# Art, Reproduction Technology, and Science: Foundations of Understanding Color

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## ABSTRACT

*Understanding Color is the fusion of today's imaging technology with our 160-century history of making pictures. Molecular physics describes the mechanisms of light-matter interactions, while painters and picture makers have led the way to understanding how we see Color. The painter's hand is controlled by his Color Vision. While Molecular Physics happens at the atomic scale, Color Vision is controlled by neurons interacting with the entire scene. The threads of Painting, Reproduction Technology, Physics, and human Color Vision weave together to make 2020's Color.*

## 1. INTRODUCTION

Our understanding of Color is both practical and scientific. The practical part is the art of painting pictures, and the technology of reproducing scenes. The scientific part is the interaction of light and matter. Physics provides understanding of electromagnetic visible light (wavelengths between 400 and 700 nm). Some molecules (colorants) modify the wavelength distribution of the illumination's light. Other atoms and molecules emit light. All of color physics happens at a sub-microscopic, molecular scale. More important, these light /matter interactions at each location in the scene are independent of all other parts of the scene. In other words, *Molecular Physics* describes local events.

Color in practical Picture Making is different. It uses the viewer's entire visual system as the most important part of the process, whether painting a landscape, or making firmware for a camera. The picture's appearance is the output of the viewer's neural comparisons of all scene elements. Appearance (sensations) depends on the interaction of all of vision, and the entire scene. In other words, human vision uses light from all parts of the scene to make the appearance of each scene element. While local *Molecular Physics* events are necessary, vision also requires neural *Spatial Comparisons* made across the entire scene to make pictures. We know this because two identical spots of light can appear different colors in the same real-life scene.

Human fascination with Pictures Making goes back to man's earliest recorded history.

- Painting requires the combination of tools and human vision to guide the artist's hand in rendering appearances.
- *Printing* goes back to rubbings of the earliest coins, and embossed clay. An artist's hand made the master, and technology made identical copies.
- Physics describes the interaction of light and matter. Although discussed by the ancient Greeks, *Molecular Physics* has advanced most rapidly in the past three centuries.
- Color Vision research describes the mechanisms used in seeing: optics of the eye; retinal cells that respond to visible photons; nerve cell response, spatial comparison of neural response; sensations, and perceptions of color.

This talk studies these four different threads of Color. More important, it emphasizes how they weave together to influence, and advance each other. To understand Color, one has to study all of its historical threads. The long history of Picture Making is the story of artists painting and printing them. In 1800, photography and studies of light/matter interactions started the Molecular Physics technologies of film, digital sensors, and displays of today.

Picture Making's biggest challenge is rendering the real-world's High Dynamic Range (HDR) of light. Painters met that challenge in 1500, and physics-based technology is fighting with it today. This talk uses HDR imaging as a test of Picture Making, and a signature of human Color Vision's mechanisms.

## 2. SNAPSHOTS IN TIME

Color becomes much more interesting when we compare the threads at the same time in history. While painting and printing made significant developments centuries earlier, physics and color vision research have recently caught up in importance for the future. The following snapshot examples illustrates how these historical threads interacted.

In 1500, at the height of the Italian Renaissance, painting was revolutionized by the use of perspective and chiaroscuro (light and dark rendition). Perspective imposed scientific rules controlling the size relationships of objects in the scene. Leonardo da Vinci invented chiaroscuro to unify the rendition of light and shadows throughout a painting. This began the rendition of High Dynamic Range (HDR) pictures. Also, Leonardo observed that colors appear most beautiful when surrounded by their opposites.

Around 1700 Newton's physics experiments separated white light's different "refrangibilities" (wavelengths) that appear red, yellow, green, blue and violet colors. He used a second prism to recombine those wavelengths into white light. Newton's Color Vision observation was:

*"For the Rays to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour."* [1] The double prism experiment, separated the physics of light from the action of human vision, namely "stirring up a Sensation". Also in 1700, Mezzotint printing plates became popular for their efficiency. By using different "rocker" tools to roughen metal plates, printers formed different tone textures, that transferred different amounts of ink to the print paper. LeBlon used three color, plus a black mezzotint plates to become the color printmaker for the French court. In Holland, Vermeer painted "Girl with Pearl Earring" rendering the model and the scene's illumination in a remarkable HDR portrait.

In 1802, Thomas Young wrote "On the Theory of Light and Colours" with a footnote suggesting that human Color Vision was trichromatic. That footnote does not explain his observation. Color-printing was everywhere in London at the time. LeBlon's 1707 Mezzotints show an example of theory following practice. in 1810, Goethe, the German poet, began a psychological branch of Color by attacking Newton's work and Newton's character. Rather than repeating Newton's experiments, Goethe held a prism in front of his eye. He did not understand what he saw. Goethe's reports about afterimages, and opponent colors emphasized human vision. Goethe missed Newton's statements about "stirring up Sensations". Nevertheless, he started two centuries of debate on the relative importance of light vs. vision.

Today, Molecular Physics has produced color pictures with remarkable improvements in the control of spectral light, with much better color purity and chroma. Color Vision research has provided many more details and measurements of Spatial Comparisons with the study of psychophysics and neurophysiology.

## 3. FRAMEWORK FOR UNDERSTANDING COLOR

Aristotle segmented his writing into books, each with related studies. This tradition of segmentation continues in Universities, with Departments, and Divisions, such as Arts, Humanities, Science, and Engineering.  But, Color is an essential part of many studies. Color does not belong to a single field: It is a fusion of all of its different parts. It builds on the integration of the best elements of competing systems.

A good example of fusion is the complete transformation of Photography over the past 40 years. In 1980, the photographic film industry made many millions of cameras and billions of photographs. By 1990, many companies made massive investments in digital photography. In 2000, mature digital products began to replace almost all film. The features of cost per picture, access to stored images, customer behavior, and especially the ability of easy transport of images on the internet morphed a very mature film industry into an entirely different digital one. Digital photography fused the best elements of old and new into today's photography.

The history of Color is the fusion of Art, Picture Making, Physics and studies of Color Vision. Some of the most important contributors to understanding color made extraordinary contributions to more than one of its fields:

- Leonardo - Painting and Color Vision
- Newton - Physics of light and Color Vision
- Maxwell - Color Matching and Color Photography
- Land - Instant Photography and Color Vision

These students of color amplified their contributions by working in several fields. Newton's double prism experiment separated different wavelengths, and then recombined them. There, he identified light's physical properties. When he described what these wavelenths looked like, he knew that he was working in another field. Newton separated the physics of light from light's action in human vision, describing it as  "stir up a Sensation".

Land was an expert in making silver halide and dye images. As soon as he saw the wide range of colors in red and white (2-color) photographs, he knew that the mechanisms controlling color appearance were fundamentally different from those controlling color in films. He knew that RGB separations, used since LeBlon, were made by local Molecular Physics interactions. He knew the human retinal receptors used the same physics-based mechanisms. Land recognized that Molecular Physics is necessary, but not enough to explain what we see. Additional mechanisms are needed to understand Color Appearance and Color Constancy. Land turned to *Spatial Comparisons across scene*.

| Year | Reported by | Idea | Field |
|---|---|---|---|
| 1000 | Alhazon | Object's light imaged on the light sensitive retina | Optics |
| 1500 | Leonardo | "Colors are most beautiful surrounded by..." | Painting, Vision |
| 1672 | Newton | "The rays are not colored ..." | Physics, Vision |
| 1707 | J.C. LeBlon | 4 color separation records, hand rockers | Color Printing |
| 1828 | Goethe | Prisms, Afterimages, Attacks on Newton | Writer |
| 1861 | J.C.Maxwell | 3 color photographic separations made with RGB | Color Photo |
| 1861 | J.C.Maxwell | Measured 3 sensitivity functions -> CIE X,Y,Z | RGB sensitivity, |
| 1872 | Hering/Helmholtz | Debate about Constancy | Psychophysics |
| 1949 | Ansel Adams | Zone System | Photographer |
| 1957 | E.H. Land | Red and White - 2 color photography | Color vision |
| 1963 | E.H. Land | 3 lightness separations to predict color - Retinex | Color vision |
| 1967 | Land & McCann | Ratio Product Reset model to predict lightness | Computer vision |
| 1968 | Hubel & Wiesel | Spatial processing in the Cortex | Neurophysiology |
| 1978 | Carver Mead | VLSI Chip design - Today's Computers | Computers |
| 1983 | Frankle & McCann | Multiresolution lightness model | Computer vision |
| 2007 | McCann & Rizzi | Calculated glare degraded retinal image<br>Receptor and neural processing | Optics<br>Matching |

**Fig. 1 List of author's foundational Ideas: Year, Idea, and Field of Study. (Historical references [2] )**

### 3.1 Personal Color Frameworks

Each of us has a personal Framework of Color. Fig.1 is the list of ideas that form the foundation of my thinking about color. It is made up of ideas from many different disciplines. In high school I loved Chemistry. In college I traveled from Chemistry to Biochemistry to Biology, while working part-time for Edwin Land at Polaroid. My work at Polaroid studied color vision, computer models of vision,, very-large format Polaroid cameras, and the reproduction of art. I set up Polaroid's first digital imaging lab in 1975 to model human *Spatial Comparisons*.

Fig. 1 is a list of essential ideas in my own research. I worked backwards from current interests to identify its most important foundations. The list includes original date, author who reported it, and the idea's Field. While these ideas are special for me, the more interesting list is the Fields they came from. It shows themes of interest in light and molecular physics, as well as how to understand vision and computer models of it. However, many of my important ideas are not main-stream to my themes. These ideas come from other Fields.

The first challenge in fusing different views is that each discipline uses its own vocabulary. Too often the same words have conflicting definitions. *Contrast* is a word common to all parts of color. But, photographers think of *Contrast* as the "*slope of response function*", while electrical engineers think of it as "*black level setting*". Painters, neurophysiologists, computer programmers add their own special meanings. Patience is necessary to wander into other Fields, particularly in learning the meaning of unfamiliar terminology.

Finding how to use the ideas from different Fields is rewarding. It can end needless debates, and generate insight and understanding. Try making your own Color Framework of the ideas that are most important to you.

### 3.2 Story of Color

The Framework in Fig. 1 leads to my condensation of research in color. The chain of events leads to seeing Color in a real-life scene:

- Light/matter interactions controls light reaching eye
    - **Molecular Physics**
- Optical Glare controls the image on the retina
    - **Glare Spread Function (GSF)**
- Receptors convert light to nerve response
    - **Molecular Physics**
- Neural processing
    - Counteracts Glare [3]
        - **Spatial Comparisons**
    - Controls Color Constancy [4]
        - **Spatial Comparisons**

The most common issue in understanding color results from applying the rules for *Molecular Physics* directly to the prediction of color appearance. Leonardo observed that Color Vision responds to the scene. This idea has been reinforced by LeBlon, Goethe, Herring, Land, Hubel & Wiesel, Dowling, and Campbell. *Molecular Physics* controls the light reaching the eye, and the response of receptor outer segments. But, it does not control appearance. There is no light from the surround in Maxwell's Colorimetry. Hence no glare, and the only *Spatial Comparison* is between the uniform spot to the minimal light surround.

Psychophysical measurements of the conversion of light to appearance have observed different results for different scenes. The appearances of spots of light lead to different models than real-world scenes. *Spatial Comparison* mechanisms are needed in real scenes and complex scene constructions.

## 4. CONCLUSIONS

Recent applications of *Molecular Physics* and engineering brought us today's color pictures. Color keeps getting better at a faster and faster rate. Nevertheless, understanding how we see Color remains a fascinating topic with problems to be solved. Understanding them needs our entire color history. While we recognize the many recent advances in *Molecular Physics*, we have a new appreciation of the role of neural *Spatial Comparisons*. Color photography's three separations are the result of *Molecular Physics*. Color Vision's three separations are the result of neural *Spatial Comparisons*. Light controls technology, but neurons control color appearance. Light/matter interactions happen in the space of molecules. Appearance involves processing the entire scene, so that models of vision demand data from all receptors. Both the mechanism, and the data required are important parts of understanding Color.

Two experimental studies are important in evaluating real-world vision: Color Constancy and HDR Color. Constancy works best in low-range scenes made of uniform reflectances. It has been measured and modeled successfully using *Spatial Comparisons*. Further, Color Constancy is inconsistent with retinal adaptation mechanisms.[5] Measurements of Color Constancy in HDR scenes have shown that edges in illumination (shadows and specular reflections) are seen the same as edges in reflectance. In HDR scenes Constancy is limited to local segments. Nevertheless, the *Spatial Comparisons* that compensate for glare combine with *Spatial Comparisons* for Constancy to model real-world color.

## 6. REFERENCES


[1] I. Newton, "Opticks", 4th ed. (1730); Dover Publications, Inc., New York, N.Y, p. 122, (1952).

[2] Historical Bibliography <https://mccannimaging.com/col_lab/Framework.html>

[3] J. McCann & V. Vonikakis, "Calculating Retinal Contrast from Scene Content: A Program", Front. Psychol., 17 Jan 2018 I https://doi.org/10.3389/fpsyg.2017.02079

[4] J. McCann, C. Parraman, A. Rizzi, "Reflectance, illumination, and appearance in color constancy", Front. Psychol., 24 Jan 2014 I https://doi.org/10.3389/fpsyg.2014.00005

[5 ] J. McCann, "Limits of Color Constancy: Comparison of the signatures of chromatic adaptation and spatial comparisons", In Proc. Electronic Imaging, IS&T, San Francisco, (2019). <https://doi.org/10.2352/ISSN.2470-1173.2019.14.COLOR-085 >