Basic Water Properties:
Attributes and Reactions Essential for Tree Life

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Water is essential to tree life. Water is a solvent, transporter, buffer, and reagent for the tree. Water is the most limiting of all essential tree resources. Trees have developed specialized organs, processes, and surfaces to use and conserve water carefully. The value of water lies with its chemical properties, physical reactions, and biological uses. This publication will review what is water, and how it supports life through its properties.

Water is the single most important molecule in trees and the ecological system that supports trees. Water is the starting point for photosynthesis capturing energy from the sun. Water is the hydraulic fluid, transportation stream, and solvent used by trees. Water usually is between 70% to 90% of the mass of a growing tree, whether the tissue is living or dead. Within each living tree cell is the water-based solution that contains, supports and dissolves a variety of materials and molecules responsible for life. This water solution of tree life is called cytoplasm.

The general properties important to our understanding of water in tree growth are reviewed in various sections of this publication, as follows:

A. Unique Qualities
B. Molecular Interactions
C. Hydrogen Bonds
D. Density
E. Polar Solvent
F. Internal Structure
G. Surface Tension
H. Capillary Movement
I. Specific Heat
J. Evaporation
K. Tensile Strength
L. Energy Relations
M. Movement and Transport
N.. Biological Foundations

Water Everywhere?

Approximately 97% of all water on our planet is in the oceans. Ocean water contains around 35,000 parts per million dissolved materials, comprised of at least 70 elements. Fresh water (less than 1000 ppm dissolved materials) represents the remaining 3% of water on Earth, 2/3's of which is snow and ice in glaciers and in the polar ice caps. Water in the atmosphere, ground water, lakes and streams comprise the rest of Earth's fresh water. Liquid and solid water covers roughly three-quarters of Earth's surface area.

Because of water's properties, it can absorb or release more heat than most other substances for every temperature degree of change. This attribute is critical to coolant systems and heat exchangers. Water buffers extreme temperature fluctuations, acting as heat reservoirs, heat exchangers, and an

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essential element of life. The global and continental water cycles make deserts and rainforests from evaporation and precipitation. The changing states of water (and the energy released) power thunderstorms and hurricanes. Water's changing states help carry the sun's energy and buffer rapid changes across the globe.

Water States

At a growing tree's temperature, water exists as a gas and as a liquid. As temperature changes, the relative proportion of water in its two primary states change. More energy propels water molecules at a faster rate, and by definition, temperature increases. As energy is reduced to water in liquid or gas form, temperatures decline. Water can eventually freeze to a solid. Depending upon its molecular energy level, it is possible to have individual water molecules in a continuous exchange between all three states.

Water in the gas phase surrounds us in the atmosphere. The most simple weather determination includes a relative humidity measure. On a large scale, water vapor blankets the Earth and acts as a greenhouse gas, keeping heat from escaping into space. Pure water freezes at 32°F (0°C) and it boils at 212°F (100°C) — at one atmosphere of pressure. Our temperature scales are set by these properties of water.

Water is an unique substance. Pure water in small portions is clear and colorless with no taste or odor. The properties of water make it both unusual chemically and critical biologically. The most basic of its interactions with other water molecules, and other materials, are associated with its electronic properties.

Molecular Form

The water molecule, the most basic portion of water, is composed of three atoms covalently bonded together. These bonds involve sharing of electrons between atoms. Two of the three atoms are small hydrogens, each with a single negatively charged electron surrounding a positive charged proton. The third atom in water is a relatively massive oxygen which has an atomic structure that easily captures and holds two negatively charged electrons. These covalent bonds between atoms in a water molecule are strong.

Water can exist in 18 different forms (isotopes). There are three types of hydrogen available for use which vary in nuclear components. There are two oxygen forms available. The lightest elemental forms of water are the most common (H_2O mw= 18). The heavier isotopes of water (mw= 19-24) are extremely rare and may not be as biologically active as standard water.

Charge Exposure

In binding to oxygen, hydrogens tend to loose their negative electrons for most of the time. The continued loss of negatively charged shells exposes the positively charged proton center of the hydrogens. The continued capture of two negatively charged electrons for most of the time, adds a greater negative charge to the oxygen atom. The ability of the oxygen to steal electrons from its hydrogen partners generates a partial charge separation within the water molecule. The partial positive and negative charges balance out within one water molecule leaving no net charge.

Individual pieces of the water molecule do not ionize or disassociate to any great extent. Ionization of water would produce fully charged negative and positive ions. Water molecules generally stay in one molecular piece, unequally sharing the hydrogen's electrons. The unequal sharing of electrons allow the hydrogens to carry partial positive charges, and the oxygen to carry partial negative charges.

H-Bonds

The interactions between water molecules involve partial negative charges attracting partial positive charges among all molecules. This partial charge attraction is called "hydrogen bonding." Hydrogen bonding is not as strong as a covalent bond between atoms, but is strong enough to require some energy to break (i.e. 4.8 kilocalorie/mole). Hydrogen bonding occurs over 1.8 times longer distances than the short covalent bonds between atoms in a water molecule. As temperatures climb, more hydrogen bonds break. At the water surface, more molecules escape from liquid into a gas form.

Hydrogen bonding occurs when hydrogen is positioned between two strongly electronegative atoms. Oxygen, fluorine, nitrogen and chlorine can participate in compounds with hydrogen bonding. Oxygens in water molecules form hydrogen bonds across one attached hydrogen. In addition, note both oxygen and nitrogen form hydrogen bonds that influence the shape or conformation of biological molecules.

Sticky Shapes

Part of understanding the partial charge attractions or hydrogen bonding is examining the shape of the water molecule. Water molecules are not straight or a perfect 90° L-shaped. There are many ways to envision three atoms in water attaching to each other. The two hydrogens can only be attached to the single oxygen in one way. The hydrogens are always at a 105° angle from each other over the surface of the much larger and massive oxygen atom. At this angle, each hydrogen presents a partial positive charge to other water molecules and materials. The oxygen presents two variable partial negative charges to other molecules.

In liquid water, every water molecule is surrounded with other water molecules except those at the edge or surface. Within liquid water, each molecule is held within a temporary framework of 0-4 hydrogen bonds that attract molecules from all directions. Even though one hydrogen bond slips to another molecule, the average number of these bonds per water molecule remains roughly the same for every energy level. The mutual attraction between water molecules is called "cohesion."

Ice Floats

As liquid water cools, more and more hydrogen bonds are formed and maintained. This increased attraction with decreasing temperature continues until 40°F (4°C) when water is at its densest. As liquid water continues to cool, the hydrogen bonding of cold water begins to reorganize into large areas of almost crystalline-like structures. As energy contents in liquid water declines to 32°F (0°C), the hydrogen bonds form a crystalline structure made of tetrahedrons shapes.

The four hydrogen bonds and the packing density of the tetrahedron crystal formed at freezing separates the individual water molecule by more space than is present between water molecules in a liquid form (with 0-4 hydrogen bonds). Solid water — ice — is less dense than liquid water, and so, floats. Water's greatest density is at 40°F (4°C). Water volumes nearing 40°F (4°C) will sink. Moving from 40°F (4°C) to 32°F (0°C), water restructures and rises to float on the surface. Water is least dense at 32°F (0°C). Within a 8oF (4oC) temperature range water can be found at its densest and lightest.

The characteristic of a solid form being less dense than the liquid form is rare. This feature does allow lakes to freeze from the top downward in Winter, and completely thaw in Spring, protecting the water column and lake floor ecological systems from damage. The liquid water density changes help in water mixing rates as well as provides environmental stimuli to a number of water creatures.

Changes

As energy is added to water, more molecular movement occurs with greater intensities, breaking more hydrogen bonds. Within the liquid state of water, there are several energy states where water molecule interactions undergo significant changes. The interactions or structures change to maintain the lowest energy level and/or simplest structure possible. The ice-to-liquid state change is clearly an important event for the biological use of water.

Additionally, 40^{o}F (4^{o}C), when water is at its densest, is an important phase change. There is a structural phase change at approximately 105^{o}F (40.5^{o}C) where the lower energy semi-crystalline patchwork of molecules grades into more energetic and less interactive water molecules. Some biological materials and processes become much less efficient beyond this point because of water properties and temperature effects.

Little Big Size

Water has a small molecular weight of 18 mass units – 16 mass units coming from the single oxygen. Other materials of water's mass and size quickly evaporate and exist as a gas at growth temperatures. Because of hydrogen bonding, water is "sticky," attracting each other and generating properties expected of a much different, much heavier compound. Water will interact with any other materials that have small irregularities in electronic composition. Water will adhere to many surfaces with many forms of partial charges and ionic forms.

Water forms a thin film around most soil and biological materials. In a landscape soil under drought conditions, there is a large concentration of water present, sticking and surrounding organic matter and clays, and filling small gaps or pores between particles. By putting soil in an oven at 212^{o}F (100^{o}C), you can drive-off most of the water, although some still will remain closely bound to various surfaces and within crystal structures. Adding water to a soil allows the surface films of water to get bigger and fill ever bigger soil pores or spaces. Any added water becomes part of the water matrix in the soil that sticks together and can be dragged into the tree.

Electric Shells

Many elements essential to trees dissolve readily in water and form ions, either positively charged cations or negatively charged anions. Ions come from the disassociation or splitting of molecules. Table salt easily ionizes into positive cation sodium (Na^+) and negative anion chlorine (Cl^-) when stirred into water. The charges on the ions cause the water to line-up and surround each in a hydration sphere or layer. The ions tend to behave as larger molecules because they are surrounded with many water molecules attracted to the charge.

In the soil, most of the essential elements are not dissolved in solution but held in organic materials or mineral compounds. There are always a portion of these elements dissolved in water and attracted to the various charges on soil particles. The small water molecule charges, in mass, tug at the surface materials and surround them (dissolve them). An individual water molecule is very small compared to most other materials and are drawn into the smallest of pores or spaces. This property helps water dissolve most things. Water coats and infiltrates life and its resources.

Polarity

Water is considered a polar substance because of its unique hydrogen bonds caused by partial electronic charges. In terms of kitchen chemistry, polar substances like water dissolve or attract other polar materials. Water can not influence non-polar materials like oils, thus oil and water do not mix and separate. Adding a soap or detergent to an oil-water mixture puts a charged "handle" on the oil and then water can dissolve it away.

Water itself can be separated into two ionic components: a hydroxy group (OH^-) and a proton (H^+). There is a chemical balance between water molecules in ionized and non-ionized states. Adding acid to water helps increase the concentration of proton (H+) ions and lowers pH. Materials added to water affect its properties. Water is generally a highly stable, non-ionized, polar molecule that acts as a nearly universal solvent.

Solvent Superb

Water is a great solvent. Where ever water flows through the soil or over tree surfaces, it dissolves and takes along valuable materials. Because of its small size and polar nature, water dissolves many materials, more than any other liquid. Water can fit into small surface faults and between molecules which helps dissolve materials. Materials that are ionic or polar can be pulled into water and surrounded by a shell of many water molecules hiding or covering any charge. Many acids, bases and salts ionize easily in a water solution and are immediately surrounded by a hydration layer or shell.

A hydration shell of water surrounding polar or charged materials makes these materials behave as if they were a larger compound. Some relatively large (at the molecular scale), but highly charged materials like clay colloids, can be suspended in water. Large molecules with many atoms can be surrounded by water which minimizes any electrostatic charges and negates any cohesion forces, helping these large molecules dissolve in water. Water is a "soft" means of dissolving many materials, especially when these materials already have a surface film of water adhering and surrounding them.

Complex Structures

Water is simply not a host of individual molecules interacting. Because of hydrogen bonding, water develops complex structural and geometrical relationships with surrounding water molecules which exist in few other materials. The potential for a maximum of four hydrogen bonds coming from a single water molecule allows water to mimic a four-sided, three dimensional structure called a tetrahedron, rather than a flat, two-dimensional triangle. As these tetrahedron stack-up, they form small areas of structure which approximate a crystalline form.

As more crystalline areas develop and line-up with each other, water can be described as having a semi-crystalline form in a liquid state. This semi-structure confers a type of stability which makes water unique. Water is dominated by this stable semi-crystalline structure up to about 105°F (40.5°C). At this temperature the energy within the water is great enough to prevent large structural areas of hydrogen bonding from occurring for long. This stability temperature is biologically significant because water which surrounds, supports, and interfaces with many tree enzymes and molecular conformations begin to subtly change properties above this temperature.

As water freezes, the tetrahedrons are set into true crystal forms. This water crystal formation leaves the relatively unstructured cold liquid water interactions behind and solidifies into a solid form less dense than the liquid it formed from. The tetrahedron structure of solid water allows ice to float, and provides the basic building blocks and shapes found in snowflakes and frost.

Surface Tension

Water molecules within liquid water are pulled equally (on average) from all sides by hydrogen bonding. Water molecules at the surface are pulled into the water mass. Without attraction from the air above, surface water molecules are held and pulled inward toward other water molecules. This pull generates what is called "surface tension."

Surface tension is a force generated by the hydrogen bonding between water molecules. Surface tension allows small items which are more dense than water to be held on the surface of the water. The water strider insect uses water surface tension as a means of transportation. Water has a strong surface tension force, like a cloth stretched across a drum head. The only other common liquid with a stronger surface tension is mercury.

Without gravity or a surface to adhere, large groups of water molecules will pull themselves into a round ball to minimize surface area per unit of volume, and so, surface tension forces. In gravity, tear-drop-shaped droplets are formed as water falls. Liquid water on surfaces to which it does not adhere well "beads-up." Water would rather stick to itself than to many surfaces. The surface tension of the water allows wind to push against it, generating waves in large water bodies. Detergent helps reduce the surface tension of water (by as much as 70%) and allows it to spread out on a surface.

Capillary Movement

There are some surfaces to which water is attracted or adheres well. These wettable surfaces cause a film of water to partially pull away from other water molecules and cling to the wettable surface. As one molecule moves forward and adhere to a surface, it pulls on other water molecules behind. Over time a layer of water will be pulled out and over a wettable surface. If a small diameter tube is made of a wettable surface material, water will pull itself against gravity, and other forces, into the tube. This characteristic of water is called "capillary movement."

Capillary movement involves three primary forces generated in liquid water by hydrogen bonding — adhesion, cohesion, and surface tension. Adhesion is the attraction of water for a wettable surface. Cohesion is the attraction of one water molecule for another water molecule. Surface tension minimizes surface area. Inside a small diameter tube, water is attracted along the walls by adhesive forces. As water is pulled along the tube surfaces by adhesive forces, surface tension and cohesion drag more water molecules along behind. When the cohesive forces of the water, tube size resistance to movement, and gravity become too great, (or surface tension is reduced) water movement in the capillary stops.

Tubular Water

One way to envision water pulled into and up a capillary tube is to use a suspension bridge model. The column of water is suspended against gravity by its adherence to the walls of the tube. Cohesive force keep all the water molecules together. Capillary movement is greater as tube diameter decreases. Extremely small diameter tubes, pores, or spaces can attract water and move it a relatively long way.

Capillary movement is responsible for within- and between-cell water movement in trees, and small pore space movements in soils. Cell wall spaces are extremely small (interfibral) and can slowly wick-up water. The water conducting tissues of trees (xylem), does not utilize capillary movement for water transport. If xylem were open at its top, a maximum capillary rise of 2-3 feet could be obtained. Xylem transport is by mass movement of water not capillary action.

Capillary movement is a matter of inches, not dragging water to the top of a 300 feet tall tree. Capillary movement components can be seen where liquid water touches the side of a glass. The water does not abruptly stop at the glass interface, but is drawn slightly up the sides of the glass. This raised rim is called a "meniscus." The meniscus is the visible sign of adhesive forces between the glass and water pulled up the side of the glass. The smaller the diameter of the glass, the greater the adhesive forces pulling-up on the water column and the less mass suspended behind.

Specific Heat

As energy is added to water, the molecules tend to increase vibration and movement. The more movement, the more hydrogen bonds are broken. Many hydrogen bonds must be broken before the average movement of an individual molecule is affected (i.e. water temperature increases). Because of the massive number of hydrogen bonds in water, it requires a lot of energy to see even a small change in water temperature. Water can absorb a great deal of energy which goes to breaking hydrogen bonds but does not lead to measurable temperature increases.

The property of absorbing significant energy before showing temperature change is a measure called "specific heat." Having a high specific heat allows water to be well suited for cooling machines and buffering temperature changes. It also means as water finally does change states, a lot of energy can be involved. For example, in a moist soil system, the water present can absorb more than five times the heat of the soil materials present.

Evaporation

As water temperature is raised to near boiling, more and more hydrogen bonds are being broken. From the surface, as select water molecules are untethered from all hydrogen bonds, they escape into the atmosphere. This evaporation process occurs at all temperatures, but is maximized at near boiling when almost all hydrogen bonds are broken and water vaporizes (changes states). The amount of energy required for changing liquid water into a gas (boiling or vaporization) is large for such a small molecule because of the cohesion – hydrogen bonding – between molecules.

Throughout liquid water, the average attractive forces between molecules is dependent upon temperature. But each separate molecule can have a higher or lower energy level than average. Water molecules with higher than average energy levels can overcome the shifting hydrogen bonds and break away. This is called evaporation when a water molecule from a liquid mass escapes into a gas phase. Because the escaping molecule had a higher than average energy level, it leaves the liquid cooler (lower in energy) upon evaporation. This process is called evaporative cooling. As liquid temperature increases, evaporation becomes faster.

Drying Force

The rate of water molecules evaporating for each temperature is a unique "vapor pressure." When the vapor pressure of liquid water equals the air pressure over it, the water boils. The standard boiling temperature of pure water is considered 212^{o}F (100^{o}C) at one atmosphere of pressure (1 bar or 760 mm Hg). Changing air pressure will change the boiling temperature (equilibrium between vapor pressure and air pressure). Temperature and air pressure are key components governing evaporation and boiling.

Water moves from areas of high concentrations to areas of low concentrations. In a tree, water evaporates from the moist inner leaf surfaces and escapes from the stomates and tree surfaces. Even at very high relative humidity levels in the atmosphere, the tree loses water because the atmosphere is chemically dry. For example, air at 98% relative humidity has a water potential which is more than 100 times drier than the internal leaf surface. Except under fog conditions (100% relative humidity), trees are always losing water to a dry atmosphere.

Tensile Strength

Water is strong under tension. The force needed to pull water apart is substantial (theoretically pure water can sustain -300 bars tension). Water in small vessels can sustain tension forces approaching 8% the tensile strength of aluminum or copper wire. Maximum tensile forces applied to water show that up to 30% of the hydrogen bonds are positioned and participate in tension loading. Unfortunately, many things negatively influence tensile strength of water.

The cell wall materials, the diameter of the water column, the amount and types of dissolved materials present, and additional discontinuities in the semi-crystalline structure of the water (H+ and OH- groups) will all lower tensile strength in a water column. Water from the soil will have dissolved materials which will affect tensile strength. Dissolved gases, when put under a negative pressure (tension in a water column), can come out of solution and form a bubble. Once a bubble is formed, it can expand and contract indefinitely in the water column and eliminate the tensile strength in the water column.

Tiny Bubbles

Gas bubble formation in water columns is called cavitation. As temperatures rise and tension in the water column increases, more gases will fall out of solution and form small bubbles. These tiny bubbles may gather and coalesce, "snapping" the water column. As temperatures decrease, water can hold more dissolved gasses until it freezes. Freezing allows gases to escape and potentially cavitates water conducting tissue when thawed. Trees do have some limited means to reduce these cavitation faults.

Energy Changes

The "heat of fusion" is the energy required to change an amount of solid water into liquid water at its melting point. Water's heat of fusion is 80 calories per gram. This energy does not change the temperature of the water but breaks approximately 15% of the hydrogen bonds in the crystalline ice which then melts to liquid water. Water is at its densest at 40°F (4°C). Between 40°F (4°C) and 32°F (0°C) water density decreases (volume expands). The transition from liquid water at 0°C to ice at 0°C requires the removal of 80 calories of heat and initiates an increase in volume and decrease in density of about 9%.

The "heat of vaporization" is the energy required to change an amount of liquid water into a gas at its boiling point. Water's heat of vaporization is 540 calories per gram (5.4 times the energy needed to raise water temperature from 32°F to 212°F (0°C to 100°C)). There is no change in water temperature as this vaporization energy is absorbed. This energy helps overcome the hydrogen bonding in the liquid water which generates steam. At 212°F (100°C), water in both liquid and gas phases exist. Steam is more reactive and energetic than the liquid water because of the additional energy put into the molecules for vaporization.

Water is very stable in heat. The bonds between atoms in pure water remain intact beyond 3630°F (2000°C). Water can be decomposed into component gases by adding small amounts of acid ($H+$) or base ($OH-$), and then running an electric current through the liquid. Pure water does not conduct electricity.

On The Move

Water movement and transportation of materials is essential to tree life. The three major forms of transport are driven by diffusion, mass flow, and osmosis forces.

Diffusion – Diffusion operates over cell distances. Diffusion is the movement of dissolved materials from high concentrations areas to low concentration areas. Diffusion can move a dissolved molecule in water across a cell in a few seconds. Diffusion does not operate biologically over larger distances. It would take decades to diffuse a molecule across a distance of one yard / one meter.

Mass Flow – Most movements we visualize are due to the mass flow of materials caused by pressure differences. Wind, gravity, and transpiration forces initiate and sustain small differences in pressure. These small differences drive water and its dissolved load of materials in many different directions. Because pressure is the driving force in mass flow, (not concentration differences as in diffusion), the size of the conduit is critical to flow rates. If the radius of the conduit is doubled, volume flow increases to the fourth power of the size increase (double conduit radius and flow rate increases by 16 times — 2^4).

Osmosis – Osmosis is the movement of water across a membrane. Membranes in living tree cells separate and protect different processes and cellular parts. Membranes act as selective filters, preventing materials with large hydration spheres or layers from passing through. Small, uncharged materials may pass freely. The driving force to move materials in osmosis is a combination of pressure and concentration forces called a "water potential gradient."

Biology

Water provides a solution and climate for specific biochemical reactions to occur. The structure or configuration of enzymes depend upon water's structural support. In addition, many reactions and their associated biological catalysts are temperature sensitive. Water provides a constant temperature bath and a stable environment for life-functions. Water is also a component or product of some biological reactions. Small amounts of water can catalyze significant changes (i.e. oxidation of iron – rust).

The photosynthetic system in a tree depends upon the oxidation of water to provide the electron resources needed for capturing light energy. The oxygens in O_2 released in photosynthesis is derived from water. The hydrogens from water is used as a source for reduction of CO_2 captured from the air.

Evapotranspiration

At tree growth temperatures, the energy required to evaporate water is the highest for any liquid. Most of the energy is used to break hydrogen bonds. Biologically, the significance of this high heat of vaporization, means when water evaporates from the leaf, a large amount of heat is needed and a large amount of evaporative cooling takes place. In addition, the water buffers rapid changes in temperature through its resistance to temperature change.

Pump-Up Cells

Water is a good hydraulic fluid. It is non-compressible and low viscosity. Water is used to expand and hold tree cells rigid and erect. Cell divisions generate individual units for expansion. Water pressure generated through osmotic changes in the cells is used to push against the cell wall and expand cell dimensions. Water expands and holds the cell at its new dimensions until cell wall fibers and lignification constrain expansion. The visible wilting and petiole drooping in trees are derived from loss of cellular pressure because of water loss.

Hard Water

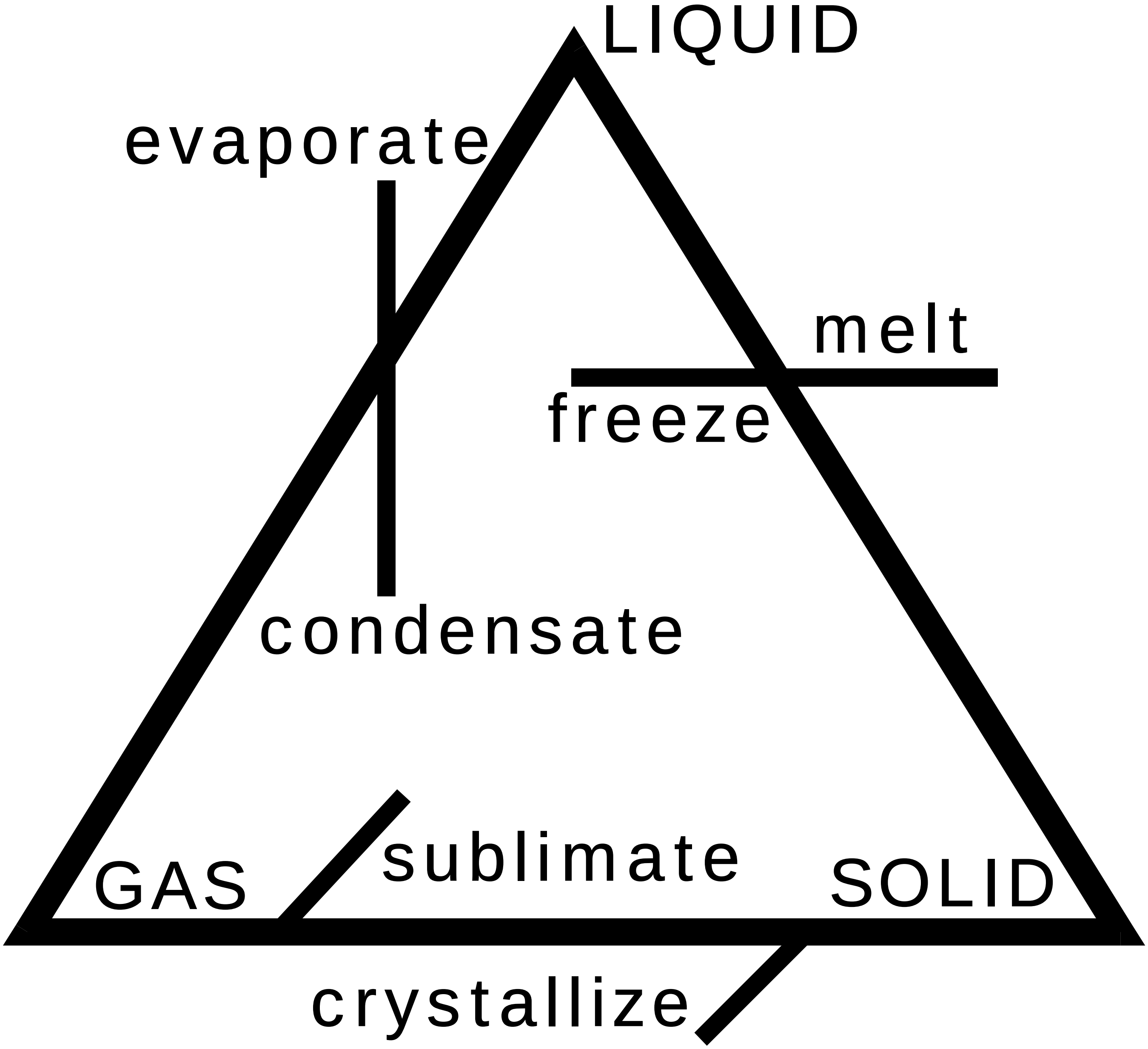
The water we take from nature can be loaded with dissolved materials, many essential to trees. When water is modified for human consumption, changes can occur which lead to long-term problems. One traditional nemesis of natural water use by humans has been dissolved calcium and magnesium salts, called "hard water." Soaps react with calcium and magnesium, generating an insoluble film. Detergents do not form this type of film. Calcium and magnesium can be removed from water by adding lime and sodium carbonate. Two insoluble products are produced which are then filtered. Ion-exchange systems trade sodium or hydrogen ions for calcium and magnesium. In addition, grey water use and chlorination systems all bring unique problems to water use for trees.

Conclusions

We live on a water planet, surrounded inside and out with water. Water is essential for life. The properties of water provide the framework, parts, and method for interacting with living processes. Water is the "problem" and the "solution." To more effectively manage trees and their water resources, an understanding of water is critical.

States of Water Triangle

(inside clockwise --
outside counter-clock wise)



LIQUID

evaporate

melt

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GAS

sublimate

SOLID

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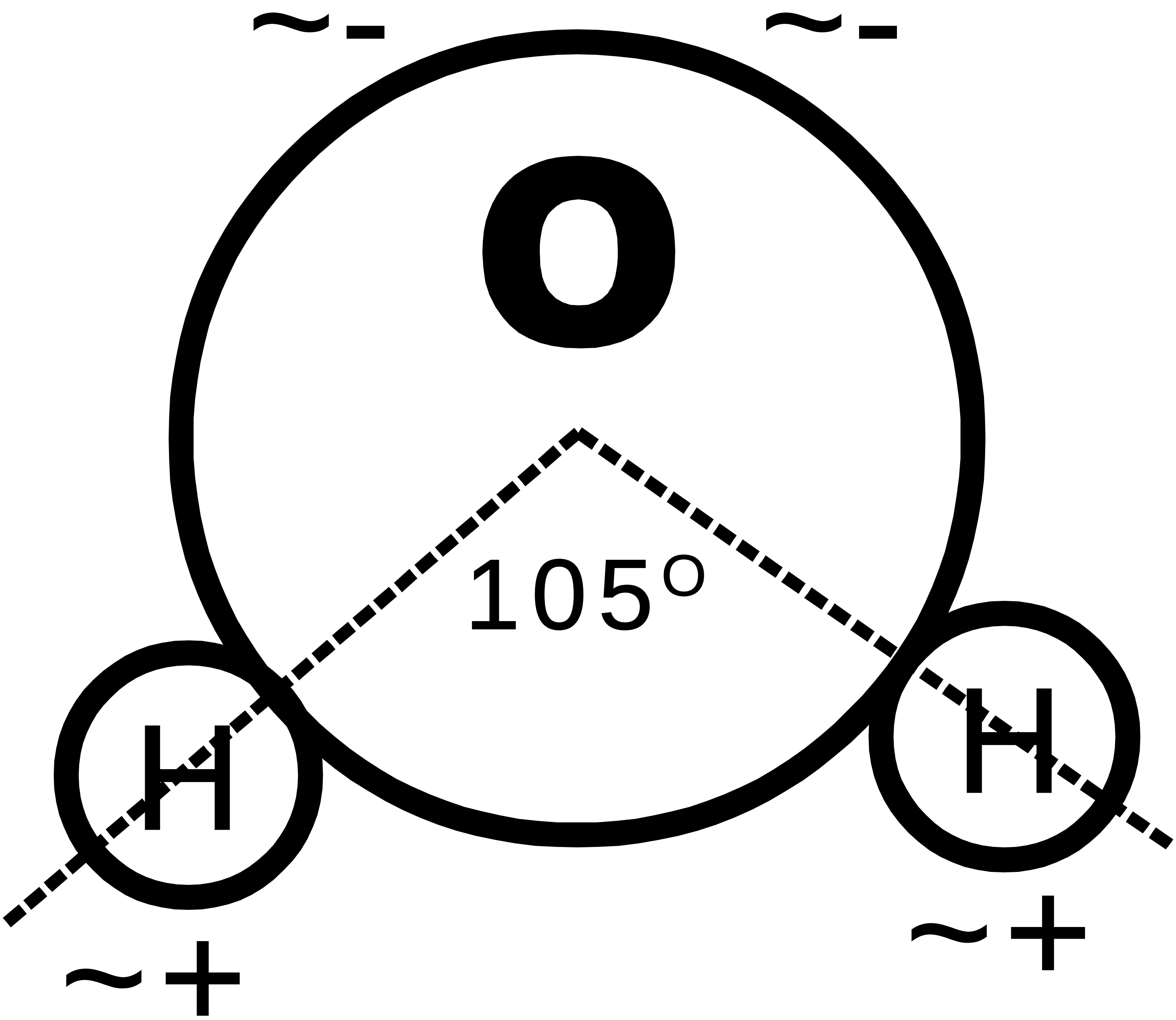
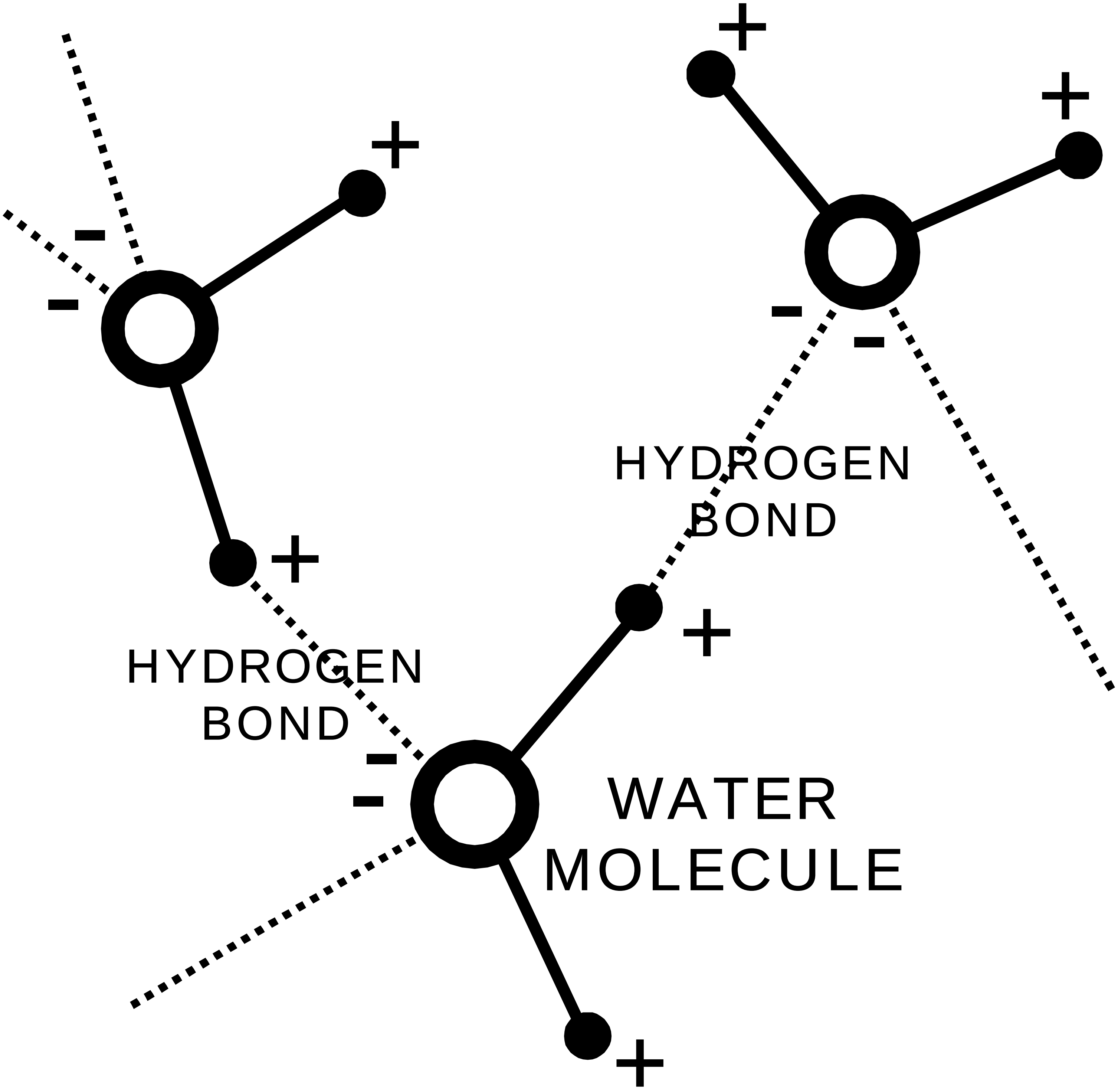


-- WATER MOLECULES ARE NOT STRAIGHT, BUT "SIDED," WITH THE HYDROGENS SEPARATED BY 105°. THE HYDROGEN (H) SIDE CARRIES PARTIAL POSITIVE CHARGES AND THE OXYGEN (O) SIDE CARRIES PARTIAL NEGATIVE CHARGES.



-- WATER MOLECULES ARE POLAR DUE TO PARTIAL CHARGES. THEY WILL LINE-UP DUE TO ATTRACTION AND REPULSION OF THESE PARTIAL CHARGES.