The Physics of Color

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Introduction to Color

What would our world be like without coloring books filled in with shades of macaroni yellow, tickle me pink, or atomic tangerine? What would the sky look like after the rain if white light were not able to expand into a beautiful rainbow across the clouds? Since the early nineteenth century, scientists and natural philosophers have been fascinated by the idea of color.[1] They sought to learn everything they could about it, including where it comes from, how humans are able to see color, and how to manipulate color for their own needs—such as finding the perfect shade for the grass in a Crayola coloring book. The study of color, or chromatics, covers a broad range of topics in physics and chemistry describing the composition and behavior of colored compounds and light. It even includes the almost biological topic of how color is interpreted by the human eye and brain. Although physics, chemistry, and biology are involved in this science, a solid understanding of optical physics is most fundamental to the advancement of chromatics as a science.

History of Chromatics

Before we delve into what we know about physics and color today, it may be useful to know how the science of color first came about. One of the earliest accounts of color-oriented thought is the “rather pessimistic view”[2] of the Greek philosopher, Plato, in about 338 B.C.:

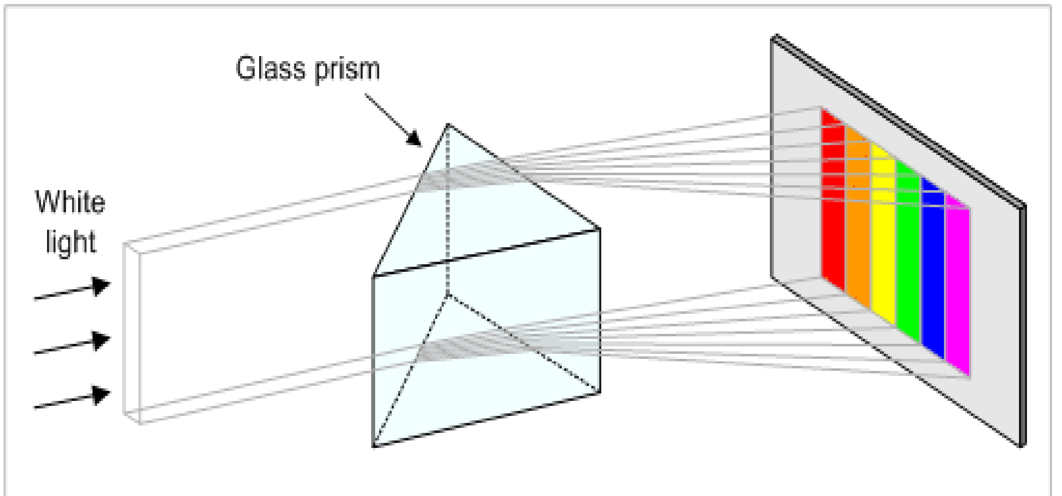
> “There will be no difficulty in seeing how and by what mixtures the colors are made […] He, however, who should attempt to verify all this by experiment would forget the difference of the human and the divine nature. For God only has the knowledge and also the power which are able to combine many things into one and again resolve the one into many. But no man either is or ever will be able to accomplish either the one or the other operation.”[3]

Luckily, a few years later in 350 B.C., Aristotle was quoted with a much more scientific, but slightly erroneous view of color and light as one single feature:

> "Thus pure light, such as that from the sun has no color, but is made colored by its degradation when interacting with objects having specific properties which then produce color."[4]

Though color has been studied since the time of Plato and Aristotle, chromatics as a science is thought to have been established around the year 1672 when English mathematician and astronomer, Sir Isaac Newton began experimenting with light.[5] In a report to the *Philosophical Transactions* for 1672, he described a detailed experiment involving light and a prism in which he first used the term "spectrum."[6] See the figure below for an illustration of his experiment.

Figure 1.1 Newton's Spectrum[7]



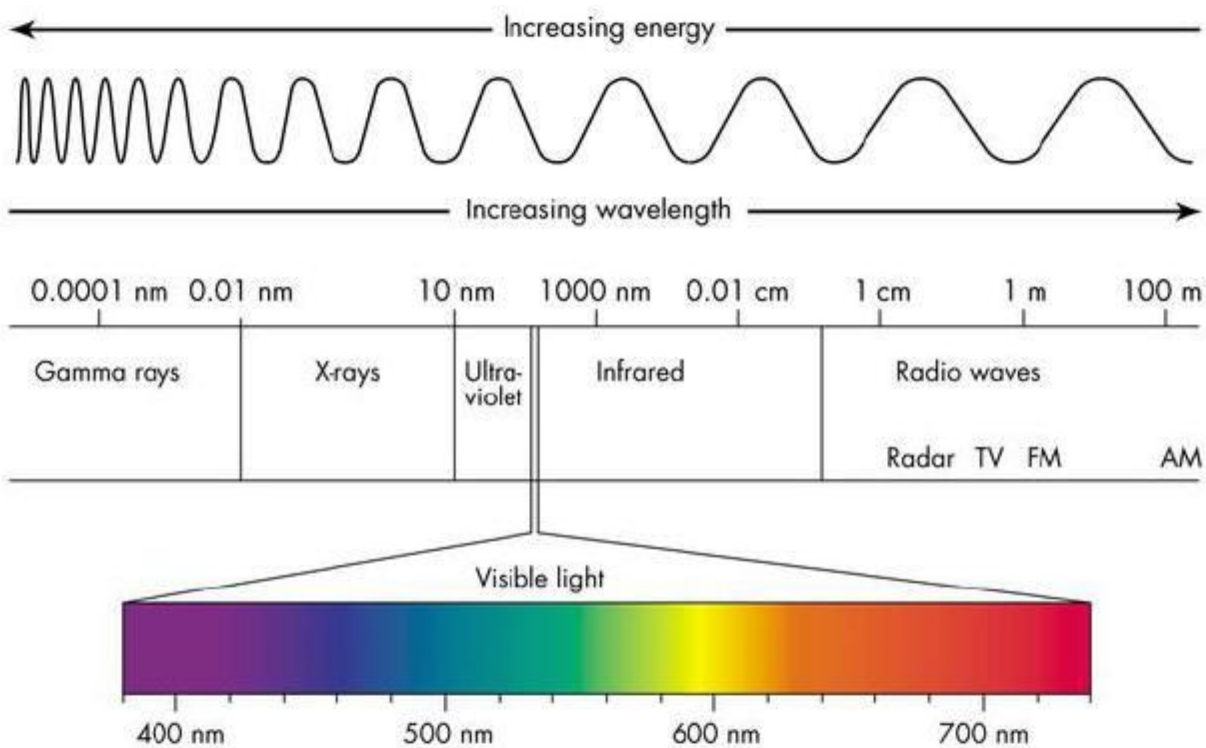
Newton's experiment for splitting white light into a spectrum

To describe what he saw, Newton "arbitrarily decided on […] seven 'fundamental' colors:"[8] red, orange, yellow, green, blue, indigo, and violet for his newly discovered 'spectrum.' These seven colors do not encompass all the shades and hues of color we know exist, but combinations and shades of these colors produce "colors that do not appear in the pure spectrum, such as the purples, pinks, and browns."[9]

Physics of the Electromagnetic Spectrum

The best explanation of why Newton saw a rainbow of color when he directed white light through a prism can be found not it chemistry or biology, but in physics. The electromagnetic spectrum was assembled piece by piece starting with Isaac Newton's discover of the visible spectrum. Sir William Hershel discovered the infrared spectrum next, followed by Johann Ritter who discovered ultraviolet light and Heinrich Hertz who discovered radio waves.[10] Once all these forms of electromagnetic radiation were discovered, the electromagnetic spectrum began to look something like the figure below:

Figure 1.2 The Electromagnetic Spectrum[11]



The types of electromagnetic radiation, and the colors of light in the visible spectrum differ in what "can be viewed as a vibration to which we assign a frequency."[12] The frequency of this electromagnetic vibration is in units of 'hertz,' or one vibration per second and increases as one moves across the rainbow from red to violet.[13] Each frequency is characteristic of a specific color on the spectrum, but not all colored light consists of merely one wavelength of light. Most colored lights are a mixture of different wavelengths and can be analysed using a model produced by a French organization, the Commission International de L'Eclairage (CIE).[14] This model "systematically measures color in relation to the wavelengths they contain,"[15] and is based on the theory that the human eye has three different types of cones which "respond differently to different wavelengths of light."[16] See figures 2.1 and 2.2 below for illustrations of the CIE model:

Figure 2.1[17]

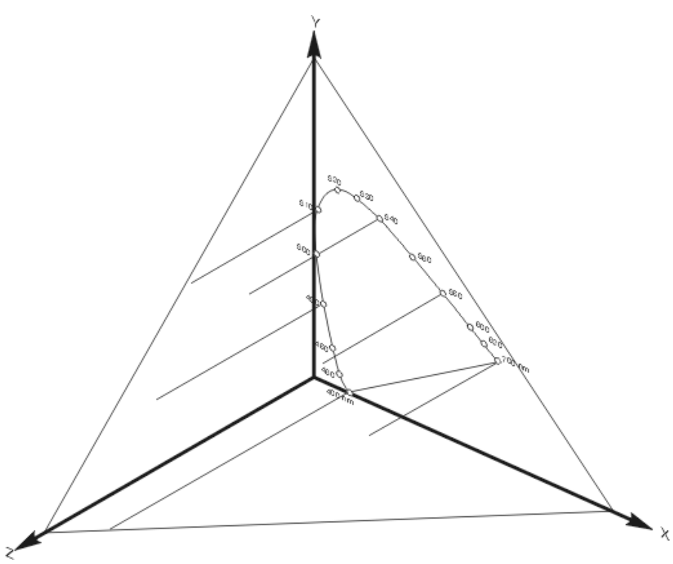


Figure 2.2[17]

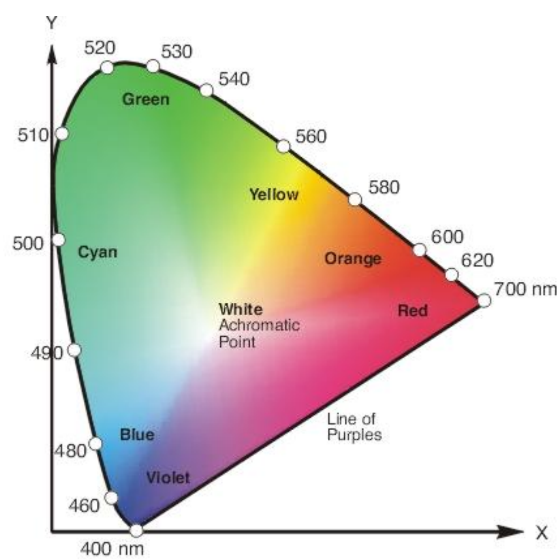
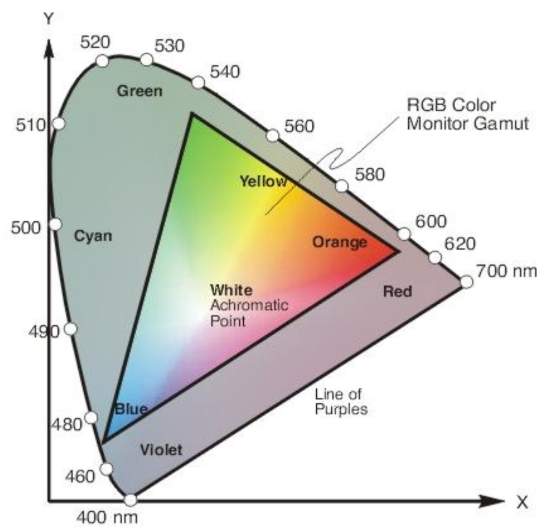


Figure 2.1 illustrates the three dimensional nature of the CIE diagram shown in Figure 2.2. In the real CIE diagram in Figure 2.2, observe how the "perimeter edge marks the wavelengths of visible light,"[17] and these edges are the "pure spectral light colors".[17] White light

is only seen when many different wavelengths are mixed and when “all three cones are stimulated.”[17] Finally, note how the line of purples at the bottom of the diagram do not have wave lengths marked for them. This is because purples are “non-spectral colors, that is they can only be seen by mixing wavelengths from the two ends of the spectrum.”[18]

A practical example of what CIE diagrams are used for is the production of gamuts, or models to “specify ranges of colors that can be produced by a particular light source”[18] such as a computer monitor. The gamut for a computer monitor contains only a small triangular section of the entire range of possible colors (See Figure 2.3 below), obtained by combinations of certain red, green, and blue phosphors.[18]

Figure 2.3 Gamut of Color Monitor[18]



Properties of Colored Light

Now, light of any color can be distinguished by three qualities: hue, saturation and brightness. Hue is the “dominant color”[19] in a color blend and is what we use to give colors names like purple, reddish orange, and green. Hue can also be defined as the “dominant saturated color”[20] of a color mixture, where saturation is “a dimension of color associated with the degree of purity of the light, the extent to which it is […] spectrally pure, rather than mixed with many other wavelengths."[19] Saturated colors are the most intense colors such as electric blue or hot pink, as opposed to dull, unsaturated colors like pale pink, or baby blue. The final feature of colored light is brightness. Brightness is "related to the total intensity of the light wave,"[19] and can be described as the visual perception in which a source appears to be radiating or reflecting light.

While slight variations of hue, saturation, and brightness can produce an infinite list of colors, experiments pioneered by James Clerk Maxwell and other physicists produced a trichromatic theory of color that states "any colored light source […] may be matched by a suitable combination of the three [primary] colored lights."[20]

Colored Objects

It's natural to think that colored objects and colored lights have identical properties when it comes to color, but there are some fundamental differences. Although a blue light and a blue pigment appear the same color, the blue light is made of light with a wavelength corresponding to that of blue, while the blue pigment appears blue to the eye because it absorbs blue's complementary color from white light and reflects back light with a wavelength corresponding to blue.[21] This causes the results of mixing pigments to be opposite the results of mixing colored lights. Colored lights mix using additive color mixing in which many colored lights combine to create a white light. Conversely, colored pigments combine using subtractive mixing where multiple pigments will form a black pigment.[21]

Fluorescence and Phosphorescence

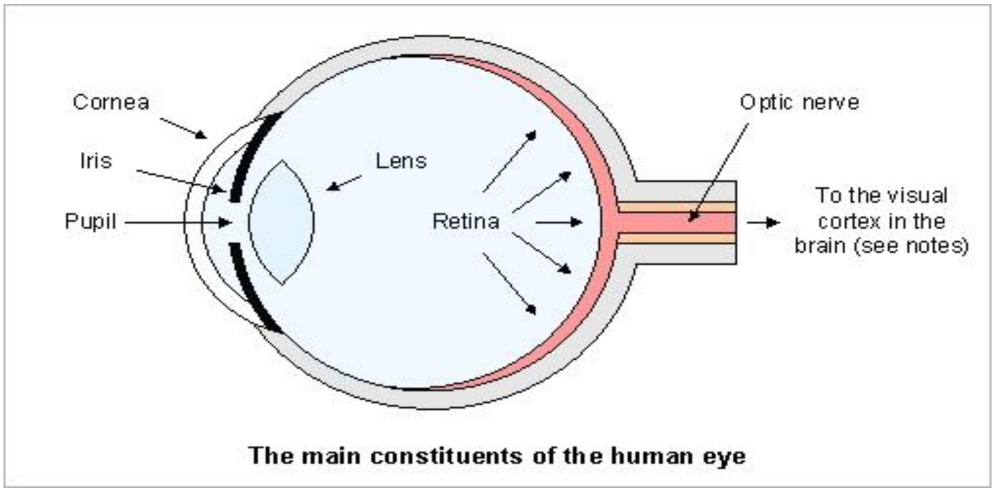
Two curious phenomena of luminescent materials such as pigments are fluorescence and phosphorescence. Fluorescence is the "emission of light from a material while being exposed to an energy source"[22] such as light, while phosphorescence is the "emission of light from a material during, as well as after, exposures to an energy source."[22] The main difference between fluorescence and phosphorescence is the orientation of the electrons' spin in the excited state. When light excites a fluorescent material, the electrons excite and "jump to a higher energy level"[22] while maintaining the spin they had in their ground state. These unstable electrons almost immediately move back to lower levels and release light as energy on their way down. A good illustration of this would be fluorescent ink. When exposed to a black light, the fluorescent ink will absorb the blue light which "excites the electrons in the ink."[22] As the electrons return to lower energy levels, they release light "in the green and yellow wavelengths."[22]

Phosphorescence is based on similar electron excitations, but the excited electrons spin opposite the direction they spun in their ground states. This "places the electrons in a metastable position from which they cannot move back into the ground state."[22] Energy from inside the material eventually moves them to a higher energy level from which they can "fall back to lower energy levels."[22] This process is significantly slower than that of fluorescent electron excitation, and as a result, the emitted light "continues after the exciting source is removed,"[22] causing the object or pigment to glow. Phosphorescent materials can be found in glow-in-the-dark paints, coloring books, stars, and even alarm clocks.

Perception of Color in the Eye and Brain

The scientific study of color and the phenomena that go along with it (like fluorescence and phosphorescence), though based firmly in topics of physics, "lies not in physics or in physiology but in the area overlapped by these sciences and the psychology of perception."[23] Even Isaac Newton acknowledged that "ultimately [color] is a phenomenon of perception."[23] Since color is first perceived by the eye, let's look at man's most basic optical sensor, the eye.

Figure 4.1 Basic Anatomy of the Human Eye[24]



Light passing through the cornea is focused by the lens on the back wall of the eye, onto the retina.[24] The retina contains "special photoreceptor nerve cells that convert rays (photons) of light into corresponding electrical signals"[24] that pass these signals "along the optic nerve into the visual cortex region of the brain."[24] These special photoreceptor nerve cells are known as rods, which cannot detect color but are much more sensitive than cones, which can observe color.

Cones come in three different varieties, one cone for the recognition of red, one for blue, and one for green.[25] There are about six million cones in the average human eye, but surprisingly this number can vary. Researchers at the University of Rochester found that the "number of color-sensitive cones in the human retina differs […] by up to 40 times—yet people appear to perceive colors the same way."[26] This leads many scientists to believe that color perception is controlled "much more by our brains than by our eyes."[26]

Conclusion

Chromatics is a science that encompasses almost all of the classic sciences: chemistry, biology, and most importantly physics. Without a firm grasp of physics and optics, it would be extremely difficult to understand concepts such as the electromagnetic spectrum, CIE diagrams, or even fluorescence and phosphorescence. But regardless of which science is most important to chromatics, most scientists agree that chromatics cannot be isolated from the knowledge of color perception in the eye and brain. Though not much detail was spent on this topic, this is a central focus of both the physiological and philosophical aspects of chromatics.

End Notes

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