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# Charting Color from the Eye of the Beholder

*A century ago, artist Albert Henry Munsell quantified colors based on how they appear to people; specializations of his system are still in wide scientific use*

Edward R. Landa and Mark D. Fairchild

Say the phrase “school bus” to any American, and the image sure to spring to mind is a vehicle of a particular color—a standard yellow that is one of the most easily recognized and evocative product colors in the United States. But how is it that all school buses across the country are exactly the same yellow color?

It is neither practical nor feasible for all school buses to be painted with the same batch of paint. Instead, specific color standards exist that assure that all paint manufactured for school buses is within a color tolerance—and that the color stays within that tolerance when the paint is applied to the bus.

Where do such standards come from? Are they simply calculations made by a physicist or chemist wield-

ing a spectrometer? When it comes to the colors that we use in life, the answer is not that straightforward. It is common to say that certain wavelengths of the electromagnetic spectrum are a given color, but in truth, it is more correct to say that those stimuli are *perceived* to be of a certain color when viewed under specific conditions. So without the human observer, there is really no color, and practical standards for color must take this factor of human perception into account.

The work of mapping human color perception began in earnest in the 19th century. This year marks the centenary of the first atlas of color, by an artist named Albert Henry Munsell.

Munsell’s vision of a systematic way to communicate color appearance has had an impact on essentially all modern systems of color measurement and specification. Today a school-bus manufacturer, for example, has access to a numerical standard based on instrumental measurements of the spectral reflectance characteristics of the paint. Undergirding these numbers are colorimetric computations based on a system called CIE, for Commission Internationale de L’Éclairage, or International Commission on Illumination. These instrumental specifications and tolerances allow paint and pigment manufacturers to formulate paint that matches the desired school-bus color more easily. CIE charts of these numbers are also backed up with physical samples that show the optimal school-bus yellow as well as limits along the perceptual color dimensions of lightness-darkness, hue

and chroma (or how much the apparent hue differs from neutral gray)—the dimensions first described and measured by Albert Munsell.

Such systems are used to create and control almost every colored product. Examples include the textiles clothes are made of, the inks used in printers, the encoding of digital television signals, the colors of signal lights, the proper cooking times for French fries, the pearlescent paints on automobiles that change color with angle, the color of the beer at the local pub and the colors of crayons that children carry off of school buses to create art in school.

## A Colorful History

Color description was an interesting problem to scientists and artists in the 19th and early 20th centuries, engaging scholars such as Germany’s Johann Wolfgang von Goethe and Wilhelm Ostwald, and the American printer and educational reformer Milton Bradley, best known today for his board games.

Munsell’s interest in the description of color began in 1879, while he was a student at the Massachusetts Normal Art School (MNAS, now the Massachusetts College of Art), when he read the then-just-published text *Modern Chromatics with Application to Art and Industry* by Columbia University physicist Ogden Rood.

Although Munsell was certainly influenced and motivated by the color systems reviewed in Rood’s book, his own system would have several features that had not been previously described, most importantly the relations

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*Edward R. Landa is a research hydrologist with the U.S. Geological Survey in Reston, Virginia. He received his B.S. in geology from the City College of New York and his M.S. and Ph.D. in soil science from the University of Minnesota. His research focuses on the behavior of metals and radionuclides in soils and aquatic environments. Mark D. Fairchild is the Xerox Professor of Color Science and director of the Munsell Color Science Laboratory at the Rochester Institute of Technology (RIT). He received his B.S. and M.S. degrees in imaging science from RIT and his Ph.D. in vision science from the University of Rochester. He was chair of the Commission Internationale de L’Éclairage (CIE) Technical Committee 1-34 on color appearance models. He is author of Color Appearance Models 2nd Ed., which serves as a reference to the fundamentals of color appearance and the formulation of specific models. Address for Landa: U.S. Geological Survey, 430 National Center, Reston, VA 20192. Internet: erlanda@usgs.gov*



Figure 1. Albert H. Munsell was dissatisfied with what he felt were arbitrary definitions of color, so in 1905 the artist published a color charting system based on how people see color. Munsell intended his system for art students, but today versions of his charts are used in fields from soil science to art restoration. Here, Roy S. Berns of the Rochester Institute of Technology performs a visual match of pigments in Georges Seurat's *A Sunday on La Grande Jatte—1884*, using color samples from a Munsell Book of Color. Berns used color matching to confirm instrumental measurements of the painting. By calculating the effects of aging on the paint pigments, Berns was able to digitally recreate the painting's original colors. As seen in close-up (a), the yellow paints, rejuvenated in the digital recreation (b), have browned with age in the actual painting (c). (Images courtesy of Roy S. Berns.)

between lightness, luminous intensity and maximum colorfulness.

After his graduation in 1881, Munsell became an instructor at MNAS, specializing in artistic anatomy and color composition. In 1892, while sketching in Venice with Boston artist Denman Ross, Munsell noted in his diary that they discussed the need for a "systematic color scheme for painters" to prepare mentally and sequentially for the laying of the palette (Ross, who taught art at Harvard, would go on to develop his own color system with a nine-step value scale in 1907).

Munsell was not satisfied with color descriptions of the day, such as "topazy yellow" or "Indian red." His quantitative research in the field seems to have begun on a summer vacation in 1898, when, to create a teaching aid for his color-composition students, he worked on distinct designations of colors and their display on wheels and spheres.

His first model used a child's globe as a base for rotary color mixtures. With the globes, Munsell was able to create and demonstrate colors of various hues that had equal lightness and chromatic balance such that they mixed to a neutral gray when the globes were spun. This allowed Munsell to demonstrate his concepts for an impressed Rood, who stated that Munsell "put an artistic idea into scientific form." Munsell also later created a portable visual photometer to allow him to accurately scale the perceived lightness of chromatic colors through visual matching to a gray scale.

Munsell's artwork focused mostly on portraits and seascapes. His painting of Helen Keller hangs in the American Foundation for the Blind headquarters in New York City. A view from the Roosevelt summer home at Campobello, painted by Munsell for the family in 1890, is displayed in the office of Franklin Delano Roosevelt's mother at

Hyde Park, New York. Thus, he was well known in the art world, but as he developed his color system, Munsell also moved easily among the science and engineering faculties in Boston. He consulted with individuals such as the noted physiologist Henry Pickering Bowditch at Harvard Medical School.

In 1905, intent on the goal that "color anarchy is replaced by systematic color description," Munsell published the first edition of his 67-page text *A Color Notation*, which described the Munsell Color System and its specification of color by measured scales of hue, value and chroma. H. E. Clifford, Gordon McKay Professor of Electrical Engineering at Harvard, provided an introduction to this volume.

Although Munsell honed his color system within a circle of scientists, he saw its broad application in general society, and his color spheres reached a wide audience. For example, around

1901, William Filene of Filene's Department Store asked Munsell to show the color sphere to the Shopkeepers' Association in Boston. In the 1920s, the Filene Company underwrote the cost of a color chart prepared by the Munsell Color Company for use in the clothing industry. At about the same time, another ear-

ly Munsell color sphere was on display and available for study at the Physical Laboratory of Columbia University.

Munsell's health declined rapidly after a 1914 trip to Europe. He underwent surgery for appendicitis in May 1917. Later that year, he gave up the studio he had occupied since 1901; several months

later it was taken over by the painter John Singer Sargent. Munsell died on June 28, 1918, at age 60. The Munsell Color Company, which was established circa 1917, carried on the commercialization of his work, selling color charts and other products under the leadership of his son Alexander Ector Orr Munsell.

Through 1946, 15 editions of *A Color Notation* were published by the Munsell Color Company. Other books followed, including the *Atlas of the Munsell Color System* published in 1915, and *A Grammar of Color*, published posthumously in 1921. No other color system from this time period has been as long-lived, commercially successful or influential.

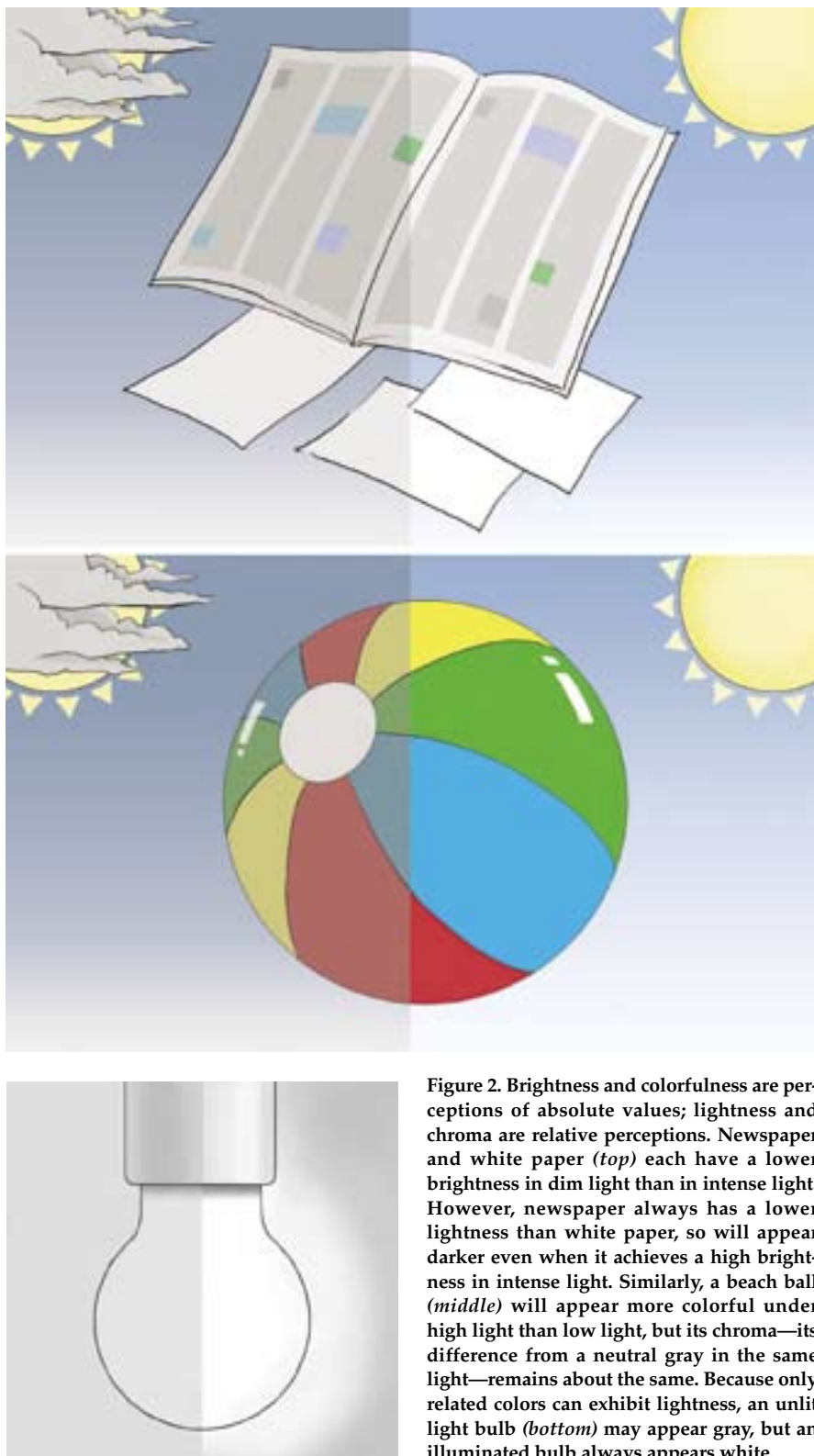
Dorothy Nickerson, who began her career as A. E. O. Munsell's secretary and laboratory assistant in 1921, did much to adapt the Munsell Color System to commercial applications and to describe its scientific basis. Her work included extensive involvement on the Optical Society of America Colorimetry Committee and historical publications on the Munsell System. Nickerson authored more than 150 papers and rose to prominence within the Inter-Society Color Council, which established its Nickerson Award in 1980.

The legacy of color research pioneered by A. H. Munsell is today honored by the Munsell Color Science Laboratory, founded at the Rochester Institute of Technology in 1983.

### Defining Color

In any field of study, it is important to have a standard vocabulary. In the study of color this vocabulary is often muddled, as terms such as "lightness" and "brightness" are casually interchanged. Even in education, treatment of color is inconsistent. To the grade-school child, color might be made up of three primaries: red, blue and yellow. The printer is taught that the three primaries are cyan, magenta and yellow, whereas the television engineer is taught that color is made up of red, green and blue. Finally, the physicist might be taught that colors are divisions of the visible portion of the electromagnetic spectrum. Although each of these concepts of color is correct in its context, it is incorrect in others.

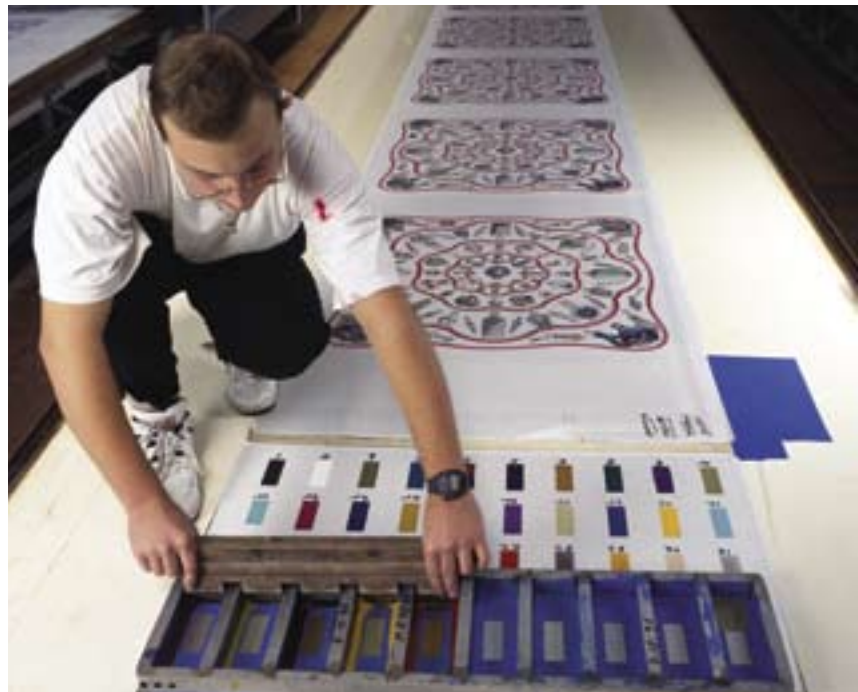
In the field of color science, the *de facto* standard for vocabulary comes from the International Lighting Vocabulary, published by the CIE, which clarifies the distinctions in various dimensions of color experience. These terms scientifically and unambiguously define the



**Figure 2.** Brightness and colorfulness are perceptions of absolute values; lightness and chroma are relative perceptions. Newspaper and white paper (top) each have a lower brightness in dim light than in intense light. However, newspaper always has a lower lightness than white paper, so will appear darker even when it achieves a high brightness in intense light. Similarly, a beach ball (middle) will appear more colorful under high light than low light, but its chroma—its difference from a neutral gray in the same light—remains about the same. Because only related colors can exhibit lightness, an unlit light bulb (bottom) may appear gray, but an illuminated bulb always appears white.



Holt Studios International (Nigel Cattlin)/Photo Researchers, Inc



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**Figure 3.** Variants of Munsell's color system are in wide use in many areas of science and technology. Botanists use Munsell Plant Tissue Charts in plant taxonomic classification and for the identification of plant diseases that lead to tissue discoloration, such as potassium deficiency in a grape plant (left). Fabric dyers use color charts to select colors and to keep their products consistent from print to print (right).

perceptual attributes that Munsell notated in his system. As such, the focus is on the object-surface color descriptors of *lightness*, *chroma* and *hue* that are those defined in Munsell's system. But first one must define the term "color" itself.

Few people, when asked, can give a precise definition of what exactly color is. It is almost impossible to do without using an example. Even the CIE resorted to the inclusion of color names in its definition of color. The most critical part of the formal definition of color to keep in mind is that it is an "attribute of visual perception"—a description of color appearance to human observers.

However, it is known that color perception varies somewhat from person to person—and within individuals during their lifetimes. For instance, as the eye's lens hardens from aging, it absorbs and scatters more short-wavelength colors, so the visual system looks through a filter that yellows increasingly with age.

With highly variable human observers having such a central role in color models, one might wonder how accurate color measurements can be made. Careful experimentation has quantified the human visual response to color and defined mathematical equivalents of average human color perception, creating "standard observers" that can be used to simulate the human visual response to color computationally.

Such systems have been standardized for nearly 75 years and are very successful in both scientific research and practical applications.

Munsell resisted some suggestions to tie his system to physical scales of wavelength because he realized this was not feasible. Instead he focused on developing a system that quanti-

tatively and systematically described the overall appearance of colors. Color scientists to this day work to create mathematical simulations as accurate as Munsell's quantification of visual observations. That is why, despite significant advances in the theory and technology of color measurement, human observers are still used as the final



**Figure 4.** Dorothy Nickerson (left) was a tireless advocate and researcher for the color system established by Albert Munsell (right). On her death in 1985, noted color scientist David L. MacAdam of the University of Rochester wrote "Alas, the prophetess of color—inspired by Munsell—is silent." (Photographs courtesy of the Munsell Color Science Laboratory.)

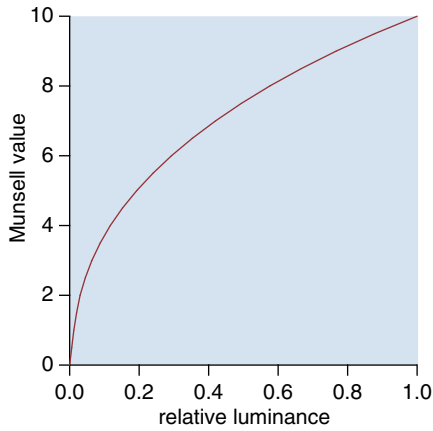


Figure 5. Color systems based on perception have a complicated relation to physical color measurement. Many combinations of wavelengths can sum to the same perceived color; for this reason, Munsell concentrated solely on color perception for the basis of his system. Munsell value, or lightness, does not increase linearly with luminance. A sample that the human visual system perceives as a middle gray (with a value of 5 in the Munsell system) has a relative luminance of about 20 percent (100 percent would look white). The relation between the other two dimensions of the Munsell system, hue and chroma, is even more complicated to relate to physical measurements of light, such as wavelength.

judges of colored products to confirm instrumental results.

Of the properties defined by Munsell, *hue* is perhaps the easiest of the color terms to understand. It is defined as the similarity of a perception to one of the perceived colors—red, yellow, green and blue—or to a combination of two of them. Hue is often described with a *hue circle*, and this is indeed the way it is described in the Munsell system.

One important point of this description, and the definition given by the CIE, is that there are unique hues—again, red, yellow, green and blue—that follow the opponent color theory first postulated by Ewald Hering in the late 1800s. Hering noted that certain hues were never perceived together, such as reddish-green or yellowish-blue. This formulated the fundamental notion that human color vision is encoded into red-green and blue-yellow channels.

Munsell's hue designation is consistent with this theory but adds a fifth principal hue, purple, to achieve another desired property: equality of perceptual hue spacing for the entire hue circle. This equality of spacing means that the perceived change in hue is equal for each equal numerical step in the Munsell hue designation. Another reason Munsell added purple as a principal hue is that there are a lot of perceptible hue steps between our perceived unique red and unique blue hues. In other words, we can discriminate many purple hues but not so many yellowish-green hues.

The attributes of *brightness* and *lightness* are very often interchanged, despite the fact that they have distinct definitions. Brightness refers to the absolute perception of the amount of light of a stimulus, while lightness can be thought of as the relative brightness. In other words, lightness is our perception of the brightness of an object relative to the brightness of an object that appears white to the human eye under similar illumination. The human visual system generally behaves as a lightness, not a brightness, detector, which can perhaps be better described with an example.

A typical newspaper, when read indoors, has a certain brightness and lightness. When viewed side by side with standard office paper, the newsprint often looks slightly gray, while the office paper appears white. When the newsprint and office paper are brought outdoors on a sunny day, they both have a much higher brightness. Yet the newsprint still appears darker than the office paper because it has a lower lightness. The amount of light reflected from the newsprint outdoors might be more than a hundred times greater than the office paper was indoors, yet the relative amount of light reflected when comparing the two has not changed with the change in illumination. Thus, the difference in brightness between the two papers, or their lightness, has not changed. The Munsell value scale is a scale of lightness.

As an interesting note, only *related colors* can exhibit lightness. *Related colors* are colors seen and judged in relation to other similarly illuminated colors. This is the reason that there cannot be a gray light bulb. When illuminated and viewed in isolation, the light bulb is the brightest stimulus in the field of view and thus appears white.

The definitions of *colorfulness* and *chroma* are very similar to those of brightness and lightness in that colorfulness is an absolute perception, whereas chroma is relative. Essentially, colorfulness describes the amount, or intensity, of the hue of a color stimulus. A gray stimulus has no colorfulness, while a vivid red would be high in colorfulness (and of red hue). Similarly, chroma is to colorfulness as lightness is to brightness.

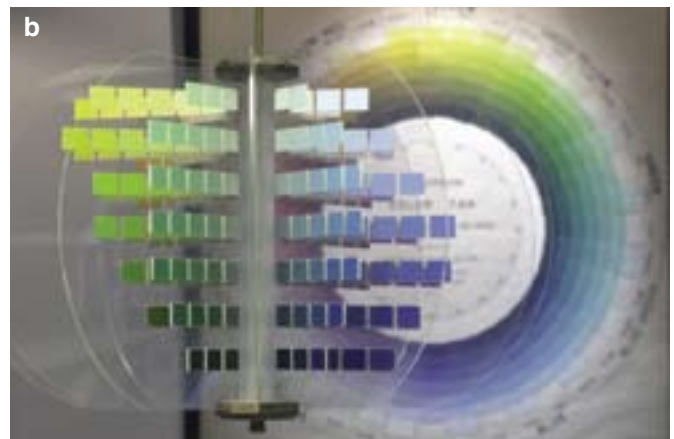


Figure 6. Munsell's first color models used globes (a) as a base for rotary color mixtures, such that the five hues of equal lightness (called "value" by Munsell) and chroma appeared as a neutral gray when the globe was spun. Later versions used a "tree" in which value increased from bottom to top, and chroma on every hue "branch" increased from center to edge (b). A Nickerson color fan, behind the Munsell tree, shows the maximum chroma for 40 hues at different values. Munsell published his original volumes in 1905 and 1915, for which he created color samples from his own visual observations. Later editions (c, facing page) involved more detailed experimentation and contained a more

As with lightness, the human visual system generally behaves as a chroma detector. When we take a colored object out into bright sunlight from a dim room, it appears more colorful. But its chroma remains approximately constant, since the brightness of a white stimulus under the same conditions increases along with the colorfulness of the stimulus.

### Making Color a System

Munsell chose to create his color system around the perceptual attributes of lightness (called Munsell value), hue and chroma because they are the three dimensions that relate most closely to our everyday experience of the colors of objects. Our visual system adapts to incredibly large changes in the color and level of illumination to help us perceive object colors as relatively stable. Thus a perceptual color system such as the Munsell system is most useful if it is enumerated in terms of the perceptual color dimensions most closely related to these relatively stable object perceptions.

One representation of the Munsell system is called a Munsell tree. The “trunk” of the tree is the value scale with dark at the bottom and light at the top. Each “branch” represents a different hue, and the “leaves” on the branches increase in chroma with distance from the center of the tree. In the Munsell system, each color is designated by its hue (with a set of letters and numbers), its value (with a number ranging from 0 to 10) and its chroma (with a number ranging from 0 for neutral grays to numbers on the order of 15 or so for the highest

chroma samples; the actual maximum chroma available depends on the particular hue and value chosen).

For example, a deep red sports car might have the Munsell designation of 4R 3/12, where 4R hue designates a hue just slightly more bluish than a unique red, value 3 indicates a slightly dark color (value 5 is perceptually midway between white and black in lightness), and chroma 12 indicates that it is a vivid red.

An important part of Munsell’s approach to building a color system was that he created each scale of a perceptual color dimension to have equal numerical increments perceptually. He divided the hue circle into 100 equal perceived hue steps and anchored it with five principal hues (red, yellow, green, blue and purple) and five intermediate hues. For each of those 10 hues, he created 10 additional smaller increments. In addition, Munsell chroma steps are about half the size of the value steps, such that a change of one step in value appears about the same magnitude in color difference as two steps in chroma.

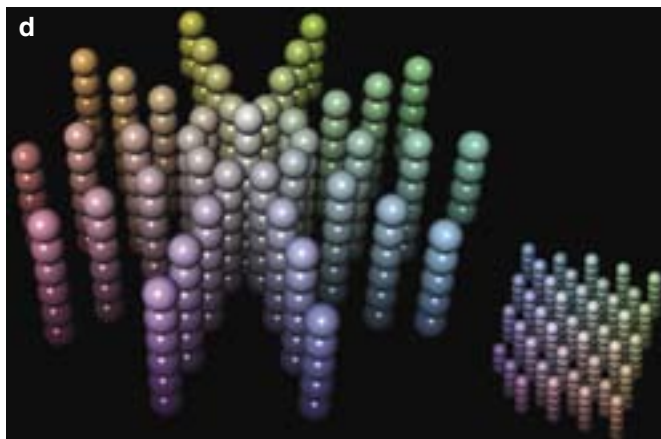
Although the colors of the Munsell system are specified by their appearance in terms of value, chroma and hue, once samples for each designation are created, the system can be recorded and reproduced using physical metrics of color. Specifically, the spectral reflectance of the samples and the spectral power distribution of the illumination are used together with standard human response functions to designate physical color coordinates known as *tristimulus values*, which are directly related to the stimulus wavelength and energy. These

coordinates ultimately define the system and allow reproduction of nominal-color samples. Such numerical color specifications allow the system to continue to be recreated even if the samples of a current embodiment should fade or be otherwise damaged.

The visual uniformity of the Munsell system has been one of the most significant attributes in making it one of the most important and influential color specifications of the last century. The first color samples in his 1915 atlas were created by Munsell himself through his own visual observations. The 1929 *Munsell Book of Color* represents a more systematic definition of the color samples than the 1905 atlas through more detailed experimentation. It can really be thought of as the classic edition of the Munsell book that brought the system into the forefront of color science.

Although the 1929 *Munsell Book of Color* was certainly a success, it was recognized that the color chips embodying the system did not accurately match the theory for all of the samples in the book (generally about 1,500 color samples). The Optical Society of America’s Colorimetry Committee—with critical contributions from Dorothy Nickerson—performed visual experiments, using more than 300,000 visual observations, to create a more accurate specification of the system in terms of instrumental color measurement. Their results were published in the 1940s and referred to as the *Munsell renotation*, which is also the current definition of the samples in the *Munsell Book of Color*.

The Munsell system evolved simultaneously with instrumental color-



systematic definition of color samples. In the 1940s the Optical Society of America undertook another revision of the Munsell color samples, creating the current standard. Modern representations of Munsell samples (*d*) include a computer rendering of the Munsell tree, shown here with a more recent color system, the OSA Uniform Color Scales, which describes the same colors in a different mathematical way. Rather than treating each of the three dimensions of color separately, as Munsell did, this system is designed to provide equal perceptual spacing in all three dimensions simultaneously. (Images courtesy of the authors.)



Figure 7. One of the first color products that Munsell had manufactured was a set of crayons. This set showed colors with a mid-level value and chroma. Munsell sold his crayons to the company that now manufactures Crayola crayons, whose color names do not reflect Munsell's systematic approach to color. (Photograph of Munsell crayons reproduced by the permission of The Huntington Library, San Marino, California; photo-montage courtesy of the authors.)

measurement techniques (the CIE system of colorimetry). The Munsell system was improved through the use of instrumental techniques to specify and produce modern Munsell samples, and instrumental colorimetry benefited from the visual data on color-attribute scaling (measurements of quantitative magnitudes of our perceptions) provided by the Munsell system.

Today, the most widely used computational color system for color material specification and tolerances is the CIELAB color space, originally published by the CIE in 1976. This color space has three dimensions to describe object color appearance. In rectangular coordinates, the dimensions are  $L^*$  (lightness),  $a^*$  (redness-greenness) and  $b^*$  (yellowness-blueness). An alternative



Figure 8. Munsell Soil Color Charts let soil scientists visually analyze samples in the field. In this view of a site in Maryland, the matrix of the water-saturated lower layer is black (designated 2.5Y 2.5/1 for hue value/chroma) due to the presence of the mineral pyrite, and the areated zone above has pale yellow streaks (5Y 7/4) of jarosite, a pyrite-oxidation product. (Photographs courtesy of the authors, Martin C. Rabenhorst of the University of Maryland, College Park and Ted Callender, U.S. Geological Survey-retired.)

representation of the same color space is in the cylindrical coordinate system of  $L^*$  (lightness),  $C^*_{ab}$  (chroma) and  $h_{ab}$  (hue angle) that corresponds with the dimensions of the Munsell system.

CIELAB has been successful in its 30 years of existence, but color science has not stood still. Current research aims to extend the CIELAB mathematical model to improve our ability to predict the appearance of colored stimuli and images under a wide variety of viewing conditions. Mathematical models attempting this complex task are known as color appearance models. The most recent, internationally accepted, model of color appearance is known as CIECAM02, for the CIE 2002 Color Appearance Model. Modern computer-graphic renderings of both the Munsell system and other systems of color specification in proposed mathematical color spaces are a great aid in the formulation of these new models of color measurement.

### Munsell's Extensive Reach

Albert Munsell originally set out to build a color system as a way to improve his teaching about color to his own art students, but it is clear that his system has had a significant impact on the art and science of color. Some areas where Munsell products are currently used include imaging-system calibration and characterization, evaluation of color vision for color deficiencies, botany for the classification of certain plant diseases and nutrient deficiencies, color coding of electrical wire and cable, food standard colors to assess the quality of French fries, olives, tomatoes, cherries and pumpkins, American National Standards Institute (ANSI) safety colors and the description of skin, hair and eye color in forensic pathology.

Even crayons have an interesting relation to the work of Munsell. The colors of the crayons themselves are standardized and controlled using colorimetric techniques similar to those described above for school buses. In addition, one of the first color products that Munsell had manufactured was a set of crayons carrying the systematic color designations of his system. Early on, Munsell sold his crayon business to Binney & Smith, the company that now manufactures Crayola crayons.

Had the sale gone another way, American children might now learn a very systematic and technically accurate way to describe color from their cray-



ons. In some countries, such as Sweden, where the Swedish Natural Color System (NCS) is a national standard, children are taught a systematic method of color specification at an early age, and commerce (such as buying paint in a hardware store) is carried out using precise numerical color specifications that are also intuitive to those so trained. In the United States, instead of asking their playmates to share the 4PB 3/10 crayon, American children are left to ask for the "cerulean" crayon and then to ask their parents "what's a cerulean?"

Despite this one near-miss for popularizing the the Munsell system, there are examples everywhere of products that have benefited from some form of color-measurement system. The brewing of beer has provided an application of instrumental color measurement for nearly a century (and probably visual color measurement for many centuries before that). The brewer Joseph Lovibond is credited with creating one of the first color-measurement instruments, the Lovibond Tintometer (a version of which is still available). The tintometer is an instrument in which a colored sample, such as some beer, is matched with a mixture of cyan, magenta and yellow filters. The amounts of these standard tintometer filters required to make a match served as a color measurement. Nowadays, tintometer values and CIE color specifications can be computationally interconverted without the need for a visual assessment.

A recent example of use of the Munsell system for visual colorimetry can be found in the work on the spectrophotometric and colorimetric analysis and reproduction of rare works of art and other cultural heritage by Roy S. Berns of the Rochester Institute of Technology. Berns performed visual matching of painted areas in Georges Seurat's *A Sunday on La Grande Jatte—1884* at the Art Institute of Chicago, and the Star-Spangled Banner in the Smithsonian's National Museum of American History—the flag that inspired Francis Scott Key to write the poem that eventually became the American national anthem. Given the value of these two pieces, it is not feasible to make repeated instrumental measurements in contact with their surface or to illuminate them with the light intensities required for non-contact measurements. Samples from a modern *Munsell Book of Color* were used to quantify visually the current colors in both pieces and to check

the few instrumental measurements that were allowed. The resulting color specifications were used to analyze the pigments in the Seurat painting and create a digital image representing the appearance of those colors when the painting was originally made. For the Star-Spangled Banner, which is now being stabilized for exhibition with a polyester backing, the measurements were used to help the Smithsonian design a new exhibit for the flag by simulating what it would look like after cleaning and with illumination by various types of light sources.

In the early part of the 21st century, the film industry is undergoing a transition to digital cinema. The century-old Munsell system is playing a role in this technological transition as well. Digital cinema projectors are capable of displaying an enormous range of colors, higher in chroma than those traditionally available in film and television systems. In utilizing these displays with existing content, it becomes necessary to map the colors available from historical displays to the extensive gamut of newer displays. One of the objectives in performing these mappings is to preserve the apparent hue of the colors in the images. The Munsell hue scales, as well as newer data on hue perception, have been used to derive mathematical color spaces that are now implemented in digital cinema systems. These color spaces have applicability to gamut mapping, the process of changing desired aim colors to colors within the capabilities of a display device while preserving the appearance of the images.

Color description using Munsell terminology is an important part of soil-profile characterization and soil mapping, providing field-discernable evidence of soil-forming processes. For example, color changes can indicate oxidation and reduction of iron compounds. When a high water table limits oxygen penetration into a soil that has developed on parent material that contains the ferrous iron mineral pyrite ( $\text{FeS}_2$ ; typically black), that mineral is stable and tends to color the soil in the lower, water-saturated horizons. When pyrite reacts with atmospheric oxygen, sulfuric acid is produced, along with the pale yellow, ferric iron mineral jarosite [ $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$ ]. As a result of this "sulfuricization" process, one sees both low soil pH and streaks of jarosite in the oxidizing zone above the water table. The presence of the distinctly colored jarosite is readily described using the

*Munsell Soil Color Charts*. Other forms of oxidized iron such as the red, ferric oxide mineral hematite ( $\text{Fe}_2\text{O}_3$ ) and the yellow-brown, ferric oxyhydroxide mineral goethite ( $\text{FeOOH}$ ) can contribute to color features. Jarosite, hematite and goethite, either synthesized or mined from natural deposits, are used as paint pigments.

Color is fascinating to almost everyone, and the scientific study of color measurement and perception has a rich and interesting history. As with all fields, many have contributed, and modern scientists can see further by standing on the shoulders of the giants that preceded them. Color science is perhaps unique in the degree to which experts in a wide range of disciplines can make important contributions. Albert Munsell is one such example in which an artist and teacher satisfied his curiosity and need to teach by developing a system that had a profound impact on color science and commerce and will continue to do so long into the future.

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