Cover Story

Life is a journey, powered by the sun, of a group of highly ordered and connected chemicals borrowed from the Earth. Death is the end of the journey when all borrowed chemicals are returned to be used again for new life.

A Touch of Chemistry

By Dr. Alex L. Shigo

Advanced modern Arboriculture is the care of the tree system based on the most current accepted tools, machines, products and techniques, and on an awareness of the scientific principles behind decisions, predictions and treatments. The tree system is made up of trees, their associates and their environment.

Arboriculture has grown from an art where muscles and skills were the major ingredients. Now it is time to add mind and science. The major science disciplines are biology, engineering, and chemistry. Of course, many other science disciplines play a role in the profession, as well as economics and communications.

Chemistry is the science of arrangements of atoms and their properties. As reactions change arrangements, the properties of the products also change. Chemistry speaks to the trees and associates at the molecular level. It is a ribbon that runs through all life processes and treatments. The use of fertilizers, water, herbicides, pesticides, mulches, soils and even proper pruning, all have a great amount to do with chemistry.

I believe many highly intelligent arborists ran from biology and chemistry primarily because of the way the subjects were taught. Students could fail by misspelling photosynthesis, or forgetting the makeup of glucose. It was not teaching: It was boring memorization. Some people wanted to be out touching trees and really learning about them.

Times are changing. Muscles and mind are now both required for the job. Some people will resist, but those who can see the writing on the wall will know that better jobs with higher wages are there for arborists who take the next steps.

Chemistry of Life

All living and non-living thing are made of chemicals. With living things, chemicals are so highly ordered in their arrangements that they repeat. Trees are bags of highly ordered arrangements of chemicals. You are bags of chemicals. The big bags are called cells, and the smaller bags within are cellular bodies and inclusions that maintain the processes of life. A major difference between your cells and those of the tree is that most of your cells have a soft, fatty, membrane boundary, whereas most of the tree's cells have a hard, tough cellulose-lignin, wall-like boundary.

Trees and people are similar also, because they have tubes that transport liquids and substances dissolved in them from one place to another, and both have chemical pathways in living cells that regulate the chemical processes. Trees have tubes of vessels, tracheids, and phloem sieve tubes. People have a digestive tube and blood vessels. The chemical pathways in living cells are routes for the constant chemical changes that support life. To hold the cells and tubes in place, people have skin and bones. Trees build their tough framework into their tubes, fibers and bark.

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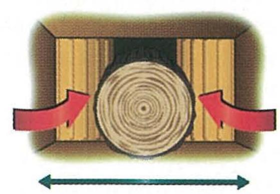

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Chemicals produced by an insect that deposited an egg in this oak twig stimulated the tree to form a gall that served as the protective home for the developing larva. Chemicals of one kind may turn on or off other chemicals in living things. These processes become more understandable when you realize that all organisms are "bags" of chemicals.

Basic Chemicals of Life

Six chemicals - carbon (C), hydrogen (H), oxygen (0), nitrogen (N), sulfur (S) and phosphorus (P) - make up about 98 percent of the weight of people and trees. Water (H_20, or two hydrogens and an oxygen atom) is the most abundant molecule in all living things. Other organic molecules are of four basic types: lipids (CH, mostly), carbohydrates (CHO), proteins (CHONS), and nucleic acids (CHONSP). Carbon is the central chemical of life. The term "organic" means that carbon is part of the molecule. (Science is full of exceptions. Diamonds, coal, oil, graphite and natural gas have carbon, but they are not organic molecules mainly because of their structure and lack of oxygen.)

Lipids

Lipids are fats, oils and waxes made up of long chains of hydrogen and carbon connected to a glycerol molecule that has three oxygens. The chains of hydrogen and carbon can take on many forms because of branching.

Suberin is a lipid that in the outer periderm of phellem waterproofs outer bark. Suberin- impregnated phellem is called cork. The chains of carbon and hydrogen in suberin are so varied that few enzymes from microorganisms are able to cleave it for an energy source. This characteristic gives corks their unique benefits for sealing bottles. Suberin is also in a layer in absorbing roots called the Casparian strip. This layer is an effective boundary essential in the absorption processes. Energy is required to transport water and elements through the

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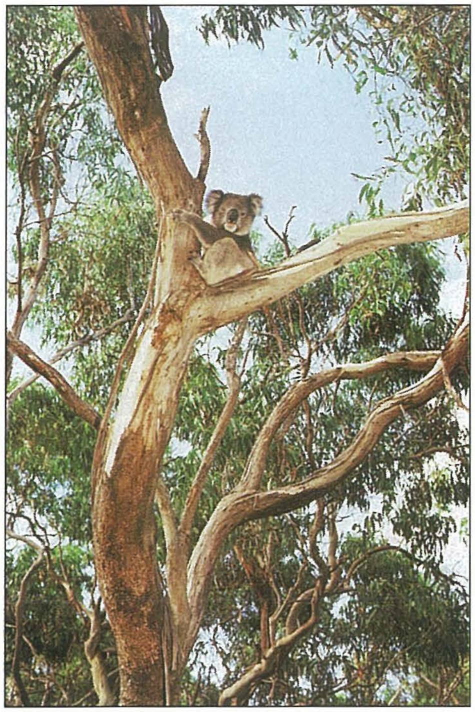

The plight of this partially blind koala is due to ignorance of tree basics. Koalas eat the leaves of only about six species of Eucalyptus. Because of fire ditches to reduce the threat of fire and over development, most of the leaves on the declining tree in the area tanned. Tanning is a chemical process of combining phenol-based substances with proteins, and the disruption of hydrogen bonds leaves the protein indigestible. The animals ate and ate, but received little nutrition. A spirochete similar to syphilis entered and was passed along by mating. Many koalas died. The good news is that development in the area was not only stopped, but many developed areas will be returned to their original state.

boundary into the tree. Suberin is also a major compound in the barrier zone that forms after wounding.

Outer bark that contains suberin is often used for mulch, since bark mulch will not be broken down by soil microorganisms because of the suberin. The bark mulch has aesthetic value, but the bark is of little value for providing energy-releasing compounds to soil microorganisms.

Some trees store fats and oils as their reserve energy source. The fats and oils are not soluble in water. Many palms store oils. Waxes on leaves and fruits are also lipids.

Carbohydrates

Carbohydrates are substances made of carbon, hydrogen and oxygen in the ratio of one carbon to one oxygen to two hydrogens. They are the energy-carrying compounds. The basic fuel for living processes is glucose, a simple sugar that contains six carbons, 12 hydrogens and six oxygens—$C_6H_{12}O_6$. The wonder of this compound is in the way in which the atoms are bonded.

A great amount of light energy from the sun trapped by photosynthesis goes into glucose. Glucose is like a mobile battery, because it is soluble in water. When the glucose reaches the living cells, it is "burned" in the presence of oxygen and provides the energy to run living processes.

Trees use energy in five basic ways: Growth, maintenance of all cell processes, reproduction, exudates and storage (mainly for new growth and defense). Growth and maintenance are linked in that growth increases the mass of an organism while

maintenance keeps the cellular bodies orderly and active. Reproduction, which increases the numbers of an organism, takes a great amount of energy from the system. Some trees have periodic heavy seed crops, while other trees, such as American elms, have heavy crops every year. Root exudates are like taxes: From 5 percent to 20 percent of the carbohydrates and other organic substances made from photosynthesis and metabolism exit the non-woody roots into the rhizosphere. These exudates are used as an energy source and building blocks by many soil microorganisms. Storage of compounds for new growth and defense is usually as insoluble starch or as oils and fats. Starch is made up of long chains of glucose. Starch is different from cellulose because of a different type of bonding.

Glucose from photosynthesis follows two different routes: Some fuels the living processes, and other glucose molecules form cellulose, which is the most abundant natural substance in the world. Cellulose is made up of twisting rope-like chains of glucose molecules. Lignins fill the spaces between the twisting "ropes" of cellulose. Lignins are natural cementing materials that give wood its unique characteristics for strength. Tree cell walls also have hemicelluloses, which are compounds made up of shorter chains of sugars.

An enzyme called amylase can change the starch chains back to glucose molecules. Many fungi have enzymes that can cleave the cellulose chains to release glucose. The wonder of glucose is that it can be an active cellular fuel, a tough material, a storage material and the basic unit of many other molecules essential for life.

Now, back to growth and maintenance as linked processes. We know how to stimulate growth: add a nitrogen source to soil or leaves and shoots will grow bigger. What we cannot do directly is add an energy source to trees. When growth increases, energy goes out of the system first. Then maintenance and defense must also increase after this for the added living matter. If stored energy is used to meet the added growth demands, little stored energy remains for defense, leaving a bigger plant with a smaller defense system. Any number of insects and microorganisms "know" this. The classic example is fire blight. Add nitrogen to a tree that has a little fire blight and the disease will spread rapidly. Add an overdose of nitrogen to trees and any number of sucking insects will be there.

The latest example is the Canadian hemlock problem caused by the hemlock woolly adelgid. Some people may argue that the added growth will support more photosynthate and this adds to the total energy budget of the system. The fact often forgotten is that the energy must come out of the system first and then the photosynthate begins to come back. Much can happen in the time between these processes that would benefit pathogens, which are opportunists waiting for a weak moment.

There is a way to indirectly "feed" a tree, and that is by the addition of composted wood and leaves to the soil. I believe we must think of the tree as the major part of an entire system. In this sense, it is possible to feed the tree system. The composted wood and leaves provide a carbon source for the many microorganisms

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that are a part of the tree system. Dose again is extremely important. High mounds of mulch about the bases of trees is not beneficial, especially if the wood and leaves are not composted.

Proteins

Proteins are compounds of amino acids that contain carbon, hydrogen, oxygen, nitrogen and, in a few cases, sulfur. There are 20 basic amino acids arranged in many ways to form proteins.

Proteins are the basic molecules that make up living matter. Animals are mostly proteins and trees are mostly carbohydrates on a weight basis. Proteins are also the central molecules in enzymes, which are substances that catalyze many reactions along the pathways of life. Enzymes are "efficiency experts" in that they bring about chemical reactions in ways that minimize the expenditure of energy. They are often likened to keys that open the doors. Or, they may be likened to knives that cleave long chains or big molecules into smaller ones. All of these actions occur in ways that minimize energy costs and keep heat down. If it were not for enzymes, living cells would run out of fuel and would heat to the point of total disruption.

A major benefit of fertilizers is that they provide nitrogen for proteins. As more proteins form, the possibility for added growth increases. Nitrogen is absorbed at the rhizoplane in two forms: as nitrate ions or ammonium ions. Nitrate is an anion that carries a single negative charge. The ammonium ion is a cation that carries a single positive charge. The molecular weight of the nitrate ion, which is made up of one nitrogen atom and three oxygen atoms, is 62. Nitrogen has a molecular weight of 14, and each oxygen is 16. The ammonium cation is made up of one nitrogen and four hydrogens that have a molecular weight of one each. It weighs 18, the same as water, H_20. A nitrate anion is three times the weight of an ammonium cation. This is extremely important, because the ammonium cation— being as small as the water molecule—often is attached to the inner surface of clay crystals. The ammonium cation is attracted to negative points in and on the clay crystals. In this way, clays hold ammonium cations as a reserve nitrogen source. A nitrate ion is too big and heavy to compete with an ammonium ion in clays.

Nitrate is usually the molecule that is absorbed by non-woody roots. The absorbing, non-woody root boundary is called the rhizoplane. In a sense, the rhizoplane is the "great discriminator." Ions pass into and out of the tree by way of the rhizoplane. When a cation moves in, an inner cation moves out. The same is true for anions. The usual cation that exits is a proton or the positively charged nucleus of hydrogen. The usual anion is the bicarbonate anion, which forms from carbonic acid, which in turn forms when carbon dioxide dissolves in water. Carbon dioxide and water are products of respiration, which is an energy-releasing process that requires oxygen. The energy released then "runs" the pathways in the living cells.

When nitrate ions enter non-woody roots, bicarbonate ions or ions made up of

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an oxygen and hydrogen exit. A bicarbonate ion is made up of one hydrogen, one carbon and three oxygens. An important point to remember is that a carbon-containing ion exits when a nitrogen-containing ion enters. When nitrate ions enter, they usually react with reserve carbons to form amino acids. So again, carbon is leaving the reserves. And even more carbon exits as root exudates.

As carbon reserves decrease, so does the potential for defense. Add to this the fact that the percentage of exudate excreted increases when trees are over-pruned or injured during construction, and the defense potential is threatened even more. Overt evidence of the decrease in defense potential is shown by the abundance of root diseases in areas where trees are commonly over-pruned, over-watered or over-fertilized. Remember, pathogens "know" how to wait for a short, weak moment in the life of an organism. When the moment comes, they are always ready.

Nucleic Acids

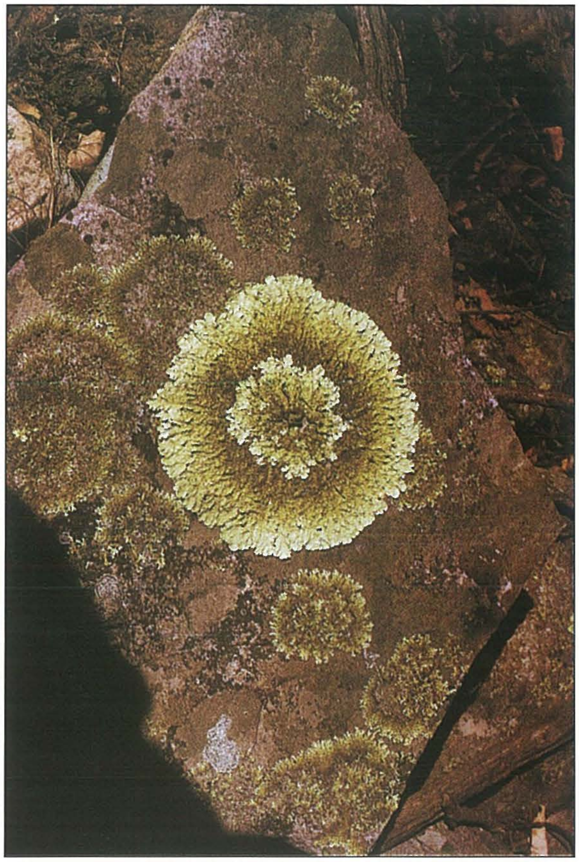
Nucleic Acids are so called because they were first found in the nuclei of cells . Nucleic acids are made up of carbon, hydrogen, oxygen, nitrogen, phosphorus and sometimes sulfur. Two nucleic acids, DNA—Deoxyribonucleic acid and RNA—ribonucleic acid, are almost household terms.

The acids hold the codes for life. DNA is like a rubbery ladder that is twisted. The "rungs" are made up of four different nitrogen-containing molecules. The combinations of groups of "rungs" are the genes that determine the makeup of an organism.

The codes within a species are basically similar in their themes, but there are countless variations on the themes. This fact accounts for the great difference between individuals within a species. This variation is very important to the people who select individual trees for superior traits. We have known for more than 25 years that some individuals of a species are able to compartmentalize wounds more effectively than others. With the great need for tough city trees, it is difficult to understand why this information has never been used.

Water

Water is the medium for the chemicals of life. For instance, we know that glucose is the basic fuel for living processes, however, it is only usable when it is in a soluble state or in water. The same can be said for the 14 elements from soil that are essential for life, as well as a long list of organic compounds.



Weathering of rocks by organic acids produced by lichens is an important process that benefits the tree system. Elements essential for life are often locked up in rocks.

Water is made up of two hydrogen atoms and an oxygen atom. The way these three atoms are bonded gives this molecule amazing characteristics. Think of the water molecule as a large balloon for oxygen and two smaller balloons for the hydrogens. The hydrogen balloons are bonded to the large balloon in a way that leaves each hydrogen atom with a small positive charge. On the opposite side of the balloon from the hydrogens, the oxygen has two small negative charges. The water molecule then has two small positive charges on one side and two small negative charges on the opposite side. Such a molecule is called a dipole because it has positive and negative ends. When many water molecules are together, one negative point is attracted to one positive point of another water molecule. The way the two negative points and two positive points are positioned makes it impossible for two water molecules to connect both positives to both negatives. The charges are small but they are enough to result in highly complex three-dimensional lattices of connected water molecules. This is why water that weighs only 18 on the molecular scale is not a gas at room temperature. The molecules normally form huge clumps of connected lattices. The cohesive nature of water explains why water will form humps on the surface of smooth glass or on the waxy coatings of leaves and needles.

The lattice structure of water molecules is a major reason it "holds together" in vessels and tracheids. The exact nature of the 3-D lattices is still not understood. When free-flowing water moves in trees, some of the water molecules "stick" to the small negative charges on cellulose molecules. The positive charges of the hydrogen of water are attracted to the negative charges of the oxygen on hydroxyls (oxygen and hydrogen bonded) on cellulose. This is called a hydrogen bond. It is like a Post-It Note. It sticks when you want it to stick, but when you pull it away, you cannot tell where it was stuck. The water that bonds with cellulose is called bound water.

The Bonds of Life

There are three major types of chemical bonds--covalent, ionic and hydrogen. Think of bonds as magnets: Covalent bonds are the strongest magnets; Ionic are next; and hydrogen the least strong. Covalent bonds hold the nitrogen in the air so tightly together that it takes a great amount of energy to break the bonds. That is good, because the air is about 80 percent nitrogen, which is in a form that is very difficult for organisms to use.

Ionic bonds are lesser magnets. Elements and combinations of elements enter and exit non-woody roots as ions. Ions have a positive or negative charge.

Hydrogen bonds are the smallest magnets. Yet in many ways, they are the major magnets of life. They hold things together and, when pressures are applied, they let things go. The more you know about hydrogen bonds, the more you will know about living processes.

There are three physical forces that we know of--gravity, electromagnetic and nuclear. Chemistry speaks primarily to the electromagnetic forces. Nuclear forces hold atoms together. Gravity and nuclear forces are primarily within the discipline of physics.

Something must hold matter together. At the same time, the matter that is held together must eventually come apart—build up, breakdown, recycling. Some force holds them together and some greater force pulls them apart. Think about how it would be

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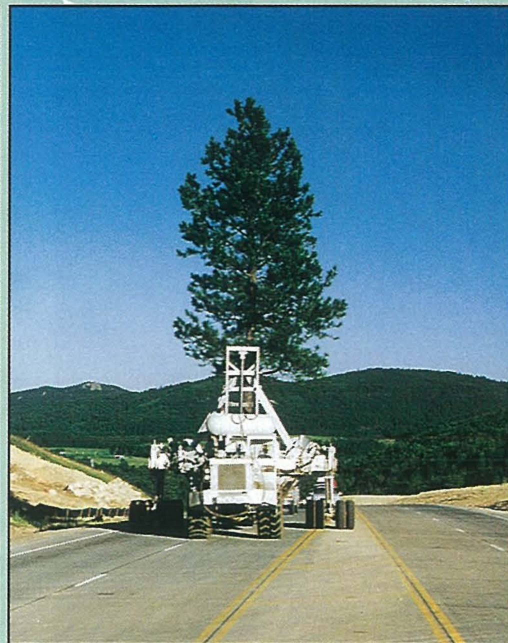

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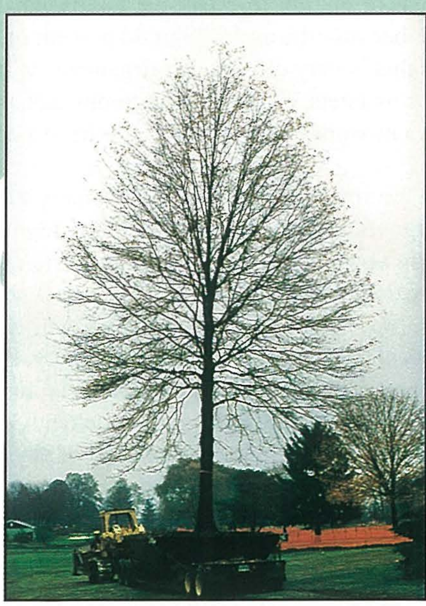

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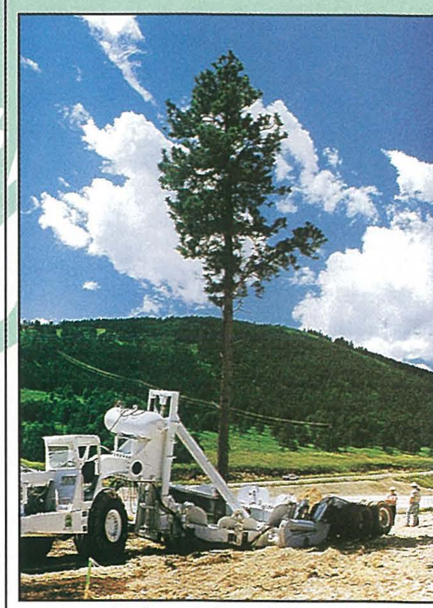

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if once matter got together, it could not be taken apart. Or think of the other extreme, that matter would be always falling apart. The wonder of natural systems is the way in which matter holds together and the way that matter comes apart.

The Tree Seesaw

Dynamic equilibrium is one of the major principles of chemistry. Dynamic equilibrium is a state of apparent balance while in reality two opposing processes are operating at a constant rate.

Natural systems are in constant states of dynamic equilibrium that are often misstated as the balance of nature. Trees are in the same state: The top supplies the energy to the bottom and the bottom supplies the water and elements to the top.

Trees can be likened to seesaws. For a seesaw to work, it must go up and down. If one end is shortened (through over-pruning), the seesaw will be more difficult to operate. If the seesaw is balanced and still, the tree is dead. If a heavy weight is placed on one side (through over-watering or over-fertilizing), it will be difficult to operate.

Some Final Points

I have discussed very briefly some organic molecules of life, water, bonding and dynamic equilibrium. Here are some examples of the ways this information is related to trees and their treatments.

1. Tanning

Many evergreen leaves tan after they mature. Tanning means that proteins bond with phenol-based molecules. In the process, the hydrogen bonds that hold the protein spirals in place are pulled away and the protein spiral collapses like a slinky toy. Once collapsed, no insect or other organism can use the protein as a food source because the collapsed spiral makes it almost impossible for an enzyme to enter and cleave the protein. This is why we tan animal skins.

2. Fiber Saturation Point

When the thick inner wall layers of fibers become saturated with water, that condition is called the fiber saturation point. The secondary wall has three layers called S_1, S_2, and S_3. The S_2 layer has an abundance of cellulose. The hydrogen bonds on the water molecules attach to the negative positions of oxygen atoms on hydroxyls that "stick out" from the cellulose. The water is now called bound water. The high amount of bound water in the S_2 layer is a major protection feature against decay-causing fungi in living trees.

3. Urea Fertilizer

Urea is the major molecule used for nitrogen in fertilizer. It is inexpensive to make. Urea is an organic molecule with a central carbon, an oxygen, two nitrogens and four hydrogens. The hydrogens form weak hydrogen bonds with positive charges and the oxygen has two weak negative bonds. The molecule is a dipole, and is very soluble in water because of the hydrogen bonds. This is the good news. The bad news is that the molecule reacts very quickly in water to release ammonia gas that can go off into the atmosphere on hot windy days and not into the soil. Also, many microorganisms contain a urease enzyme that splits the molecule to release ammonia. Many fertilizers are now including a chemical to slow the action of the urease in order to minimize loss of nitrogen as ammonia gas.

4. Over-watering

If high turgor pressure is essential as a protection feature against infection, why not add lots of water to make sure you maintain a high turgor pressure? If you do, the plant wilts or the palm heart is infected. How can this be? The seesaw and absorption in the soil are the answers. When too much water is added to soil, the oxygen content is decreased. When oxygen is low, non-woody root respiration will be low. When respiration is low, very little carbon dioxide and water will be formed. As a result, very little carbonic acid will form. When carbonic acid is low, very little bicarbonate ion will form. Bicarbonate anion is a major player in absorption. For nitrate ion to enter the non-woody root, an anion must exit. When bicarbonate anion is low, nitrate anion entering the non-woody root will be low. The seesaw states that extremes kill. Too little is not good, and too much is not good. If you load the soil with water, absorption of essential elements and water decreases because respiration and bicarbonate ions decrease.

5. Pesticides and Herbicides

Most pesticides and herbicides kill by blocking a chemical pathway within the cells, usually by the alteration of enzymes. The alteration is such that a chemical compound almost the same as the real enzyme "fits" into the real enzyme's usual position, but it does not work. Chemicals designed to kill specific organisms usually have an enzyme-blocking chemical for some enzyme specific to that organism. More broad-range killer chemicals alter some other chemical essential for living processes. For example, arsenic "fits" into the position occupied by phosphorus in the molecule ATP, adenosine triphosphate. ATP is the universal "money handler" in organisms. Arsenic is an analog for phosphorus. The problem for the organism is that arsenic does not do the job of ATP, and the cash flow system of the organism disrupts. Other broad-range chemicals work in similar ways.

6. Chlorosis

When nitrate anion enters a non-woody root, bicarbonate anion exits the root. When bicarbonate anion dissolves in water, the pH will increase in the rhizosphere. The pH could be two or more units higher right after fertilization with urea. First, urea forms ammonia, which dissolves in water to form a strong base. Then, when bicarbonate anions enter the rhizosphere water they are also bases. If this takes place in soils that are already high in pH, and if trees that have genetic codes for optimal growth in low pH soils are planted there, it is possible that some chlorosis could occur. As pH increases, iron and manganese form insoluble precipitates rather than ions in water. When iron and manganese are low, processes of photosynthesis decrease. The other side of the urea story is that after two to four weeks, the pH will decrease if certain bacteria are present and active. This seesaw effect with pH changes is more common than recognized in the rhizosphere. The problem is that when the pH conditions favor pathogens, it does not take long for them to infect.

7. Taxol and Cancer

I end with this example because a very valuable chemical from yew trees shows great promise as a control for some forms of cancer. Taxol does it it by blocking the pathways that lend elasticity to the cell's inner cytoskeleton. What does that mean? When cells divide rapidly, as they do in some cancers, the inner cell cytoskeleton stretches to accommodate the genetic apparatus that transfers the genetic material. If that apparatus is not elastic, it will not stretch as two cells begin to form from one. Instead, it resists stretching and may even break, thus preventing cell division. Since some cancers are cell divisions out of control, taxol slows this division process. The side effects are that the same slowing of cell division also takes place in normal healthy cells. But cancer cells multiply so much faster than normal cells that this side effect is far outweighed by the benefits.

Why Do I Need to Know This Stuff?

The answer is simple: You do not need to know this stuff if you are satisfied with your job and wages. If you are pleased with your position and pleased with the thought that you will be doing the same things for the same wages the rest of your life, fine!

If you want to advance—not only in your job but as a person who gets enjoyment out of understanding the way things work—then you need to know this stuff. The people who want this stuff rarely ask the question of why they need it because they already know the answer.

I believe arboriculture will become more of a science, and it will follow the same route as modern medicine. So far, the early history of medicine fits very well with the developing profession of arboriculture. TCI

Dr. Alex L. Shigo is the owner of Shigo and Trees, Associates of Durham, NH.

The Safety Mind-Set and the Color Code of Awareness

By Donald F. Blair

If you were to study a railroad yard, you could begin to understand how my mind works. A large freight yard has a vast complex of rails running parallel to each other in order to stage and organize thousands of individual cars into freight trains. The vast complex of track is channeled and narrowed through switches until a single track emerges from one end.

I have a broad base of interests and hobbies seemingly unrelated to my profession as an arborist stored in box cars, gondolas and flat cars. I enjoy reading, thinking and writing about things other than the basic skills of arborists, and being able to relate my other interests to my profession helps to keep my focus.

Years ago, the Gunner's Guru, Col. Jeff Cooper, developed a model for mental awareness entitled, "The Combat Mind-Set and the Color Code of Awareness." In Cooper's line of work, the wrong mind-set or lack of awareness to a pending combat situation can get you killed. Arborists have also been killed "in the line of duty" because they failed to recognize or be aware of hazards in the workplace.

Cooper's model identified four states or conditions of mental awareness: White, Yellow, Orange and Red.

In condition White, you are in the most relaxed state possible. A good place to be in White is at home, on the couch watching the game or reading this article in *TCI* magazine. Engrossed in your relaxation, you're basically oblivious to your surroundings and the fact that your 3-year-old and 5-year-old are getting ready to pounce on you in a classic envelopment from two sides. A bad place to be in White is on the job, either when meeting the client or getting the work done. I have a classic example of what can go wrong when you meet someone in condition White, later in this article.

Condition Yellow is also a relaxed state, but you maintain just enough control over your perimeter to be able to warn "the boys" to cut it out before they can get the drop on you. On the street, a person in condition Yellow is in a casual state of alertness. You would be aware of the people on the street, the mugger coming toward you, the dog poop on the sidewalk (before you step in it) or the piano-shaped shadow you are standing in that is getting larger and larger.

Condition Yellow gives way to Condition Orange as the next state of alertness. You move into Orange as you identify potential threats to your safety. In Orange, you are mentally preparing a plan of action should the flag go up.

Condition Red means the bull is charging! You are officially in harm's way and you need total concentration upon the technical aspects of getting yourself out of this situation alive and unharmed.

Cooper's model, of course, relates the Color Code to the intensive training in defensive combat that he developed for law enforcement, security and military personnel. Cooper relates White to a police officer on the street so totally engrossed in writing a ticket that she fails to notice the out-of-control bus careering toward her.

In Yellow, while walking a beat, the officer is relaxed but observant of the people and activities going on around her.

Orange places the officer on full alert as she chases a purse snatcher down the street and into a blind alley. In Orange, she has to be prepared to defend herself from attack by knife or gun, react appropriately in defense or take cover in an instant.

In Red, the flag is up! The purse snatcher has emerged from behind a dumpster with