FOODS AND BEVERAGES appeal to consumers through appearance, and color is an important visual cue. Coffee is not as bright or varied in color as many foods and beverages, but coffee enthusiasts do have preferences of roast degree and can observe this by the color of the coffee. While offering a variety of coffee flavor experiences is a key element in marketing specialty coffee, when customers find something they like, they purchase it again. If what they purchase doesn’t provide the same experience as the previous purchase, they are likely to think less of the roaster.

For roasters, the degree of roast is an essential consideration in balancing flavor attributes. A “Nordic” light-roasted coffee has a great deal of acidity but little caramelization and body. A medium to full city roast has more complex aromatics and a balance of acidity and body. Slightly darker roasts of the type used for Northern Italian espresso emphasize sweetness and body, and the darkest roasts are dominated by “roasty” aromatics and burnt-sugar tastes. The character of the green coffee can be either emphasized or modified through the timing and final degree of roast, and this can be measured in terms of color.

But coffee often looks better than it tastes. If it is known that the green coffee is of good quality, the problem is likely in the roasting. What went wrong?

In production roasting, the goal is to produce the intended roast degree and flavor development consistently. Sensory determination is the primary method of quality control, but it is useful to have instrumental confirmation to examine the roast in greater detail. While roasters have flavor attributes on their mind when they design a coffee, measuring the roast so these attributes can be consistently reproduced is essential for quality control. There are a number of machines on the market that are capable of performing this task. This article looks at how the color of roasted coffee can be measured and what one can conclude from the results.

Instrumental measurement can give clues as to what has occurred during the roasting process, but other information is needed as well. As with all lab methods, sample preparation and instrument calibration will affect accuracy.

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PART 1
The Science Behind Color Analysis

What to Measure?

There are two crucial processes that occur during roasting:
(1) development of flavor attributes, mainly sugar-browning reactions, and (2) degradation of compounds. Both processes occur as the result of application of heat over time. The final degree of roast and the time in which it was produced is an indication of how much heat was absorbed by the coffee. From that, one can make a reasonable assumption about the processes that took place. Roast measurement usually seeks to quantify either development or degradation.

What is observed or measured in terms of visual cues is the result of three phenomena:
- The color of the light illuminating the subject by the light source or emitter. This is the result of all different wavelengths of light emitted by the source.
- The optical properties of what is being examined, measured or perceived (the subject). The subject will either absorb or reflect the light being emitted by the illuminant.
- The observer or, in the case of an instrumental measurement, the sensor. The observer perceives the light reflected from the subject and, if the wavelengths of the source are quantified, can conclude or measure which wavelengths have been absorbed.

What one sees or what a machine measures is the interaction between the colors of the illuminant and the color of the subject itself. The capability to perceive this combination depends on the ability of the eye or sensor to “see” the resulting wavelengths of light being reflected. With perception by eye, one’s ability to perceive is limited to the visible spectrum, but some instruments are not so limited.

Instruments designed to measure degree of coffee roast differ in what they measure and how the results are reported. Instruments that measure visible color as perceived by human beings are intended to measure the degree of sugar browning produced as the result of roast; other instruments measure different roasting processes, such as the degradation of compounds, using ranges of color that cannot be perceived by the human eye. What is being measured depends on the illuminant and sensor used. How the results are reported depends on how the machinery translates those measurements into a standardized scale.

Measurement of Color

One perceives different colors because of the innate human ability to perceive light waves of specific wavelengths. A wave (Fig. 2) is a vibration with a certain wavelength; different wavelengths result in different colors. Visible color is light in the area of 400 to 700 nanometers (Fig. 3, pg. 42), but there are other non-visible wavelengths. While there are many methods of measuring roast, they all seek to measure reflected wavelengths.

Like most sensory perceptions, not everyone sees the same wavelengths; some cannot distinguish between red and green and some cannot perceive different colors at all (color blindness). All wavelengths of light combined together are perceived as white; absence of any wavelength of light is black.
A Scale of Different Colors

A raw color measurement consists of several individual measurements of the different wavelengths of light being reflected. This is often illustrated in the form of a histogram showing the intensity of reflected light at various wavelengths. The different spectra can then be used to illustrate a "spectral curve." This measurement of the reflection depends on the wavelengths of light illuminating the sample (Figures 4-7).

As color analysis evolved, different scales for reporting colors were developed. Most of these were directly related to the graphic arts or areas where precision and consistency of visible color were important, such as in the clothing industry. However, as the technology developed and became more precise, color analysis was applied to other disciplines in ways that did not depend only on the visible spectrum.

A major challenge in the history of science has been to develop scales that are consistent enough for scientific quantification, analysis and comparison. This becomes more difficult when the scale also should correspond in a meaningful way to a sensory experience, such as taste, as one’s senses do not always operate in a linear or predictable way. Developers of color measurement scales sought to simplify the complex interaction between light and the perceiver into something that was consistently measurable and corresponded to human experience.

The discovery of the spectrum of light is credited to Sir Isaac Newton (1643–1727) in his work *Opticks*. He believed different colors were the result of subtle particles that had mass and followed the laws of physics. J. C. Maxwell (1831–1879) theorized that color was made up of...
waves. Earlier, Thomas Young (1773–1829) had discovered that color was light (no light equals no color) and Helmholtz had determined that the observer was the final arbiter of what could be seen as the result of that light. These discoveries and the RGB (red-green-blue) scale were used to create the first “color wheels,” in which a color could be quantified in terms of the three aspects that could be mapped in three dimensions. The three-dimensional representations are called tristimulus color spaces.

At this point, the two major aspects of color perception were quantified: Newton had discovered that color was light (no light equals no color) and Helmholtz had determined that the observer was the final arbiter of what could be seen as the result of that light. These discoveries and the RGB (red-green-blue) scale were used to create the first “color wheels,” in which a color could be quantified in terms of three aspects that

be combined to produce all colors in the visible spectrum. To get closer to the actual difference in sensory perception, the CIE L*a*b* system was developed. This scale was based on experimental data of human color matching. This allowed more precise definitions of color similarity and especially color difference, referred to in most equations as ΔE. This L*a*b* system was adopted by the food industry for various applications.

All of the tristimulus systems (RGB, XYZ, L*a*b*, etc.) are mathematically defined in such a way that they can be converted from one to another. The XYZ, L*a*b*, etc. systems are mathematically defined in such a way that they can be combined to produce all colors in the visible spectrum.

To get closer to the actual difference in sensory perception, the CIE L*a*b* system was developed. This scale was based on experimental data of human color matching. This allowed more precise definitions of color similarity and especially color difference, referred to in most equations as ΔE. This L*a*b* system was adopted by the food industry for various applications.

Other Measurements of Roast Degree

Measuring the color of roasted coffee in terms of one of the systems above corresponds to the degree of browning that has taken place. However, one may have noticed that these systems that the color brown—the one most associated with coffee—is not readily apparent. Also, the measurement of brown color does not directly indicate the type of sugar browning that took place. For example, development of furanochromes requires a temperature of at least 200 degrees C, and pyrazines also require higher temperatures. Both are important coffee aromatics.

Measurement of the visible spectrum indicates the intensity of brown (intended to reasonably correspond to sugar browning). In certain segments of the food industry, methods were devised for specific applications. For example, in the late 1970s a system was designed to determine tomato ripeness, in which a tomato was cut in half and a single “ripeness” value derived from the ratio of green reflectance to red reflectance. This ripeness ratio was referred to as the Agtron number, named after the machine that used a red neon lamp and green mercury vapor lamp to determine tomato ripeness, in which the organic compounds associated with roast start to develop, and 0 indicates total reduction of organic compounds. (The scale on the machine goes from 0 to very light roast to 0 for complete degradation.)

Similarly, Agtron developed two widely used scales of coffee roast degree: gourmet and commercial. On the gourmet scale—the one most widely used in specialty coffee—a 0 to 20 is considered the point at which the organic compounds associated with roast start to develop, and 0 indicates total reduction of organic compounds. (The scale on the machine goes from 0 to very light roast to 0 for complete degradation.)

This scale is used as a reference throughout the coffee industry, regardless of the type of instrument. However, not all instruments measure the Agtron number in the same way; most work out a correlation with the particular measurement technique they are using. In instrument specifications, the Agtron gourmet number is sometimes referred to as the SCAA number.
More recently, research performed by other companies has led to different scales based on observed changes in coffee roast degree. Most of these are based on the red or near-infrared area of the spectrum.

**PART 2**

**Applying Color Analysis to Coffee Roasting**

**Using an Instrument for Quality Control**

As coffee roasting businesses grow, the founding roaster typically delegates some of the responsibility for roasting to others, operates multiple roasting facilities, and/or uses a variety of roasters for production. This creates a critical challenge for a growing business—how to maintain the quality customers expect when so many variables affect production. Formal quality control procedures can ensure consistency.

Quality control programs start with a standard—in this case, the ideal coffee flavor profile, which is the result of the green coffee and roast parameters. To establish a standard, it is suggested that several roasted prototypes of the green coffee be roasted to the approximate desired degree and cupped. One can either select one of the prototypes or produce another prototype based on what is found at the cupping table.

Once the standard coffee is determined, the following specifications are created:

- **Measurement of degree of roast of both whole bean and ground coffee.** The whole bean is darker than the ground and the difference between the measurements will indicate the rate of penetration of the heat and the amount and type of sugar browning that took place. The specification should include the target and the distance from the target measurement that is allowed.
- **Process measurements, or the “roast log” attributes of time and temperature, especially at what point gold, first crack, second crack (if present) and finish occur.**
- **A description of the sensory aspects that should be present and their relative intensities.** For example, the intensity and type of acidity, mouthfeel and finish should be detailed. This doesn’t need to be overly specific, but it should indicate what makes this particular coffee unique.

With these specifications, one can use the roast degree and process measurements to indicate how close any batch is to the ideal. If measurements are too far from the standard, one can use the descriptive sensory aspects to investigate the closeness to the intended flavor balance.

To get accurate color analysis results, sample preparation procedures must be rigorous and consistent. It is common for different operators to get different measurements from the same instrument and sample because of sample preparation variability. Coffee is not homogeneous in color. Small beans are darker than larger beans, and when the coffee is ground, the particles from the outside of the bean are usually darker than the particles from inside due to the progression of heat from the outside inward. Grind size, packing, density and distance from the sensor all will affect the measurement.

For most instruments, one is directed to smooth the surface without packing it, with an absence of “dimples” or low spots. If one can observe a difference, the machine likely will measure a difference. Especially when one is making comparisons, the sample must be prepared the same way each time.

Timing also is a factor. If the coffee is measured fresh out of the roaster, it will appear and measure lighter than if the same sample is measured several hours or days later. Part of the standard should include an approximate timing guide.

**Figure 9 -- The three dimensional L*a*b* space**

<table>
<thead>
<tr>
<th>White (L=100)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>“a” dimension (red to green)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“b” dimension (yellow to blue)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“L” dimension (black to white)</td>
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**THE COLOR OF COFFEE | Using Color Analysis in Quality Control (continued)**

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Key Elements of Color Analysis Instruments

With color, there is a chain of perception that begins with the eye sensing the wavelength, then sending a message to the brain, where one becomes conscious of and interprets the stimulus. Measuring devices have their own mechanical chain of perception, first sensing the wavelength, processing the stimulus, then converting it into a scale for output.

Instruments have been built to perceive multiple areas of the wavelength spectrum. Most instruments measure the sample in a closed, light-proof area. The sample is illuminated with a certain wavelength of light before measuring. Sensors often can be adjusted or calibrated to perceive a specific combination of wavelength bands.

When considering a machine for color measurement, one should examine the following:

- What is the light source? If the measurement is to be taken under ambient light conditions, one should plan to use a consistent light source to minimize variability. If the machine provides its own light source but not in a sealed area, light pollution from external sources must be considered. If there is a sealed area, one must consider how the source is to be calibrated or maintained so measurements are consistent and accurate.

- How does the sensor work? One consideration is how large an area is being measured. For most color meters, the actual area of measurement is very small. However, this small area can be amplified through the use of lenses or by taking multiple measurements and averaging them. Other considerations include the sensitivity of the sensor and in which spectra it can sense.

- What is the light scale used to report the measurement? Some use the Agtron scale or another widely used color scale. Knowledge of these scales is necessary to accurately interpret the measurement.

- How are samples prepared? What kind of sample preparation is necessary and how will (inevitable) mistakes in sample preparation affect the accuracy of the data reported?

If there are several roasting facilities involved, one also should consider inter-instrument agreement and calibration. The measurements made at each facility should reflect the same level of roast as those taken at other facilities.

Color Meters

Color instruments measure the color that corresponds to the amount of sugar browning that has taken place during the roast. However, as noted previously, the degree of sugar browning will not necessarily guarantee the intended flavor attributes are present, as the actual sugar-browning chemicals may vary according to heat applied and timing of the roast. If using a color meter for evaluation of roast, the standards must include the process aspects (time and temperature, or “roast curve”) to ensure the intended chemical changes are produced. One advantage to using color meters is that the same instrument can be used for the evaluation of green coffee. Another is that, because the standards of color measurement are well established and precisely quantified, inter-instrument agreement can be assumed.

In general, color meters are based on two technologies, the colorimeter and the spectrophotometer. A colorimeter measures the sample by passing the reflected light through a red, green and blue filter to try to duplicate the standard observer’s perception. A photodetector quantifies the amount of light passing through the filters and reports the results in terms of one of the tristimulus scales. These instruments are less expensive but may not be as accurate as more recently designed machines. Spectrophotometers break the reflected light from the sample into a range of different colors on the spectrum. The resulting spectra then pass to a diode array that measures that wavelength of light. This method is more accurate than a colorimeter, but the instruments are more expensive.

Examples of color meters include the HunterLab ColorFlex EZ Coffee spectrophotometer and the Konica Minolta CR-410C colorimeter. Both units are capable of reporting results in terms of the SCAA number. The HunterLab ColorFlex uses an optical geometry to increase the area of measurement. The Konica Minolta has a small aperture that requires multiple measurements for accuracy. Both instruments measure the sample from the bottom of the sample dish, so the optics of the sample dish must be considered; scratches will affect the results and the dishes can get contaminated.

The HunterLab ColorFlex EZ Coffee instrument uses a xenon white light source for consistency and to approximate normal daylight color. The illumination is focused in a circle at a 45-degree incidence to the sample, allowing the light to be measured from different angles, correcting any effect resulting from sample preparation. Its diode array measures the intensity of color at every 0.1 nanometers (nm) within the visible 400 to 700 nm range, but it focuses mainly on the 640 nm measurement, which the company’s research shows is the optimal measurement for coffee roast. The instrument reports the results in four ways: SCAA number, roast classification (“light,” “medium,” etc.), CIE L’a”b” scale, and the company’s own HunterLab Coffee Color Index (HCCI).

The Color of Coffee | Using Color Analysis in Quality Control (continued)

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Karen Gordon
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Matt Appelbaum
mattappelbaum@coffeeholding company.com

Coffee Holding Company, Inc.
3475 Victory Blvd.
Staten Island, NY 10314

Telephone: (718) 832-0800
Toll Free: 1-(800) 458-2233
Fax: (718) 832-0892

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Coffee-specific Instruments

Because of the obvious need for measurement of roast degree and its importance in quality control, several instruments have been designed especially for coffee. As noted previously, the “brown-ness” or darkness of coffee can correspond to the degree of roast, but the brown portion of the spectrum is small. One also needs to consider the process that produced the roast degree.

The Agtron is one of the first instruments to employ methodology specifically developed for coffee. Near-infrared (non-visible) light illuminates the coffee to sense a selected group of quinones (byproducts of the degradation of chlorogenic acids that occur during roasting). The sensor measures certain (proprietary) wavelengths to determine the likelihood of voids between the beans may cause the reading to be darker than the actual sample. Madison Instruments produces (analytical) instruments, which uses near-infrared illuminants to measure degree of roast. The sample is prepared similar to the Agtron, leveling across the sample plate or filling a glass dish before measurement. Ambient light does not affect the result due to the use of filters. The sensor integrates the reflectance of the entire area of the sample (about 3.5 inches in diameter) and results are reported in terms of the SCAA number, with electronic temperature compensation. It has a calibration disc that should be used daily, or more often, depending on the environment. Administrator functions include the built-in RoastMatch wizard, which allows one quickly to create and store various calibrations for inter-instrument agreement.

There are two types of Agtron machines (with some differences in individual models within these types): a closed system (the M-20) and a bottom-measuring system (the M-55). With the M-50 series, the machine is calibrated each time the drawer is opened. A disk is provided for calibration of the M-15. Inter-instrument agreement can be attained with adjustments available; one must have a dead stale sample—one that has been ground and oxidized for at least 30 days without significant moisture added—to measure in each machine.

(Using such a sample ensures that changes in color are no longer taking place over time.) The machine should be serviced and the infrared lamp replaced annually.

Sample preparation for the Agtron is of major importance in attaining an accurate reading. The surface of the sample must be reasonably uniform without “dimples.” The particle distribution as the result of grind also is important; it was observed by one lab that eliminating the larger and smaller particles by measuring only the particles in the No. 16 screen of a standard set of particle analysis screens (particles of approximately 1.18 mm) resulted in the most replicable measurements. Whole bean coffee can be measured, but the likelihood of voids between the beans may cause the reading to be darker than the actual sample.

Madison Instruments produces (analytical) instruments, which uses near-infrared illuminants to measure degree of roast. The sample is prepared similar to the Agtron, leveling across the sample plate or filling a glass dish before measurement. Ambient light does not affect the result due to the use of filters. The sensor integrates the reflectance of the entire area of the sample (about 3.5 inches in diameter) and results are reported in terms of the SCAA number, with electronic temperature compensation. It has a calibration disc that should be used daily, or more often, depending on the environment. Administrator functions include the built-in RoastMatch wizard, which allows one quickly to create and store various calibrations for inter-instrument agreement.

A handheld version is available as well as a laboratory bench top model. ColorTrack uses a laser for the light source, which rarely needs to be replaced and never needs to be recalibrated. The bench-top model has a carousel that turns the coffee sample so approximately 200,000 measurements are taken (10,000 per second over a 20-second measurement period). Because coffee color is not homogeneous, the setup includes standard deviation over the surface as well as the average of all measurements. Reports also include graphic representations, similar to the histograms and spectral curves discussed earlier. The ColorTrack measures the sample directly (without glass or other reflective surfaces) and the laser technology is not “surface sensitive” (does not depend upon distance, angle incidence or smoothness of surface), so sample preparation has a minimal effect on results. The measurement focuses on the 780 nm wavelength to report results in terms of the Agtron number. A handheld version also is available.

While the primary method of evaluating coffee quality is sensory analysis, the use of color measurement technology can assist in improving quality and consistency. To optimize the use of these technologies, roasters must understand the technical aspects of color measurement and integrate these measurements into a quality control program that also takes into account the roasting process and sensory parameters for each coffee roasted.

PAUL SONGER has been in the specialty coffee business for more than 30 years, first at Allegro Coffee Co. in Boulder, Colorado; then Coffee Analyst in Burlington, Vermont. He holds a certificate in sensory analysis from the University of California at Davis. He currently works as a consultant on sensory and technical issues regarding coffee and serves as head judge for the Cup of Excellence coffee competition program.

What’s Next?

The COAL of modern quality control programs is to prevent out-of-spec products from being produced, not simply rejecting poorly produced products, but measurement of color in all of the cases examined in this article occurs after the roast takes place—too late to make adjustments. Out-of-spec coffee must be donated, reused in another product or shipped off, often representing a loss for the roaster. Future technology could be capable of measuring color changes as the roast progresses. (There are infrared measurements for temperature; but at present these are difficult to use.)

This type of measurement is technically difficult because one would need to have a dependable light source and a quick way of reading what is reflected. However, instruments for measuring color during roasting have been investigated and currently Fresh Roast Systems (makers of the ColorTrack) is exploring the manufacture of such a system.