Abstract. Instrumentation for color measurement is relatively well developed in terms of a convenient and accurate tool for the plant breeder. This paper discusses the development of a color solid and the meaning of a color reading in terms of the Judd-Hunter solid. Carrots are used as a specific example with references to squash, sweetpotatoes and red fruit juices. Color measurement can be used to predict the appearance of a fruit or vegetable which in turn can be used to predict the consumer acceptance in terms of appearance for the product. These methods are fairly accurate and are limited only by the ingenuity of the operator to present the sample to the instrument. The readings will reflect the visual impact from all factors which affect the color. It is unlikely that a color reading can be used to follow the development or degradation of a single pigment unless the system under study has only one predominant pigment. Such cases are relatively uncommon with fruits and vegetables.

The role of the plant breeder in today's sophisticated society is a complicated one indeed. The creation of a new fruit or vegetable is difficult enough even when the goals are well defined. Unfortunately, often they are not and usually this is not the fault of the plant breeder. Markets for particular fruits and vegetables are changing emphasis and obviously the goals must change with them. A fruit or vegetable will seldom serve two types of markets equally well. Often a product designed for both markets serves neither one well.

Tools for the plant breeder

Some plant breeders have been criticised by members of the public for their concentration on yield and appearance to the detriment of taste, odor and nutrient value. This criticism is unjust in my opinion for several reasons. Most important, perhaps, is that often the analytical tools to do the evaluation are either not available or are prohibitively expensive. The tools for the job is the area I would like to develop today, particularly in the area of color.

I am in sympathy with an individual who sets out to create a fruit or vegetable for a particular purpose. What tools are available to help him towards this goal? Traditionally, such problems as yield, resistance to disease, cold hardiness, cultural habits, response to fertilizers, resistance to nematodes, etc., have been measured subjectively except for simple ones such as yield. The education of a plant breeder is usually adequate to handle decisions in this area. However when one gets out of the traditional disciplines associated with horticulture and attempts to answer the charges of the workers in nutrition and food acceptance, both the decisions and the finances become more difficult.

What tools are available to the plant breeder to answer the charges that the nutritive value and the flavor are receiving no attention? In nutrition, to assess the content of protein, fat, carbohydrate, vitamin and mineral content requires a well equipped chemical laboratory. To assess the amino acid distribution of a protein for an evaluation of the biological value of protein requires an amino acid analyser - a very expensive instrument. There are as yet no quick inexpensive methods to do a proximate analysis on a product although there are some very good leads in this direction. When one adds to these complications the number of samples that a plant breeder would like to handle, it is small wonder that nutritive value is not a popular subject.

What tools are available for assessment of the three main quality attributes of a food product, namely color, texture and flavor? I chose the order for a purpose because it reflects roughly the success of objective evaluation. The workers in flavor evaluation have utilized the advances in gas chromatography for isolation of volatile components and mass spectrometry for identification of the hundreds of compounds found in nearly every food. The major problem it seems to me in this area is the limited success in correlating volatile components with organoleptic evaluations. To be sure this is a very complicated problem and some successes are evident but progress is likely to be slow. The texture workers are a little better off because equipment such as the Shear Press and the Instron are available even though there seems to be some lack of agreement on just what is being measured. This is a very active field of research at present.

Research workers who desire to measure color are in a much better position because good instruments are available and there is considerable agreement both as to theoretical considerations and to nomenclature. The color of an object is part of the overall visual impact and, in my opinion, is the most important of the three. If the color is unappealing, a consumer will seldom bother to rate the texture and flavor.

The concepts of a colorimeter

A colorimeter is an instrument to reproduce optically and electronically the physiological sensation of the human eye. A colorimeter measures color as such and is not to be confused with the earlier use of the word colorimeter in chemical analysis. Instruments used for estimating the amount of a chemical are called color comparators and absorptimeters. Spectrophotometers can, of course, be used for both chemical analysis and calculation of color coordinates.

The design of a modern colorimeter can best be understood by an analogy to the way the human eye sees color. We have two anatomically distinct types of receptors in the human eye - the rods and cones. The rods are concerned with black and white vision in dim light and have no color function. There are three types of cones in the human retina, one sensitive to red, one to blue and the other to green. They are anatomically indistinguishable and it was only three years ago that physical evidence was obtained that they were different even though Helmholtz had postulated 80 years ago that they had to be different. The human eye receives light reflected from an object to the retina and a signal from each type of cone is sent to the brain. The brain interprets the signals and assigns a "color" to the object.

A simple colorimeter can be designed to duplicate the response of the human eye (5). In Fig. 1, three projectors with a red, green and blue filter, respectively, in front of the lens, shine a colored beam on a screen. Another projector with a filter of unknown color is projected

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on the same screen. If the operator can vary the amount of red, green and blue light reaching the screen, he can match almost any color. Then the unknown color can be described by the amount of red, green and blue required to match it (Fig. 2). This principle has been used in several visual colorimeters to define the fundamental color solid. The colorimeter itself is too crude for every day use but the data can be used to define a much more appropriate color solid. The triangle in Fig. 2 is shown in the left hand portion of Fig. 3 and a new set of stimuli called X Y Z are shown. The G R B primaries are physically realizable in the laboratory whereas the X Y Z primaries are not. The X Y Z points were chosen for mathematical convenience and the fact that they cannot be made physically does not detract from their usefulness. Although it is not quite true, for ease of remembering, the X value may be considered as degree of redness, Z blueness and Y greenness. The Y value also carries all the brightness factor. In the right hand side of Fig. 3, the coordinate axes are shifted until the X Y Z triangle is right angled and of course the G R B is distorted. The X Y Z diagram is accepted world wide as the fundamental color solid. Every realizable color will have three coordinates which locate the point within the color solid. When one says “Measure the color,” he is asking for the three coordinates which locate a point in space.

The design of a colorimeter

The problem in designing a colorimeter to duplicate the response of the human eye can be appreciated with the setup in Fig. 1. We can shine a spectral color, say a blue of 400 nm, on the screen and ask the operator to match it with his red, green and blue controls. We can repeat the process for 410 nm and so on through the spectrum. The data obtained can be transformed from G R B units to X Y Z units and plotted as in Fig. 4. The curves obtained will represent how the human eye sees the spectral colors. This information is all an optical engineer requires to design an instrument to duplicate the response of the human eye. A set of glass filters with transmission curves shaped like those in Fig. 4 are shown in Fig. 5 in a simple colorimeter. A photocell and meter can be used to take a reading of the light reflected from an object through each filter in turn and the readings are the X Y Z values of the object. Every colorimeter uses this basic principle.
Newcomers to the science of colorimetry may be confused by the types of readout used by various models of colorimeters. For example, the Hunterlab instruments, the Color-Eye, the Colormaster and the Lovibond Tintometer, all use a different color solid and hence different coordinates but they all have one thing in common. They all give three coordinates to locate a color in space. If one wants to convert data from one system to another, the conversion equations are available but it should be realized that the equations are only approximate, not exact. 

The Judd-Hunter system as illustrated in Fig. 6 is the color solid used by both the Gardner and the Hunterlab instruments and seems to be the most popular in the food field in America. Most of the color data on horticultural crops in America is in this system. It is relatively simple to understand with +a for degree of redness, -a for greenness, +b for yellowness and -b for blueness. The degree of lightness or darkness is represented by the vertical L or Rd scales. The algebraic quadrant concept is very familiar to us in view of early mathematical training so it is easy to visualize a color in this system.

The measurement of color

The mathematical solid used to describe or locate a color in mathematical terms is an expression of the light modification properties of the sample and as such is a physical definition. The sensation of color as we see it is a psychological phenomenon. The "measurement of color" is actually a psychophysical measurement, but we have come to accept the phrase in terms of its purely physical interpretation. We should realize that when we do so, the entire objective physical light-modifying property of a sample may not be entirely or adequately measured and certainly the adaptive powers of the eye are not taken into account. On the other hand the psychological measurement of color, i.e., the subjective sensory methods, will be influenced by the total visual impact. This is the reason why there are some discrepancies in the relationship between objective physical methods and subjective sensory methods. This theme was well developed by Little and Mackinney (17).

The relationship between visual color and instrumental color is empirical in many food applications. One reason is that the equations relating the two are fairly rigorous for either clear transparent solutions or homogeneous opaque flat surfaces. Most foods are neither as they both absorb and reflect light, i.e., they are translucent. Better techniques are becoming available to handle translucent samples in terms of the Kubelka-Munk equations (15).

Orange vegetables

We can illustrate this situation with carrots. The breeding of carrots for more acceptable color, uniformity, vitamin A content and general quality has been an active field of research in recent years (1, 2, 3, 4, 6, 7, 14, 18, 19). One theme is evident in nearly all the papers. The authors have attempted to relate color and carotenoid content with indifferent degrees of success. Weckel and coworkers (19) concluded that Hunter a or L values did not reflect the carotenoid content. Shallenberger and Wallace (18) as well as Bradley and coworkers (1, 2, 3, 4) reported that the a/b ratio was well correlated with visual color. Bradley and coworkers reported that the a/b ratio showed lower correlations with total carotenoid content or with the beta-carotene/alpha-carotene ratio than with visual color. This was particularly true with the Waltham Hi C variety. These observations are probably all correct for various reasons. Let us look at what is being measured. Weckel and coworkers did not report how the color measurement was performed so it is difficult to evaluate this concept. Bradley, Gabelman (14, 16) and their coworkers evaluated color by blending carrot slices with water or citric acid and measuring the color of the puree. Color was expressed as the a/b ratio. This is a measure of hue in the Munsell system. In Fig. 7, a low ratio would be near the +b axis and would be yellow. A high ratio would be near the +a axis and would be red. Actually the figure obtained as the a/b ratio is the tangent of the angle obtained by the line joining the point to the origin and the vertical axis (8). In Fig. 7, the a/b ratio is the tangent of angle OEF for the sample with coordinates at E. Angle OEF = angle E O C which is the angle the point E makes with the vertical axis. This function is tangential, not linear, but is not too bad if one is between the limits 2.0 and 0.2. If the ratio is outside these limits, one should use the actual angle not the tangent.

Apparently the ideal "well-colored" carrot has a deep orange hue, i.e., a high a/b ratio and in turn a high carotenoid content. The reason why the a/b ratio reflects the yellow to red hue change is evident...
from Fig. 8. This shows a model system involving reflection curves of beta-carotene solutions absorbed on filter paper. As the concentration of beta-carotene goes up, the portion of light reflected in the 400-500 nm range goes down. In other words, the 400-500 nm portion of the spectrum is removed from white light (curve F) and the resultant color shifts from yellow to red. This relationship is true for beta-carotene and differs in degree with other carotenoids. To express the color of a carrot slurry we have to weigh the color or "tinctorial power" of each pigment according to the following regression equation. Color = a p (beta-carotene) + b q (alpha-carotene) + c r (gamma-carotene) + d s (delta-carotene) + e t (zeta-carotene) + f u (xanthophylls) + g o (other pigments)

where a, b, c, d, e, f and g are the amounts of each carotenoid and p, q, r, s, t, u, and v represent the respective tinctorial power of each pigment. This would take care of the pigment contribution to the color as represented by the absorption (K) value in the Kubelka-Munk equation. There is also a scattering component (S), caused by the fragments of cells and the starch grains. A sample with a high content of starch grains would appear lighter and with less definition of the absorption or reflection curves due to beta-carotene. The size of the cell fragments also influences the scattering effect and differences in degree of homogenization will change the colorimeter reading. Thus there are at least nine factors which will affect the color in a carrot slurry so one would not really expect the total carotenoid content or the 4/b ratio to correlate well with the color reading. It will occur to the reader at this point that this approach is rather absurd in terms of labor and there really isn't much point in doing it. The obvious answer to this anomaly is to define the aims of the experiment. One should use a colorimeter to measure objectively the color or total visual impact of a sample. Correlations of color readings with visual judgments are pretty good for most products. The color data can be used to predict consumer acceptability of a product. In this case it is preferable for the color readings to be performed on the sample as the consumer sees it, with a minimum of sample preparation.

If one would like to use color data to predict the content of a chemical component such as beta-carotene in carrots, one has to be sure that the only variable is beta-carotene. Colorimeter readings have been successful for breeding work on the orange varieties of sweetpotatoes (13) since in these cases the yellow to red hue shift is mainly a function of beta-carotene content. This pigment comprises approx. 80% of the total carotenoid. With the yellow varieties of sweetpotatoes in which the beta-carotene can be as low as 20% of the total pigment, and with many varieties of squash (9), beta-carotene is not the predominant pigment and correlations of color vs beta-carotene content are likely to be much more erratic. Correlations of total carotenoids are likely to be erratic because the weighting factor for each pigment as described previously. The obvious answer to this problem is that if one wants to measure the pro-vitamin A content of a sample one would have to do it chemically not colorimetrically unless the investigator was reasonably certain that only the compounds contributing to pro-vitamin A content were varying in the experiment.

Bradley and Smitte (1) reported that the Hunter 9/b ratio of raw carrots did not correlate very highly with the 4/b ratio for canned carrots. There may be several reasons for this. First, the thermal treatment probably isomerized up to 10% of the carotenoids thereby changing the tinctorial power and/or ratio of each carotenoid. It may also have changed the ratio of pigment to pigment-protein complex, as well as the degree of esterification of some of the xanthophylls. It will certainly have changed the physical state of the starch components thereby changing the scattering constant. In other words, the physical state of the compounds contributing to the color is probably quite different in the raw and processed products.

The problems involved with carrots, squash and sweetpotatoes are fairly similar in that they all involve a suspension of an oil-soluble pigment in an aqueous media. Tomato juice is similar yet less complicated because the lycopene pigment is so predominant (over 90% of total pigment). Yellow tomatoes would show the same problems as carrots, but less so, because the scattering coefficient due to starch granules is much less important. Carrots were chosen as an example because they present a more complicated system.

**Red fruits**

If one chooses to work with a water soluble pigment in aqueous media, say red fruits containing anthocyanins (raspberries, red currants, grapes, etc.) for manufacture into a juice, the problem is simpler (12). The fruit can be crushed, filtered and read in a colorimeter which gives tristimulus values by transmission rather than reflection. The color of the juice can be located accurately in color space and is a good indication of the total effect of the pigments present. Usually there is more than one pigment present so if one wanted to follow the development or degradation of an individual pigment component, there is no alternative to a chemical analysis. Transmission colorimetry has been of considerable value in the characterization of color of wines, cranberry juice cocktail, boysenberry juice, and many other products (12).

If one chooses to work with water soluble anthocyanin pigments *in situ* in a fruit or vegetable where there is obviously unequal distribution as compared with a clear juice, the problem is more complicated. An example of this would be fresh cranberries (10). The pigment is confined to the outer layers of the berry in heterogeneous distribution. A reflectance spectrum will not relate too well with chemical pigment determinations because a little red pigment in a white berry is very obvious. The same amount of red pigment in a deep red berry would not even be apparent. The moral is clear in this case. If the berries are to be used for manufacture of a juice, then a chemical determination of pigment in the berries is most desirable. If the berries are to be sold as fresh fruit, then a color reading on the berries themselves will be most useful. Color readings on whole fruit such as cranberries can be obtained with a spinner or a large area aperture (11). With larger samples such as apples or peaches, each fruit can be rotated (8) or several readings can be taken on various portions of the stationary sample.

**Interpretation of color**

The interpretation of color data can sometimes be confusing if less than the complete picture is provided. When we say the color of sample A is such and such, we provide the three coordinates to locate a point in color space. If we say sample A differs from sample B in such and such, we usually mean the length of the line joining the two points in color space. If we say a family of samples falls within these color limits, we mean the solid within the color solid which will contain all the samples. This concept of course is closely related to color tolerances (11) and we can only portray the limits of color by one dimensional slice or two dimensional plot or three dimensional slice in the Hunter system could be an a vs b and an L vs a plot (11). Such plots will provide the full picture of color variations within a family.
of samples, but obviously are useless for an analysis of variance. For statistical treatment, we cannot treat each color as an independent variable since they are not independent. This has led to the demand for one-figure representations of color, such as the Hunter a/b ratio, but these give only part of the picture. In this case the L value is neglected. The safest procedure to reduce three dimensions to one is to use a regression equation. This approach has not been too popular in the past because of the labor involved, but should be no excuse today in view of almost universal computer facilities.

The ability to obtain a color reading on a given product is limited only by the ingenuity of the operator. If one can get the instrument light beam reflected back into the instrument in much the same way as we see the object the chances are good that the correlation of instrument reading and visual evaluation will be fairly high. Instrument readings are much more convenient and less expensive than a panel evaluation. They can be a real advantage to a plant breeder who has to deal with hundreds, if not thousands, of samples. It would be very nice if the color readings were well correlated with a desired chemical component, but this will not usually be the case.

There are many ways in which we expect the objective measurement of color and the interpretation of objective measurements with visual evaluations can be improved. This is one of the tasks we have set for our laboratory. However, the present state of development of objective color measurement is such that the plant breeder can use it with confidence to develop more acceptable products.

Literature Cited