Water 101 – Contractor's Introduction
to the Properties of Water

Arguably, most participants in the building construction and design trades tend to lack a basic understanding of the properties of water that can lead to problematic water accumulation within exterior walls and roofs.

An essential knowledge base for these building professionals is provided with the seven fundamental aspects of water outlined below:

1. **Water molecules are very small.**

   The water molecule (H_2O) consists of two hydrogen atoms and one oxygen atom. A cubic inch of water contains approximately 600 sextillion (600,000,000,000,000,000,000,000) water molecules. A snowflake may be comprised of 180 billion (180,000,000,000) water molecules.

2. **Water molecules are 'polar'.**

   The water molecule is both *asymmetrical* and *polar*. In simple terms, the electronic charge of these molecules is unevenly distributed. The relatively large oxygen atom has a partial negative electrical field; the two smaller hydrogen atoms have a partial positive field.

One large oxygen atom → ⊖ ← Two small hydrogen atoms
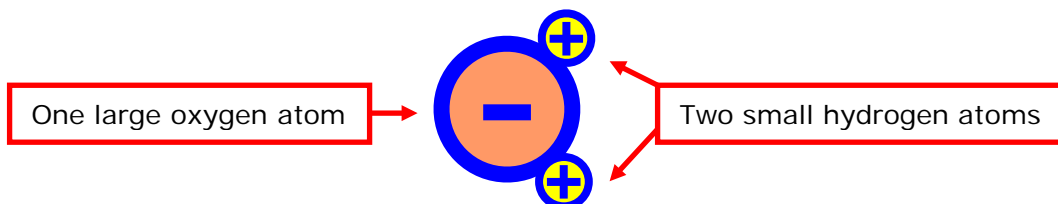
   (Many common molecules are *polar*, exhibiting electrical field differentials of varying strength; however, there also are many others that are *nonpolar* – the electronic charge is evenly distributed.)

3. Water molecules are 'sticky'.

Similar to the commonly observed interactions between magnets, the attractive/repulsive forces (i.e., '*opposites attract*' & '*likes repel*') between a water molecule's positively charged hydrogen atoms and the negatively charged oxygen atoms of other polar molecules (not just water) are relatively strong. Through a process known as **hydrogen bonding**, polar molecules tend to attract and stick to each other unless stronger forces (e.g., gravity) sunder these bonds.
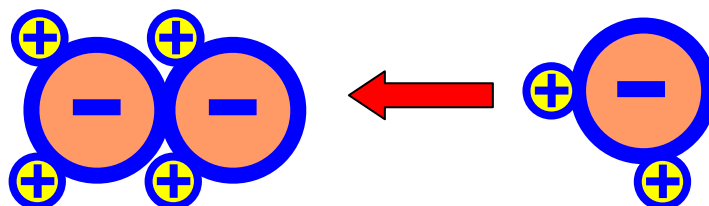
What happens when you exhale close to a glass surface? The glass 'fogs up' – many of your exhaled water molecules have become stuck to the available oxygen atoms at the glass surface, in a fashion similar to throwing Velcro-hooked balls at a Velcro-looped wall. The asymmetrical shape of the water molecule provides a variety of bonding formations, allowing diverse configurations that include countless one-of-a-kind crystalline snowflakes.

The ability of these water vapor molecules to stick to many material surfaces, such as the gypsum wallboard in your living room, is called **adsorption** (not to be confused with **absorption**, which describes capillary movement of moisture). Similarly, what does a nonsmoker notice after departing a gathering of cigarette smokers? The nonsmoker's clothes (and hair) smell of cigarettes due to smoke molecules having become stuck (**adsorbed**) to other polar molecules.

4. Water molecules are little bundles of energy.

As Albert Einstein famously reported, all matter (from molecules to rocks to plants to animals to planets, and beyond) is comprised of a particular level of **energy**. Energy can be described as the capacity to do **work**, which consists of the transfer, transformation or organization of energy. Energy's many forms can be transformed, via work, into alternate forms of energy. For example, increased *thermal energy* (heat) is transformable into increased *kinetic energy* (speed or momentum) of water molecules or automobiles or spaceships.

All molecules have the potential for accomplishing work; however, due to their sticky nature (*i.e., their exceptional ability to form strong hydrogen bonds*), water molecules have an unusually high heat capacity (*i.e., a greater ability to hold thermal energy prior to transformation into an organized form of energy*) that makes them particularly efficient workers. Acting in concert, the 'gazillions' of water molecules that we encounter every day have the capacity for prodigious work.

Water, like all carriers of energy, always moves from areas of high energy potential to areas of low. <u>Fundamentally, every condition we encounter with water is due to energy flowing from an area of greater concentration to an area of lesser</u>. If there is an accessible route, no matter how small, **wet** always moves toward **dry** and **warm** always moves toward **cold**.[1]

5. **Vapor, liquid and ice simply represent three distinct stages of energy transfer.**

   Every action of water (from evaporation and condensation to powering the turbines of hydroelectric plants to the melting of the polar icecaps to the deterioration of wood stud framing) is explained by the transfer of **energy**. At the range of ambient temperature suitable for human life, water is the only substance that can be commonly observed in the three stages of energy transfer: as a gas (vapor), a liquid and a solid (ice).

   All around us, water molecules are moving (*kinetic energy*) in all directions at varying speeds that increase or decrease as the ambient temperature (the pool of *thermal energy* that powers the vapor molecules) rises or falls. The velocity of each molecule varies in dependence to its energy level and to the overall supply of energy; however, at room temperature the average speed of these numerous molecules is more than 1,000 miles per hour.[2]

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[1] Reference the Second Law of Thermodynamics, which describes the one-way flow (from *more* to *less*) of energy in a closed system.
[2] The actual distance traveled by these speedy little water molecules is substantially impacted by their numerous ricocheting collisions with other molecules.

Like ricocheting billiard balls, at such velocities most of these speedy water molecules simply have too much momentum to 'stick' (i.e., adsorption due to hydrogen bonding) to other molecules during their collisions, and thus remain dispersed as water *vapor*.

At the slower molecular speeds that result from cooler temperatures, some of the interacting water molecules create loosely associated groups that constantly form, break and reform their hydrogen bonds within the group. These grouped molecules tend to have sufficient energy/momentum to avoid a fixed bond with other water molecules within the group but most cannot escape from the overall cohesive attraction of the pack. Even though the continual bonding and rebonding process at this state may best be described as 'flickering', the total quantity of bonding simultaneously occurring within the group at any point in time is sufficient to produce the familiar *liquid* form to this vibrant mass of water molecules.

As we see when we pour our morning glass of milk, these flickering bonds provide a tremendous flexibility (fluidity) to the shifting mass of interconnected molecules – allowing it to take the shape of virtually any container.

As the liquid water cools further, the hydrogen bond connections between the slowing molecules are maintained for longer periods before breaking and later reforming. The density of the cooling liquid increases as the compressive forces of the more stable hydrogen bonds tend to condense the molecules into a tighter mass. In other words, cold liquid water is denser than warm liquid water. Similar to warm air rising to the top of a room, warm water will float above cold water.

Finally, at about 39°F, the cooling liquid reaches its maximum possible density, at which point an interesting thing happens – the water molecules begin to reorganize into the crystalline structures that comprise solid water (*ice*). Due to the asymmetrical shape of each water molecule, a hexagonal three-dimensional crystal shape is the most efficient form of the hydrogen bonding process that results in ice formation.

In ice, the once energetic and freely roaming water molecules have transformed much of their remaining energy into their fixed hydrogen bonds.[3]

Ice is less dense than liquid water (i.e., ice floats) due to the empty space within each of the rigid hexagonal three-dimensional crystal formations. In other words, as liquid water freezes into ice, its volume expands – building professionals who work in northern climes have experienced the destructive *freeze-thaw* effects of expansion and contraction at the transitional zone between liquid and solid water. You can easily test this expansion by putting a full glass of water into a freezer – the resulting ice will expand above the top of the glass and can be sufficiently powerful to break a closed container.

All of this *work*, transforming individual vapor molecules into a solid mass, is the result of *energy transfer* between water molecules. What happens if we then supply a source of additional energy (from a nearby fire, for example) to the ice? Reenergized molecules, both individually (as vapor) and in clusters (as liquid), will break free from their hydrogen bonds. Radiant energy from the fire has become transformed into kinetic energy, allowing these molecules to escape from their icy prison.

6. Water is the 'universal solvent'.

What happens when you put a cube of sugar into liquid water? The sugar dissolves because the positively charged hydrogen ends of the water molecules have sufficient strength to pull the slightly polarized sugar molecules apart from the sugar cube. The result is a *solution* in which water is the *solvent* and the sugar molecules are the *solute*.

In other words, the adhesive attraction of the polar water molecule is stronger than the cohesive forces holding the polar sugar molecules in cubic form.

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[3] Until the surrounding temperature drops to 0° Kelvin (-459° F or -273° C) these fixed ice molecules continue to experience some degree of movement or vibration within the limits of their bonds.

Water often is called the **universal solvent** because it can pull apart so many substances, whether comprised of polar molecules or charged ions (salt, for example). Water can dissolve more substances (albeit, generally in a less spectacular manner) than sulfuric acid.

7. **Water and oil (or wax or silicone) don't mix.**

What happens when you put a chunk of paraffin wax into water? The simple answer is 'not much'. The wax is comprised of nonpolar molecules that remain unaffected by the pull of the positively charged hydrogen wings of the water molecule.

The general rule of thumb is '*like dissolves like*'. To dissolve the nonpolar wax you will need to use a nonpolar solvent, such as gasoline.

Interestingly, molecules known as **surfactants** (<u>surf</u>ace <u>act</u>ive <u>agents</u>) are polar on one end (and thus attractive to water) and nonpolar on the other end (and thus attractive to oil or grease).

What happens when you add warm water and soap (a surfactant) to a sink filled with greasy pans? The soap molecules attach themselves to both the grease molecules and the water molecules, allowing you to rinse the entire mess down the drain.

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Armed with our understanding of these seven fundamental aspects of water, we can better design and build structures, extending their service life and reducing their maintenance, and we can better evaluate the performance of existing buildings.

Key questions encountered in the field are addressed below:

a. What is 'surface tension' and 'capillary action'?

At the surface boundary of the liquid state a relatively taut 'skin' occurs as the combined attractive forces of hydrogen bonding produce an inward orientation of the outer molecules. It is this **surface tension** that allows water bugs to skitter across pond surfaces …
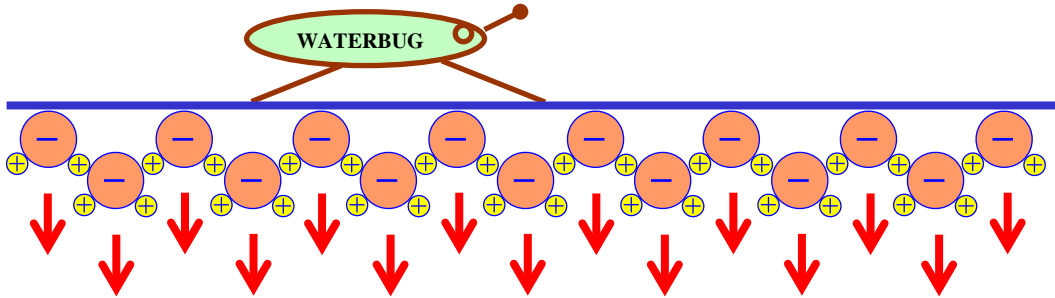
… and helps keeps water from climbing out of its container:

Liquid water in a partially filled glass will attempt to climb the walls of the container as the water molecules seek to form hydrogen bonds with available oxygen molecules in the glass surface. The only thing that prevents the water molecules from climbing to the top of the glass in their quest for more bonding is the mass of water molecules already bonded to them – air pressure pushing down on the surface of the liquid provides a counteracting force resisting the molecules' efforts to ascend the walls.
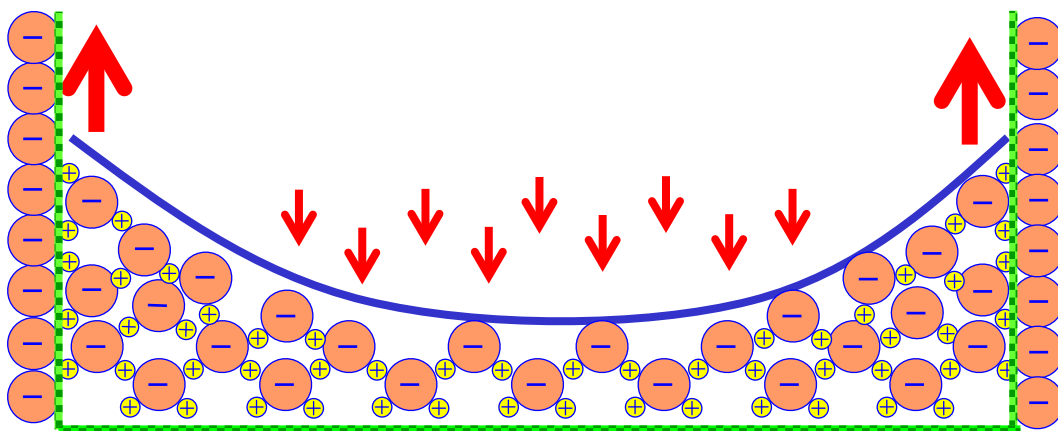
The molecules can climb only up to the point at which the opposing forces are in equilibrium. In our typical glass of water the height of this ascent may not be noticeable; however, envision a much narrower container – a glass 'capillary tube' of 1/16" diameter. The attractive forces that drive the water molecules to climb the walls remain the same, but due to the smaller surface of the liquid, the counteracting force resulting from air pressure[4] is greatly diminished, allowing the chain of water molecules to climb much farther up the wall before reaching the point of equilibrium between the opposing forces.

In summary, when liquid water molecules are enclosed in very small spaces by materials with available (unbonded) ends of oxygen molecules[5] the forces of hydrogen bonding may allow the water molecules to travel (**capillary action**) a significant distance 'uphill' before counteracting forces prevent further movement. In the building trades, failure by a designer or contractor to address this fundamental property of water can result in the localized 'wicking' shown in the Photo below.

Photo 1 – Backside of Removed Panel Siding Reveals the 'Wicking' that Can Occur When a Porous Material Is Installed Tight (No 'Capillary Break') to a Horizontal Base Flashing

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[4] Our atmosphere consists of a mix (~ 78% nitrogen, ~ 20% oxygen, ~ 1% argon, ~ 0% to 4% water, and many others in lesser amounts) of gas molecules, including water vapor, in continual kinetic motion. These speeding molecules repeatedly collide with other molecules and adjacent surfaces. 'Air pressure' is the pushing effect of these molecules against any surface.
[5] E.g., the chemical composition of wood is ~ 49% carbon, ~ 6% hydrogen, ~ 44% oxygen, and small amounts of other elements.

Imagine metal roofing panels installed with a 2″ <u>unsealed</u> overlap at a 3:12 slope – capillary action can draw great quantities of rainwater into the small space between the overlapping panels. At this low 3:12 slope, the counteracting forces of air pressure and gravity may not be sufficient to prevent the water molecules from climbing to the top of the overlap and dispersing into the underside of the panel. Similar construction at a 12:12 slope may perform satisfactorily due to the greater resisting forces; however, the potentially problematic condition should be addressed by sealing the overlap, blocking the route of moisture infiltration.[6]
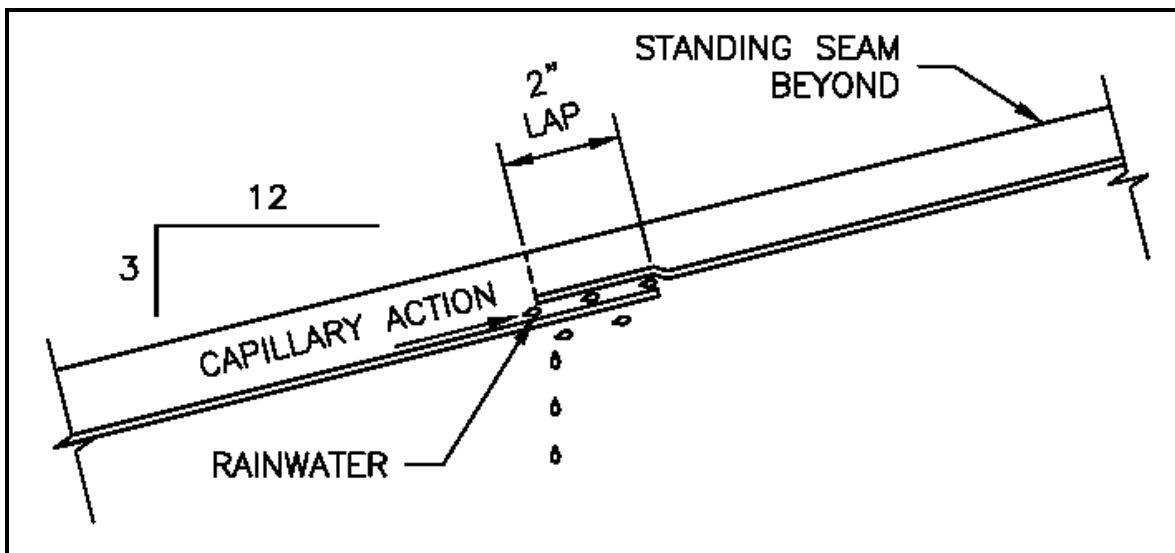

Figure 1 – Interior Leakage Due to Capillary Action at Unsealed Overlap

Now imagine asphalt shingles also installed with a 2″ unsealed overlap at a 3:12 slope. Is the threat of capillary action as great? No, because asphalt roofing (unlike metal) is comprised of nonpolar molecules. Water molecules simply cannot carry out the hydrogen bonding process with bitumen molecules, which explains why asphaltic roofing materials are a natural choice for a discontinuous (i.e., many overlapping sections) weather protection system.

While these two extreme examples greatly oversimplify the issues (failing, for example, to discuss the role of the nonpolar coating product that protects the metal roofing, and not considering the

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[6] Note that in ***low slope*** (1:12 to 4:12) roof applications, water also can be 'pushed' through openings by wind pressure, a condition that will look very similar to capillary movement of water.

potential for hydrogen bonding of water molecules to the fire-protective granules found at the top surfaces of the asphalt shingles), a general conclusion can be drawn – the designer or contractor who does not understand the potential moisture-resistive (or moisture-attractive) performance differences between various building products likely will someday become the subject of legal action by a dissatisfied building owner.

Similarly, consider a fundamental difference between OSB (oriented strandboard) and plywood panel sheathing: wax is a key component of the OSB manufacturing process.

- *"A small amount of wax (usually less than 1.5% by weight) is added in the OSB manufacturing process to improve the board's resistance to moisture and water absorption."*[7]

A rough rule of thumb is that a standard 4'x8' OSB or plywood panel weighs 25 pounds per 1/4" of thickness. Thus, a typical 7/16" OSB sheathing panel can be expected to contain more than 1/2 pound of wax. Clearly, the addition of this nonpolar substance will affect the 'moisture exchange' performance of the compressed wood strands that comprise the OSB panel.

Solely due to this issue, when compared to plywood, OSB can be expected to better resist water infiltration[8] (due to the lack of hydrogen bonding between the water and wax molecules) but also to suffer a decreased ability to dry out when allowed to become wet, for the same reason.[9]

Such performance differences can become critical if excess quantities of water reach the engineered wood sheathing due to design or construction failures.

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[7] *Binders and Waxes in OSB*, Technical Bulletin 118, Structural Board Association, Toronto, 1996
[8] This resistance to moisture infiltration is negated at cut panel ends or other areas (e.g., drilled holes) at which the wax protective layer is removed.
[9] There are several key factors that explain the moisture exchange performance differences between OSB and plywood. For additional discussion of these issues, reference L. Haughton and C. Murphy, *'Moisture Exchange' Performance of OSB and Plywood Structural Panels*, June 2003 issue of Interface magazine (Vol. XXI, No. 6), Roof Consultants Institute, Raleigh, NC

b. What is 'condensation' and 'evaporation'?

Evaporation simply is the transformation into *vapor* of a hydrogen bonded water molecule that has gained sufficient kinetic energy to break its bond. Place a bowl of water out under the summer sun: the liquid water will *evaporate* as the water molecules are reenergized.

Condensation is the opposite. Reduced levels of available energy (i.e., cooling temperatures) result in an increased amount of hydrogen bonding of the slowing water molecules – the de-energized vapor *condenses* into liquid.

- A great example is morning **dew**: during the day, increased thermal energy causes (by evaporation) an increased number of vapor molecules in the air; however, the cooling temperatures at night eventually reach a level at which the de-energized vapor molecules must begin condensing onto the nearest cool surfaces, thereby producing dew. The temperature at which condensation begins is called the *dew point temperature*.

Note in the Photo below the pattern of morning dew formation at a Seattle school building in winter months. The dew has formed only at the fiber-cement siding surfaces that are not warmed by the conductance of interior heat through the underlying steel framing.

Photo 2 – Morning Dew Forms Only at Fiber-Cement Siding Areas Not Warmed by the Underlying Steel Framing (Coe Elementary School, Seattle)

At normal temperature levels (in your living room, for example) the evaporation and condensation processes are occurring simultaneously – at the same time that some of the room's many water molecules no longer have sufficient energy to remain unbonded, other molecules are breaking their hydrogen bonds at the room's surrounds (e.g., the gypsum wallboard) to become ambient vapor. The proportional balance between the processes of evaporation and condensation is determined by two factors: the amount of available ambient energy and the amount of available moisture.

Unless energy or moisture is added or subtracted from your room, its air and its porous hygroscopic[10] components will reach **equilibrium moisture content** levels at which a balanced rate of energy exchange is occurring during the continual transformations of ambient vapor to hydrogen bonded moisture and vice versa.

- The moisture (energy) transfer processes at and within your wallboard that work to achieve equilibrium moisture content consist of vapor *adsorption* and liquid *absorption*.

- The driving force behind the **energy exchange** process necessary to achieve this moisture equilibrium is the Second Law of Thermodynamics, which requires, as a fundamental law of the universe, that when two pools of energy are connected the greater pool will flow into the smaller pool until equilibrium is reached.

What happens when you turn up the thermostat for your heating system? The additional thermal energy added to the room unbalances the energy exchange equilibrium and results in increased evaporation from the surrounds (i.e., your wallboard gets dryer) until a new point of balanced energy transfer is reached between the continual processes of evaporation and condensation.

Similarly, what happens when you frame an exposed wood structure during winter rains? The ongoing processes of energy exchange favor

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[10] Hygroscopic materials are those that, due to their *porosity*, are capable of continually exchanging moisture (by adsorption and desorption) with surrounding air and other materials to achieve an equilibrium moisture content representing the current energy balance between the continual processes of evaporation and condensation. Wood, gypsum, masonry and stucco are typical hygroscopic construction materials; in contrast, steel, vinyl, glass and bitumen materials are not hygroscopic.

an evaporation/condensation balance that results in increased moisture levels within the wood framing elements. Conversely, after the structure has been 'closed in' and heated, a new evaporation/ condensation balance results in release of this moisture (as vapor) into the interior, potentially promoting conditions of deterioration or mold growth at some other area if adequate ventilation is not provided.

Note that a failure to provide sufficient energy (heat) to promote the evaporative drying of the wet wood framing inevitably will result in conditions of deterioration or mold growth. There is no alternative force with sufficient power to sunder the strong hydrogen bonding that occurs between the water molecules and the wood molecules. In other words, the building professional who believes that ***gravity*** will remove excess moisture held within typical framing and sheathing elements is courting disaster. Removal of such moisture requires the application of additional energy to break hydrogen bonds and to disturb the equilibrium of the energy exchange processes.

- *"Capillary and adsorbed moisture can only be dried by evaporation because it takes more energy to break the attractive forces than gravity can supply."*[11]

c. What is 'relative humidity'?

In the example above, the term ***relative humidity*** can be used to express the percentage of the available energy in your room that has been used to 'free' (via evaporation) sufficient water molecules from your wallboard (and the room's other hygroscopic materials) to reach a level of energy exchange equilibrium between the continual processes of evaporation and condensation.

- A relative humidity ('RH') of 50% means half of the available energy must be used to reach the dynamic level of energy exchange equilibrium between the moisture contained within your room's surrounds and the ambient vapor molecules bouncing back and forth between its walls.

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[11] J.F. Straube, *Moisture, Materials & Buildings*, HPAC Engineering magazine (April 2002), Cleveland, OH

- Similarly, at 90% RH all but 10% of the available energy must be used to achieve the level of evaporation required to reach dynamic equilibrium.

- At 100% RH, there no longer is sufficient available energy to maintain a moisture exchange balance between the water vapor in the room's air and the moisture contained within the room's surrounds; therefore, in a manner similar to the operation of a pressure relief valve, some of the excess moisture must be dumped from the system. This relief is provided by the transformation (condensation) of some ambient vapor into free liquid water – in other words, it begins to rain at the coolest surfaces of the walls within your room.

In summary, the term ***relative humidity*** simply represents the percentage of available energy being used for the evaporation necessary to maintain a moisture exchange balance between your room and its surrounds.

How does the RH level change if you turn up the thermostat? The total available energy has been increased; therefore, RH is decreased (the <u>percentage</u> of available energy being used to maintain the dynamic moisture exchange balance via evaporation has been lessened).

Conversely, turning down the thermostat means a greater percentage of the decreased supply of energy must be used to achieve equilibrium; i.e., the room's *relative humidity* has been increased.

In brief, increased energy (i.e., the thermostat is turned up) results in:

- A decreased level of adsorbed/absorbed moisture at walls and other hygroscopic surrounds as a new evaporation/condensation balance is achieved;

- An increased level of water vapor in the room's air; and

- A decreased relative humidity.

Similarly, a decreased supply of energy (i.e., the thermostat is turned down) results in:

- An increased level of adsorbed/absorbed moisture at walls and other hygroscopic surrounds as a new evaporation/condensation balance is achieved;

- A decreased level of water vapor in the room's air; and

- An increased relative humidity.

Relative humidity can be considered a value that expresses the current operational efficiency of the energy equilibrium process. At 50% relative humidity, the system is running efficiently; the condensation/evaporation balance is easily achieved and a significant surplus of energy remains available to handle increased demands that may occur. At 85% RH, the system is being pushed to its operational limits.

- What happens when you walk into a conditioned room with an 85% relative humidity? As you sense the room's 'muggy' atmosphere, you notice sweat accumulation on your body. Due to the diminished operational efficiency of the room's moisture exchange system, timely evaporation of your body's perspiration no longer is possible.

- Conversely, what would you experience if the room had only 20% RH? Your body's surface moisture would be so efficiently transformed into vapor that your skin soon may become overly dry and 'chapped'.

It is important to note that for our human interaction with the evaporation/condensation energy exchange process, relative humidity values generally have no clear meaning unless the corresponding temperature values (i.e., the amount of available energy) also can be determined. 85% RH has a far different meaning to a Chicago resident on a hot 'sticky' August morning than it does to a Seattle resident on a cool drizzly March day.

However, even if the ambient relative humidity is the only known energy exchange value for your room, the hygroscopic performance of the room's porous inanimate elements can be determined with fairly close precision. For any hygroscopic material, a particular

relative humidity value closely corresponds (over time[12]) to a particular moisture content value. At the range of temperatures we typically encounter, this property is <u>not</u> temperature dependent: in other words, whether the temperature in your room is 40°F or 90°F, an ambient RH of 80% will result, over time, in approximately the same moisture content within a hygroscopic material within the room.

For example, a table published by the U.S. Forest Products Laboratory in the **Wood Handbook**[13] provides the following moisture content values for wood in a state of energy equilibrium with its surrounding environment at 80% relative humidity:

Temperature (F°)	Relative Humidity (%)	Moisture Content (%)
30	80	16.5
40	80	16.5
50	80	16.4
60	80	16.2
70	80	16.0
80	80	15.7
90	80	15.4

Compare the above values with those encountered with wood that is in a state of energy equilibrium with its surrounding environment at 40% relative humidity:

Temperature (F°)	Relative Humidity (%)	Moisture Content (%)
30	40	7.9
40	40	7.9
50	40	7.9
60	40	7.8
70	40	7.7
80	40	7.6
90	40	7.4

Clearly, at a particular RH value, the moisture content of wood at a state of energy equilibrium is closely approximate at any typical ambient temperature. This physical property applies (with differing moisture content values, of course) to any hygroscopic material.

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[12] RH values can change quickly due to increases/decreases in available moisture or energy. The resulting changes in moisture content of the surrounding hygroscopic materials proceed much more slowly.

[13] *Wood Handbook – Wood as an Engineering Material*, Forest Products Laboratory, U.S. Department of Agriculture, Madison, WI. 1999

For each hygroscopic material, the relationship between relative humidity and moisture content can be expressed graphically with a **sorption isotherm**.

A typical published sorption isotherm for plywood is provided in the Figure below. Note that at about 80% RH (no matter what temperature) the moisture content of the plywood begins to increase exponentially. Due to the decreased supply of available energy to support water vaporization, the moisture exchange balance must be achieved by storing (first by *adsorption*, followed by capillary *absorption*) exponentially more water molecules within the hygroscopic material.
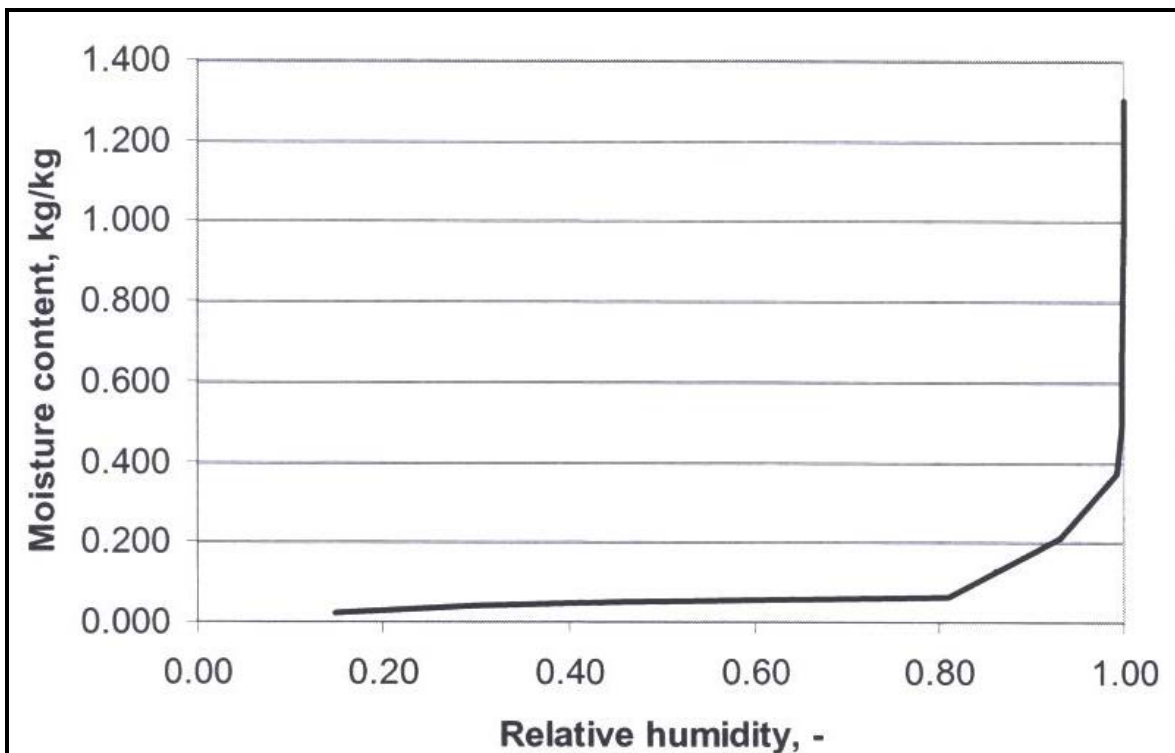

Figure 2 – Sorption Isotherm for Plywood, Published by Oak Ridge National Laboratory[14]

Extended periods of ambient 80% RH are not uncommon in many parts of North America. As can be seen, the moisture content of a plywood material (e.g., sheathing installed behind lap siding) exposed to this humidity level remains satisfactorily low; however, even a small amount of additional ambient moisture within the wall assembly (such as increased moisture vapor associated with leakage from a

[14] A.N. Karagiozis, *Building Enclosure Hygrothermal Performance Study – Phase 1*, Oak Ridge National Laboratory, ORNL/TM-2002-89. www.ornl.gov/ornlhome/publications.htm

failed flashing) can rapidly raise the overall moisture content of the plywood panel. Similar conditions occur with all porous (hygroscopic) construction materials, albeit each material has a unique sorption isotherm[15] and a distinct RH level at which the MC begins to increase dramatically.

It is clear that solely due to ambient relative humidity the designer and contractor working with hygroscopic construction materials must exercise greater care in a relatively humid environment, such as Seattle or Chicago, than in a non-humid climate, such as Albuquerque, because in the humid climates the construction materials have a diminished buffering ability to hold excess moisture until the next drying period.
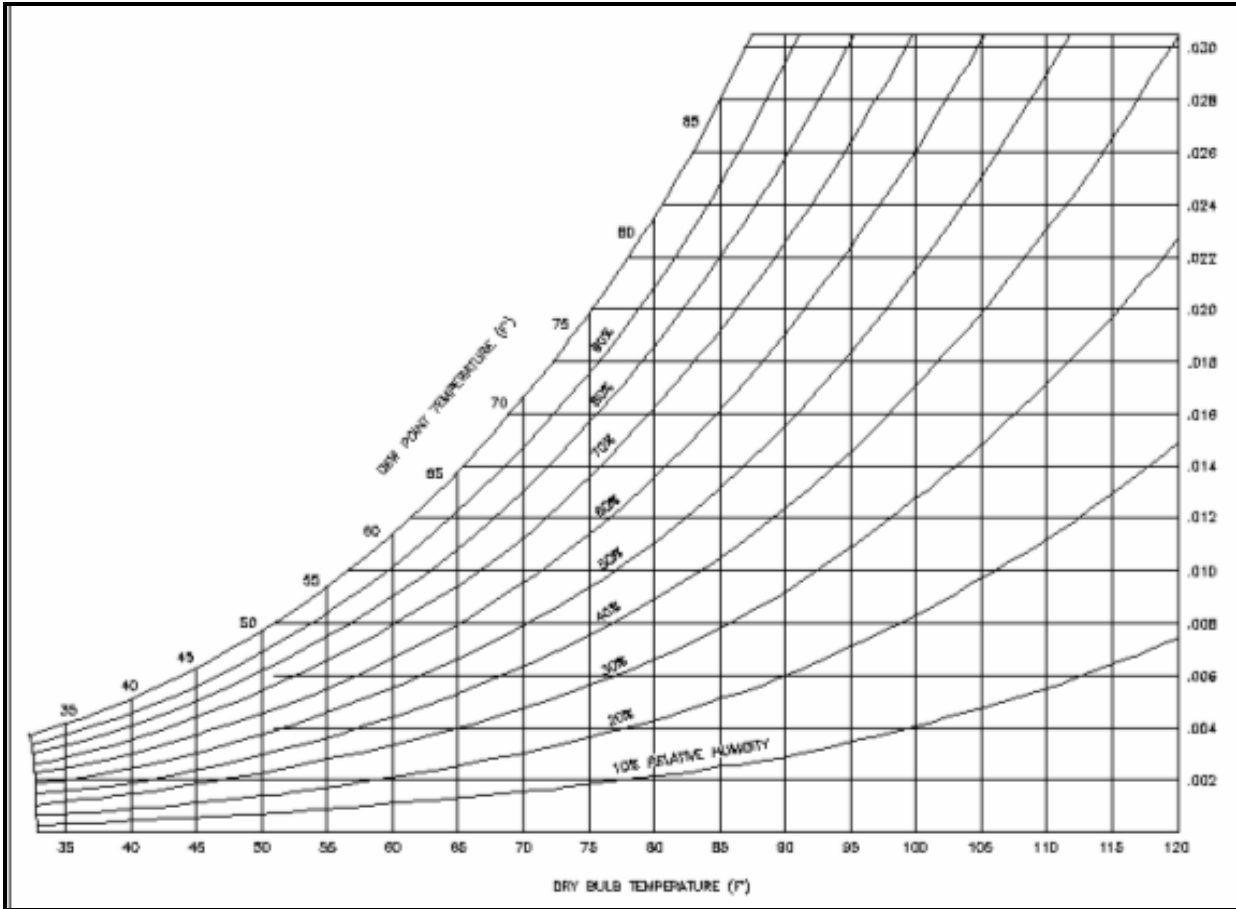
d. What is a 'psychrometric chart'?

By definition, 'relative humidity' is a nonlinear humidity value defined by interacting levels of energy and water molecules. This thermodynamic nonlinear relationship between the amount of available energy and the amount of moisture vapor in the surrounds often is described graphically with a **psychrometric chart**[16] (psychrometrics is the science of air-water interaction). A simplified psychrometric chart is provided on the following page.

- The x-axis in the psychrometric chart quantifies the amount of thermal energy available to power the evaporation/condensation processes.
- The y-axis (at right) quantifies the amount of ambient vapor (pounds of moisture per pound of dry air) – this is the **humidity ratio**.
- An x,y point on the graph identifies the corresponding relative humidity.
- Dew point temperature is equivalent to 100% RH.

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[15] Note that for each material, its *sorption isotherm* can be considered to represent average values between its *adsorption isotherm* (which depicts the rate of increasing moisture content as relative humidity increases) and its *desorption isotherm* (which depicts the rate of decreasing MC as RH decreases). Under conditions of falling RH, the moisture content of most hygroscopic materials will be somewhat higher than for the same RH values when the relative humidity is rising. In simple terms, it is somewhat easier for water to enter a hygroscopic material than to exit the material. The lag effect between the MC values in the adsorption and desorption curves is termed *hysteresis*.

[16] Reference the *2001 ASHRAE Fundamentals Handbook* published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, www.ashrae.org

gypsum wallboard at the unventilated space behind the bookcase. What is the relative humidity at this wallboard facer and why is black mold growing on it?

The ambient moisture content of the room (.008 pounds of water vapor per pound of dry air) certainly remains the same in all areas, even at the cold wall behind the bookcase; therefore, as revealed by the psychrometric chart, the ambient RH at the wallboard facer is increased to approximately 95%. This higher RH equates to an increased equilibrium moisture content of the paper facer and the underlying gypsum wallboard. In other words, the wallboard and facer are wetter (due to adsorption, followed by absorption) behind the bookcase than the wallboard elsewhere in the room. Such additional moisture can be sufficient to promote the growth of many common mold species, particularly if the wet substrate (e.g., the pulp paper facers of standard gypsum panels) provides an especially nutritious 'ready-to-eat' meal for some mold species.

Fortunately, after using your psychrometric chart to understand why mold is growing on the wall behind your bookcase, you also see that the condition can be remediated by: a) insulating the wall, and/or b) repositioning the bookcase or otherwise providing ventilation from the conditioned interior to this 'dead air' space. In both cases, your actions result in increased thermal energy at the air-to-wall transition and corresponding reductions in both the ambient RH and the equilibrium moisture content of the wallboard.

e. **If water molecules are so small, how do the permeable asphaltic building papers and polyolefin 'housewrap' products prevent water entry?**

All Code-compliant building papers and housewraps must provide a minimum level of vapor permeance (for moisture vapor migrating from the interior) while simultaneously resisting water penetration (in liquid form) from the exterior. Asphalt saturated building papers are manufactured to provide both an absorptive barrier to water infiltration (rated in minutes) and a buffering capacity for holding some excess moisture until drying conditions return.

The manufacturers of the various housewrap products face a different situation in which their polyolefin products have no absorptive capability and easily could be manufactured as a true vapor barrier – thus, the critical question is how best to provide a degree of vapor permeability to the material while retaining satisfactory resistance to liquid penetration.

Some housewrap manufacturers (e.g., Amowrap and Typar) address this issue with 'micro-perforations' (many tiny holes punched through the material); others (e.g., Tyvek) manufacture a tight overlapping fibrous material *"engineered to create extremely small pores which readily allow moisture vapor to evaporate but are so small that liquid water has a very difficult time penetrating."*

- (Note that Tyvek publishes data and images that indicate their product's tiny pores are even tinier than the tiny pores in their competitors' products).

- Similar materials are used by Gore-Tex and its competitors to manufacture weatherproof clothing that 'breathes' (allows exfiltration of the vapor molecules produced by our active body) while resisting infiltration of liquid water.

These materials generally work as designed because the hydrogen-bonded mass of water molecules that comprises a raindrop or other small cluster of liquid water is too large to fit through the tiny holes. The cohesive forces of liquid water are greater than the typical forces (air pressure, for example) trying to push individual pieces of the liquid body through the holes. In simple terms, the skin (surface tension) of the liquid mass is too tough to be broken by the forces attempting to push the bonded collection of molecules through the tiny holes.

Be aware, though, that these same physical properties may also serve to trap liquid water (e.g., due to leakage or condensation) that may occur behind the micro-perforated wall wrap, roof membrane or raingear material unless this liquid mass can be heated sufficiently to produce vaporization.[17]

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[17] In contrast, traditional non-perforated kraft building papers and felts have a limited capability to safely absorb the same 'trapped' water, allowing it to later escape to the building exterior.

f. Can we apply soap to housewraps, building paper & breathable clothing?

Soap is a powerful surfactant – the attractive power of the polar end of a soap molecule is sufficiently strong to sunder the surface tension of liquid water, ripping individual molecules and smaller clusters loose from the condensed mass.

Now that the liquid's skin has been broken, individual water molecules may pass through the tiny pore passages within these 'breathable' materials. This condition commonly can occur when lap siding is pressure-washed unless care is taken to prevent infiltration to the building wrap of the soapy pressurized water.
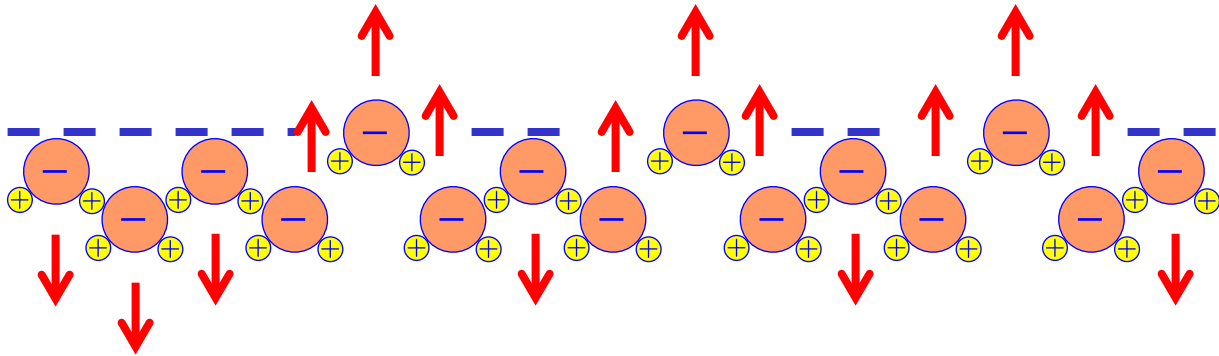
g. Why and when is a vapor retarder necessary?

A vapor retarder, often 6-mil polyethylene sheeting, may be installed to prevent unintended vapor *diffusion* – the movement of moisture vapor from areas of high concentration to low concentration.

- If the vapor retarder is installed in a complete and continuous manner, including taped and sealed joints and perimeter transitions, then the system also serves as an 'air barrier' to block moisture convection – the physical conveyance of moisture by air movement.

- Note that a taped and sealed housewrap comprising the exterior weather resistive barrier also can serve as an 'air barrier', blocking moisture convection into the wall assembly from the exterior.

Remember that the Second Law of Thermodynamics tells us that if there is an accessible route, no matter how small, *wet* always moves toward *dry* (less wet). Therefore, the vapor retarder (if required) always should be installed on the warm-in-winter side of the insulation, thus guarding against vapor diffusion into the wall from the typically more humid warm interior (or exterior, in southern climates).

- However, it also should be noted that compliance with this prescriptive guidance can be a confusing process in mixed climates where, at different periods during the year, the warm humid side of the wall instead may be found at the exterior (or interior, in southern climates).

Proper design of the vapor retarder system is made even more difficult by the roles played by other wall materials in resisting vapor movement. Dry plywood sheathing, for example, functions as a vapor retarder if the joints are installed tightly; however, if the plywood sheets becomes wetter (e.g., due to high relative humidity or building envelope leakage) then the vapor permeability of the sheathing material increases significantly.

In summary, proper design and specification of the vapor retarder system is not a simple process. In many instances, the building would be better served if no vapor retarder was installed or if the typical polyethylene sheeting were simply replaced with an interior paint with low vapor permeability.

In all cases, superior building envelope performance can be achieved by the proper design/installation of mechanical ventilation systems that can maintain relative humidity levels that are sufficiently low to eliminate any need for an interior vapor retarder. In this manner, wet exterior cladding (e.g., stucco) can dry both toward the exterior and toward the interior, thus greatly reducing the risks associated with excess moisture buildup within the wall assembly.

In short, the best approach is to simply maintain low levels of interior humidity; however, a vapor retarder often is necessary if wintertime RH commonly exceeds 40%. The higher the interior humidity levels, the tighter performance required from the vapor retarder.

h. How does water migrate into, through and out of wood?

The mechanisms for water migration within a wood product occur at the cellular level. As depicted in the Figure below, water in 'green' or freshly harvested wood is located both within the cell walls and within each cell's *lumen* (the hollow space within the cell). When wood is dried during manufacture of lumber, all liquid water in the lumen and much of the water within the cell walls is removed.
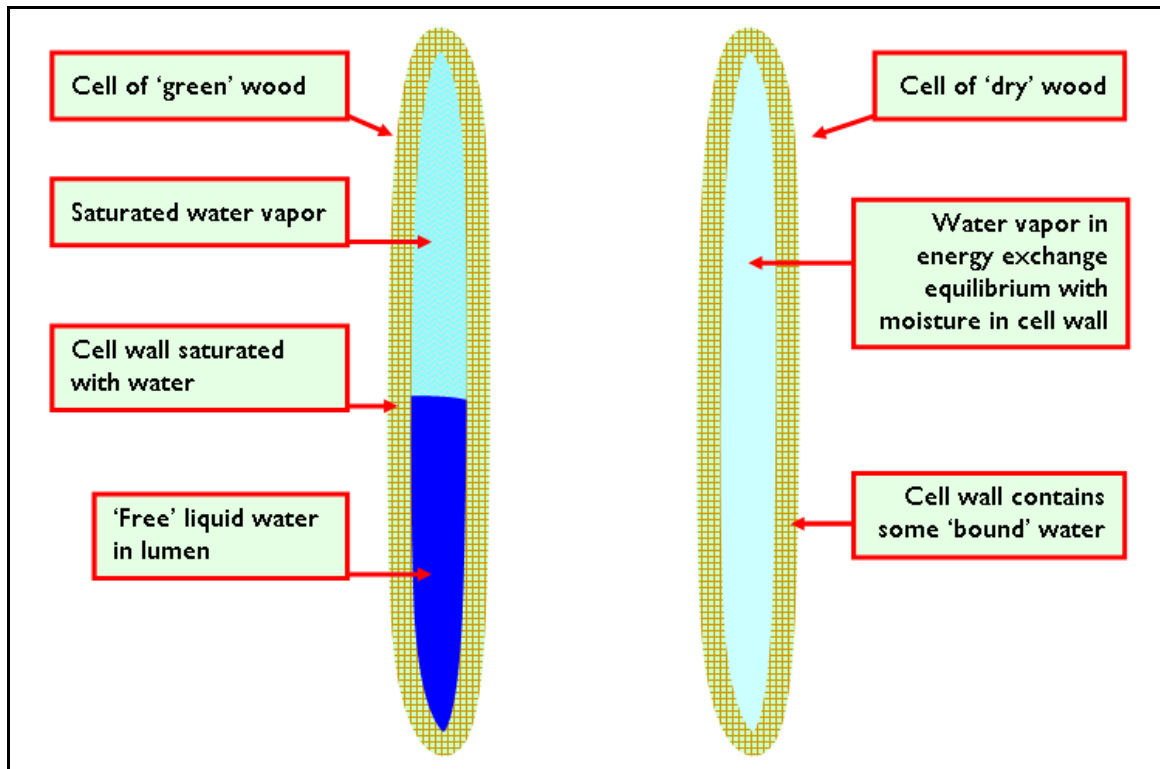

Figure 4 – A 'Green' Wood Cell Contains Liquid Moisture within the Lumen. In Contrast, Wood with a Moisture Content less than the 'Fiber Saturation Point' Contains Only Moisture Vapor within the Lumen

- Similar to the process of energy exchange equilibrium discussed above that occurs between your room's ambient environment and its hygroscopic surrounds; the lumen (like a very small room) always contains sufficient water vapor to maintain an energy balance with the liquid water in the hygroscopic cell walls.

- The point at which the cell wall is fully saturated but the lumen remains void of liquid water is termed the **fiber saturation point** ('FSP'). This transition zone varies between wood species but typically occurs at about 28% to 30% moisture content.

- *"To simplify discussion, the liquid water found in the lumen of wood is often referred to as* free water*. The water within the cell wall is called* bound water*. This is an appropriate description, since the free water is relatively easy to remove and so is the first to be lost in the drying process. Bound water is held more tightly because of surface adsorption* [due to hydrogen bonding] *within the wood structure. The lower the moisture content below FSP, the more tightly bound is the remaining water."*[18]

- (Note: wood species, such as redcedar or teak or redwood or rosewood, that are high in extractives (additional substances that may impart a unique odor or color to the wood) tend to have a lower fiber saturation point because the extractives are located at sites within the cell wall that otherwise would attract water. Compare the fiber saturation point for southern yellow pine (29%) and Sitka spruce (28%) with western redcedar (18%), teak (18%), redwood (22%) and rosewood (15%).

When 'dry' lumber comes in contact with additional moisture, water molecules become 'bound' (adsorbed) within the cell wall as they form 'hydrogen bonds' at available hydrogen sites within the cellulose, hemicellulose and lignin elements that are the primary constituents of the wood cell. Further contact with additional moisture results in hydrogen-bonding of extra layers of water molecules to the base layer of water molecules bound to the cell wall constituents.

To accommodate the additional influx of water molecules the constituents of the wood cell wall must expand (**swell**), which can cause great distress to the installer or user of the wood product who has not made allowances for such expansion. Continued contact with additional moisture leads eventually to saturation of the cell wall and then the formation of free water within the cell's lumen.

- No further swelling of the cell wall occurs after it reaches the fiber saturation point.

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[18] J.L. Bowyer, R. Shmulsky and J.G Haygreen, *Forest Products and Wood Science – An Introduction (Fourth Edition)*, Iowa State Press, Ames, Iowa. 2003

At this point, movement of water within the wood product is occurring via two primary modes: *adsorption* (hydrogen bonding, primarily at open oxygen sites within the cell wall constituents) and *absorption* (capillary conduction via the interconnected lumens of free water within the lumens).

- Capillary conduction of free water is the most efficient form of moisture movement – in other words, after the moisture content of a wood material reaches the fiber saturation point further movement of excess moisture throughout the product is accelerated.

- Movement of free water between the cell lumens occurs via small cell-wall perforations called 'pits' (which are used by the living tree to transport moisture and nutrients from cell to cell).

Due to capillary activity and pressure differentials, free water within fiber-saturated wood cells will move to those adjacent cells that can accommodate additional moisture. Over time, water from a single source (a missing deck-to-wall flashing, for example) can migrate throughout a wood product, filling every cell beyond the fiber saturation point, causing significant diminishment of the product's structural performance properties and also promoting wood decay.

Under drying conditions, the processes work in reverse. As necessary to achieve an energy exchange balance, free water moves from full lumens toward empty lumens, while moisture at the surfaces evaporates. Eventually, over an extended drying period, all of the free water will be removed from the wood and any further release of moisture will occur from within the cell walls.

- Due to the additional energies required to break hydrogen bonds during this process, for equal amounts of bound water *drying* takes longer than *wetting*.

i. How does an increased moisture content reduce the physical properties of wood?

Wood derives its strength from the tight bonding at the molecular level of long intertwined strands of *cellulose* and *hemicellulose* (comprised of various types of glucose and other simple sugars resulting from the process of photosynthesis) bound together by

lignin, a complex phenolic polymer that provides rigidity to the stranded cellular structures. These intertwined molecular strands have many open hydrogen atoms at various locations that are available for hydrogen bonding if water molecules are present.

As the small water molecules infiltrate the stranded cellular structures and form hydrogen bonds, their physical presence forces the strands apart – thus minutely diminishing the combined strength and rigidity of the intertwined strands. Finally, after all of the open hydrogen atoms have been bonded with individual water molecules, additional stacking of water molecules will occur as they piggyback atop the first layer of water molecules. These additional molecules continue to physically force the strands a bit farther apart (**swelling**) – further diminishing the strength & rigidity of the mass of intertwined strands.

- This bonding process continues until the fiber saturation point – the point at which no additional water molecules can bond within the intertwined strands of cellular mass. Any additional 'free' moisture that may form within the cell lumen does not affect the physical properties of the wood material.

The process of swelling or shrinkage thus occurs between 0% ('ovendry') moisture content and the FSP (typically 28%-30% MC). Due to the vertical orientation of the wood cell, the amount of swelling or shrinkage is minimal in the longitudinal direction of the cell but quite significant in the sideways (radial and tangential) directions.

For example, the published shrinkage values (green to ovendry) for coastal Douglas-fir are 4.8% in the radial direction and 7.6% in the tangential direction.[19]   Thus, assuming the fiber saturation point of Douglas-fir is 30% MC, a green flatsawn 12″ wide (actual) board would measure ~ 11½″ {12″x [1-(.076 x 18/30)] = 11.45″} after drying only to 12% MC.

As it was shrinking during the drying process, the Douglas-fir board would be gaining strength as the wood fibers became more tightly bound (see Figure below):

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[19] *Wood Handbook – Wood as an Engineering Material*, Forest Products Laboratory, U.S. Department of Agriculture, Madison, WI. 1999

	Modulus of Elasticity (MOE)	Modulus of Rupture (MOR)
Coastal Douglas-fir (green)	156,000 psi	7,700 psi
Coastal Douglas-fir (12% MC)	195,000 psi	12,400 psi

Figure 5 – MOE & MOR Increase Significantly During the Drying Process
◇ **Note: MOE measures resistance to <u>bending</u> (elasticity)**
MOR measures resistance to <u>breaking</u> (the load a beam can carry)

In short, simply drying the green Douglas-fir board to 12% MC increases its breaking strength by 61% and its resistance to bending by 25%.

j. How does an increased moisture content promote wood decay?

Similar to weeds spreading in your garden, decay fungi germinate on wood products from simple spores, which may come from a nearby infection source or from ground contact in the lumber storage yard or other storage or handling failures. After germination, the fungi grow long slender threads called *hyphae* (many hyphae growing together are called *mycelium*) that produce metabolites that cause biochemical breakdowns of the wood mass into simple molecules that feed the fungi. The hyphae spread within the wood via existing holes and pits and by boring new holes during the feeding process. **The presence of free water within the lumen is critical for the feeding fungi:**

- *"For enzymes and other metabolites to diffuse into the cell walls and for the by-products to enter the hyphae, some water must be present. Water also is needed for the breakdown process catalyzed by enzymes."* [20]

The biochemical feeding process requires free water both as a means of transporting the destructive metabolites to (and into) the wood cell and as a means of transporting the food (the simple molecules produced by breaking down the cellulose, hemicellulose & lignin) back to the hyphae of the hungry growing fungi.

- *"Therefore, one of the best ways of preventing wood decay is to ensure that not enough water is present to permit the fungi to do their job. Generally, very little danger of decay exists if wood is below the fiber saturation point."* (ibid.)

[20] J.L. Bowyer, R. Shmulsky and J.G Haygreen, *Forest Products and Wood Science – An Introduction (Fourth Edition)*, Iowa State Press, Ames, Iowa. 2003

In short, without free water in the cell lumens (i.e., at moisture content levels above the fiber saturation point) decay fungi cannot proliferate.

- If the moisture content of the wood is somewhat below the FSP (in the range of 22%-28% MC) then some level of mold growth may occur because some of the 'bound' water molecules of the almost saturated wood will not have very tight bonds and therefore can be pried free by the expanding hyphae.

- Below 20% MC, the hydrogen bonds of the bound moisture are so tight that no moisture is available to promote fungal germination or growth.

Like your garden plants, fungi need *oxygen*, *food*, *water* & *favorable temperature* conditions to grow. The simplest of these factors to control is water:

- *"To avoid 90 percent of the problems associated with wood products, three rules should be followed: 1) keep wood dry, 2) don't let wood get wet, and 3) maintain a separation between wood and water (Suddarth 2001)."* (ibid.)

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In conclusion, it is important to recognize that, *"For a moisture-related problem to occur, it is necessary for at least four conditions to be satisfied:*

*1. A moisture **source** must be available.*

*2. There must be a **route** or means for the moisture to travel.*

*3. There must be some **driving force** to cause moisture movement.*

*4. The material(s) involved must be **susceptible** to moisture damage."*[21]

As discussed in this brief, the **driving forces** that cause moisture movement (e.g., gravity or air and vapor pressure differentials or other manifestations of the Second Law of Thermodynamics) are fundamental properties of nature; therefore, preventing water infiltration and resulting damage at the typical building project requires close attention during the design/construction processes to potential moisture **sources** and **routes**.

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[21] J.F. Straube, *Moisture in Buildings*, <u>ASHRAE Journal</u> (January 2002), <u>www.ashrae.org</u>

Also note that removal of any moisture trapped <u>within</u> the wall assembly (e.g., due to leakage at a failed flashing) also requires a route for the moisture to exfiltrate the wall and a **driving force** to push the moisture along this route. Thus, in many instances, severe deterioration will result from relatively incidental amounts of water entry simply because there is no **escape route** and/or no **driving force** to facilitate removal of the trapped moisture.

For example, again consider an unvented wall assembly with moisture (in liquid form) trapped behind a polyolefin housewrap, which is designed to resist *liquid* water penetration but to allow *vapor* movement through the micro-perforated material. Clearly, unless this trapped liquid is somehow transformed into vapor, the housewrap material (unlike traditional asphalt-saturated building paper, which has a limited capacity to absorb liquid moisture) blocks the preferred escape route to the exterior (assuming a favorable direction of the vapor drive within the wall).

All forensic investigations of water damage should include evaluations of the source(s), route(s) and driving force(s) of the problematic moisture.

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RECOMMENDED READING LIST:
- ✓ Any available publication by Dr. John F. Straube: (www.buildingscience.com)
- ✓ Any available publication by Dr. Joseph Lstiburek: (www.buildingscience.com)
- ✓ J.L. Bowyer, R. Shmulsky and J.G Haygreen, *Forest Products and Wood Science – An Introduction* (Fourth Edition), Iowa State Press, Ames, Iowa. 2003
- ✓ *Wood Handbook – Wood as an Engineering Material*, Forest Products Laboratory, U.S. Department of Agriculture, Madison, WI. 1999
- ✓ A.N. Karagiozis, *Building Enclosure Hygrothermal Performance Study – Phase 1*, Oak Ridge National Laboratory, ORNL/TM-2002-89
- ✓ Donald P. Gatley, *Understanding Psychrometrics* (Second Edition) ASHRAE, Inc., Atlanta, GA 2005
- ✓ W.A. Rose, *Water in Buildings – An Architect's Guide to Moisture and Mold*, John Wiley & Sons, Inc., 2005

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Author's note: I crafted the first iterations of this 'Water 101' brief in the early-2000's in Seattle while training as a building envelope consultant under Colin Murphy's tutelage at Exterior Research & Design, LLC (now known as Trinity|ERD – www.TrinityERD.com). Colin's invaluable guidance and assistance remain much appreciated.

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