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Color Science and Color Photography

For high-fidelity reproduction of color, films and television would use principles defined by Maxwell and elaborated by Ives. Color scientists are coming back to old ideas that have been neglected for many years.

by David L. MacAdam

COLOR SCIENCE IS based on important contributions of many well known figures: Isaac Newton, Thomas Young, Hermann Helmholtz, Hermann Grassman, James Clerk Maxwell and Erwin Schrödinger to mention only the most prominent. Seemingly as an aside, incidental to one of his lucid lectures, Maxwell invented three-color photography. He explained the principle on which all modern color photography, color printing and color television are based. Despite years of development, however, those who practice those arts still have much to learn from Maxwell and Frederic Ives, who first practiced, interpreted and championed Maxwell's idea, and from the science of color that grew out of the work of Maxwell, Ives and Ives's son Herbert.

Experimental color science has advanced greatly since Maxwell's time. We know how to plot the colors on a map from which we can determine such quantities as hue and purity. We can also plot tolerances based on human vision and the ability of the human eye to discriminate between nearby colors. On a map of all colors the tolerance limits around any point make an ellipse, but unfortunately on a simple map, these ellipses on different parts of the map vary greatly in size. If you take a projection of a small portion of the map, you can easily make the tolerance ellipse into a circle as one maps a small portion of the earth on a plane. But only with an impossibly complex surface can you hope to map all colors so that tolerance ellipses become equal circles everywhere.

Equations and computers simplify the matter of setting up standards and tolerances. And when appropriate standards are established and these standards are used to make a color film that responds as Maxwell and Ives said it should, you can get extremely accurate color photographs—good enough, in fact, to satisfy flower fanciers.

Maxwell and color

Maxwell's principle was that it is not necessary to recreate the spectrum of a color to make a color photograph. He identified the much less difficult criteria that are sufficient for fully satisfactory reproduction of color as far as human vision is concerned. For complete color matching, he pointed out, only three quantities need be controlled, rather than the myriad quantities, shown by a spectroradiometric curve, that are required for complete, physical specification of a colored light or a colored object. The simplicity of Maxwell's so called "trichromatic" principle made color photography feasible. Modern color photography,

The author is head of the image-structure department at Kodak research laboratories, where he has worked since he got his PhD at MIT in 1936. He has worked on color measurement, automatic recording and automatic computing of colors. He is the editor of the Journal of the Optical Society of America. This article is a shortened and revised version of the 21st Hurter and Driffield lecture presented last year in London.

color printing and color television are all based on it.

It matters not whether the three controls Maxwell prescribed are exercised by three superimposed or mixed dyes or pigments (as in so called "subtractive" processes, exemplified by almost all modern color photographs) or by physical control of three ultimately superimposed, differently colored lights (as in rather rarely practiced "additive" color photography and in all contemporary color television) or by combinations of the additive and subtractive methods (as in all commercial color printing with the halftone screens invented by Frederic Ives). All of these processes work by controlling, more or less independently, the amounts of light from the three thirds of the visible spectrum that Maxwell identified.

Maxwell was quite specific about the required character of the controls. He said that three photographs should be made with spectral sensitivities proportional to the three spectral sensitivities that Young had shown can be attributed to the eye to account for all of the infinite varieties of spectral distributions that can look alike (that is, "have the same color"). The three photographic plates, thus sensitized, with which Maxwell proposed to analyze and record all of the colors of nature were the prototypes of all of the photographic plates and films that have been used for color photography ever since and of the camera tubes of color television.

Ives's contribution

Since the matter was quite incidental and obvious to Maxwell and since the photographic materials available to him were quite primitive and unsuitable for his purpose, Maxwell did not try long nor succeed in carrying out the quantitative details of his idea—the mimicry of the spectral sensitivities of human eyes. Thirty years later, Frederic Ives had much more suitable materials, and also the single-minded persistence required to carry out Maxwell's idea and to demonstrate its validity to a skeptical and even hostile world. But his success had little influence on the development of modern color photography. Through his son Herbert, however, it had a significant influence on the modern technology of color measurement that very effectively supplements spectroscopy (spectrophotometry) in all industries that supply colored products. That technology is a scientific discipline in itself; it owes basic contributions also to Grassman, Arthur König and Schrödinger and is properly called the "science of color."

In the half century since Frederic Ives was active, color photography has developed quite independent of and without further basic contributions from physics. Chemistry has contributed all of the real innovations to which we owe modern color photography. In the process, the principle that guided Maxwell and Ives was half forgotten and misunderstood. Although advances in sensitizer chemistry made possible quite accurate fulfillment of Maxwell's principle (the spectral sensitivities of the film should simulate those of the eye), little or no effort was made to do so, and in most instances contradictory teachings led to greater departures from the proper sensitizations than characterized color photography at the beginning of the 20th century.

Fortunately color television escaped this diversion; despite all its other shortcomings, color television has clearly vindicated Maxwell and Ives. I hope to complete the rehabilitation of Maxwell's principle with some photographs made with a color film that conforms to it as closely as is feasible with modern means.

But first, let us establish our foundation in color science.

Matches and measurement

Color can be measured with a reflection spectrophotometer. Such an instrument determines the fraction of light reflected by a sample for every wavelength of the visible spectrum. The solid curve in figure 1, for a green sample, shows that it reflects about 40% in the middle of the spectrum, which is green, and only about half as much near the ends of the visible spectrum, which are blue and red. But the curve shows that it reflects some light of every wavelength. This is true of all samples. The dotted curve in figure 1 is for another green sample. Although the curves are quite different, the samples from which they were made look alike (that is, they "match") when they are compared in the light from an incandescent tungsten lamp. They do not match, however, but have quite different colors when they are compared in daylight.

Color specifications are not spectrophotometric curves, even though spectrophotometric measurements are required in case of dispute. Color specifications take the human eye into account.

The three curves, labelled $\bar{x}$, $\bar{y}$, and $\bar{z}$ in figure 2, recommended in 1931 by the International Commission on Illumination, represent normal color vision. They are called "color-mixture functions."

Tristimulus values

Since colors look different in different kinds of light, we have to decide what kind of light we want to use. Let's use daylight, the spectral distribution of which is shown by the curve labelled E in figure 2. Now at every wavelength, multiply the reflectance R of the sample by the height E of the curve for the light source to obtain the curve $R \times E$, which shows how much energy of each wavelength in daylight is reflected from the green sample. Then, for each wavelength, multiply the height of the $R \times E$ curve by the heights of the three curves $\bar{x}$, $\bar{y}$, $\bar{z}$ for normal color vision. The results are shown by the three curves at the bottom of the chart. Finally, find the area under each of these three curves. Label these areas, X, Y and Z; we call them the "tristimulus values" of the sample. We agree that if they are exactly the same as the tristimulus values of the standard, the sample matches the standard.

Easier methods have been devised for getting these results, but we needn't go into the details. A bright high-school graduate can be quickly taught to do the job, using a desk calculator. He or she will require about 10 minutes per sample. When we have hundreds of samples to do per week, we compute the X, Y and Z directly with an accessory connected to the spectrophotometer, or we digitize the spectrophotometric results and do the integrations on an automatic computer. By digitizing the spectrophotometric data we can get color specifications for any number of light sources, and even for color photography and color television, instead of for the eye. The same data are simply reused for each additional source or receiver for which we want results. The sample need not be put back on the spectrophotometer. We can do this several years later, even if we have thrown away the sample.

Error and tolerance

Now it would be easy if the X, Y and Z of the sample always came out exactly equal to the values for the standard. But they never do. We have to accept slight differences. This means we never get an exact color match, and we have to agree on tolerances.

Because it is practically impossible to express tolerances in terms of X, Y and Z, we have to look into the matter further. For many purposes, slight errors of overall (called "luminous") reflectance depend differently on the conditions of examination than do tolerances of color quality.

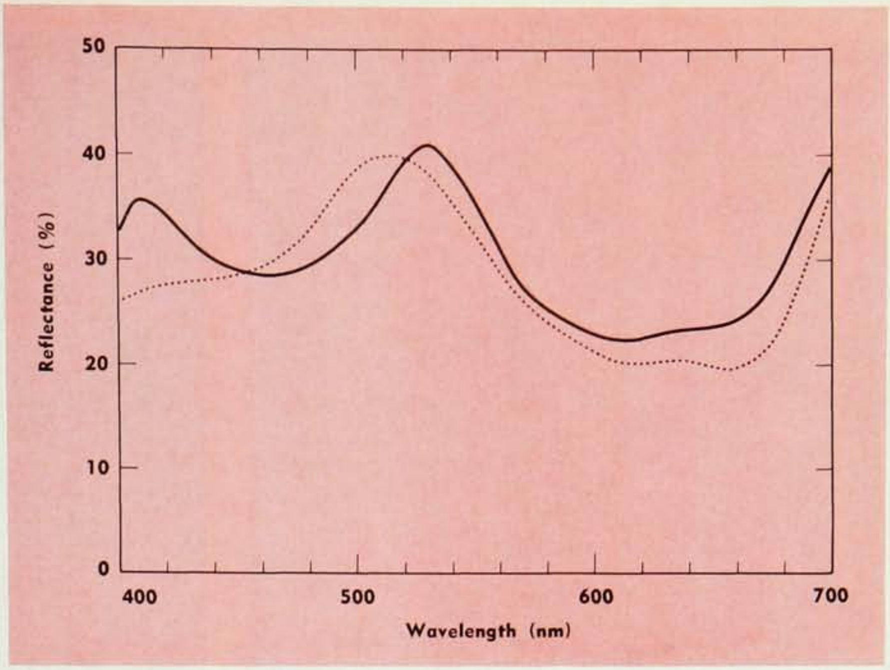
Luminous reflectance is indicated simply by the second tristimulus value Y. Therefore, if the sample has a lower Y than the standard, the sample looks too dark.

We specify a color quality by figuring the proportions of X, Y and Z in their sum. We may think of X as red, Y as green and Z as blue even though Y alone also specifies the luminous reflectance. The proportion of red in the color is $x = X/(X+Y+Z)$. The proportion of green in the color is $y = Y/(X+Y+Z)$. We don't need to calculate the proportion of Z in the mixture; it is enough to tell the proportions of red and green; the rest is blue. If the tristimulus values are all equal, the color is white or gray. If one of them is much greater than the others, that is, of course, the dominant color. That is also the dominant color if that color is only a little bit more than the others, but then the saturation, or vividness of the color is low, as in a pastel or a tint.

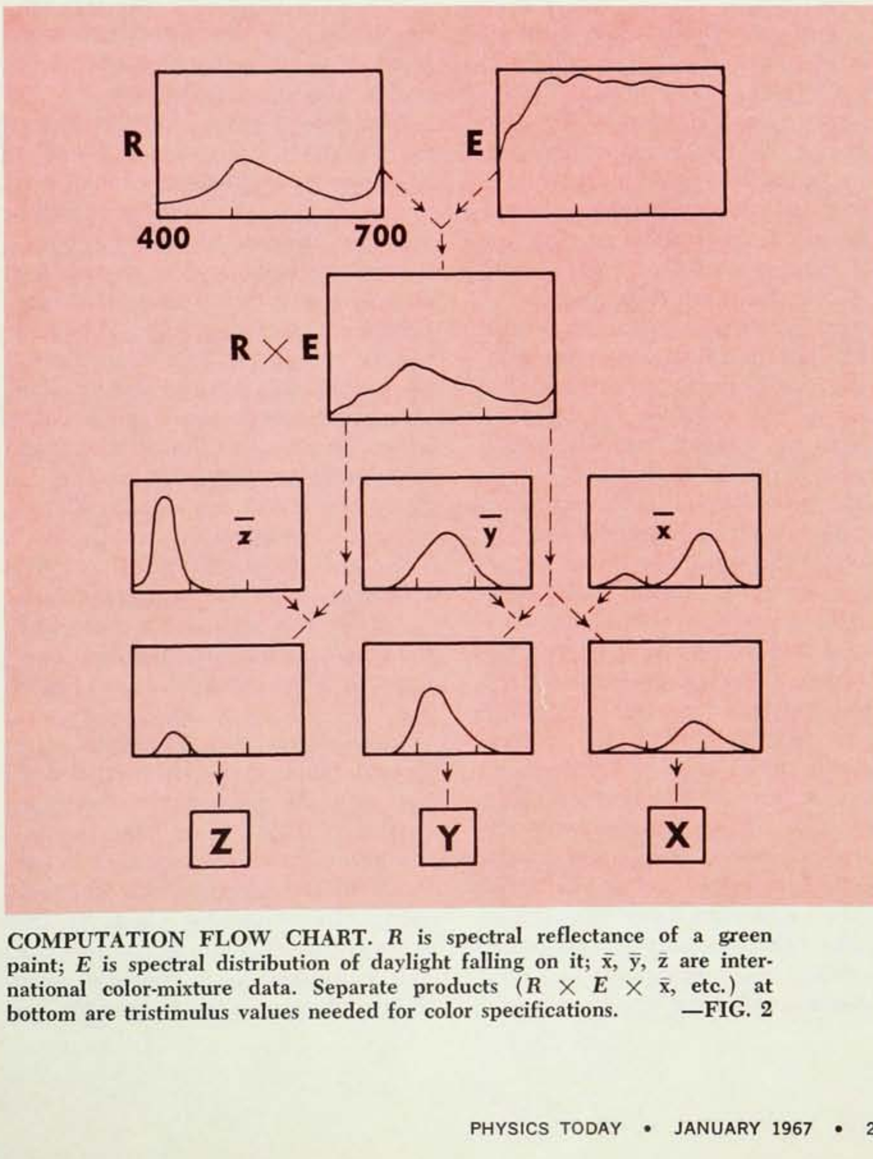
The color map

If I go further with examples like this, everyone will get confused, including me. It would be like telling a motorist the latitude and longitude of the place for which he asked directions. A map is the best way to answer; so let's make a map for colors.

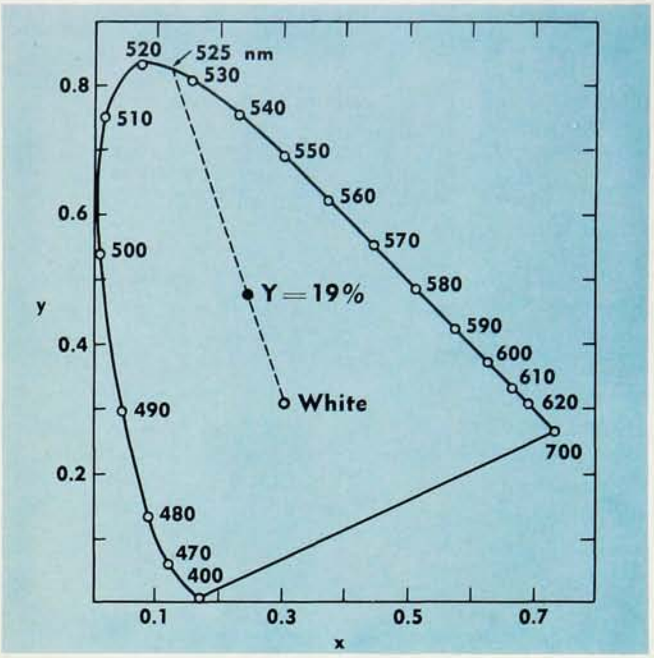
We use x like longitude and y like

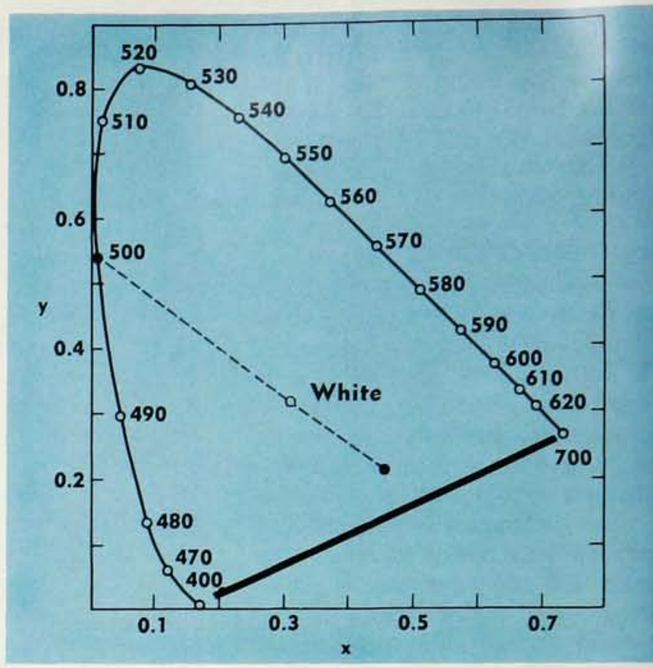


SPECTRAL REFLECTANCE of two green samples. To the normal human eye they match in tungsten light but not in daylight. —FIG. 1



COMPUTATION FLOW CHART. R is spectral reflectance of a green paint; E is spectral distribution of daylight falling on it; $\bar{x}$, $\bar{y}$, $\bar{z}$ are international color-mixture data. Separate products ($R \times E \times \bar{x}$, etc.) at bottom are tristimulus values needed for color specifications. —FIG. 2





latitude. Figure 3 shows such a map. This is usually called the "chromaticity diagram," but I think it is helpful to call it a "map of color quality." White and gray are represented by the point in the middle; the colors of the spectrum are on the curved boundary. Intermediate colors are between white or gray and the spectrum locus. This is a map of color quality only; the amount of color, or luminous reflectance, is not shown. Just as we indicate the heights of hills on a road map, if we want to indicate the luminous reflectance of a color on this map, we may write a number on it beside the point representing the color quality.

The spade-shaped outline represents the most vivid colors, which are the colors of the spectrum. It encloses all colors; no colors can be made corresponding to places outside the spectrum boundary. The curved part of the boundary at the left represents the colors of the short-wave end of the spectrum, from violet at the bottom through blue and bluish-green to green at the top. The nearly straight part of the boundary represents the long-wave colors, from green at the top through yellow and orange to red at the lower right-hand corner. This much of the boundary of real colors, consisting of the left, upper and right portions is called the "spectrum locus." The straight line that closes the bottom is the boundary of the most saturated, or vivid, reds, red-purples, true purples and purple-violets.

The closer a point is to the center, the less vivid or saturated is the color it represents. But except for that, it is qualitatively similar to the part of the spectrum represented by the intersection of the boundary curve with the straight line drawn through the color point from the white point. Therefore we can specify the color conveniently by drawing that line and finding what wavelength is represented by the point where that line cuts through the spectrum boundary. For the example in figure 3 it is 525 nanometers. This is called the "dominant wavelength." The dominant wavelength is not the highest point on the spectrophotometric curve. The only way you can find the dominant wavelength is by drawing such a line as that shown in figure 3.

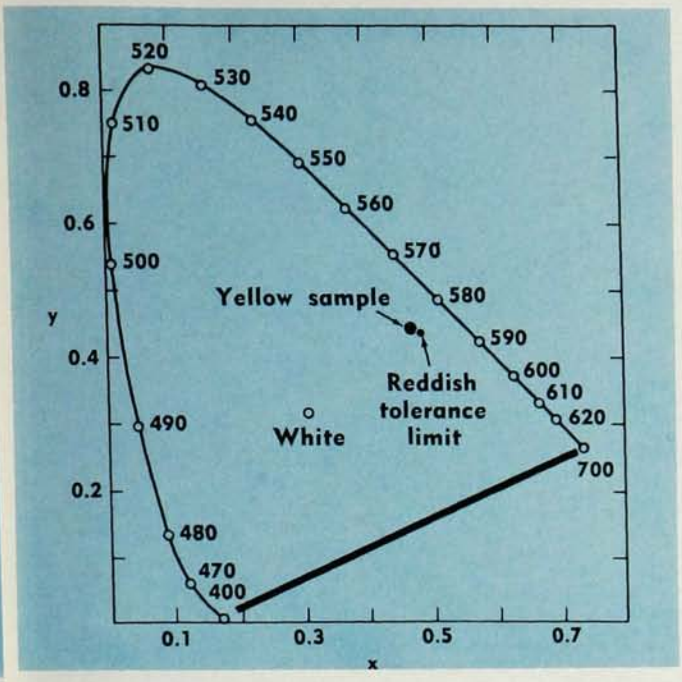
Lines drawn from the white point through points in the lower portion of the map do not cut the spectrum boundary. The straight boundary of the purples does not represent colors found in the spectrum. To interpret colors represented by points in the lower portion of this map, we draw the line backwards, as in figure 4, from the point representing the sample, up through the white point, until it cuts the spectrum boundary. Then we call the wavelength where that line cuts the spectrum boundary the "complementary" wavelength of the purple.

For all cases, the distance of the sample point from the white point (measured as a percentage of the length of the line through the sample point from the white point to the nearest boundary) is called the "purity" of the sample.

The slightest separation of points in any direction, in any region of the color map, represents a real color difference, which may be quite visible. The bigger circle up to the right in figure 5 represents the standard for a certain yellow material. Down to the right from it, a very small distance, the small circle represents the reddish tolerance limit. Any samples represented by points farther than that from the standard point are too red. Carloads of material have been rejected as being too reddish on this basis.

Tolerance ellipses

These points are so close together that it is inconvenient and dangerous to work at this scale. We had better use a map of the immediate vicinity of our standard yellow. The point representing the yellow standard is in the middle of the cluster in figure 6; the red-



COLOR-QUALITY MAP, usually called "chromaticity diagram," has wavelengths in nanometers around spectrum locus. Open circle represents average daylight and white or gray samples in daylight. Point labeled "Y" = 19%" represents a green reflecting 19% as much daylight as perfect white. Intersection of dashed line with spectrum boundary shows that 525 nm is dominant wavelength of green sample. Since distance from white to green point is 33% of distance from white to boundary, purity of green sample is designated as 33%. —FIG. 3

COMPLEMENTARY WAVELENGTH of a purple sample is at intersection of spectrum locus with line drawn from sample point through white point and extended to boundary. —FIG. 4

TOLERANCE LIMIT. Standard yellow (large circle, upper right) has a reddish tolerance limit shown by smaller circle. —FIG. 5

dish limit is down at the right; the greenish limit is up at the left; the high-purity or strong limit is up at the right and the low-purity or weak limit is down at the left. The differences are small, but they are important. Because they are so small, color has to be measured very accurately if the measured differences are to be reliable for evaluating visible color differences. Short cuts, "good-enough" instruments and carelessness are simply not good enough for the purpose.

The set of tolerances shown in figure 6 was set up a quarter of a century ago in terms of dominant-wavelength and purity limits; they are represented by a quadrilateral whose corner is sketched in figure 6. But what about the sample that is strong and reddish but represented by the point just barely within the corner of the quadrilateral? The quadrilateral, of which a corner is indicated in figure 6, would justify acceptance of such a sample. But we now know that its difference from the standard is visually about 40% greater than the difference between the standard and any of the four tolerance limits. For equal noticeability in such cases, the tolerance boundary should be the ellipse shown in figure 6. That ellipse excludes and dictates the rejection of that strong reddish sample.

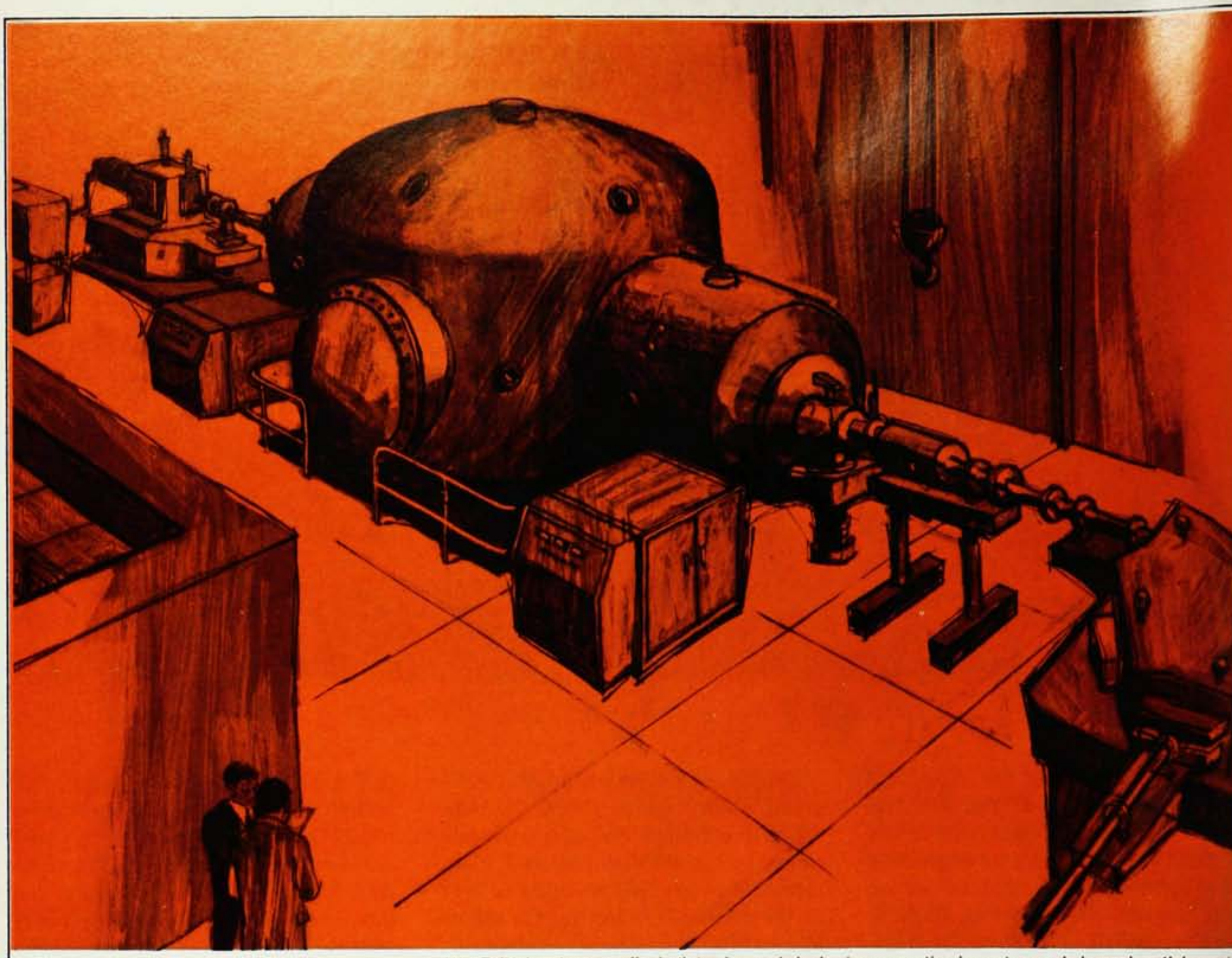
Similar tolerances for other colors—green, blue, purple, red, orange, white, brown and various pastels—are shown by the ellipses in figure 7. They represent differences ten times as large as the tolerance shown by the ellipse in figure 6. The tolerance ellipses had to be expanded so we could examine them all simultaneously. We may slide the nearest ellipse, taking care not to twist it, and center it on any intermediate standard color. But, for standards midway between two of these ellipses, or near the middle of a group of three or four of them, it is difficult to guess what should be the size and shape of the ellipse or even which way it should point.

We need a method for interpolating among these ellipses. If we take the standard values of x and y (the coördinates of the center of any ellipse) and subtract them from the values of x and y for any point on the same ellipse, and call the differences Δx and Δy, then we can find three numbers, call them g_{11}, g_{12} and g_{22}, for which $[g_{11}(\Delta x)^2 + 2g_{12}\,\Delta x\,\Delta y + g_{22}(\Delta y)^2]^{1/2} = 10$.

Tolerance contours

The experimental ellipses gave us 25 sets of g's, one set of three for each of the 25 standard colors. I wrote the values of g_{11} at the locations of the centers of the corresponding ellipses on an outline map of colors. I treated those numbers like altitudes on a map and sketched contour lines just like those on a relief map. For any location you please on the map, these contours indicate the value of g_{11}; it can be taken as the value for the tolerance ellipse centered at that location. I did the same for the values of $2g_{12}$ and g_{22} and sketched two other contour maps. Those maps have been used quite widely to interpolate values of the g's. They are not reprinted here because they have been published in several other places and because they have now been supplanted by algebraic formulas for coefficients that play the same roles as the g's. Centered on any standard color, a tolerance ellipse has its long axis tipped at an angle θ (measured counter-clockwise from the horizontal toward the right, east) given by $\tan 2\theta = 2g_{12}/(g_{11} - g_{22})$. The length of the longest radius of the ellipse is $(g_{22} + g_{12}\cot\theta)^{-1/2}$. The length of the shortest radius is $(g_{11} - g_{12}\cot\theta)^{-1/2}$.

When all that is needed is a decision whether samples are within or outside tolerance, you need not compute the angle or the lengths of the axes or draw the ellipse. Simply subtract the x's to get Δx and subtract the y's to get Δy. Then the amount of color dif-



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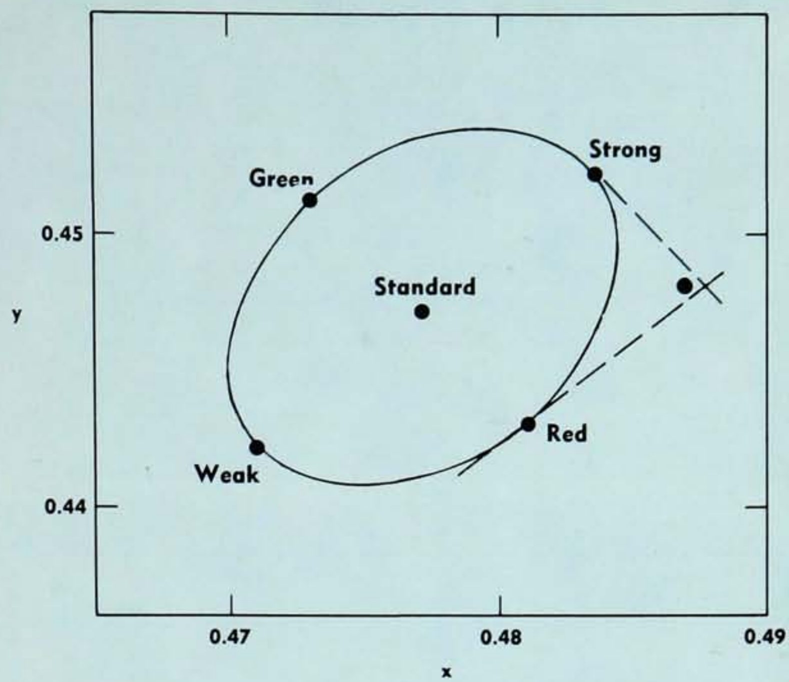
TOLERANCE BOUNDARIES. Enlarged representation shows that yellow sample represented by dot just inside dashed corner is not within tolerance although it is neither so reddish as the red limit nor so pure as the pure limit. —FIG. 6



ference is given by $\Delta c = [g_{11}(\Delta x)^2 + 2g_{12}\,\Delta x\,\Delta y + g_{22}\,(\Delta y)^2]^{1/2}$.

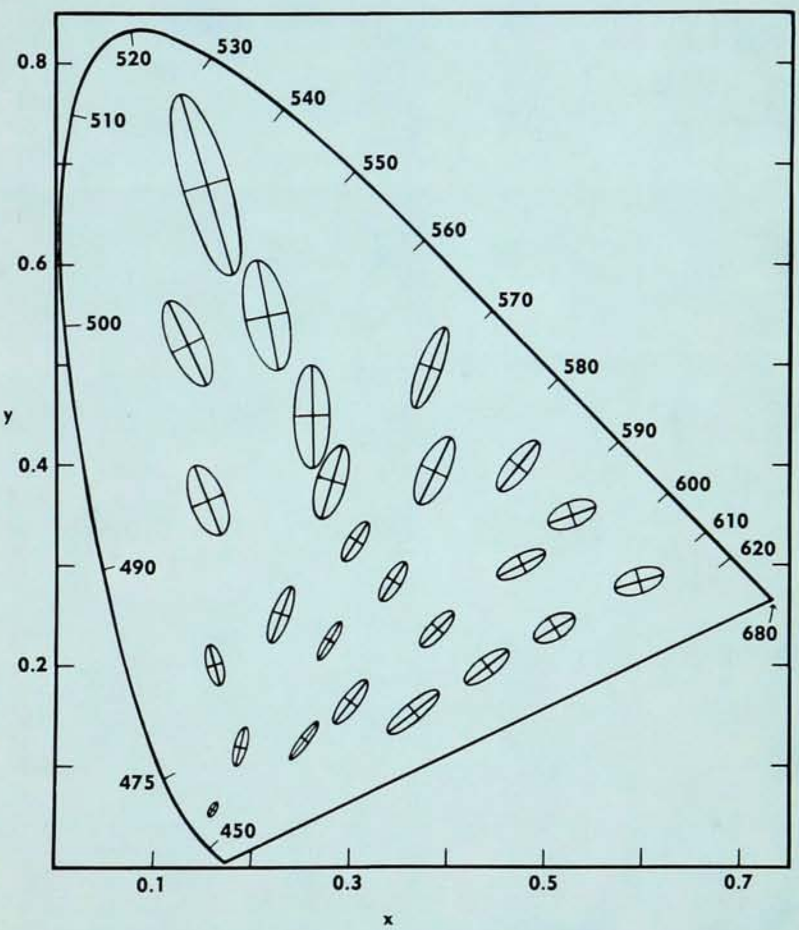
If Δc is less than 1, the sample is within the tolerance; if Δc is more than 1, the sample is outside of the tolerance. After trying a few, you may decide that my tolerances are too tight, in which case you can change the requirement. If you double my tolerances, then values of Δc less than 2 indicate acceptable color matches and greater values are outside of the relaxed tolerance.

My whole discussion of tolerances, so far, has been based on the assumption that your samples have practically the same lightness (luminous reflectance Y) as your standard. If the Y of the sample differs more than ¼% from the Y of the standard, subtract them to get ΔY and compute $\Delta c = [g_{11}(\Delta x)^2 + 2g_{12}\,\Delta x\,\Delta y + g_{22}\,(\Delta Y)^2 + g_{33}(\Delta Y/Y)^2]^{1/2}$. The coefficient g_{33} is simply 10 000 for large, uniform samples with edges clean and sharp so that they can be compared critically. When the color quality is exactly right, that is, when Δx and Δy are both zero, $\Delta c = 1$ corresponds to a 1% error in luminous reflectance Y alone. This is a tight, but not an extremely tight, tolerance.

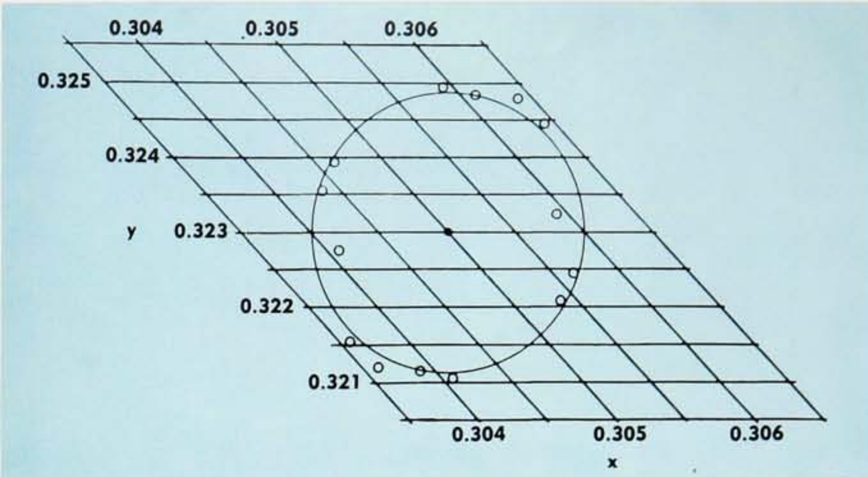
Regional maps

When many samples have to be compared with a single standard, it is more convenient to use a different projection of the map of colors, on which the tolerance figure is a circle. Such a projection can serve for only one map, but we can do it for the region containing any standard color of interest.

This procedure is like using a different projection of a geographical map to reduce the distortion that is caused by the spherical shape of the world. On a Mercator projection that is satis-



TOLERANCE ELLIPSES (10 times enlarged) around 25 standard colors. vary greatly in size. —FIG. 7



TOLERANCE CIRCLE is converted from a tolerance ellipse by use of suitably inclined and compressed y scale in section map. —FIG. 8

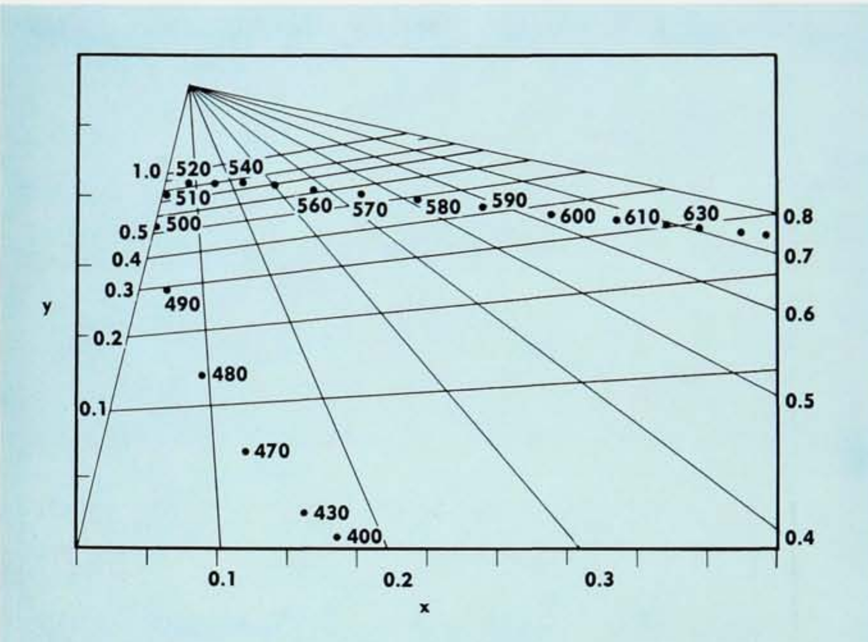
factory for England, Greenland appears much too big, like the ellipses in the upper part of our map of colors. If we were interested in studying Greenland, we should get a better map. In the same way, we can get a better map of the green or any other portion of our map of colors. The latitude and longitude lines were equally spaced, horizontally and vertically, in figure 3. To get the undistorted map of the small region we want, in which the tolerance figure is a circle, we need only incline the y lines (longitude) at the angle ω given by $\cos \omega = g_{12}/(g_{11}g_{22})^{1/2}$ and use a scale of y (along the upward slanting lines) that has the ratio $(g_{22}/g_{11})^{1/2}$, compared to the horizontal scale. If we graph the x's and y's for our samples on these scales, the acceptable ones are inside the circle that is centered on the standard and which has the radius $g_{11}^{-1/2}$ measured on the horizontal x scale. Figure 8 shows such a map for the neighborhood of white. Sets of several dozen such maps, together covering the whole world of colors, are available.

Uniform chromaticity scale

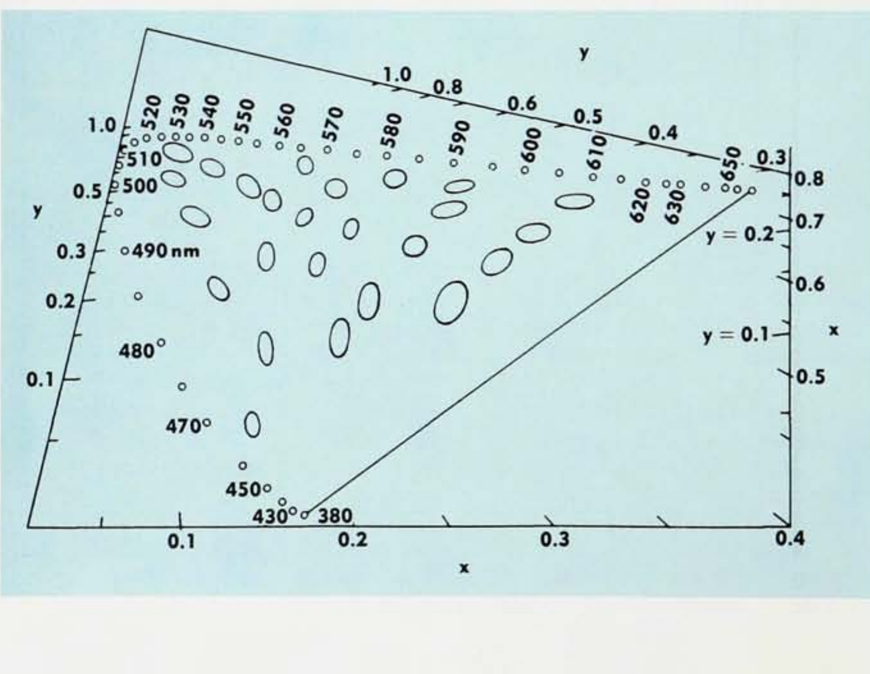
For many years people hoped that a single new map would serve for the whole world of colors. They call such a map the "uniform-chromaticity-scale diagram." Figure 9 shows the best one that has ever been suggested. In it the x and y lines are not parallel, but converge to points.

But figure 10 shows the tolerance ellipses drawn (ten times enlarged) on it. The ratio of greatest to smallest radius is still about 4:1. That's better than nearly 30:1, which is the ratio in figure 7, but it isn't satisfactory for critical tolerance work.

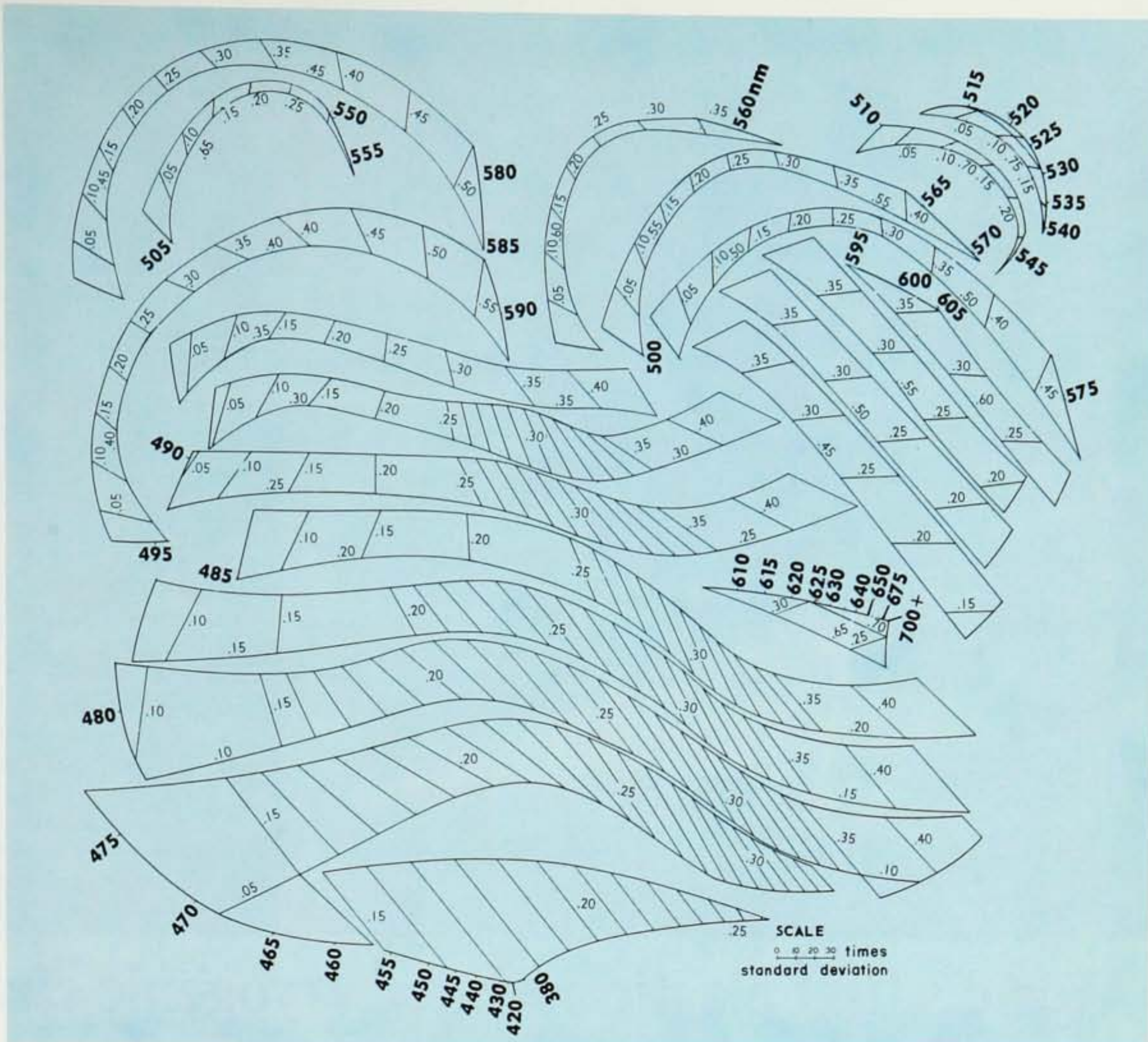
In an attempt to get a satisfactory



UNIFORM-CHROMATICITY diagram can be approximated with this projection of figure 3. —FIG. 9



NEW ELLIPSES on approximation to uniform-chromaticity-scale diagram have size ratios of 4:1 instead of 30:1 of figure 7. —FIG. 10



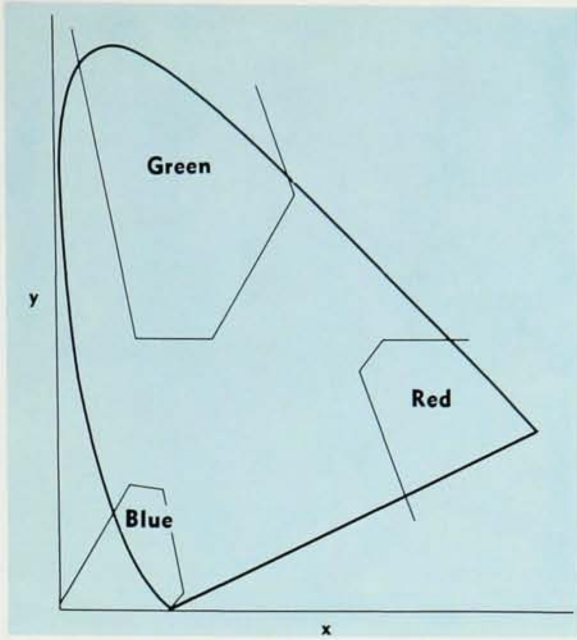
QUADRILATERAL STRIPS, made by assembling adjacent quadrilaterals like that of figure 8. —FIG. 11

uniform-chromaticity-scale diagram, I cut out the parallelograms, having the angles and scale units I have been explaining, that correspond to each of the squares between the x and y lines of figure 3. I fastened them together into strips, and traced the edges of those strips with smooth curves (figure 11). Finally, I cut out the strips and fastened them together. Figure 12 shows the result. It is a strongly curved surface on which all of the tolerance figures are circles of equal size. This surface cannot be flattened without distortion; flattening would make the tolerance figures ellipses again, and quite unequal.

Although it was a lot of fun trying, I conclude that the surface portrayed in figure 12 is of no use for tolerance work. In my opinion, the local maps,

UNIFORM-TOLERANCE SURFACE was assembled by fastening together strips of figure 11. All tolerance ellipses are equal circles. —FIG 12

each of a different size and shape, provide the only satisfactory tolerance diagrams. Recently, I have used a fast automatic computer to establish a machine method for evaluating color differences. This method eliminates the arbitrariness of the crudely sketched g contours and the ambiguities of interpolating among them. The modified formulas are ideally adapted for the use of modern computers. I won't go into details here since they have been published and are available for any who are interested. I may note, however, for geometers and others who may be interested, that they are very simple algebraic expressions, so that the Gaussian curvatures of the color surface (figure 12) or the Riemannian curvatures of color space can easily be evaluated, as suggested by but not possible for Helmholtz, Schrödinger, Ludvig Silberstein, Alexander Wundheiler, Hermann von Schelling and others.

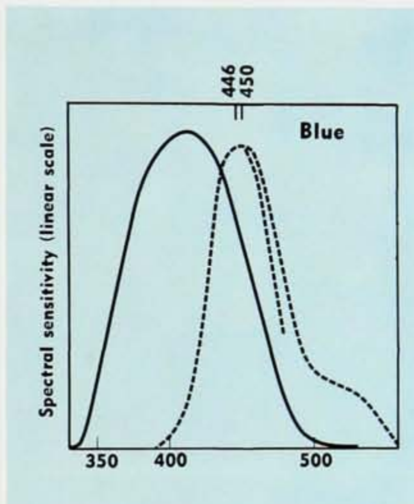


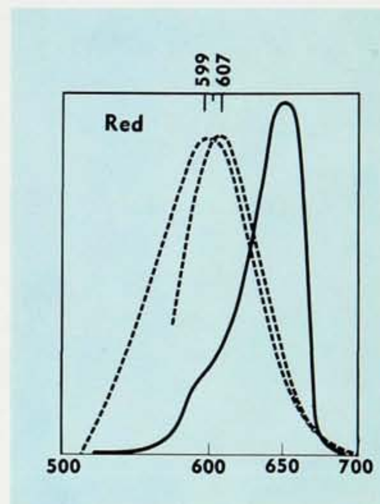
PRIMARIES can be selected anywhere in these regions of the chromaticity diagram, and they will correspond to the spectral sensitivities (color-mixture functions) displayed in figure 14. —FIG. 13

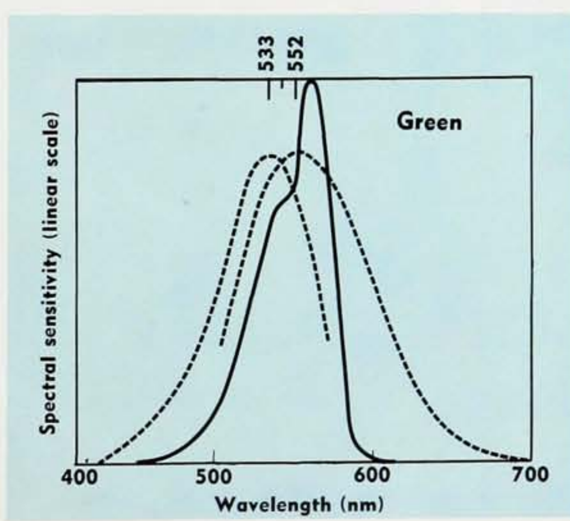
Color functions and photography

We are now, I think, ready to talk about color photography again. The Maxwell criterion advocated by Ives calls for spectral sensitivities defined in terms of the color-mixture functions $\bar{x}$, $\bar{y}$, $\bar{z}$ shown in figure 2. The precise requirements for the spectral sensitivities depend on the dyes used in the final color print or transparency or on the color filters used to project the separation positives in an additive system or on the colors of the phosphors excited in a color kinescope used in color television.

The spectral sensitivities appropriate for use with various possible sets of phosphors or projection filters (called "primaries") are linear combinations of the standard color-mixture functions, $\bar{x}$, $\bar{y}$ and $\bar{z}$. Only the numerical coefficients of the combinations are different for different sets of primaries. Widely different selections of primaries call for amazingly similar spectral sensitivities. If the chromaticities of the primaries are anywhere within the large regions shown in figure 13, the appropriate spectral sensitivities are limited to the narrow ranges shown by the broken curves in figure 14. Note the slight differences of the wavelengths of the maximum sensitivities written above each set of curves.







SPECTRAL SENSITIVITIES of available color film (solid lines) compared with extreme variations (broken curves) of sensitivities for primaries shown in figure 13, in other words, the Maxwell-Ives limits. —FIG. 14

IDEAL COLORS compared with those of conventional film. Figures at left are with one of the best currently available color films; those at right are with film whose design aims at Maxwell-Ives curves. Redish cast on flowers at left is well known and objectionable; colors at right are correct. —FIG. 15

The most apparent differences are near the wings of the prescribed spectral-sensitivity curves. But those differences are of slight significance because the spectral sensitivities are low in the wings. Furthermore it is so difficult to obtain spectral sensitivities resembling these that sensitizations that result in curves anywhere within the indicated limits would be triumphs of photographic technology. For this reason they could justifiably be used with any reasonably conceivable set of primaries.

In a subtractive process of color photography, the effective primaries wander around in the chromaticity diagram, depending on the spectral characteristics and concentrations of the color-synthesis dyes at each spot in the picture. This is in contrast with the additive system, in which the primaries remain fixed, determined only by the phosphors or the projector lamps and primary filters. But although they wander, the chromaticities of the effective primaries of any respectable subtractive process remain within the regions shown in figure 14. For the same reason that any spectral sensitivities within the limits corresponding to those regions can be used in an additive system with any set of primaries located in these regions, the wanderings of the effective primaries in a subtractive system are insignificant. The slight effects of such changes on the strictly corresponding spectral sensitivities are insignificant compared to the enormous disparities of the spectral sensitivities of all generally available color films from the limits that are implied by the Maxwell-Ives prescriptions. In figure 14, spectral sensitivities typical of a modern color film (solid curves) are superimposed on the Maxwell-Ives limits.

Ideal color films

Experimental films whose sensitivities conform much more closely to the

Maxwell-Ives limits have recently been made. Figure 15 shows three pairs of comparison pictures taken on a conventional film and on the experimental film. The top pair shows some bluish sand verbena photographed in the Anza Borego Desert of California. The photograph to the left was taken on one of the best currently available color films. Notice the reddish cast on the flowers. This is well known and disapproved by flower fanciers. It is attributable to the excessive far-red sensitivity that is quite apparent in the curves for the typical modern film. To the right is the picture of the same scene taken within a minute of the other, on a film whose spectral sensitivities were designed with the Maxwell-Ives curves as aims. Although this is an experimental film, and therefore not as perfectly adjusted as the other film in many other respects, the colors of the flowers are right in this picture. The second pair of pictures is of blue anemones in the Descanso Gardens, Los Angeles; the third pair is of bluish orchids in the horticultural hall in Golden Gate Park, San Francisco. In all cases, the pictures at the right show the correct colors. The false appearance of the flowers in the pictures at the left is a direct consequence of excessive sensitivity to the extreme red wavelengths of the visible spectrum, where chlorophyll and many related botanical colorants have sharp decreases of absorption. Figure 14 shows that, according to the Maxwell-Ives prescription, the maximum of the red sensitivity, for color photography should be between 599 and 607 nm, and the half-maximum sensitivity should be at a wavelength not greater than 640 nm. For the typical color film used in these tests, the maximum sensivity is at 655 nm and the half-maximum sensitivity is at 675 nm. So we should not be surprised that the experimental film, which conforms much more closely to the Maxwell-Ives prescription, gave us the much more realistic pictures.

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