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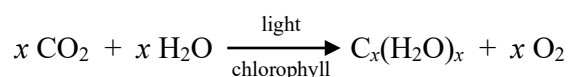
THE CHEMISTRY OF AUTUMN COLORS

Every autumn across the Northern Hemisphere, the lengthening nights and falling temperatures induce trees to prepare for winter. In these preparations, they shed billions of tons of leaves. In certain regions, such as our own, the shedding of leaves is preceded by a spectacular color show. Formerly green leaves, depending on the species, may turn to brilliant shades of yellow, orange, and red, as well as brown. These color changes are the result of transformations in leaf pigments.

Paper Birch



The green pigment in leaves is chlorophyll. Chlorophyll absorbs red and blue light from the sunlight that falls on leaves. Therefore, the light reflected by the leaves is diminished in red and blue and appears green. Chlorophyll actually includes two pigments, chlorophyll *a* and chlorophyll *b*. The molecules of these compounds are large: $C_{55}H_{72}MgN_4O_5$ for chlorophyll *a*, and $C_{55}H_{70}MgN_4O_6$ for chlorophyll *b*. The molecules of chlorophyll are attached to the membranes of disc-like structures, called chloroplasts, inside the cells. Chloroplasts are the site of photosynthesis, the process in which light energy is converted to chemical energy. In chloroplasts, the light absorbed by chlorophyll supplies the energy used by plants to transform carbon dioxide and water into oxygen and carbohydrates, which have a general formula of $C_x(H_2O)_x$.



In this endothermic transformation, the energy of the light absorbed by chlorophyll is converted into chemical energy stored in carbohydrates (sugars and starches). This chemical energy drives the biochemical reactions that enable plants to grow, flower, and produce seed.

Chlorophyll is not a very stable compound; bright sunlight causes it to decompose. To maintain the amount of chlorophyll in their leaves, plants continuously synthesize it. The synthesis of chlorophyll in plants requires sunlight and warm temperatures. Therefore, during summer chlorophyll is continuously broken down and regenerated in the leaves of trees.



Sugar Maple

Another class of pigments found in the leaves of many plants is the carotenoids. These leaf pigments absorb blue-green and blue light. The light reflected from them thus appears yellow. Like the chlorophylls, carotenoids are also large molecules and are also contained in the chloroplasts. There are two types of carotenoids. Some are hydrocarbons, compounds that contain only carbon and hydrogen, such as beta-carotene ($C_{40}H_{36}$). Others, called xanthophylls, contain atoms in addition to carbon and hydrogen, an example being lutein ($C_{40}H_{56}O_2$), which also contains oxygen. The carotenoids function to protect the chlorophyll from oxidation and as accessory absorbers. They absorb energy from light of different colors than that absorbed by chlorophyll, and the energy they absorb is transferred to chlorophyll. Because leaves contain much more chlorophyll than carotenoids, the carotenoids have little effect on the color of the leaves, as long as chlorophyll is present.

A third class of pigments that occurs in leaves is the anthocyanins. Anthocyanins absorb blue, blue-green, and green light. Therefore, light reflected by leaves containing anthocyanins appears red. Unlike chlorophyll and the carotenoids, anthocyanins are not attached to cell membranes. They are made in the cell by an energy-consuming process that is initiated by light. As they are made, they are released into the cell sap. Anthocyanin pigments are responsible for the red skin of ripe apples and the purple of ripe grapes. Because exposure to light is required to produce the red pigment, apples often appear red on one side and green on the other; the red side was in the sun and the green side was in shade. Similarly, leaves on a tree are reddest on the sunny side.

During summer, the leaves of trees are factories producing sugar from carbon dioxide and water by the action of light on chlorophyll. Water and nutrients flow from the roots, through the branches, and into the leaves. The sugars produced by photosynthesis are transported from the leaves to other parts of the tree, where some of the chemical energy is used for growth and some is stored. The lengthening nights of autumn trigger changes in the tree. One of these changes is the depositing of a corky layer between the branch and the leaf stem. This layer protects the branch surfaces that will be exposed when the leaf falls, but it also interferes with the movement of nutrients into and out of the leaf. Another autumn change in the leaf is the start of active destruction of the leaf's pigments. The destruction of chlorophyll progresses more rapidly than that of the carotenoids. As chlorophyll is destroyed, the green color of the leaf fades, leaving behind the yellow color of the carotenoids. In some trees, anthocyanins form in autumn, and these pigments cause the yellowing leaves



Red Oak

to turn first orange and then red. Red maples, red oaks, and sumac produce anthocyanins in abundance and display the brightest reds and purples in the autumn landscape. In other trees, such as the beech, as the yellow carotenoids are destroyed, their color is replaced by the brown that results from the oxidation of tannins in the leaf.

The range and intensity of autumn colors is greatly influenced by the weather. Warm, wet weather delays the disappearance of chlorophyll and the appearance of anthocyanins. Cool, dry weather favors the destruction of chlorophyll. Sunny weather promotes the formation of anthocyanins. So, the brightest autumn colors are produced when dry, sunny days are followed by cool, dry nights.

Sumac



In recent years, autumn colors have been attracting more and more tourists and travelers to prime color regions: New England, Michigan, and Wisconsin. (In Wisconsin, the fall-color tourists spend over \$1 billion.) The right combination of tree species and likely weather conditions produce the most spectacular displays in these regions. States in these regions maintain a fall foliage “hotline,” keeping color watchers apprised of the peak viewing locations and times. In Wisconsin, [this information is provided by the Division of Tourism](#). The U.S. Forest Service also provides [information on fall colors at our National Forests and Grasslands](#).

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REFERENCES

“The Colors of Autumn Leaves as Symptoms of Cellular Recycling and Defenses Against Environmental Stresses,” Helen J. Ougham, Phillip Morris, and Howard Thomas, *Current Topics in Developmental Biology*, 2005, Vol. 66, pp. 135-160.

“A Cellular Timetable of Autumn Senescence,” Johanna Keskitalo, Gustaf Bergquist, Per Gardenström, and Stefan Jansson, *Plant Physiology*, August 2005, Vol. 130, pp. 1635-1648.

HIGHLY RECOMMENDED READING

[How to Read the Tree Leaves \(The New York Times\)](#)

ADDITIONAL READING

[Climate-warmed leaves change lake ecosystems, Dartmouth-led study finds](#)

[A Year in the Life of a leaf \(Washington Post\)](#)