

# Introduction to Color Models

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A *COLOR MODEL* IS A structured system for creating a full range of colors from a small set of defined primary colors. There are three fundamental models of color theory. As shown in Figure 1.1, these models are as follows: (1) the Red, Green, and Blue (RGB) color model of lights and display originally explored by Isaac Newton in 1666; (2) the Cyan, Magenta, Yellow, and Key Black (CMYK) model for printing in color originally patented by Jacob Christoph Le Blon in 1719; and (3) the Red, Yellow, Blue painters model fully summarized by Johann Wolfgang von Goethe in 1810 [1]. Figure 1.1 shows a visual summary of these three fundamental models of color theory.

## 1.1 THE RGB COLOR MODEL

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As shown in Figure 1.2, the RGB color model assembles the primary lights of Red, Green, and Blue together in various combinations to produce a broad range of colors. Red and Green lights are combined together to produce Yellow light. The RGB color model is termed as an additive color model in which the combination of the Red, Green, and Blue primary lights produces White light. The RGB color model is used in various technologies producing color images, such as conventional photography and the display of images in electronic systems. Examples of the RGB input devices include image scanners, video games, and digital cameras as well

## 2 ■ Applying Color Theory to Digital Media and Visualization

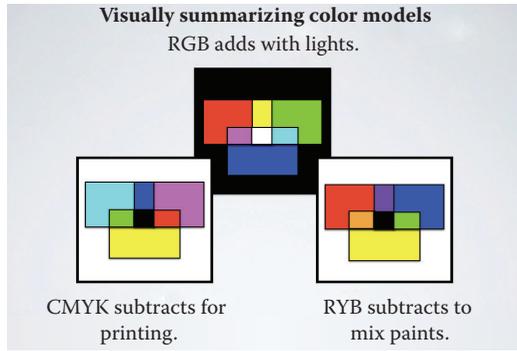


FIGURE 1.1 Visual summary of color models. The Red, Green, and Blue (RGB) color model is an additive color model for displays. The Cyan, Magenta, Yellow, and Key Black (CMYK) color model is a subtractive color model for printing. The Red, Yellow, and Blue (RYB) color model is designed for mixing colors with paints. (Images created by Theresa-Marie Rhyne, 2016.)

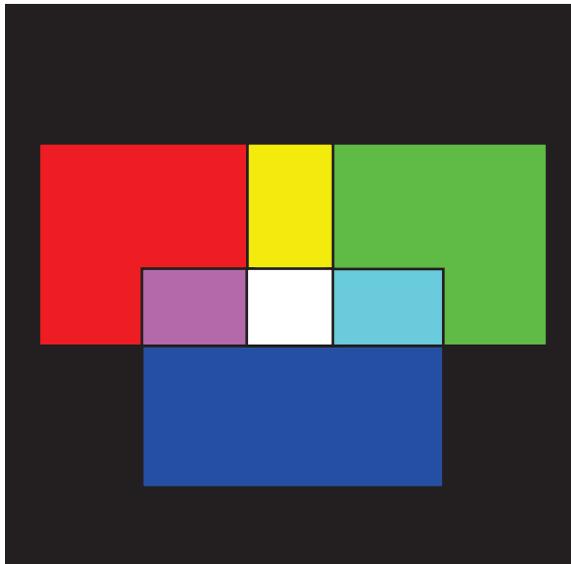


FIGURE 1.2 Illustration of the RGB color model. (Image created by Theresa-Marie Rhyne, 2016.)

as television and video cameras. RGB output devices encompass the broad range of television-set technologies and video projector systems, along with computer and mobile phone displays. The RGB color model has a solid logic in terms of physics and the human perception of colors. Next, we provide a historical overview of this logic.

In 1666, Isaac Newton explored the dispersion of White sunlight into a rainbow of colors. His experiments involved holding a glass prism in the path of sunlight coming through a hole in a dark room. The White light split into Red, Orange, Yellow, Green, Blue (actually Cyan), Indigo (frequently referred to as Dark Blue), and Violet. Newton asserted that different colors combined to produce the White light. Newton published his findings in a book entitled *Opticks*, in English, in 1704 [2]. Newton's rainbow color map for light has become the fundamental approach in the design of today's visualization and digital media presentations. Newton also developed the initial concept of the color wheel that we will highlight in Section 1.4 of this chapter on color models. Although Newton did not define Red, Green, and Blue as the primary colors, his research was the first step in showing that color lights combine together to produce a broad array of additional colors. In Figure 1.3a, we diagram the conventional arrangement of what Newton defined as the dispersion of the

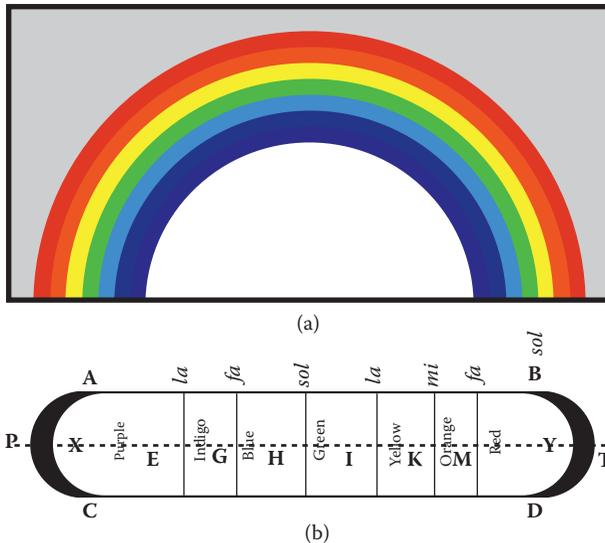


FIGURE 1.3 (a) Rainbow diagram showing the conventional arrangement of colors (Red, Orange, Yellow, Green, Blue [actually Cyan], Indigo [Dark Blue], and Violet). (Based on Newton, I., *Opticks: or a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light*, Samuel Smith and Benjamin Walford, London, United Kingdom, 1704. Image created by Theresa-Marie Rhyne, 2016.) (b) Redrawing of Isaac Newton's diagram of the spectrum of light. (Adapted from Newton, I., *Opticks: or a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light*, Samuel Smith and Benjamin Walford, London, United Kingdom, 1704. Image created by Theresa-Marie Rhyne, 2016.)

#### 4 ■ Applying Color Theory to Digital Media and Visualization

White light into a rainbow of colors. In Figure 1.3b, we show an adapted version of Newton's original drawing of the spectrum of colors from his book *Opticks* in 1704. Newton's notations in the diagram refer to an analogy he developed where the seven colors of the rainbow correspond to the musical concept of seven sound intervals displayed by an octave.

The RGB color model was actually defined in regard to the theory of trichromatic color vision. In 1802, Thomas Young, in a lecture entitled *On the Theory of Light and Colours*, postulated that each human eye had three types of photoreceptors (today referred to as cone cells). Young further proposed that each photoreceptor is sensitive to specific ranges of the visible light. In 1851, Hermann von Helmholtz, in his book *Treatise on Physiological Optics*, added to the theory further by noting that the three types of cone photoreceptors are long preferring (Red), medium preferring (Green), and short preferring (Blue). We will highlight these color vision concepts further in Chapter 2.

In 1861, during a lecture on his color studies at the Royal Institute in the United Kingdom, James Clerk Maxwell provided the first widely recognized demonstration of the RGB color model as well as what is often called the first color photograph [3]. In his lecture, Maxwell showed an image of a tartan ribbon photographed by a professional photographer on three plates through Red, Green, and Blue-Violet filters, respectively. Combining these filtered images together onto a screen produced a reasonable color display of the tartan ribbon. Figure 1.4 shows Maxwell's demonstration

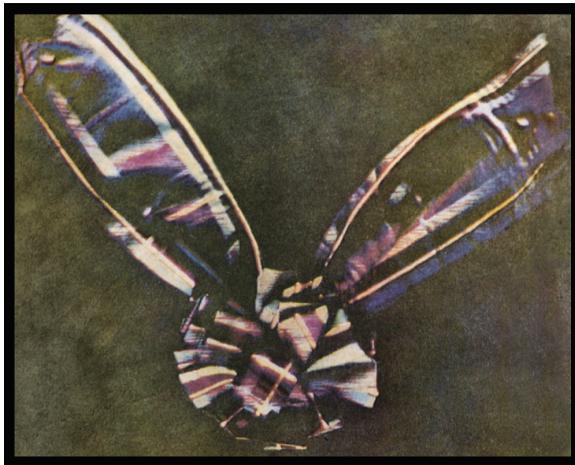


FIGURE 1.4 Image of a tartan ribbon that James Clerk Maxwell demonstrated in his 1861 lecture on the RGB color model. This image is also considered the *first color photograph*. (From Maxwell, J.C., *Br. J. Photogr.*, August 9, 1861, public domain.)

that was revolutionary in 1861. This concept is now used in present-day video projection systems and is fundamental in regard to television, video, computer, and mobile phone displays.

## 1.2 THE CMYK COLOR MODEL

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The CMYK color model is designed to support color printing on White paper. The CMYK color model is termed as a subtractive color model in which the starting point begins with a White or light surface. Color pigments reduce the reflection of the original White light. The color inks thus *subtract* from the original White surface. Typical output devices for the CMYK color model include color inkjet, laser, and dye-sublimation printers. Each device has its own particular technology for color image reproduction. Figure 1.5 shows the CMYK color model.

Historically, for color printing processes to work, individual plates were created for the Cyan, Magenta, and Yellow (CMY) color pigments. The plates were registered over top of each other to produce full color images and the process was called a three-color printing process. When the primary pigments of CMY were combined together as inks, in equally large

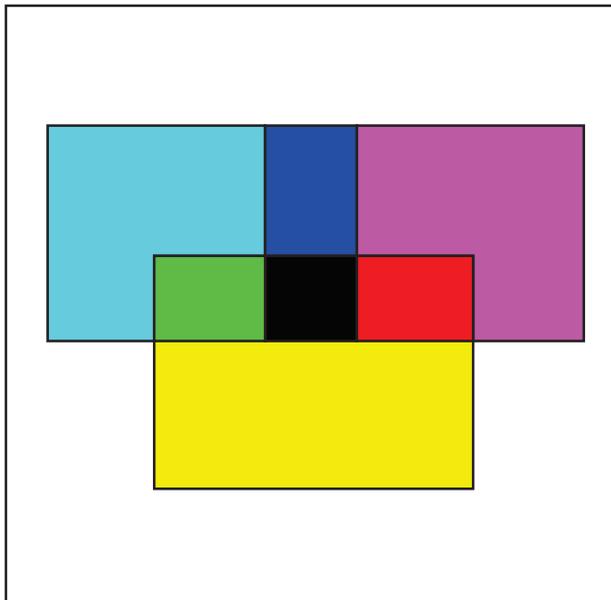


FIGURE 1.5 Illustration of the CMYK color model. (Image created by Theresa-Marie Rhyne, 2016.)

amounts, the result was a Black color. When color printing was put into practice, combining the CMY inks together became an expensive process and, in some situations, certain papers were unable to absorb all of the ink required. As a result, the color printing process was modified to allow for a Black plate to support the printing of Black text and other Black elements with the CMY printing plates being registered or “keyed” against the Black plate. This color printing process and its associated model was thus termed the CMYK color model. CMYK is thus a four-color printing process.

Today, when a digital image is printed, the RGB numeric values of the image are converted to the CMYK numeric values of a printer. In theory, the RGB and CMYK color models are complementary to each other. Various combinations of the Red, Green, and Blue primaries of the RGB color model produce CMY. The reverse is true for the CMY primaries where combinations of the CMYK color model produce Red, Green, and Blue. In practice, these combinations are not purely complementary since the RGB color model involves lights and the CMYK color model involves pigments. Colors selected and matched on an RGB mobile phone can appear with different intensity, perhaps even more subdued, when reproduced on White paper via a CMYK ink jet printer. Figure 1.6 shows the complementary relationship between the RGB and CMYK color models.

Three- and four-color reproduction processes were first patented in 1719 by Jacob Christoph Le Blon. Le Blon actually used Red, Yellow, and Blue (RYB) inks on individual metal plates with a Key Black registration plate as

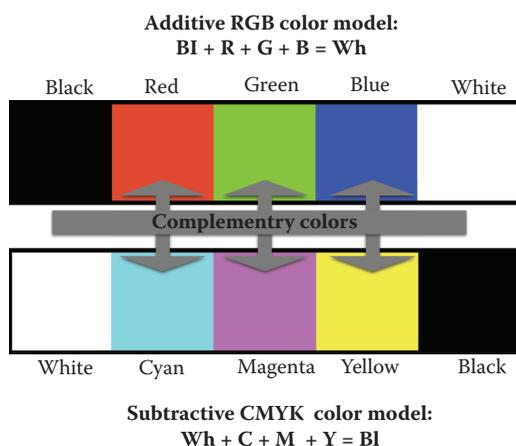


FIGURE 1.6 Diagram of the complementary relationship between the RGB color model and CMYK model. (Image created by Theresa-Marie Rhyne, 2016.)

the foundation for his color reproduction methods. Like the CMYK color model, the RYB color model is also a subtractive model. We will highlight the RYB painters color model in the following section.

### 1.3 THE RYB COLOR MODEL

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The RYB color model is a subtractive color model for mixing painting pigments. It is usually the first color model that we learn at an early age, perhaps in kindergarten. Starting with White paper, RYB color pigments when combined together yield Black, similar to the CMYK color model. Secondary colors that result from mixing primary pigments include the following: (1) the combination of Red and Yellow to yield Orange, (2) the combination of Yellow and Blue to yield Green, and (3) the combination of Blue and Red to yield Purple. The RYB color model is used in the arts and arts education. Figure 1.7 shows the RYB color model.

As discussed previously, Newton published his rainbow color map findings in 1704. During that period, production and reproduction of color images was performed with paint pigments on a White or cream canvas. Painters relied on the RYB color model for mixing and understanding colors. The theory of trichromatic (RGB) color vision had not been postulated. Although mirror displays existed, photographic, television, video, computer, and mobile display technologies with Red, Green, and Blue lights had not been developed. The RYB color model of the eighteenth century was the foundation of theories of color vision.

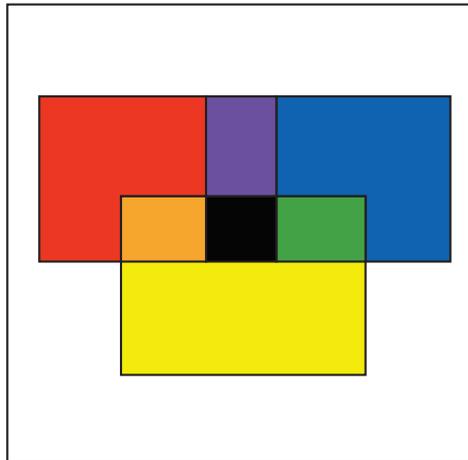


FIGURE 1.7 Illustration of the RYB color model. (Image created by Theresa-Marie Rhyne, 2016.)

As a result, it was difficult for painters to understand how to incorporate Newton's observation (dispersion of White sunlight into a rainbow of colors) into their working knowledge of the RYB color theory. Therefore, Newton's observations were very misunderstood and frequently challenged by painters and other visual artists in the eighteenth century. It was not until the nineteenth-century developments of RGB color vision principles that the relationship between additive and subtractive color models, as shown in Figure 1.6, was understood. In the following section, we will highlight the evolution of color theory based on the color wheel concepts introduced by Newton and later modified by eighteenth-century artists and scientists.

#### 1.4 OVERVIEW OF THE HISTORICAL PROGRESSION OF COLOR THEORY

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As noted in Section 1.1, Isaac Newton developed the initial concept of the color circle or the color wheel. His diagram, shown in Figure 1.8, was published in his 1704 book, entitled *Opticks*. Newton transitioned individual spectral colors, observed in his prism experiments, into a closed color circle. He selected seven colors to correspond to the musical concept of seven sound intervals displayed by an octave. Newton decisions on specific colors were based on aesthetic preferences rather than on scientific principles. He chose Red, Orange, Yellow, Green, Blue (actually Cyan), Indigo (frequently referred to as dark Blue), and Violet. Newton's *Opticks* book went on to become one of the most widely read scientific books of the eighteenth century. His rainbow color map concepts and establishment of the color circle or color wheel continue to influence us even today. In Section 2.11 of Chapter 2, we will highlight some of the difficulties in using the rainbow or Newtonian color map as a default color scheme for current visualization and visual analytics efforts.

In 1766, over 60 years after Isaac Newton's writings on the color circle, Moses Harris published his *Natural System of Colours* book. Moses Harris was an entomologist and engraver in England [4]. In his book, Harris described the RYB color model and demonstrated the wide variety of colors that resulted from combinations of the three primary colors. His observations built upon the writings of Newton as well as Jacob Christoph Le Blon's patented three-color separation printing process of 1719. Harris was particularly focused on the classification of colors and the relationships between specific colors. As a result, he made the first known published attempt to diagram the RYB color wheel. He defined

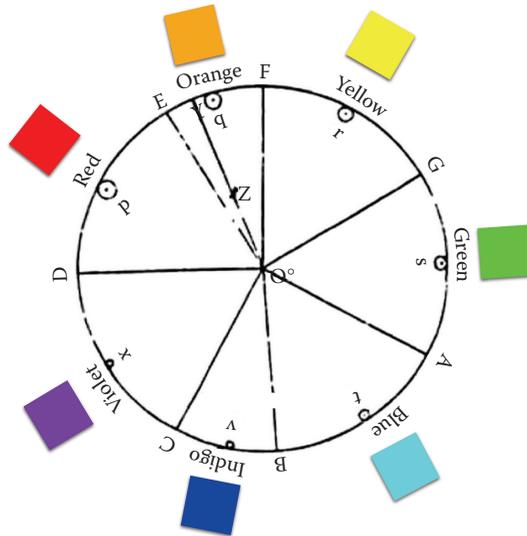


FIGURE 1.8 Adapted from Isaac Newton's Color Circle diagram that appeared in his 1704 *Opticks* book. We have added color squares to highlight Newton's text descriptions of colors noted in the circle diagram. (Adapted from Newton, I., *Opticks: or, a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light*, Samuel Smith and Benjamin Walford, London, United Kingdom, 1704. Image adapted by Theresa-Marie Rhyne, 2016.)

a *prismatic* or primary color wheel for Red, Yellow, and Blue as well as a *compound* color wheel for the secondary colors of Orange, Green, and Purple. Harris' color wheels were divided into arc segments to diagram pure colors as well as shades and tones. At the center of the wheel, the three primaries mix together to form Black. This would later be defined as a subtractive color model. Scientists, artists, and engravers valued Harris' color wheel since it served as a simplified and practical way to quickly visualize the relationships among colors and allowed for matching colors to existing samples. Figure 1.9 shows Moses Harris' prismatic and compound color wheels.

In 1810, Johann Wolfgang von Goethe published *Zur Farbenlehre* (translated into English as *Theory of Colours*) that became the foundation for color theory in regard to the RYB color model. In his book, Goethe challenged many of Newton's writings on the physics of color and introduced a systematic exploration of the physiological and psychological effects of color. Goethe proposed a symmetric color wheel composed of colors that oppose or complement each other. His writings discussed how

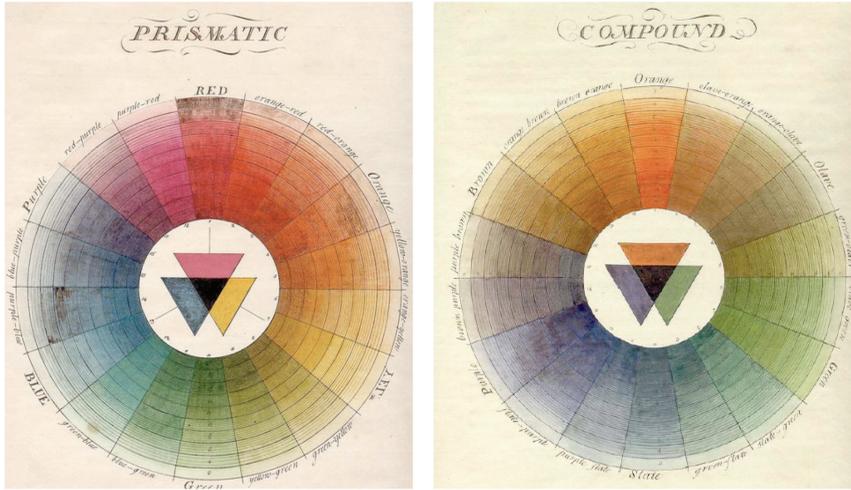


FIGURE 1.9 The prismatic and compound color wheels published by Moses Harris. The natural system of colors. Leicester-Fields: Laidler; 1766. (From Harris, M., *The Natural System of Colours*, Laidler, Leicester Fields, London, 1766, public domain.)

complementary colors cancel each other out to produce Gray or Black when mixed as pigments. He also noted that when two opposing colors are placed next to each other, humans perceive the highest or strongest contrast for these two particular colors. His diagram, shown in Figure 1.10, included Yellow opposing Violet, Orange opposing Blue, and Green opposing Magenta. The inclusion of Magenta by Goethe was a departure from the Newtonian views of color. Magenta is a nonspectral color and thus was not included in Newton's definition of fundamental colors. Goethe viewed Magenta as the mixture of Violet and Red that completed the color circle or the color wheel. The role that Goethe defined for Magenta is still applied today in modern color systems. He also intentionally recognized the psychological effect of Magenta appearing as an afterimage resulting from intensely viewing Green. Figure 1.10 shows Johann Wolfgang von Goethe's color wheel of complementary or opposing colors.

Goethe's book was a catalog of his color studies and observations. He also noted Red and Green as complementary pigments in regard to the RYB color model. It appears Goethe slightly merged additive color concepts of what later became the RGB color model of lights with subtractive concepts of the RYB color model of pigments in his many observations. These kinds of inconsistencies and Goethe's direct attack on Newton's

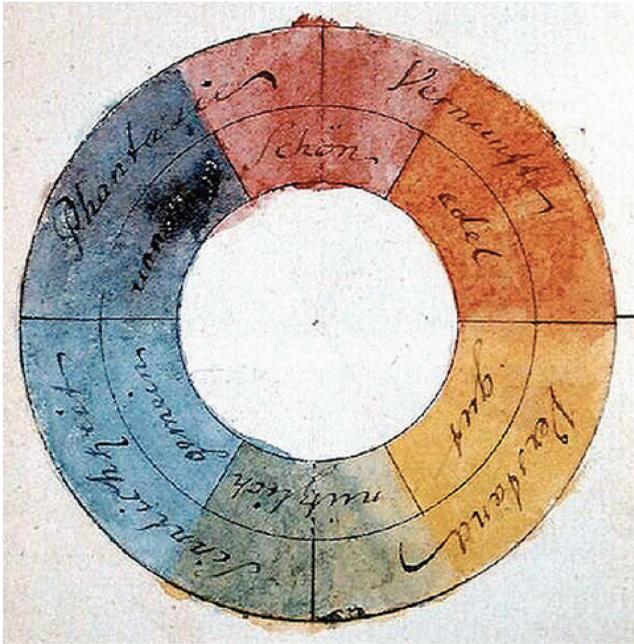


FIGURE 1.10 Johann Wolfgang von Goethe's color wheel. (From Wolfgang von Goethe, J., *Goethe's Theory of Colours*, Translated with notes by C. L. Eastlake, R.A. F.R.S., John Murray, London, United Kingdom, 1840, public domain.)

color observations resulted in scientists dismissing many aspects of Goethe's book. In 1840, Charles Eastlake published an English translation of Goethe's *Zur Farbenlehre* book and entitled it *Theory of Colours*. Eastlake, in his English version, omitted many of Goethe's statements that challenged Newton's color observations. This allowed the reader to focus more directly on the physiological and psychological color studies noted by Goethe. Painters embraced Eastlake's translation of *Goethe's Theory of Colours*. Goethe's writings went on to become widely adopted as one of the foundations of color theory by the visual arts community.

In 1824, Michel Chevreul, a highly regarded French chemist, was appointed as the director of the dyeing department at the Gobelin Tapestry factory. His chief task was to investigate the causes of fading in tapestry threads. Chevreul realized that the difficulties were not with the dyes, but rather with simultaneous color contrast between adjacent threads. After 4 years of study, in 1828, Chevreul published his first paper on his observations, entitled *Memoir on the influence that two colours can have on each other when seen simultaneously*. In 1839, after much effort to achieve effective color reproduction of his

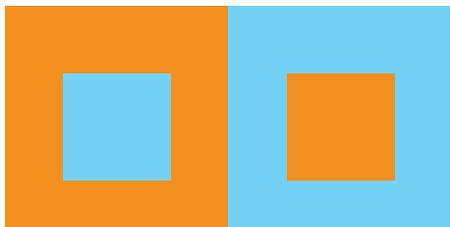


FIGURE 1.11 Example of simultaneous contrast between Orange and Cyan (Light Blue) squares. (Image created by Theresa-Marie Rhyne, 2016.)

diagrams, Chevreul published his book *De la Loi du Contraste Simultané des Couleurs*. The French book was translated into German, English, and other languages [5]. In 1854, Charles Martel published an English translation entitled *The Principles of Harmony and Contrast of Colours, and their Application to the Arts*. Additionally, Chevreul went on to publish three other books on color. Chevreul's books were widely read by painters and other artists who applied his concepts in their image creation and design processes. His writings on color harmony and simultaneous contrast are considered part of the foundations of color theory that are still applied today. Figure 1.11 provides an example of Chevreul's principle of simultaneous contrast.

For this example, I consider Orange and Cyan squares placed next to each other and inside each other. These hues have high contrast according to the RYB color model. Notice that the Cyan (light Blue) square on the Orange background appears larger than the Orange square on the Cyan background. These two colors also appear to amplify or intensify each other when the colors are viewed together. The viewer perceives these colors as altered; however, the hues have not actually changed. These are some of the simultaneous contrast principles that Chevreul presented in his books.

In his writings on color, Chevreul diagramed a color wheel with 12 main color units of Red, Reddish Orange, Orange, Orange Yellow, Yellow, Yellowish Green, Green, Greenish Blue, Blue, Violet Blue, Violet, and Violet Red, with six zones in each color unit. This resulted in a total of 72 segments for his color wheel based on the RYB color model. Complementary (e.g., intensely contrasting) colors were placed directly opposite to each other on the color wheel. Chevreul called this color wheel a *chromatic diagram*. I show an example from his first book on *The Principles of Harmony and Contrast of Colours, and their Application to the Arts* in Figure 1.12.



FIGURE 1.12 Michel Eugène Chevreul’s color wheel or chromatic diagram that emphasizes complementary (opposing) colors. (From Chevreul, M.E., *De la loi du contraste simultané des couleurs et de l’assortiment des objets colorés*, Translated by C. Martel as *The Principles of Harmony and Contrast of Colours*, Longman, Brown, Green and Longmans, London, 1839, public domain.)

## 1.5 AN EXAMPLE OF COLOR THEORY APPLICATION

Here, we highlight an example of the application of our simultaneous contrast knowledge to a visualization problem. Our task is to develop a color scheme for a *treemap* visualization. In the field of Information Visualization, a treemap permits the display of hierarchical data by creating a set of nested squares. Each branch of the tree is defined with a rectangle and tiled with smaller rectangles that represent sub branches. Color and size dimensions of rectangles are correlated with the tree structure. This allows seeing patterns in the data that would be challenging to detect in other ways. Treemaps can effectively display thousands of items simultaneously. Ben Shneiderman at the University of Maryland’s Human–Computer Interaction Lab invented the treemap visualization method in the 1990s [6]. Returning to our task of building a color scheme for a treemap visualization, I recall that the artist Piet Mondrian also worked in squares and rectangles. In his paintings, Mondrian preferred to use the primary colors of the RYB color model [7]. Figure 1.13 shows a color display structure similar to the paintings of Mondrian that I created with Paletton’s Color Scheme Designer [8]. Color Scheme Designer is an online tool for creating color schemes that I will discuss further in Chapter 5.

For our treemap visualization, we need two colors and decide to apply an Orange and Cyan (light Blue) complementary color structure noted in Goethe’s writings. However, I recall the concepts of simultaneous contrast noted by Chevreul, which is shown in Figure 1.11. As a result, I do not place these colors precisely adjacent to or inside each other, vary sizes of the rectangles, and reduce the color brightness of the color selections. Figure 1.14

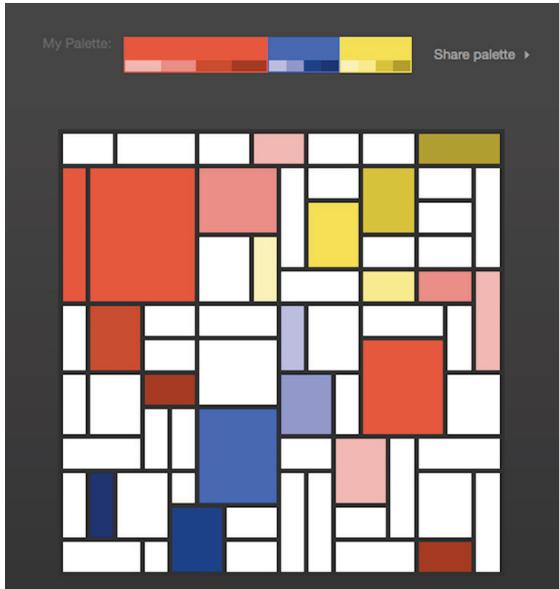


FIGURE 1.13 An RYB color scheme design using a display structure similar to the paintings of Piet Mondrian. I used Paletton’s Color Scheme Designer to create this image. (Based on Paletton, Color Scheme Designer, Available at <http://www.paletton.com>, 2016. Image created by Theresa-Marie Rhyne, 2016.)

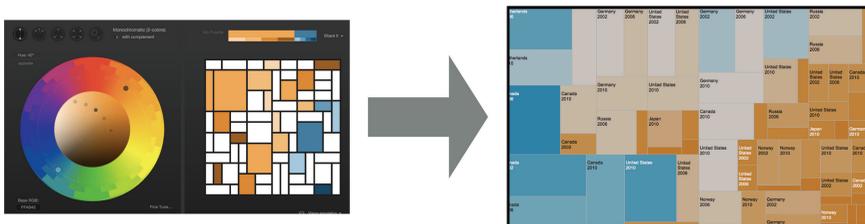


FIGURE 1.14 An example of color theory application using an Orange and Cyan complementary color scheme. (Based on Paletton Color Scheme Designer, available at <http://www.paletton.com>, 2016; and Tableau Public Software, available at <https://public.tableau.com/s/>, 2016. Image created by Theresa-Marie Rhyne, 2015.)

shows the Mondrain-like Orange and Cyan color map created with Color Scheme Designer on the left. On the right, in Figure 1.14, I show the application of the Orange and Cyan color scheme to a treemap visualization created with Tableau Public Software (<https://public.tableau.com/s/>). Tableau Public Software is a freely available tool for building visualizations, especially from tabular data. Tableau Software Inc. provides this free version, with limited functionality, in addition to their commercially available products [9].

## 1.6 CONCLUDING REMARKS

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In this chapter, I reviewed the following three key color models: (1) the RGB color model for displays, (2) the CMYK color model for printing, and (3) the RYB color model for paints. Next, I provided a brief overview of the historical progression of color theory. I will revisit the historical evolution of the color wheel and color harmony in Chapter 4. In Chapter 2, I will focus on color vision concepts that are key to furthering our understanding of the RGB color model for displays.

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