INTRODUCTION TO COLOR

By Deane B. Judd[1]

I am somewhat embarrassed at being referred to as a "color expert." One of the difficulties of a so-called color expert is that nearly everyone knows a good deal about some phase or other of color and expects the expert to know more. He is supposed to discuss chromophores with the chemist, mordants with the dyer, spectrophotometric curves with the physicist, color specifications with the engineer, and color sensation and perception with the psychologist.

Color has many different meanings. The chemist and dyer may refer to a pigment or a dye as a color, the physicist may mean a spectrophotometric curve, the psychologist may mean a sensation, but to the man in the street, and the woman in the store, color is a property of objects and lights themselves.

All of these meanings for color make sense to those who use them, and there is a good deal of sense to all of them. In our discussion of the specification and use of color in evaluating the appearance of materials it would be desirable to take some one meaning for the term "color." It may as well be admitted now, however, that there is small hope of achieving a uniform usage for the term "color" however desirable it might be from the standpoint of avoiding confusion. Let us therefore see first what can be done toward defining color from the commonsense point of view, and later see what departures from this definition are required for color specification and measurement of materials.

Psychological Definition of Color

We shall not be too far from the commonsense definition if we say that color is everything that is seen by the eye. That takes in too much territory, of course, but it gets across the general idea. The eye also sees shape, texture, and flicker. Maybe it would be more accurate to say that color is the nonshape, nontemporal, nontextural aspect of appearance. This is a rather negative definition; and it would be embarrassing if we discovered later that we should have made other exceptions. So let us try a more positive form of definition. *Color is that aspect of the appearance of objects and lights which depends upon the spectral composition of the radiant energy reaching the retina of the eye and upon its temporal and spatial distribution thereon.* Let us not stop to argue over every word of this definition, however amusing it might be to do so. Suffice it to say that this definition is the best I can do to put the commonsense idea of color into words of as many as four syllables.

Of course, everybody sees color, and knows about it much more thoroughly through his own eyes than he ever is likely to from a definition composed of four-syllable words. Everybody organizes his own color experience and can describe it in more or less understandable terms. The difficulty comes

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about from the fact that each one's color terms refer to his own special problems. The textile dyer says that these two colors differ in strength, because one looks to him as if produced by more dye than the other. The artist says they differ in warmth because he is interested in producing a warm or a cool effect.

So let us get away from all special interests and purposes. Let us see how a man on a desert island would sort out a batch of colored papers washed up on the beach in a trunk.

ATTRIBUTES OF COLOR

First he spreads them out on the sand to look at them and finds a purely chance arrangement or disorder. Then he notices that a certain group of the colors lack an important characteristic possessed by the others; that is, they lack *hue*. He separates the colors into two groups—chromatic colors, those that possess hue, and achromatic colors, those that do not possess hue. He notes that the achromatic colors can be arranged in a single series extending from black at the bottom through a series of dark grays, middle grays, and light grays to white at the top; this series varies in lightness alone. Furthermore, for each chromatic color he notes that there can be found a gray of the same lightness, called the equivalent gray.

Then he turns his attention to the chromatic colors and sorts them out, putting all the reds together, then the yellows, greens and blues; and he also notes that there are others falling intermediate to these groups so that a whole circle can be set up, each part of which differs from the neighboring part by only a small step. This classification is by hue.

Of course, some of the colors of a given hue are found to be dark colors while others are light; he has already noticed this fact by comparison with the lightness scale of achromatic colors. But by sorting out all colors of the same hue (say red) and same lightness (say medium lightness) he discovers that there still are variations. The mode of variation is more subtle than the other attributes; it is called saturation. He finds that saturation supplies the basis for his very first step toward order; for achromatic colors (black, grays, white) saturation is zero; for chromatic colors, greater than zero. Saturation is proportional to the color departure from the equivalent gray.

Since there are three attributes of object-color, our hypothetical desert islander finds that he cannot arrange all of the colors in the trunk in a single plane diagram and still keep them in order. He can make an orderly arrangement of all colors of the same lightness, however; so he divides up the colors into groups, each group of about the same lightness; then arranges each group separately, and by placing the darkest colors on a disk, the next lighter group on a higher disk, as in a layer cake, he builds up a solid representation of all three attributes of color. Lightness is represented by distance above the base plane; hue, by angle about the central or black-gray-white axis; and saturation by distance from the axis. This space representation, in which each point represents a color, is called a color solid.

MODES OF APPEARANCE OF OBJECT COLORS

Now suppose that our lonely color expert had found his trunk filled, not with colored papers, but with dye solutions in test tubes. If he had been a dye chemist in his laboratory, he would have classified them, perhaps, first according to molecular structure, then according to concentration or strength, and he would have paid no attention to their appearance. But, he has nothing but his eyes to guide him, so he proceeds just as he did with the colored papers, and arrives at exactly the same attributes of color for transparent volumes, as he did for opaque surfaces. He can describe the difference between the colors of two dye solutions in terms of hue, lightness, and saturation just as aptly as that between the colors of two papers. But there is one distinguishing mark in the color solid for transparent volumes; the topmost point in the solid, occupied by white in the solid representing the colors of surfaces, is now occupied by a color known paradoxically as colorless, see Fig. 1. This is the name by which the color of perfectly transparent objects (plastics, glasses, crystals) and media (water, alcohol, oils) which do not absorb any light has come to be known.

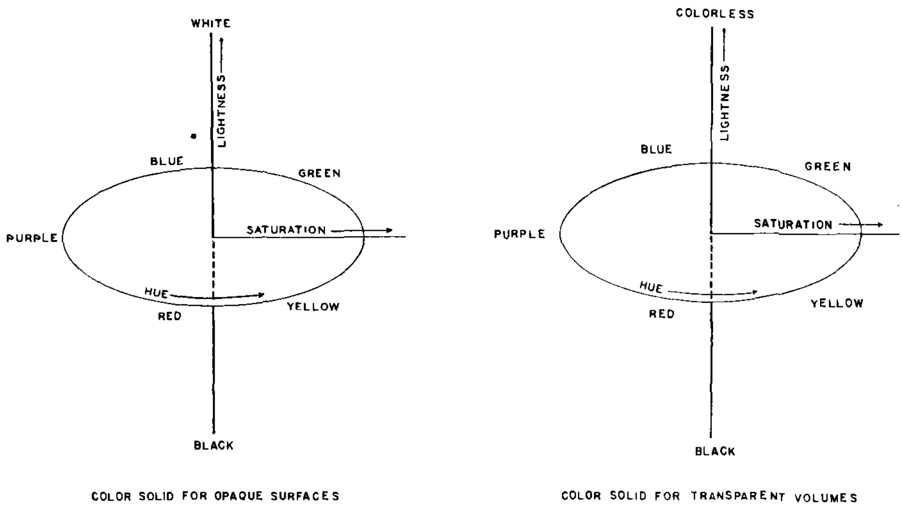


FIG. 1.—Dimensions and Fixed Points of Two Object-Color Solids.

The attributes of colors perceived as belonging to opaque surfaces are the same as those of colors perceived as belonging to transparent volumes. However, lightness for opaque surfaces varies from black to white, that for transparent volumes between black and colorless.

USEFULNESS OF THE COLOR SOLIDS

What has been gained by recourse to the man on the desert isle? Have we found a system less useful because it is not adapted perfectly to use by dyers, painters, chemists, botanists, physicists, artists or any special use? No, as a matter of fact, description of color by hue, lightness and saturation is used to some extent by all of them and above all by our friends, the man in the street and the woman in the store. Hue is the most prominent attribute of color, and is usually the first thought of. Color and color differences are universally described by such terms as red, yellow, green, blue and purple. The adjectives suggested by the attribute *lightness* are *light* and *dark*, universally used to describe color; and those suggested by the attribute *saturation* are *strong* (intense) and *weak* (dull). The term *strong* means saturated, and *weak* means not saturated. But it should be admitted right away that the dyer and dye chemist do not use the terms *strong* and *weak* in this sense, nor indeed are they used as strictly color terms by the dyer since the precise meaning of stronger varies for him from one dye to another even though the same color may be dyed by means of each. The substitute terms, *intense* and *dull* have sometimes been used.

A recent important study has been carried out by one of the du Pont Laboratories to see whether those trained in the detection of color differences for special purposes and the description of them in special terms could make use of the simple terms suggested by the object-color solids. It was discovered that not only was this possible, but there was actually a significant gain in agreement among the descriptions; and it was considered reasonable to ascribe this gain to the greater simplicity of the terms. This result is the more surprising because it appears likely that the maximum benefit of the simplified terms would be achieved only after the observers had become thoroughly familiar with the concepts so as to experience the color differences directly in accord with them. Many of the observers in this experiment were forced by unfamiliarity to judge the differences in terms of their previous training, then to translate them more or less accurately into hue, lightness, and saturation.

The various color solids not only organize in the simplest possible way, our throughts about color and color differences, but they also permit us to understand special color terms which would otherwise be obscure. Such terms as paler, deeper, cleaner, muddier, blacker and whiter, refer to paths or directions in the color solid. Thus, *paler* means both lighter and weaker, and its opposite *deeper* means both darker and stronger. Blacker means closer to black in the color solid, and so on. The term, *depth* of color is used in a number of A.S.T.M. specifications. The color solids have been used as guides in the selection of terminology for the I.S.C.C.-N.B.S. method of designating colors (**11**).[2]

TECHNICAL DEFINITION OF COLOR

We have seen how the commonsense definition of color leads to the various forms of object-color solid, in which each point represents a single color characterized by its particular hue, lightness, and saturation. One might readily suppose that measurement of the color of a given object consists merely of locating the proper point in the appropriate color solid. There are several reasons why this will not work. In the first place hue, lightness, and saturation are psychological quantities and can be determined by visual estimate only. There are long techniques for carrying out such estimates with considerable accuracy, but any rapid estimate is much too imprecise for engineering use. Secondly, no two observers would get the same result; and gross discrepancies would be frequent. And lastly, and by far the worst, each object has not one but many colors depending upon the amount and spectral composition of the illumination and upon the other colors in the visual field at the same time. An object in a given situation has a certain color or appearance, but in another situation a quite different appearance. This fact is well known, but frequently overlooked. It is well recognized by milady in the purchase of an evening gown. She must know the colors used in the decoration of the ballroom, and, if possible, the colors of the other gowns to be present. If everyone else is wearing a vivid red dress her own moderate red gown might be re-

[2] The boldface numbers in parentheses refer to the reports and papers appearing in the list of references appended to this paper, see p. 13.

duced to mauve by simple retinal fatigue. So it is not possible to determine exactly what point in the color solid represents the color of an object no matter how much we know about the object itself by physical measurement.

Now it is very awkward to be forced to have a different color specification for a given specimen for each different viewing situation. So practical considerations dictate a restriction of conditions. Color measurement is therefore customarily carried out so as to refer first to a standard background, second for each illuminant separately, third for a standard observer adopted to be representative of observers of normal color vision, and fourth by psychophysical quantities which correlate more or less well with the psychological attributes, hue, lightness and saturation.

The quantity that is measured in modern colorimetry is therefore somewhat too restricted to correlate perfectly with the psychological definition of color, the most important restriction often not recognized being that the measurements give a reliable indication of appearance for one background only. So valuable has modern colorimetry proved, however, that it is very tempting to redefine color as the quantity measured by colorimetry. The basis for this redefinition is that we perceive objects only by means of the light which comes from them; therefore let us define color as an aspect of light, only, somewhat as follows: *Color is that aspect of the appearance of light which depends upon its spectral composition.* Formulation of the strict technical definition of color has been accomplished only recently by the Committee on Colorimetry of the Optical Society of America whose report is now in preparation. To trace the full implications of this definition including the complete argument by which an object may be said to have color in spite of the fact that color is defined as an appearance aspect of light, only, takes up many pages of the report; so no attempt will be made to elaborate the argument further at present. Suffice it to say that the work has been carefully done, and deserves to be studied thoroughly by anyone writing color specifications because it will necessarily exert a profound influence on colorimetric practice for many years to come.

The technical definition of color is called a psychophysical definition. Color by this definition may be evaluated by physical measurements taken on the illuminant and object combined with information obtained by the psychological act known as color matching. Color is specified by reference to a point in some psychophysical color system which correlates more or less closely with the purely psychological arrangements given by the color solids. All of the color systems to be mentioned hereafter will be psychophysical systems.

PHYSICAL INSTRUMENTS AND APPEARANCE OF OBJECTS

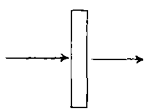
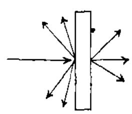
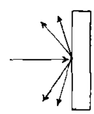
Physical measurements of objects which correlate with color and its mode of appearance are made with the spectrophotometer and the goniophotometer. The spectrophotometer compares in spectral composition the radiant energy leaving an object with that incident upon it. The two beams of radiant energy are first decomposed into their spectral components, and then compared photometrically wave length by wave length. The spectrophotometer yields primary information relative to color and is used in the A.S.T.M. Standard Method of Test for Spectral Apparent Reflectivity of Paints (D 307 – 39).[3] The goniophotometer determines

[3] 1939 Book of A.S.T.M. Standards, Part II, p. 815.

the angular distribution of radiant energy leaving an object. It yields primary information relative to glossiness and transparency which are aspects of appearance closely associated with color and with its mode of appearance.

Table I shows the correspondence between physical characteristics of the object, the geometry of the measurement, the instrument, the way its color is judged, and the color solid appropriate to representation of its color.

TABLE I.—CORRELATION BETWEEN PHYSICAL MEASUREMENT OF THE OBJECT AND ITS COLOR.

	Transparent Sample, Measured on the Spectrophotometer	Translucent Sample, Measured on the Spectrophotometer and Goniophotometer	Opaque Sample, Measured on the Spectrophotometer and Goniophotometer
Geometry of the measurement			
Quantity measured	Amount and spectral distribution of transmitted energy	Amount, spectral and angular distribution of emitted energy	Amount, spectral and angular distribution of reflected energy
Color judged by	Transmitted light	Transmitted and reflected light	Reflected light
Appropriate color solid	Volume-color solid	....	Surface-color solid

Transparent materials require the use of the spectrophotometer only. In practice, specimens are most frequently color matched with material standards prepared for that purpose; but the standards themselves are usually specified by spectrophotometric measurements. These standards are discussed by Scofield.[4]

Translucent materials require the use of both spectrophotometer and goniophotometer. The practical methods of handling translucent materials are described by Sawyer.[5] Here again the instruments giving a complete analysis of the angular and spectral distribution of the transmitted and reflected radiant energy are seldom used. But in the development and testing of the optical theory on which practice is based, frequent use of the spectrophotometer and goniophotometer have been made. The quantity of primary interest is transparency; this quantity is not an attribute of color but determines its mode of appearance.

Opaque materials also require both the spectrophotometer and the goniophotometer. The use of the spectrophotometer for determining the color of opaque materials is discussed by Parker.[6] This instrument is used not only for the study of working standards of color discussed by Godlove,[7] but also increasingly for the specimens themselves. The goniophotometer yields primary information relative to glossiness which, although not an attribute of color, is so important an aspect of appearance that color and glossiness have often to be considered together.

COLOR SPECIFICATION BY COMBINATIONS OF LIGHTS

We come now to the methods of expressing spectrophotometric results.

[4] See p. 18.
[5] See p. 23.
[6] See p. 47.
[7] See p. 37.

We have already seen that a standard illuminant must be chosen. In this way we can characterize all objects in accord with the reflected or transmitted energy which leaves them. There are two chief ways of specifying such energy: first, by color match with an additive combination of three fixed lights or primaries; and second, by color match with an additive combination of two lights, one fixed such as daylight, the other variable, such as the various parts of the spectrum. The first way is known as tristimulus specification and is important because it permits an easy reduction of spectrophotometric data. The best-known example of the fixed-light, variable-light way is by dominant wave length and purity; this way is important because it yields variables which correlate to a degree with the psychological color attributes, hue and saturation. The fixed light is usually the same as the illuminant and is represented by the origin of a system of polar coordinates.

Tristimulus Specification.—We have already seen that object colors viewed under constant conditions by our desert islander vary in three independent ways. We should therefore not be surprised that three lights are required in an additive mixture to color match the beams of light leaving such objects. The amounts of the three fixed lights or primaries constitute the specification. If the photometric field be illuminated by two components of tristimulus specification, X_1, Y_1, Z_1, and X_2, Y_2, Z_2, respectively, the specification of the resultant is simply: $X_1 + X_2$, $Y_1 + Y_2$,

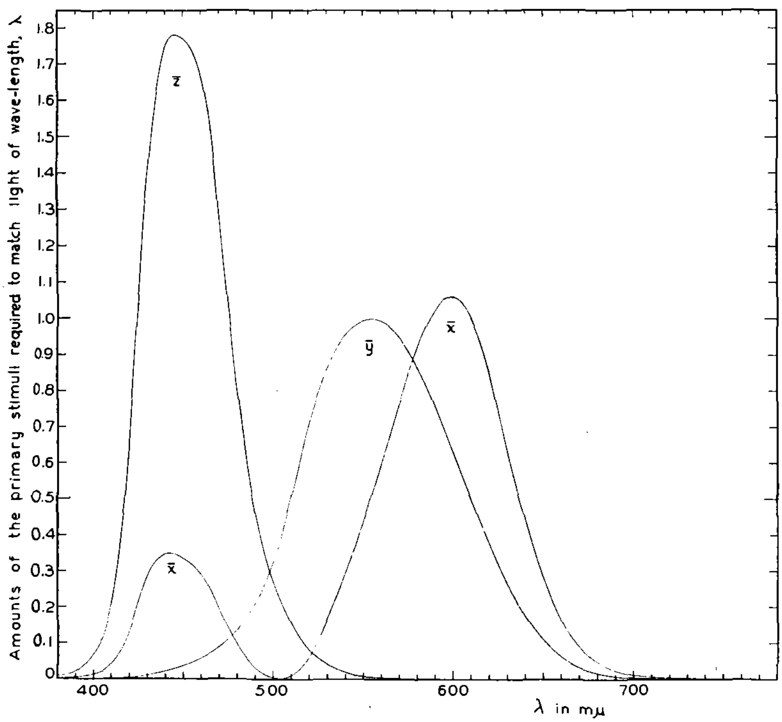


FIG. 2.—Tristimulus Specifications of the Various Parts of the Spectrum According to the 1931 I.C.I. (or C.I.E.) Standard Observer and Coordinate System; see also Table II.

$Z_1 + Z_2$. The same principle applies, of course, to additive combinations of any number of lights. This simple law has been repeatedly verified for a large middle range of brightnesses, and when it is recalled that any light may be considered as the sum of the various parts of the spectrum, it is evident that the color specification corresponding to any spectrophotometric curve can be computed by simple addition. Of course we have to know the tristimulus specifications of each part of the spectrum. These specifications vary somewhat from observer to observer and may be given for any one of a wide number of primaries. It is almost universal practice, however, to use tristimulus specifications of the spectrum according to the standard observer and primaries recommended in 1931 by the International Commission on Illumination (3, 4, 8). Figure 2

TABLE II.—THE 1931 I.C.I. STANDARD OBSERVER.

Trichromatic Coefficients			Wave Length, (mμ)	Tristimulus Specifications of the Equal-Energy Spectrum			Trichromatic Coefficients			Wave Length, (mμ)	Tristimulus Specifications of the Equal-Energy Spectrum		
x	y	z		$\bar{x}$	$\bar{y}$	$\bar{z}$	x	y	z		$\bar{x}$	$\bar{y}$	$\bar{z}$
0.1741	0.0050	0.8209	**380**	0.0014	0.0000	0.0065	0.5125	0.4866	0.0009	**580**	0.9163	0.8700	0.0017
0.1740	0.0050	0.8210	**385**	0.0022	0.0001	0.0105	0.5448	0.4544	0.0008	**585**	0.9786	0.8163	0.0014
0.1738	0.0049	0.8213	**390**	0.0042	0.0001	0.0201	0.5752	0.4242	0.0006	**590**	1.0263	0.7570	0.0011
0.1736	0.0049	0.8215	**395**	0.0076	0.0002	0.0362	0.6029	0.3965	0.0006	**595**	1.0567	0.6949	0.0010
0.1733	0.0048	0.8219	**400**	0.0143	0.0004	0.0679	0.6270	0.3725	0.0005	**600**	1.0622	0.6310	0.0008
0.1730	0.0048	0.8222	**405**	0.0232	0.0006	0.1102	0.6482	0.3514	0.0004	**605**	1.0456	0.5668	0.0006
0.1726	0.0048	0.8226	**410**	0.0435	0.0012	0.2074	0.6658	0.3340	0.0002	**610**	1.0026	0.5030	0.0003
0.1721	0.0048	0.8231	**415**	0.0776	0.0022	0.3713	0.6801	0.3197	0.0002	**615**	0.9384	0.4412	0.0002
0.1714	0.0051	0.8235	**420**	0.1344	0.0040	0.6456	0.6915	0.3083	0.0002	**620**	0.8544	0.3810	0.0002
0.1703	0.0058	0.8239	**425**	0.2148	0.0073	1.0391	0.7006	0.2993	0.0001	**625**	0.7514	0.3210	0.0001
0.1689	0.0069	0.8242	**430**	0.2839	0.0116	1.3856	0.7079	0.2920	0.0001	**630**	0.6424	0.2650	0.0000
0.1669	0.0086	0.8245	**435**	0.3285	0.0168	1.6230	0.7140	0.2859	0.0001	**635**	0.5419	0.2170	0.0000
0.1644	0.0109	0.8247	**440**	0.3483	0.0230	1.7471	0.7190	0.2809	0.0001	**640**	0.4479	0.1750	0.0000
0.1611	0.0138	0.8251	**445**	0.3481	0.0298	1.7826	0.7230	0.2770	0.0000	**645**	0.3608	0.1382	0.0000
0.1566	0.0177	0.8257	**450**	0.3362	0.0380	1.7721	0.7260	0.2740	0.0000	**650**	0.2835	0.1070	0.0000
0.1510	0.0227	0.8263	**455**	0.3187	0.0480	1.7441	0.7283	0.2717	0.0000	**655**	0.2187	0.0816	0.0000
0.1440	0.0297	0.8263	**460**	0.2908	0.0600	1.6692	0.7300	0.2700	0.0000	**660**	0.1649	0.0610	0.0000
0.1355	0.0399	0.8246	**465**	0.2511	0.0739	1.5281	0.7311	0.2689	0.0000	**665**	0.1212	0.0446	0.0000
0.1241	0.0578	0.8181	**470**	0.1954	0.0910	1.2876	0.7320	0.2680	0.0000	**670**	0.0874	0.0320	0.0000
0.1096	0.0868	0.8036	**475**	0.1421	0.1126	1.0419	0.7327	0.2673	0.0000	**675**	0.0636	0.0232	0.0000
0.0913	0.1327	0.7760	**480**	0.0956	0.1390	0.8130	0.7334	0.2666	0.0000	**680**	0.0468	0.0170	0.0000
0.0687	0.2007	0.7306	**485**	0.0580	0.1693	0.6162	0.7340	0.2660	0.0000	**685**	0.0329	0.0119	0.0000
0.0454	0.2950	0.6596	**490**	0.0320	0.2080	0.4652	0.7344	0.2656	0.0000	**690**	0.0227	0.0082	0.0000
0.0235	0.4127	0.5638	**495**	0.0147	0.2586	0.3533	0.7346	0.2654	0.0000	**695**	0.0158	0.0057	0.0000
0.0082	0.5384	0.4534	**500**	0.0049	0.3230	0.2720	0.7347	0.2653	0.0000	**700**	0.0114	0.0041	0.0000
0.0039	0.6548	0.3413	**505**	0.0024	0.4073	0.2123	0.7347	0.2653	0.0000	**705**	0.0081	0.0029	0.0000
0.0139	0.7502	0.2359	**510**	0.0093	0.5030	0.1582	0.7347	0.2653	0.0000	**710**	0.0058	0.0021	0.0000
0.0389	0.8120	0.1491	**515**	0.0291	0.6082	0.1117	0.7347	0.2653	0.0000	**715**	0.0041	0.0015	0.0000
0.0743	0.8338	0.0919	**520**	0.0633	0.7100	0.0782	0.7347	0.2653	0.0000	**720**	0.0029	0.0010	0.0000
0.1142	0.8262	0.0596	**525**	0.1096	0.7932	0.0573	0.7347	0.2653	0.0000	**725**	0.0020	0.0007	0.0000
0.1547	0.8059	0.0394	**530**	0.1655	0.8620	0.0422	0.7347	0.2653	0.0000	**730**	0.0014	0.0005	0.0000
0.1929	0.7816	0.0255	**535**	0.2257	0.9149	0.0298	0.7347	0.2653	0.0000	**735**	0.0010	0.0004	0.0000
0.2296	0.7543	0.0161	**540**	0.2904	0.9540	0.0203	0.7347	0.2653	0.0000	**740**	0.0007	0.0003	0.0000
0.2658	0.7243	0.0099	**545**	0.3597	0.9803	0.0134	0.7347	0.2653	0.0000	**745**	0.0005	0.0002	0.0000
0.3016	0.6923	0.0061	**550**	0.4334	0.9950	0.0087	0.7347	0.2653	0.0000	**750**	0.0003	0.0001	0.0000
0.3373	0.6589	0.0038	**555**	0.5121	1.0002	0.0057	0.7347	0.2653	0.0000	**755**	0.0002	0.0001	0.0000
0.3731	0.6245	0.0024	**560**	0.5945	0.9950	0.0039	0.7347	0.2653	0.0000	**760**	0.0002	0.0001	0.0000
0.4087	0.5896	0.0017	**565**	0.6784	0.9786	0.0027	0.7347	0.2653	0.0000	**765**	0.0001	0.0000	0.0000
0.4441	0.5547	0.0012	**570**	0.7621	0.9520	0.0021	0.7347	0.2653	0.0000	**770**	0.0001	0.0000	0.0000
0.4788	0.5202	0.0010	**575**	0.8425	0.9154	0.0018	0.7347	0.2653	0.0000	**775**	0.0000	0.0000	0.0000
0.5125	0.4866	0.0009	**580**	0.9163	0.8700	0.0017	0.7347	0.2653	0.0000	**780**	0.0000	0.0000	0.0000
Totals											21.3713	21.3714	21.3715

shows these specifications for the equal-energy spectrum; and Table II gives them.

The advantage of having all colorimetric specifications given in the same system, and so immediately comparable, is very great; furthermore, the coordinate system chosen has advantages in routine computation; so it was adopted in Great Britain, Germany, and France as well as in this country and its use is constantly spreading. The I.C.I. system is used in the A.S.T.M. Tentative Method of Test for Color of Lubricating Oil and Petrolatum by Means of A.S.T.M. Union Colorimeter (D 155 - 39 T),[8] and it will undoubtedly be used in many A.S.T.M. specifications yet to be drafted.

Although the theory of tristimulus specification of color is simple, the choice of primaries to accord with easy routine reduction of spectrophotometric results has introduced features which are somewhat puzzling. The following questions and answers about the 1931 I.C.I. standard observer and coordinate system may be helpful. Of course, from a practical standpoint these questions might just as well not be brought up; you can go ahead and use the system on faith, but most of us would rather know some of the answers even though they do not affect the practical use of the system.

Question 1.—What are the primary lights of the I.C.I. system? Where can I purchase them?

Answer.—You cannot purchase them; they are all imaginary. You can easily draw a graph of energy distributions of these imaginary lights having the requisite colorimetric characteristics, but these distributions will be found to have negative ordinates for some portions of the spectrum (6, p. 516).

Question 2.—Why were not actual lights that can be set up and used taken instead of fictitious lights?

Answer.—Actual lights would lead to tristimulus specifications of the spectrum negative for some portions of the spectrum. It is better to have non-negative specifications than to have negative lights. You have to use the specifications in computation all the time but you could not use the primary lights even if they were real.

Question 3.—Why could not real lights be used?

Answer.—Because we do not have a real standard observer either. He is nothing but a column of figures obtained by averaging.

Question 4.—How do you know that the imaginary lights selected are the correct ones?

Answer.—Any three lights, real or imaginary, may be selected, that is, provided only that no two of them can be combined to color match the third. There is, therefore, no "correct" selection. The choice is based on convenience only (6, p. 544).

Question 5.—What is so convenient about the I.C.I. system?

Answer.—Well, for one thing you can easily find the candlepower of a light from its tristimulus specification.

Question 6.—How can I get candlepower of a light from its tristimulus specification?

Answer.—The candlepower is directly proportional to the amount of the second primary, Y, (1). This comes about from the fact that the second curve, the $\bar{y}$-curve, is the standard luminosity function (6, p. 544).

Question 7.—If the luminosity comes from the Y light, what is the luminosity of the X light and the Z light?

[8] 1939 Book of A.S.T.M. Standards, Part III, p. 598.

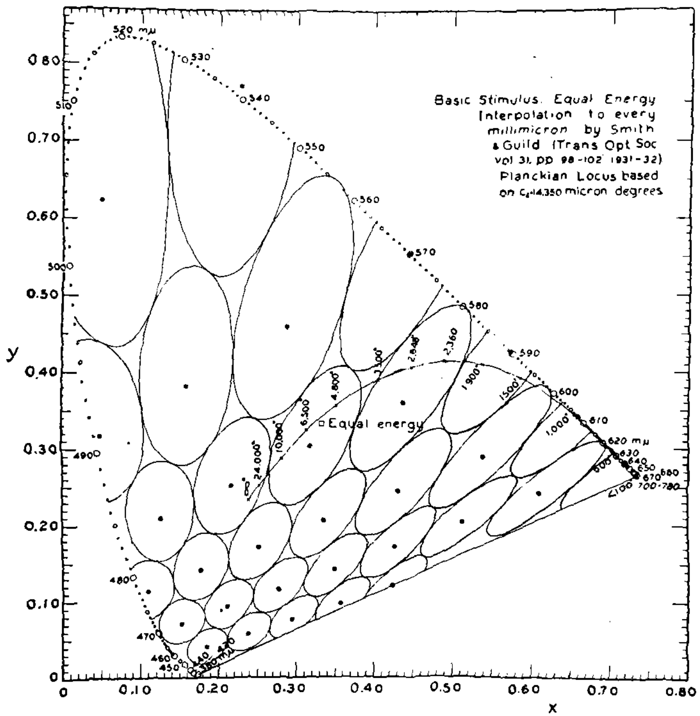


FIG. 3—Chromaticity (or Mixture) Diagram Formed by Plotting in Rectangular Coordinates the Trichromatic Coefficient, *x*, Against the Trichromatic Coefficient, *y*.

These trichromatic coefficients refer to the *1931 I.C.I. (or C.I.E.)* standard observer and coordinate system. The small circles indicate the chromaticities of the various parts of the spectrum; see Table II.

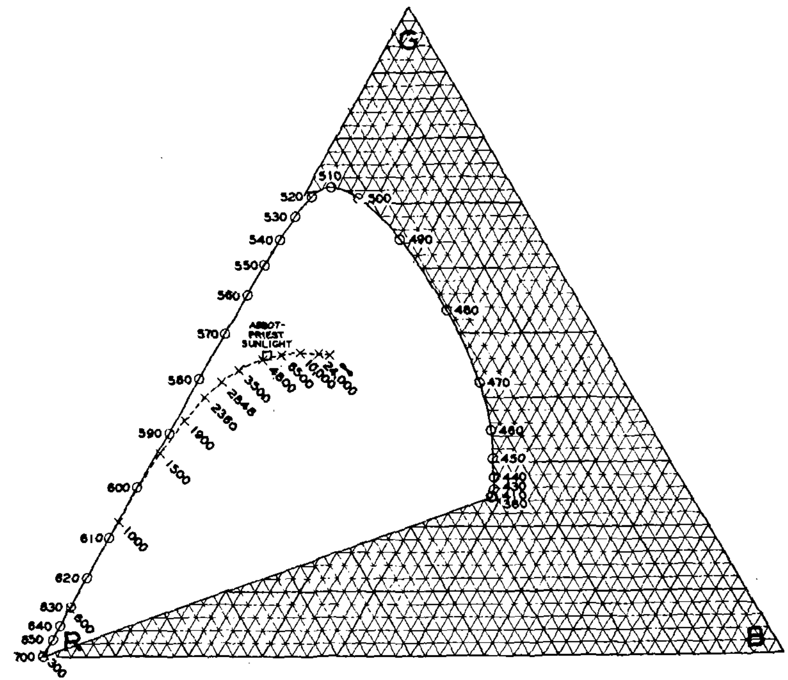


FIG. 4.—Uniform-Chromaticity-Scale Triangle According to Judd.

Other color systems having substantially the same chromaticity spacing have been devised by MacAdam, by Breckenridge and Schaub, and by Scofield.

Answer.—They have zero luminosity.

Question 8.—How can you call anything that has zero luminosity a light? How can there be a nonluminous light?

Answer.—There cannot be any such thing as a nonluminous light; as already stated, these lights are imaginary.

Well, that is enough of a catechism. The outstanding disadvantage of this colorimetric system is that the specifications resulting from it fail to suggest the color readily. It is nearly always necessary to represent chromaticity separately. This is done by use of a chromaticity diagram obtained by plotting $X/(X + Y + Z)$ against $Y/(X + Y + Z)$; see Fig. 3. These fractions are called trilinear coordinates or trichromatic coefficients and are designated (x, y, z), the z-coordinate being an abbreviation for $Z/(X + Y + Z)$. By plotting a point (x, y) on such a chromaticity diagram or map to represent a specimen, the chromaticity relationship with other specimens is made clear. Table II gives the trichromatic coefficients of the spectrum colors.

Recently there has been an effort to supplement the standard coordinate system by choice of other primaries which yield a chromaticity spacing of colors more in accord with that in the constant-lightness planes of the surface-color solid. Such systems, known as uniform-chromaticity-scale systems, have been proposed by Judd (9, 10), MacAdam (12), Breckenridge and Schaub (2), and by Scofield (16). The Scofield proposal, made to A.S.T.M. Committee D-1 on Paint, Varnish, Lacquer and Related Products bears a further resemblance to the constant-lightness planes of the surface-color solid because it places gray at the origin of the coordinates. Figure 4 shows the Judd uniform-chromaticity-scale triangle. A family of equal tangent circles on this triangle has been transferred to the (x, y)-diagram of the Standard I.C.I. system (Fig. 3) and the resulting ellipses serve to indicate the chief distortions of that diagram. If the improved spacing of the various uniform-chromaticity-scale triangles proves to be of practical importance, we may expect to see color specifications increasingly given both according to the standard system and according to some uniform-chromaticity-scale system. Attempts to explore the practical advantages of such alternate color systems should be encouraged.

Polar-Coordinate Specification.—The great advantage of the fixed-light, variable-light method of color specification is that it lends itself to the use of polar coordinates. The variables may therefore be made to correlate fairly well with the psychological attributes hue and saturation which are also plotted in polar coordinates, hue being plotted as the angle, saturation as the radius.

The most widely used variables are dominant wave length and purity. Dominant wave length (3, 8, 13, 14) is the wave length of the spectrum light required to be added to the fixed light to color match the specimen; purity (3, 5, 7, 13, 14, 15) is the ratio of the amount of the spectrum light to the total amount of the two-part combination. This definition of purity is a convenient one, but the choice is not too happy for the production of good correlation with saturation. By this definition, the colors of the spectrum have constant (unit) purity; but they are usually perceived as of rather widely varying saturation. In spite of this handicap, it is fairly easy to learn how to visualize the color of a surface from its reflectance, dominant wave length, and purity. Oftentimes a color specification is given both in tristimulus terms and by dominant wave length and purity, and thereby becomes more easily understood. Either form may easily be computed from the other.

COLOR SPECIFICATION BY MATERIAL STANDARDS

By far the great majority of color specifications are administered by material standards of color, and often they bear the whole brunt of the specification, no more fundamental specification being given. Sometimes it is feasible to define them so that they may be reproduced from easily obtainable materials, as in solutions of inorganic salts, many of which are used in A.S.T.M. tests. Preparation of opaque color standards is more difficult, but in the standard magnesium-oxide surface on which present spectrophotometric practice discussed by Parker[9] is based, these difficulties have largely been overcome.

Since color specification by material standards is discussed in some detail by Scofield[10] and Godlove,[11] it will be sufficient here to point out why material standards of color are so practical in spite of the difficulties of impermanence.

We have just seen that technical colorimetry based upon additive combinations of lights requires four restrictions: (*a*) standard background, (*b*) accurate accounting of the illuminant, (*c*) use of a standard observer, and (*d*) use of psychophysical quantities which correlate with the psychological attributes, hue, lightness and saturation. The use of a material color standard makes immediately plain that the essential act required of the observer is simply that of color matching. Note first that the specification succeeds regardless of surroundings provided only that both sample and standard are viewed against the same surroundings. Second, accurate specification of the illuminant is often not required because it is found that change in illuminant produces an effect of the second order. Similarly in the third place, small variations in color vision from one normal observer to another produce only a second-order effect; so a standard observer is not required. And finally, the only use of the psychological attributes, hue, lightness and saturation arises in the description of the differences between specimen and standard. This simplicity accounts for the success of material standards of color.

Many A.S.T.M. specifications embody material color standards devised for one particular test. Reference to the index to A.S.T.M. standards and tentative standards shows in fact that the Society has made wide use of such standards. Many of these are mentioned by Scofield[10] and Godlove.[11]

SUMMARY

A distinction has been drawn between the psychological definition of color and the technical definition. Color standards based upon combinations of lights and those based upon collections of material standards have been discussed. This discussion is intended to prepare the ground for the more detailed accounts of color specification and use in evaluating the appearance of materials which follow.

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[9] See p. 47.
[10] See p. 18.
[11] See p. 37.

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DISCUSSION

MR. FRANK GOTTSCH[1] (*presented in written form*).—Mr. Judd has set before us high and wonderful ideals. I would not attempt to elaborate on my part of his exposition. That which impresses me, however, is the great gulf that exists between those ideals and their practical realization. It is thought that progress has recently been made in bridging this gulf, as will be shown later in the symposium. I shall try in a few words, and in a novel way, to summarize the situation.

I am thinking of myself and of the words of Pope "fools rush in where angels fear to tread." Mr. Judd is entitled once more to commendation on his ability to think his way about in this great and beautiful garden that looks to many of us like a "riot of color."

I well remember my first great impression of color—my "introduction to color." I was about five years old and had been given a package of pin wheel papers of many colors. I did not make pin wheels of these, but like the man on the desert island I went off and sat alone for about two hours and actually did most of the things the desert island man did. Furthermore, I experienced great thrills when I held one color close to another and discovered many pleasing combinations. Not long before this my grandmother had read to me "Alice's Adventures in Wonderland" by Lewis Carroll. I feel very much like Alice now, very small and very frightened.

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I can see and hear Alice at the tea party.

The Hatter looked hard at Alice and shouted, "I don't like the color of your dress. I don't like red."

"My dress is not red," said Alice with some anger. She thought that personal remarks were rude. "My dress is rose colored."

"You do not understand color," said the Hatter. "If you understood color you would know that the dominant wave length settles that. The dominant wave length is red, so your dress is red."

"All I know," answered Alice, "is that my father, who is an artist, told me my dress was rose, and that he could see the blue in it—'an undertone,' he called it."

"Neither one of you can think straight about color," broke in the March Hare. "To understand color you have to think about it. You could never understand colors by just looking at them."

"I don't know how I can think about color," replied Alice. "Perhaps you can tell me how to think about color."

"It is this way," said the March Hare, straightening up in his chair, "you have to imagine it all."

"I can't see how I am going to think of and understand color without some kind of a light. I know that you cannot see anything, not even a color, in the dark," said Alice very meekly.

"I see that all this is in your 'mind's eye,' " announced the Hatter, giving the sleepy Dormouse a pinch, which made him squeal.

"Well, you have to have an *imaginary*

light," explained the March Hare. "This imaginary light shines through, or shines upon something, anything. Then there is an imaginary person who is supposed to be looking at the light that comes through or from the surface of anything. The imaginary person then imagines that he can divide the light coming from this into three parts. Actually one of these parts is not as imaginary as the other two. The one part that is not so imaginary as the others is thought of as being quite similar to all of the original light. The other two parts are absolutely imaginary."

"I would much rather learn about color by looking at something," said Alice. "It gives me a headache to try to think this way. All I can do is to see a thing or not to see it, and to imagine about a thing or not to imagine about a thing. I am really unable to imagine something that is only partly imagined by somebody else. Is there not something that would help me think about all this?"

"Our house is full of such helps," replied the Hatter. "There are cylinders, bricks, barrels, layer cakes, trees, pyramids like they have in Egypt, maps, circles, triangles and diagrams."

"Are any of these painted with any kind of colors?," asked Alice very humbly.

"No," said the Hatter. "These are not made so that you can see the color; they have no color. They are made so that you can THINK about colors."

"I wish," said Alice, "that I could find somewhere a collection of the beautiful colors I saw in the wonderful garden which was just beyond the little door that opened with the golden key. When winter comes I know that all the flowers will be dead, and I would like to remember some of them better by looking at these colors again."

"You can do that," explained the Hatter. "There are color cards, color packs, color books, color albums, color atlases, and color dictionaries, but these are incomplete."

"Why are they incomplete?" asked Alice.

The March Hare here screamed so loud that Alice could just understand what he said:

"Because they have not been able to find the right colors of paints and inks to make them. For one thing, there is no violet paint or violet ink."

"I *knew* that violet was not the same as purple," said Alice, nodding her head very wisely.

"I think that violet *is* the same as purple," blurted out the Hatter. "In the rainbow, if you make one end overlap the other end it makes purple or violet. It doesn't matter which you call it."

"I heard all that," said the Dormouse without opening his eyes. "The Caterpillar has a top painted with different colors which he used to spin to find out the color his wings were going to be some day. It has turned nearly black. He doesn't use it any more."

No one paid any attention to these remarks. "At any rate," said the March Hare, "when you think about this you have to think of three things to understand it. It is like a stool with three legs. If it does not have three legs it couldn't stand up."

"I can't see the connection between stools and colors," said Alice.

"There isn't any," murmured the Dormouse, in his sleep.

"Maybe," said Alice, "if they could mix lights I could understand this better. Once when we were in town last winter it was raining. I saw the most beautiful colors formed by the mixing of the lights from a number of those new advertising signs as they shone on the wet pavement."

"This *is* being done," replied the

March Hare haughtily. "Perhaps we can see this if we hurry and go to the Queen's Exhibition."

"Maybe," said Alice, "if they had a way of actually taking these colors apart and showing me what the different colors were made up of, and then putting all these parts back again to make up the original color, I would understand it all, without having to think so hard."

"That *never* has been done," said the March Hare very solemnly. Pulling his watch out of his waistcoat—the same watch that he had dipped into the tea—he rushed off with the Hatter crying, "Hurry, Hurry, Hurry, we will be late at the Exhibition."

Alice ran after them saying, "But tell me, please, what is meant by 'minus green'?" They did not answer.

They left the Dormouse asleep with his head on the table.

MR. W. M. SCOTT.[2]—When I first went into the textile industry I found that in that industry there had grown up from long practice the custom of matching colors, or matching shades, as they call it, with a very weird and fanciful combination of dyestuffs, usually ranging up to eight or ten different dyes, and there seemed to be no rhyme or reason to it. These dyestuffs covered practically the whole gamut of hue, and the dyer would add a little more of one or a little less of another to match some particular shade.

I found with a true conception of the color solid and of the three attributes of color—hue, lightness, and saturation—that it became perfectly possible to point out the way in which any given shade could usually be matched with perhaps three dyes or four at the most. This was accomplished by selecting one dye of a hue slightly on one side of the shade to be matched, another dye with a hue slightly on the other side, and then perhaps a third dye to give depth (or darkness) or to bring the shade nearer to gray.

Thus, when taught to think of color from the standpoint of its three attributes, the dyer found it considerably easier to match his shades with a smaller number of dyestuffs and to arrive more quickly at the desired result.

Then again, this conception of the color solid overcame a difficulty which men who had been working in dyeing establishments for a long time still seemed to have, namely, a confusion between the two characteristics of lightness and saturation. That was probably due to the fact that if you have an undyed textile, whose color is rather high in lightness, that is, near to white, and you add to it a blue dyestuff, you are not only increasing the saturation of its color, but you are also making it darker, as Mr. Judd pointed out. It was the confusion of those two attributes in the minds of the men in the textile industry which did a lot toward increasing the difficulty of their expressing color to each other and complicated their own thinking of color.

A third way in which this conception of the color solid helped out was in the interchange of color information from one person in the organization to another. Mr. Judd has mentioned this point and has briefly touched upon the development of a new method for describing color, known as the I.S.C.C.-N.B.S. method, which has been developed at the National Bureau of Standards and is based on those three attributes of color illustrated by the color solid.

My contribution to this subject, then, is the thought that a true conception of the color solid does simplify the average person's thinking on color and also his ability to transform or transmit his ideas

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on color to other persons in the same field.

MR. DEANE B. JUDD[3] (*author's closure*).—I wish to comment on Mr. Gottsch's remarks by admitting that there has been a great gulf between color specification by the tristimulus method and its practical application in commerce. To reduce this gulf has been one of the efforts of the Colorimetry Section of the National Bureau of Standards ever since 1919. Recently some appreciable success has been achieved due in no small part to the activity of the Inter-Society Color Council. No doubt many of those coming into contact with tristimulus colorimetry for the first time experience a bewilderment very similar to that of Alice in Wonderland. Perhaps we all have experienced it in some degree or other in our attempts to correlate the numerous methods of color designation, and I believe that the remarks of Mr. Gottsch's Alice, besides being entertaining, may encourage others in spite of the impression of unfamiliarity to push forward with confidence that results of practical value are possible.

Mr. Scott has pointed out the need for organization of color perception as an aid to color matching by dyeing of textiles. The mode of this organization determines very largely the language by by means of which color information and ideas are exchanged. When everyone shall have learned to express his ideas in a universally understood color language, when manufactures can control the colors of their products, when the customer can order a color and get what is ordered, then we could say that the gulf between theoretical colorimetry and its practical application has been bridged. Although we are progressing, it appears that this colorimetric utopia will continue to elude us for many decades.

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