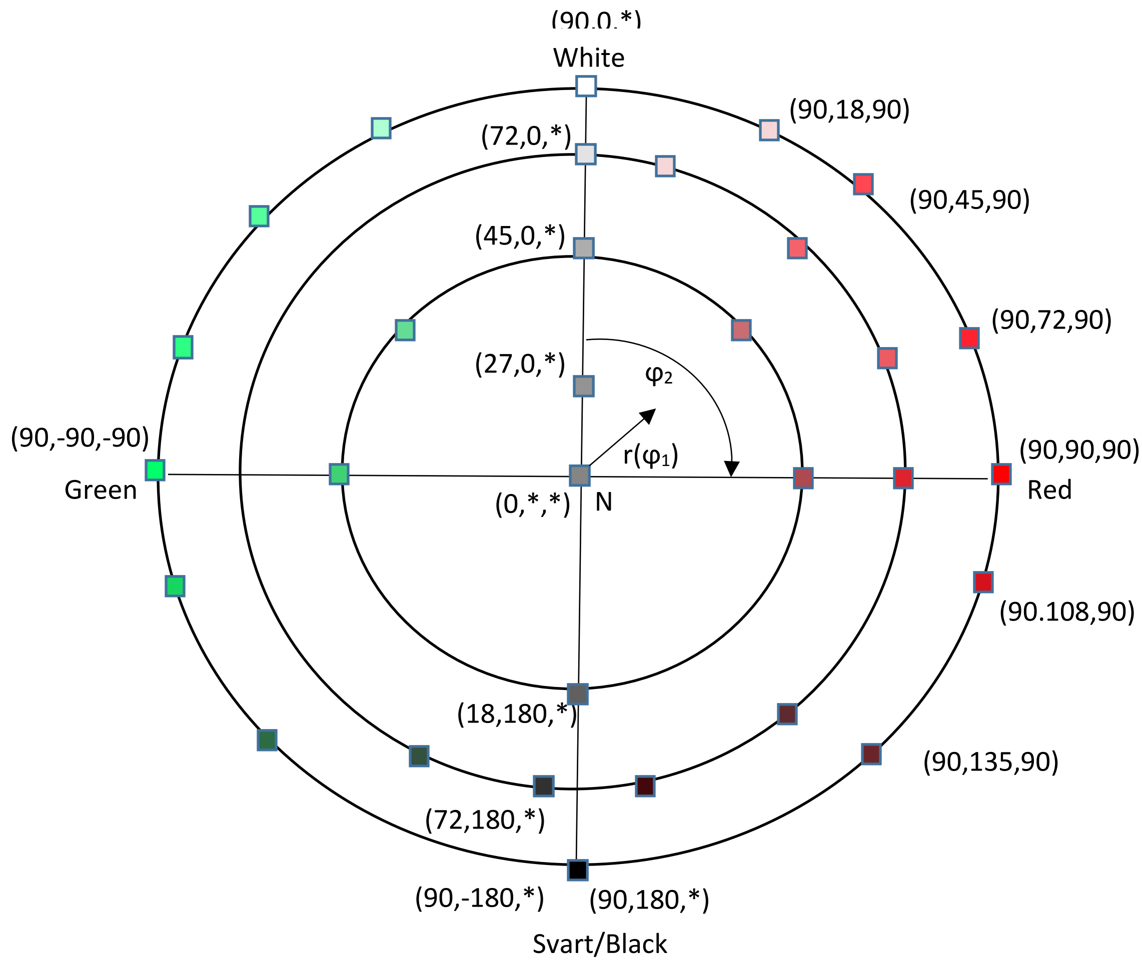

Figure 9 - PCS Red-Green White-Black Hemisphere Projected Onto 2D Disc

In Figure 9, the φ_1 angle of Figure 7 has been replaced by a distance, or radius, vector from the Origin N to the color points on the disc. So in the projection, φ_1 becomes like a radius (r) polar coordinate. In Figure 9, two concentric inner circles are shown inside the outer circle at φ_1=45 and φ_1=72. In the full visualization, the disc would be filled with nested concentric circles all the way from the outer circle to the midpoint at N. The projected disc can be restored to a hemispherical shape by "pushing" the midpoint N out into the third dimension.

In a manner analogous to the above projection of a two-dimensional hemisphere surface onto a flat two-dimensional circle, the full three-dimensional PCS hemisphere surface can be projected onto a three-dimensional solid sphere, as shown in Figure 10.

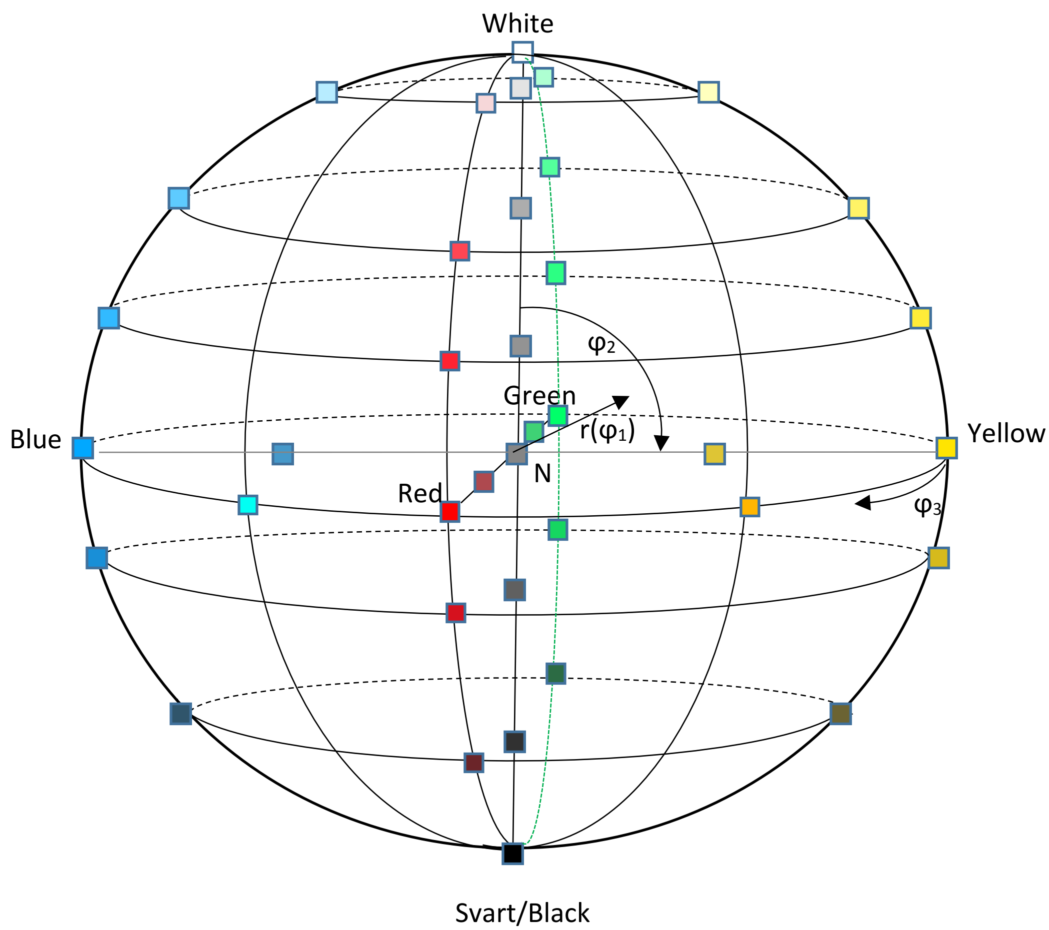

Figure 10 - PCS Hemisphere Projected Onto Solid 3D Sphere

In Figure 10, the Neutral (N) north pole of PCS has been projected into the center of a solid three-dimensional color sphere. The totally non-neutral hues White, Black, Yellow, Blue, Red and Green and their non-neutral intermediates (e.g. Red-Blue, Blue-Green, Green-Yellow, Orange, Light-Red, Dark-Red, etc.) have now been projected onto the outer surface of the sphere. Partially neutral hues have been projected onto the surfaces of smaller, concentric spheres, and are not shown, for clarity sake. But some partially neutral hues are shown on the axis lines from N to White-Black-Yellow-Blue-Red-Green.

Figure 11 shows the PCS projected spherical surface for half-neutral hues (i.e. "half-chromaticized" or φ_1=45°). The sphere's diameter is half that of the outer sphere shown in Figure 10.

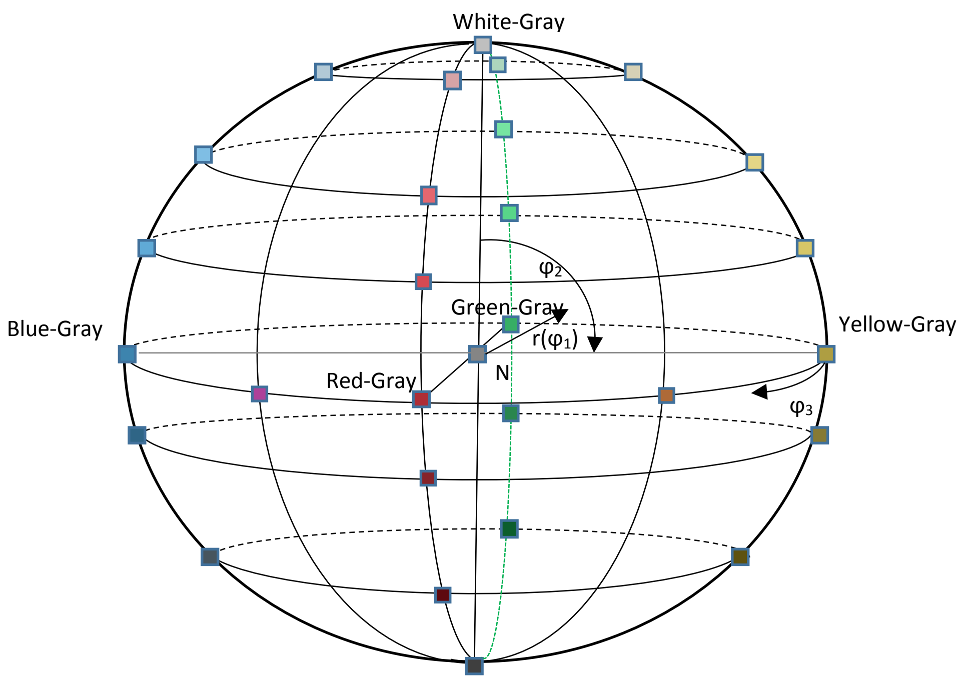

Figure 11 - PCS Hemisphere Projection - φ_1=45°

The projected spherical surface of Figure 11 fits inside the spherical surface of Figure 10, along with an infinite number of other nested spheres at different levels of chromaticness, to form a solid sphere of projected PCS color points. Just as for the two-dimensional disc of Figure 9, this full set of nested spheres can be restored to its higher dimensional hemispherical surface by “pushing” the midpoint N out into the fourth dimension. (Visualizing this maneuver is a challenge.)

Interestingly, the solid sphere of PCS colors formed by the fully nested set of PCS projected 3D spheres is very similar to the 3D color space of NCS. Then why do we bother to “push” the PCS space into a fourth dimension, which is much harder to visualize? The reason is because the PCS 3D surface of a 4D hemisphere is more likely to be a better representation of the actual physical color space that is used for color qualia perception by the brain’s visual cortex, as will be explained later.

PCS Differences from MCS/NCS

One major advantage of the Polar Color System over MCS and NCS is its elegant spherical symmetry. Even though PCS is complicated by four-dimensional geometry, the simplicity of its spherical symmetry makes it likely that the PCS model represents actual human color perception more closely than MCS or NCS. If that is the case, then the color spacings in PCS will more closely match the human color experience than MCS or NCS.

Along with its geometry, PCS differs from MCS/NCS in the centrality of pure Neutral to its color scheme. In PCS, Neutral (N) is at the central north pole of all color schemes. All colors, including White and Black, mix with Neutral in the direction of their opponent color. White and Black do not have special status in PCS, as they do in MCS/NCS. In both MCS and NCS, White and Black occupy a special central column that causes them to mix with other hues in a manner different from the way that hues mix with each other. In PCS, White and Black are normal opponent colors that are positioned on the hemisphere 90^{o} from Neutral just like other hues, and that mix with themselves and with other hues just like any of the other colors.

The symmetry of PCS among the White-Black, Yellow-Blue and Red-Green colors centered on Neutral also makes it likely that the PCS model is closer to reality than MCS or PCS. This symmetry allows a single physical mechanism to explain all the PCS colors in a unified manner, as opposed to a potential mechanism that could explain a central MCS/NCS White-Neutral-Black column along with a colored sphere or cylinder around the column.

Color Blindness and Enhanced Color Acuity

For some applications, PCS agrees in principle with MCS/NCS. Since PCS, like MCS/NCS, is based on the color opponency hypothesis, it explains color blindness in a similar manner. Monochromacy (total color blindness) in humans happens when a defect in the retina's cones or rods causes only a single channel of information to be sent to the brain's visual cortex to be converted into color perception. In this situation, the brain is forced to use a single dimension of the color system. In the MCS/NCS systems, the logical choice is the White-Black dimension, since the White-Black column is central to the system. In PCS, the White-Black dimension is only one of many dimensions symmetrically positioned around the color hemisphere, so its selection is arbitrary. This means that if PCS is closer to reality, then some monochromatic people's brains may choose dimensions other than White-Black for their "Black-and-White" experience.

In human dichromacy, two channels of color information get passed to the visual cortex. In this situation, the brains of most people choose to use the White-Black and Yellow-Blue dimensions of the color system. Thus, their perception of Red-Green is reduced or eliminated.

Human trichromacy is the normal condition. Most humans send three channels of information to their visual cortex, which gives them the ability to perceive colors in all three of the PCS color space dimensions.

A (very) few people have tetrachromacy, in which four channels of color information are sent to the visual cortex. Some fish, birds, insects and animals also have tetrachromatic vision. Tetrachromacy is said to be "four-dimensional", since four levels of information are used. But the four levels can still be specified with three dimensions of color perception. For example, the avian color space can be modeled as a four-sided tetrahedron in three dimensions.

The avian tetrahedral color space does have an increased color range into the ultra-violet, as compared to the normal human color space. This increased range could be incorporated into PCS by adding ultra-violet "hues" to the Blue-Yellow dimension, or by adding another dimension altogether if ultra-violet has its own opponent color.

Some birds and butterflies may have pentachromatic color vision, in which five channels of color information are sent to the visual cortex. Mantis shrimp can have up to sixteen channels of color information. These additional channels may provide increased color differentiation acuity, they may reduce the requirements for mental vision processing, and they may provide increased sensitivity to ultra-violet light and polarized light. But they don't appear to add more dimensions to the color space.

PCS Explanation of Color Vision Perception (How We See "Red")

As mentioned above, the spherical nature of PCS provides a natural explanation for how color qualia information might be sent to the brain's visual cortex. This is because a single point source can be used to deliver a spherical distribution of colors that become available to a receiver. Consider a dance floor rotating disco ball. That disco ball is a small object whose two-dimensional surface can transmit a spherical distribution of lights and colors into a large three-dimensional room. This idea can be extended up into four dimensions, in which a small four-dimensional "disco ball" could transmit colors in a spherical distribution consistent with the three-dimensional surface of a PCS hemisphere.

So how might a point object, or small microscopic spherical object, give rise to a spherical distribution of color qualia in the visual cortex? One possible route to an explanation involves the following aspects of biological brain activity:

- Homochirality
- Chiral-Induced Spin Selectivity (CISS)
- Conscious ElectroMagnetic Information (CEMI)

Homochirality

Chirality is an asymmetry in an object in which the geometry of the object cannot be superimposed on its own mirror image. For example, a human hand is a chiral object. The mirror image of a right hand is a left hand, which cannot be superimposed on the right hand. (That's why a right-handed glove won't fit on a left hand.)

A chiral molecule is an asymmetric molecule whose molecular structure cannot be superimposed on its own mirror image. Similar to human hands, chiral molecules are either left-handed or right-handed. Biological molecules are typically chiral, and large biological molecules made up of chains of chiral building-block molecules are always "homochiral", i.e. their chains contain either 100% left-handed or 100% right-handed molecules. For example, amino acids in biological cells are always 100% left-handed, and carbohydrates in cells are always 100% right-handed.

In contrast, non-biological mixtures that contain chiral molecules are almost always "racemic", i.e. they contain equal amounts of right-handed and left-handed molecules. It is not known exactly how homochirality emerged in the origin of life. However, because of the enormous entropic costs required to build and maintain homochirality, it appears that it must be essential for the existence of life, as discussed in the next section.

Chiral Induced Spin Selectivity (CISS)

Homochiral molecules within living cells are capable of acting as spin filters that can select and synchronize the spin of the electrons streaming through them. This spin synchronization leads to quantum coherence of the electrons, which greatly increases the transmission yield and efficiency of the electron flow. This increased yield and flow allows living cells to function with much lower input energy requirements and waste heat production than any non-biological system. For example, a supercomputer that matched the processing speed and functionality of a 10-watt human brain would require enough energy to power a building.

CISS is what allows living cells to manage and operate an astronomical amount of coordinated biological processes with limited amounts of energy extracted from the sun and the environment, and without overheating and burning themselves up with excess waste heat. Synthetic chemist James Tour gives an interesting explanation of the biological requirements for homochirality and CISS in Episode 11 of his lecture series on "Abiogenisis: Origin of Life."

Conscious ElectroMagnetic Information (CEMI)

Chiral-Induced Spin Selectivity in living cells leads to Quantum Coherence, Quantum Entanglement, and Quantum Criticality within the cells. Within brain cells, these quantum effects lead to Quantum Consciousness. There are many exciting areas of research being conducted today in Quantum Consciousness. One of these areas that applies to color perception is Conscious ElectroMagnetic Information (CEMI).

In CEMI theory, neurons in the brain generate synchronous coherent patterns in an ElectroMagnetic (EM) field. Multiple neurons provide input that is integrated into a single EM field. A component of this EM field is then transmitted back to other neurons to form a single subjective experience of consciousness. The integrated, coherent nature of the EM field is what allows the conscious mind to process and analyze multiple factors simultaneously from a complex set of information, e.g. the visual information from a human face.

The conscious experiences of color qualia are produced when color information from the retina are resolved into color hue selections within the visual cortex. When a color is selected based on the brain's processing of the visual information from a particular region of the retina, multiple neurons fire synchronously to configure that color information onto the appropriate pixel within the mental image portion of the EM field. Because of the integrated nature of the EM field, the colors of every pixel of the mental image are experienced simultaneously by the consciousness, which itself then simultaneously causes multiple output neurons to fire. That's why we are able to view and react to the entire visual field, say of a pure blue sky, as a single conscious experience.

The way that multiple pixels of the brain's mental image are configured to produce a single image may suggest an analogy to the way that a television screen's pixels are "painted" onto a TV screen. One difference, though, is that a TV paints its screen pixels one-at-a-time, sequentially, in a "rastor scan" pattern across and down the screen. In contrast, the brain uses massively parallel processing to simultaneously code the full set of millions of mental pixels in the visual EM field many times each second.

But what causes the actual subjective qualia of "red" or "blue" to appear in our mind's eye? PCS theory proposes that the EM field is inherently "colorized", i.e. that the EM field has a color property that is manifested based on a color orientation. Apparently, when EM particles like electrons are somehow oriented, or "polarized", in a single "direction", then the EM field that they produce exhibits a certain color hue. Perhaps the hue is emitted from the EM field in that direction, or perhaps the field acts as a window into a colorized dimensional background that shows through it.

The colorized hues of the EM field are not actually "seen" visually by the conscious mind. Instead the conscious mind directly experiences the "redness" or "blueness" of the EM field, since the EM field defines the conscious mind itself. The visual field portion of consciousness actually "becomes" red or blue, or it becomes "one" with redness and blueness, as the brain is integrated with the EM field. Then, as with other parts of the conscious EM field, the colorized features of the internal visual field cause other neurons to fire, thereby enabling the color consciousness itself to act as a causal agent for subsequent mental processing.

So when I experience the sight of a deep blue sky, my brain configures the orientation of the visual portion of its EM field so that it turns blue, and I experience that blueness directly. When I view the beautiful colors of a Notre Dame stained glass window, my brain configures the pixels of its EM visual field to act like millions of microscopic prom dance disco balls that actually fill my mind's eye with a kaleidoscope of colors. When my Dad looked at my Mother with a glint in his eye and conceived me – no, wait – that's something different.

PCS Color Dimensions

The spherical symmetries of the PCS system integrate naturally with the proposed EM colorized orientations. This is because spherical symmetries naturally occur when elementary particles interact within spatial dimensions. But how do the three color dimensions of PCS relate to the spatial dimensions of our Universe?

Since the PCS model space is a three-dimensional surface of a four-dimensional hypersphere, and since our Universe appears to be a three-dimensional surface of space that is expanding into a fourth dimension, it is tempting to assign the three PCS dimensions to the three spatial dimensions of our Universe. Indeed, we could imagine the Neutral (N) apex of the PCS hemisphere as being oriented in the direction of the universal expansion. The three PCS dimensions then become the normal three dimensions of space that we experience every day.

But this is likely not the case. The reason is because our personal physical orientation is not fixed within the three spatial dimensions. We move around and orient are brains physically in any of these directions. It is difficult to think of a process in the brain that could manage three color dimensions whose orientations are constantly moving and changing relative to the brain's position.

Instead, it is more likely that the three PCS color dimensions correspond to three higher physical dimensions of space, i.e. higher dimensions as proposed by string theory. These higher dimensions are active at the elementary particle level, but are unaffected by our physical movements in our normal three-dimensional space. In this scenario, our brains could be configured to convert visual information from the retina into colorized orientations of EM particles within the fixed reference frames of these three higher color dimensions.

The use of higher physical dimensions also gives the PCS model flexibility in case it needs to add extra dimensions, e.g. in the case of tetrachromacy or higher levels of color vision.

PCS Extensions

There is some evidence that the perceptual color space may involve more or different opponents than the standard Yellow-Blue and Red-Green. For example, Pridmore (2012) proposes three complementary colors Yellow-Blue, Red-Cyan and Green-Magenta. And, as we've mentioned before, avian color space indicates that the opponent pair Yellow-Blue may be extended into Yellow-UltraViolet. Any of these configurations can be incorporated into PCS by adding opponent color dimensions as required, and by modifying the color sequences within each dimension.

Another potential extension to PCS is to add other sensory qualia that are not limited to color vision. Along with vision, an integrated qualia space can also include hearing, smell, taste and touch (and perhaps several others). In an extended version of PCS theory, these additional qualia could correspond to inherent EM properties of additional higher physical dimensions of space. Then in this extension not only does the brain's EM field become colorized, but it also "sings" in one or more audio dimensions, smells and tastes in one or more olfactory dimensions, and aches or itches in a tactile dimension.

PCS provides an interesting potential explanation for why the extra compactified dimensions predicted by string theory are included in the overall geometry of our Universe. Along with requirements for mathematical consistency, these extra dimensions may provide the means necessary for essential sensory abilities to be available for use by advanced biological life.

Testing PCS

One test of PCS is that the hue distributions and mixtures on its color surface should correspond more closely to human perception that other color systems. For example, a perfect Uniform Color Space would be one in which the same geometrical distance anywhere within the space would reflect the same amount of perceived color distance.

Direct testing of PCS activities in the brain may become possible as Quantum Consciousness research progresses. Currently the conscious EM field hypothesized by CEMI is too weak and localized inside the brain to be detected or manipulated by external instruments. If technology improves to the point where the conscious EM field can be detected or controlled within an experimental setting, then it may become possible to artificially invoke and control mental color qualia (and other sensory qualia) for testing purposes. Then the actual perceptual color space could be systematically mapped and analyzed, and compared to the PCS model and to others.