The central role of wood biology in understanding the durability of wood -- coating interactions

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Abstract:

To design effectively for durability, one must actively and honestly assess the material properties and limitations of each of the components in the design system; wood or wood composite, and the coating. Inasmuch as wood coatings are manufactured to specified tolerances from known materials, we have control of that component of the system. Compared to manmade substrates such as steel, with wood we have virtually no control over the material properties of the substrate in coated wood systems. Despite this lack of control, with sufficient understanding of wood and the wood – coating interface, we can design coatings to meet specific criteria. Our understanding of wood and the specific nature of wood – coating interfaces is thus what limits our ability to design coatings in a highly targeted fashion. To begin to identify the aspects of wood structure relevant to coating durability, wood must be understood as a material of biological origin.

Wood is a biologically renewable material, and there is no property of wood – physical, chemical, mechanical, anatomical, or otherwise – that does not derive directly from the fact that a tree made wood to suit the tree's purposes. This paper outlines the general anatomy and chemistry of wood in a biological context, and demonstrates ways in which this information is relevant to understanding wood coatings. In particular, a discussion of wood structure in the context of microbial attack is presented to draw attention to the critical but oft-overlooked role of biological attack in experimental systems with wood or wood composite materials as a substrate. By understanding the general structure and origin of wood in a broader context, we can begin to formulate a framework to characterize wood – coating interactions and, ultimately, design specific coating systems that mitigate the weaknesses of wood as a material and capitalize on its strengths.

Introduction:

Wood, whether a softwood such as pine, spruce, or fir **(Figure 1 A,C),** or a hardwood like oak, maple, or birch **(Figure 1 B,D),** is a material of complicated but predictable structure and function, all the properties of which are derived from the way in which the tree made it, to suit its arboreal needs. Understanding the structure, composition, and function of wood from a biological point of view allows us to understand wood as a material for human purposes. Specifically, understanding the relationship between the biological nature and origin of wood and its material properties and weaknesses permits us to target specific remedies for wood's shortcomings and make full use of its strengths.

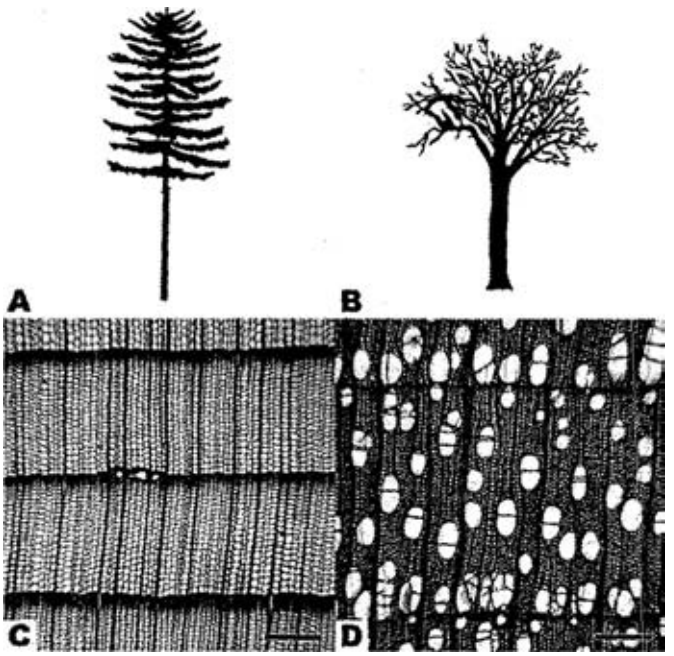

Figure 1. A,B Silhouettes of trees. A. A generic softwood. B. A generic hardwood. C,D. Cross sections of wood. C. Spruce, a softwood. D. Birch, a hardwood. Scale bars = 300µm.

Wood structure

As a material of biological origin, wood derives all its properties from the: properties of its component parts, the cells. To give a sense of perspective, a one foot long 2x4 of Douglas-fir has on the order of 400 million cells. The many thousands of different woods around the world derive their properties from differences in the size, shape, type, relative proportion, chemical components, and chemical contents of their cells. It is therefore imperative to establish a basic understanding of the structure and chemistry of a generic, model cell, and then to discuss various types of cells in actual woods, as well as their functions in the tree. By examining the function of the cell in the living tree we can better understand the nature of the cell in its native context and thus make better inferences about its role in wood. Informed in this way, we can more reasonably expect to understand the durability of coatings applied to wood.

Cells

When a generic cell in wood comes into being, it is composed of two domains, a cell wall and a protoplast. The cell wall is a tough material that encloses, protects, and is exuded and synthesized by the soft and rather squishy protoplast within. As a young cell, the protoplast produces what is known as a primary cell wall. As this generic cells develops toward functional maturity, the cell wall is greatly thickened by the addition of a secondary cell wall, and in most cells in most woods, the protoplast subsequently commits programmed cellular suicide, leaving only an empty, open space - the lumen (pl. lumina or lumens) - behind (Figure 2 B, C). In some cells, however, the protoplast remains intact, carrying on its biological role in the tree. The former class of cells is dead at functional maturity, and the latter is alive at functional maturity. This distinction is not wholly academic, as will be discussed later.

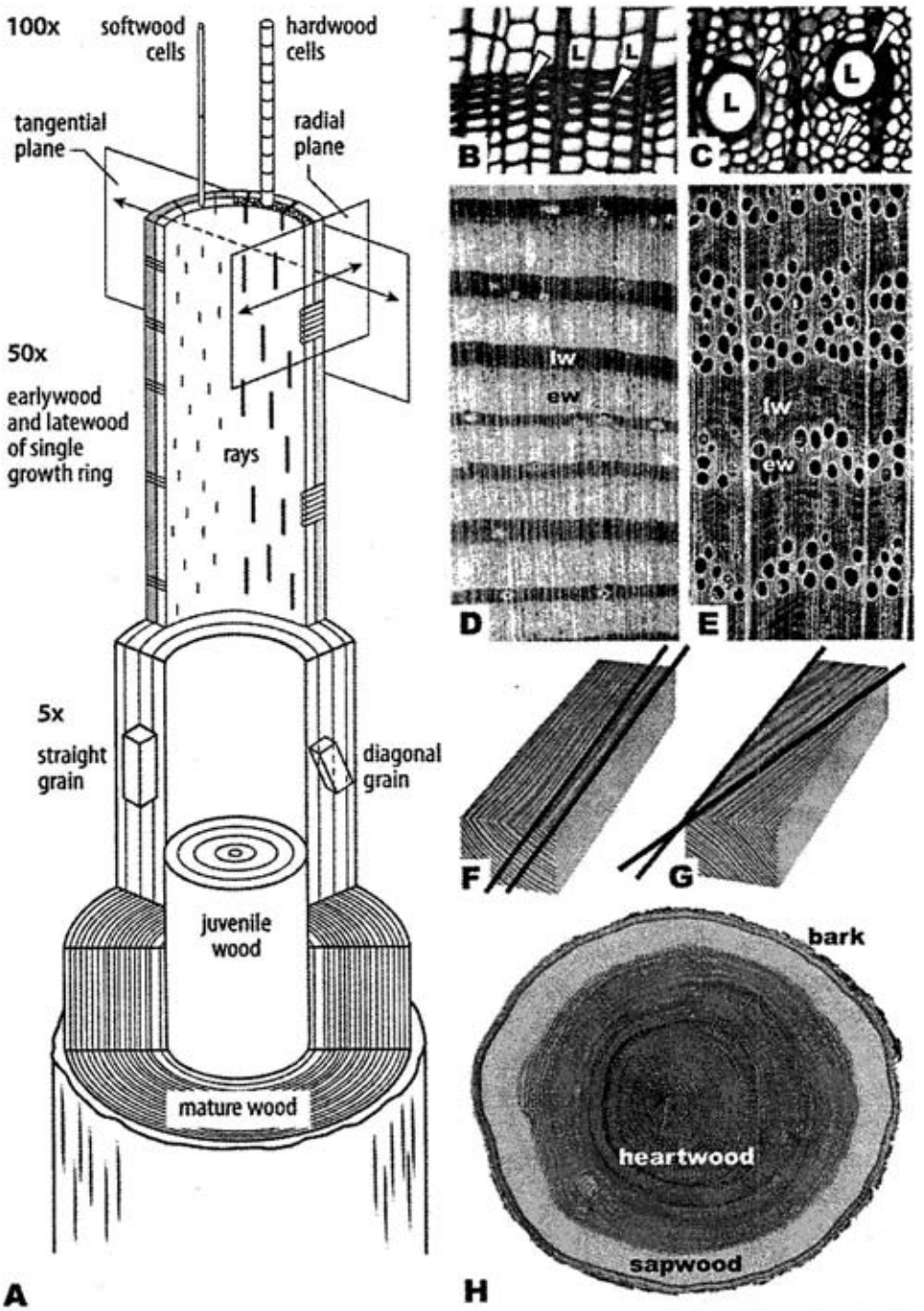

Figure 2. A. Schematic diagram of a tree at various scales of magnification, indicated by approximate times magnification to the left. B,C. Cell walls (arrowheads) and lumina (L) in a softwood, B, and a hardwood, C. D,E. Low magnification view of growth rings in a softwood, D, and a hardwood, E. ew denotes earlywood, lw denotes latewood. F,G. Demonstrations of the angle of the grain relative to the long edge of a board; F is straight-grain and G is diagonal grain. H. A labeled transverse section of an oak trunk.

Cell Walls

The primary feature of the individual cells of wood that sets it apart from other plant tissue or organs (leaves, for example) is that virtually all the cells in wood possess a thick secondary wall.

The secondary wall is synthesized by the protoplast in three layers, S1, S2 and S3, from the outside to the inside of the cell. With the addition of each layer, the protoplast in squeezed into a progressively smaller volume. That is to say, cell walls thicken by growling inward. Between any two cells is a semi-amorphous zone known as the compound middle lamella, which is formed of parts of each cell's primary cell wall. Inasmuch as it occurs between cells, the compound middle lamella is the area responsible for holding the cells together. Additional details on the fine structure of cell walls is not necessary for our purposes, but a few comments on the chemical composition of the cell wall are critical to our understanding of wood as a substrate for coatings, since the coating must interact at a chemical level with wood.

There are two main chemical fractions in the cell walls of wood, one of which is divided into two subcategories. The structure and arrangement of these chemicals within the cell wall determine their properties. Most discussions of the chemical components of cell walls discuss the properties of each component in isolation. While this is a convenient didactic method that maintains clarity and facilitates recollection, it largely misses the point of the beauty of the cell wall; each component is chemically distinct, and each component does have its own material properties, but it is the synergistic cooperation among the components that gives rise to the properties of the cell wall itself.

The most distinctive, and in many ways the linch-pin, component of the cell wall in cells in wood is lignin. Some authors will refer to lignin as the glue that holds wood together and explain that it is a polyphenolic, chemically complex polymer formed by free radical polymerization. Other authors will refer to lignin as the matrix substance in which the other components are embedded. Still other authors will describe lignin as a relatively hydrophobic encrusting substance that occurs on the surface of the other components, protecting them from enzymatic attack. Lignin is described by some as the rigidifying component in the cell wall, a stiff but brittle compound. All of these descriptions are at least in part correct, as far as they go, but a fuller understanding must wait until the other components are discussed, for only in concert with the other components is the most meaningful interpretation gleaned.

The other main chemical component of the cell wall is holocellulose, which is the sum of the cellulose and hemicellulose fractions. Both cellulose and hemicellulose are polysaccharides, cellulose being a straight polymer, many thousands of units long, and hemicelluloses being shorter, branched molecules usually of only a few hundred units. They each have affinity for hydrogen bonding to themselves and each other to form super-order agglomerations of indeterminate size. As macromolecules, both have a high affinity for water (hygroscopicity) and are formed by the cell via normal cellular enzymatic processes, thus leaving them relatively susceptible to the normal cellular degradative processes of harmful biologic agents.

The simple fact of the matter is that in conceptually reducing cell walls to their component parts, the coordinated whole is lost by atomization. In wood, a cell wall without lignin would collapse under its own weight and unfavorable aspect ratio (more on this topic of cell shape below). A cell wall without cellulose would bear little weight other than its own without sudden failure, and a cell wall without the hemicelluloses would likely not tie together the material properties of the cellulose and lignin into a functional unit. In this regard, a useful analogy for the cell wall and it components is the balloon-kite string-epoxy model.

A Model for the Cell Wall

The model is as follows: the inflated balloon (of the type used by clowns to twist into animals) is the protoplast of the cell. If you continue to inflate a balloon with no regard for its capacity, it will eventually rupture. The same is true of plant cells taking up water, so all plant cells have at least a primary cell wall to resist these forces. Tissues with primary cell walls rely on the pressure of the protoplast to keep the tissue rigid; wilted lettuce is an example of a loss of this pressure. To model this, imagine a balloon at full but not overfull inflation, wrapped snugly on all sides with kite string that was moistened and then allowed to dry. If the string covers all the balloon correctly, you will be unable to force more air into the balloon, because the string will provide the strength to resist the force of the air. Now, imagine that you must form a self-supporting structure of hundreds of such balloon-sting assemblages. You can imagine that so long as the balloons are inflated and interconnected, the structure could retain strength. Begin to pop those balloons, however, and the strings will collapse. For the purposes of our model, the strings represent the cellulose and hemicelluloses of the cell wall (and indeed kite string, when cotton, is roughly 98% cellulose); they have great tensile strength to resist the forces of the balloons, but without that internal pressure cannot even support themselves, let alone anything else, much like a bicycle tire with a burst inner tube. If we put the balloon-string structure under tension, it would unravel to great lengths, but once unraveled would be strong.

Now, imagine the same inflated balloon. Instead of wrapping the balloon with string, we coat it with a thin layer of epoxy that we permit to cure. Compared to an uncoated balloon, the balloon-epoxy assemblage can withstand higher pressures, and one could build a self-supporting structure. If one popped all the balloons, the structure would still stand under its own weight, but if we subject it to any significant shock, it will break and crumble. Put under tension, this structure would fail suddenly, and under only a small load. In this model, the epoxy is lignin, and a lignin-only cell wall would not be viable.

Now, imagine a case in which we combine all the components; as we wrap the balloon with kite string, we apply epoxy to the string and balloon and allow it to penetrate the string and cure. The resulting coating on the balloon will resist tremendous pressure from the balloon, but what is more, even when the balloon is gone (not just popped, but removed entirely) the structure left behind will be self-supporting. If loaded the string will impart some flexibility to soften the brittleness of the epoxy, but the epoxy will add rigidity to the string, thus preventing crumbling or collapse. If placed under tension, the epoxy will help hold the string in place and prevent unraveling, and the string will provide enormous tensile strength, preventing the breakage of the epoxy. Such a string-epoxy structure, a model cell wall, is strongest in tension, compression, and in resisting circular forces within the cell, such as internal pressure (the balloon) or the converse, a vacuum or negative pressure. The model cell is weakest in bending perpendicular to the long axis of the cell, but if many of these model pieces are then assembled with epoxy between them, the resulting structure takes on increasing strength perpendicular to the long axis of the cells.

Knowing that wood is made of cells, each of which has a cell wall with characteristic chemical composition, and a lumen where once a protoplast dwelt or where remnants of which still remain, is not enough to understand wood as a substrate for coatings. Individual types of cells must be enumerated in the context of the three main functions of wood in a living tree;

mechanical support, conduction of sap, and synthesis and storage of biochemicals. Once the cell types and their functions are explained, wood as a coatings substrate can be more clearly understood.

Cell Types

For the purposes of this paper, we are going to break the cell types into four basic classes: parenchyma cells, tracheids, fibers, and vessel elements. The first two cell types are found in softwoods, and the first, third and fourth are those that comprise the cells of hardwoods. We will discuss each type in the context of the three prime functions of wood as mentioned before: conduction, mechanical support, and synthesis and storage of biochemicals **(Table 1).**

Parenchyma Cells

Parenchyma cells are characteristically brick-shaped cells (roughly 2-3 times longer than wide, **Figure 3; Figure 6B, arrows)** that are alive at functional maturity, and are either ray parenchyma or axial parenchyma cells (see axial and radial systems, below). They are the biochemical workhorses of wood, responsible for all functions that require a living cell, such as active transport of materials, defense responses after wounding, and the synthesis, exudation, and accumulation of extractives (see below). These living functions are the critical common traits among these cells. The fact that parenchyma cells are alive at functional maturity means that the protoplast is retained in the living tree, and in a piece of lumber, the remnants of the protoplast will still be in the lumen of the cell. This is most important in the context of the biological vulnerability of wood, and will be addressed later. The synthesis role in wood is always performed by parenchyma cells, and much of the storage function is performed by them as well, though the other cell types, when taken out of active service to the tree, are also used as passive storage areas.

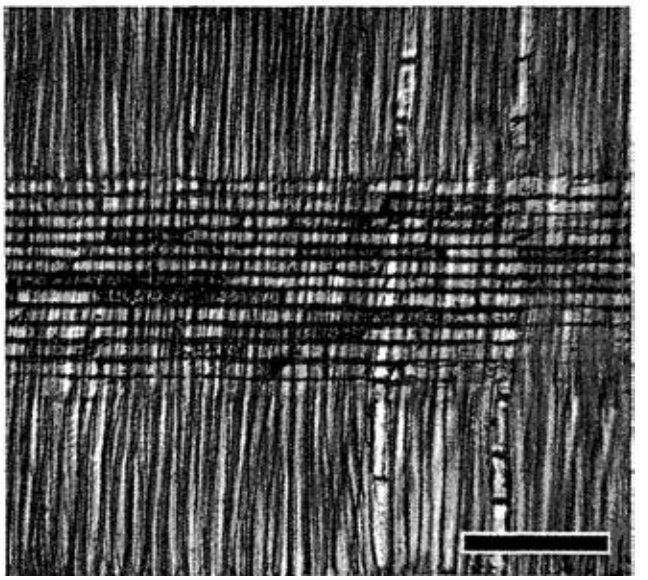

Figure 3. A microscopic view of parenchyma cells in wood; the parenchyma cells in the radial system are running left to right. There are also two stacks of parenchyma cells in the axial system in the right half of the photo. Scale bar = 200µm.

Tracheids

Tracheids are the defining cell of a softwood. Along with parenchyma cells, they are the only two cell types found in softwoods. Given that softwoods have to serve the three basic roles of wood, but have only two cells to do it, it follows that one cell type must do double-duty, and that cell type is the tracheid. Tracheids are long, thin cells, often hundreds of times longer than they are wide (often 3-7mm in length and 25-40µm in diameter), and they are specialized for both mechanical support and conduction of sap **(Figure 4).** Their great length represents a step toward conductive efficiency, and their relative narrowness and thick cell walls provide mechanical strength. As they are conductive cells, they are dead at functional maturity and thus have nothing but cell walls; their lumina must be clear of the protoplast and all remnants so that sap can flow freely from the roots to the needles. The conductive path between tracheids is mediated by pits, thin areas in the walls much like screen doors through which water can flow **(Figure 5).**

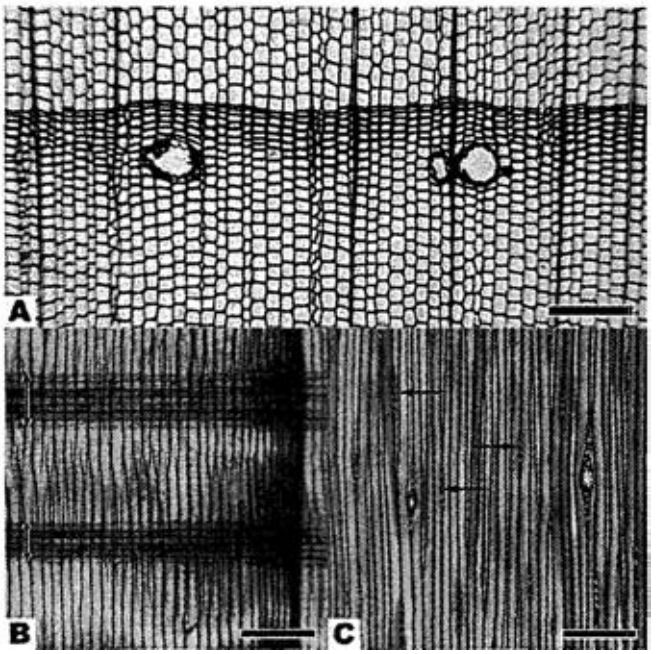

Figure 4. The microscopic structure of a typical softwood. A. Transverse section, scale bar = 150 µm. The bulk of the wood is made of tracheids, the small rectangles of various thicknesses. The three large, round structures are resin canals and their associated cells. B Radial section and C, tangential section, showing rays (arrows). The size and shape of the vertically oriented tracheids can be seen here. Scale bar = 200 µm.

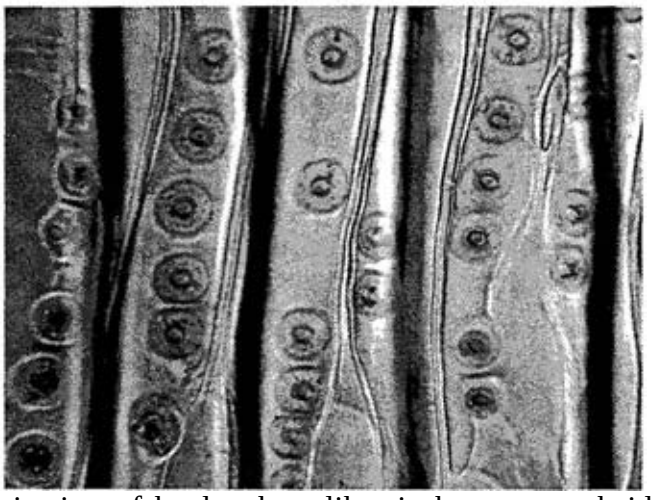

Figure 5. A microscopic view of the doughnut-like pits between tracheids through which water flows in the living tree.

Fibers

Fibers are the mechanical cells of hardwoods. They are akin to tracheids in terms of their overall shape, but are typically several times shorter (400µm -2mm), and thicker-walled **(Figure 6; Figure 7B).** From the tree's perspective, since the function of the fiber is to provide mechanical support, there is no need to maintain an active protoplast in the cell, so fibers are generally dead at functional maturity. This is an issue of convenience and resource allocation for the tree rather than a necessary condition, inasmuch as fibers are non-conductive and thus do not require an empty lumen to function.

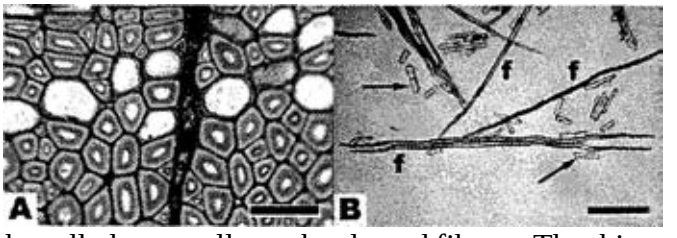

Figure 6. A. The thick-walled grey cells are hardwood fibers. The thing-walled cells with large lumina are parenchyma cells, and the black vertical line is a ray. Scale bar = 30µm. B. Chemically separated hardwood cells. Fibers are indicated by f, and parenchyma cells are denoted by arrows. Scale bar = 300µm.

Vessel Elements

Vessel elements are the defining cells of hardwoods. They are short, wide cells, in shape ranging from barrel-like to straw-like in their dimensions (roughly 50µm - 300µm in diameter, and 200µm - 1.5mm in length. **Figure 7A).** Unlike all other cells discussed, vessel elements bear openings on each end known as perforations. Perforations are large holes through which water can flow in an unrestricted way into the next cell **(Figure 7 B,C).** This feature is of critical importance to the living tree, and confers conductive efficiency superior to that in conifer wood. It is further important in the context of the biological vulnerability of wood, as each stack of connected vessel elements (known collectively as vessels) can present a route for bulk flow of coatings, carriers, or an entry route for microorganisms.

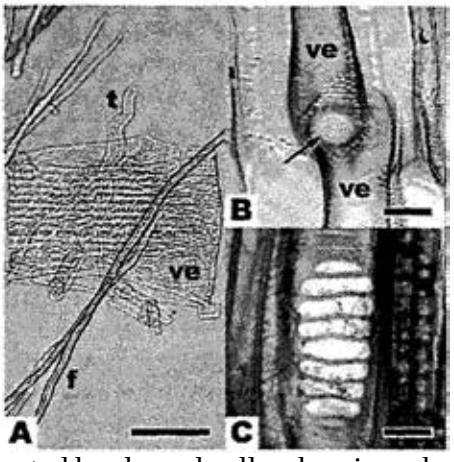

Figure 7. A. Chemically separated hardwood cells, showing a barrel-like vessel element (ve), a long, thick-walled fiber (f), and another fiber-like cell (t). Scale bar = 200µm. B. A microscopic view showing the connecting perforation (arrow) between two vessel elements (ve). Scale bar = 30µm. C. A special type of perforation plate, called a scalariform (ladder-like) plate, due to the horizontal bars crossing the opening. Scale bar = 30µm.

Table 1. Cell types, basic properties, and functions in the living tree across softwoods and hardwoods. * indicates necessarily dead at functional maturity.

	Softwoods	**Hardwoods**
Living	**Ray parenchyma** - storage and synthesis **Axial parenchyma** - storage and synthesis	
Dead (passive storage after heartwood formation)	**Tracheids*** - conduction and mechanical	**Vessel elements*** - conduction **Fibers** - mechanical

Axial and radial systems

Imagine a national interstate system that runs from the west coast to the east coast in one unbroken straight shot composed of tens of thousands of lanes, all parallel. Now, assuming you are starting in Atlanta, GA, let's say you want to travel to Seattle, WA. You have a long east-west journey to make, and a long north-south journey to make. If you are to travel on this interstate and follow typical driving conventions, you will be able to move north-south by gradual lane changes in which the attitude of your vehicle is still predominantly east-west; you will only angle your car a few degrees from the direction of the roadway to effect your lane change. Because you have over 1,500 miles of east-west distance in which to change lanes, you should be able to go from Atlanta to Seattle. If you were asked to travel from Atlanta to New York City, you could not make the trip without orienting your car well out of the acceptable range. This arrangement of lanes running east to west is the interstate traffic version of the

bundle of straws model of wood; it is a fine approximation in one direction. While for some contexts this model is appropriate, for the purposes of this paper it does not suffice.

In the models above, both the lanes of traffic and the straws represent the along-the-grain cells in wood. This is known as the axial (or longitudinal) system. The axial system, though it generally represents 90% or more of the volume of a block of wood, is only one of two systems; the other is the radial system. The radial system is not represented in the bundle of straws model, but in the interstate model, it could be represented by north-south pathways interconnected to, but independent of, the east-west lanes. In wood, the relationship is geometrically more complicated; a road system is effectively two dimensional, but wood is markedly three dimensional. The radial system is composed of structures called rays that are oriented from center of the tree out to the bark, and though in many cases not visible to the untrained naked eye, are present in great numbers in all woods. Virtually all the cells in the radial system are parenchyma cells, which means that they are alive at functional maturity, filled with protoplasts, and thus, the assertion of many textbooks notwithstanding, not well-suited to the radial bulk flow of water. They are instead the main players in the day to day biochemical housekeeping of living wood, presenting an efficient pith-to-bark path for nutrients, sugar, hormones and other molecules critical to the biology of the tree.

Growth rings

Much as the various chemical components of the cell wall work together to form an integrated structure, the same can be said for individual cells working together to form coherent structures within wood at a larger scale. A convenient scale of observation for this phenomenon is the growth ring. In the temperate world, a growth ring is the layer of cells produced as a continuous sheet of wood covering the entire tree in one growing season, typically a year. The term "annual ring" is thus just a distillation of this concept, with the built-in bias of a temperate frame of reference. Contrary to popular belief, many tropical species do indeed exhibit growth rings, though not in response to winter, per se, but more commonly in response to seasonal changes in precipitation (Worbes 1995, Worbes 1999, Callado et al. 2001). To circumvent this issue of defining a growth ring based on seasonality, here we will look at it as physiological entity formed by the tree; a growth ring is the cohort all cells produced in a given interval that share greater connectedness and developmental relationship with each other than with members of another cohort. In other words, a growth ring is a single-dose work-unit of wood in a tree **(Figure 2A, 50x portion).**

Growth rings can be broadly categorized on the basis of their disposition of cells across the width of the ring; they are broken into rings with no change across the ring **(Figure 8A,D),** rings with steady or gradual change across the ring **(Figure 8B,E),** and rings with sudden or dramatic change across the ring **(Figure 8D,F).** In the case of rings with sudden change, it can be easily observed that there are two domains within the ring. The two domains are known as the earlywood (the first-formed wood of the ring that is closer to the center of tree) and the latewood (the later-formed wood of the ring that is closer to the bark of the tree) **(Figure 2D,E).** In the case of rings where there is only gradual or no change across the ring, delimiting the earlywood and latewood is a less clear proposition. In general, however, it is safe to assign the first 25% of a growth ring to the earlywood, and the last 25% to the latewood, in cases where a clear

distinction cannot be made. The remaining 50% of the ring is not easily assigned to one class of the other without highly detailed microscopic observation and a clear set of rules to define the classes anatomically.

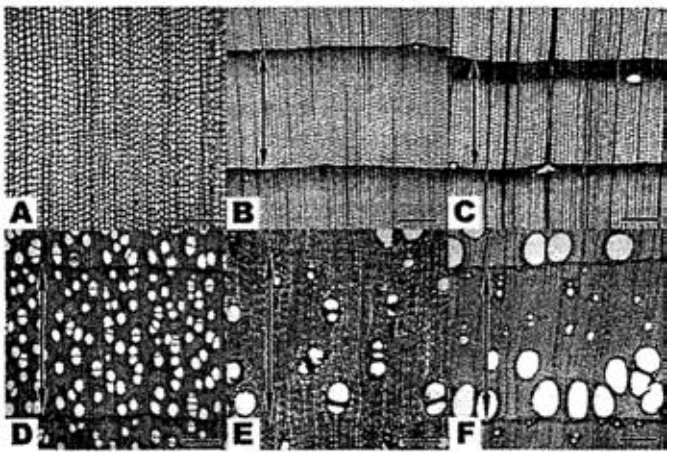

Figure 8. Transverse sections of woods showing types of growth rings. Arrows delimit single growth rings, when present. A–CSoftwoods: A. No transition within the growth ring (growth ring absent). B. Gradual transition from earlywood to latewood. C. Abrupt transition from earlywood to latewood. D–FHardwoods: D. Diffuse porous wood (no transition). E. Semi-diffuse porous wood (gradual transition). F. Ring porous wood (abrupt transition). Scale bars = 300 µm.

Inasmuch as most of the woods that are typically coated are softwoods (e.g. decking, siding, windows, fascia, fencing) a few words in this section about the cell-to-cell connections in softwoods are in order. The quickest and easiest path for the movement of materials in wood is always along the grain, as that is the overwhelming orientation of the cells in wood, and in softwoods that is accomplished mostly by cell to cell movement through pits in the radial walls of the tracheids (see below for descriptions of radial and tangential walls). Lateral movement in wood is generally easiest within a growth ring, and in most woods is most facile in the tangential direction within the wood.

Zones in the tree

When discussing the general layout of the wood in a tree, there is a basic distinction that is often clear to the naked eye, that of heartwood and sapwood **(Figure 2H).** Heartwood is the inner wood of the tree, often darker in color than the sapwood, no longer functional in the transport of sap within the tree, and it bears no living parenchyma cells. Sapwood is the strip of wood immediately under the bark actively involved in the conduction of sap. Sapwood lacks appreciable pigmentation in most cases, and its parenchyma cells are active and alive. Historically, botanists considered heartwood a dumping ground for cellular by products, many of which were pigmented, and thus the accumulation of the compounds that lend the color to heartwood, referred to collectively as extractives, was considered an accidental or incidental process in trees. A more contemporary view now recognizes heartwood formation as a normal and intentional part of the aging process in the tree. Heartwood represents the oldest wood in the tree, and may be highly pigmented or without any clear pigment at all. It may occupy most of the wood in the trunk, or it may be a narrow core at the center of the tree. It may have a neat

boundary with the sapwood, or it may be unclear where one ends and the other begins. In some species, such as aspen, there is no compelling difference between heartwood and sapwood for most applications.

For other species, such as western redcedar, the distinction is critical, as the resistance to decay fungi, so prized in western redcedar, is found only in the heartwood, and that property is in fact imparted by the accumulated extractives. Apart from position within the trunk of the tree, the main differences between heartwood and sapwood have to do with the accumulation and storage of extractives (Hillis 1996). That is to say, there are no consistent or compelling structural or anatomical differences between heartwood and sapwood. This is an important fact, as it helps to separate and clarify a second way of looking at the trunk of the tree and dividing into two domains.

This second way of viewing the trunk of the tree is to divide it into two domains, the differences between which can quite extreme, but which cannot be differentiated by the naked eye with any certainty. This is the division between juvenile and mature wood **(Figure 2A, lower section).** In short, juvenile wood is the earliest growth rings of the tree, and it has different cellular anatomy, cell wall chemistry, and gross wood properties from later-formed mature wood. There is no simple formula to determine the proportion of juvenile wood in a stem, and there is generally no clear cutoff between juvenile wood properties and mature wood properties within any one tree. In plantations of Southern Pines in the US, it is not uncommon for the first 5 to 15 or more rings to exhibit juvenile wood characteristics (Larson et al. 2001). Such characteristics include reduced stiffness and extreme longitudinal shrinkage. Juvenile wood is most studied in softwoods, and may be less of a problem in hardwood lumber. The specific functions of juvenile wood in the living tree are not well understood. A convenient way to remember the comparative instability of juvenile wood is to make a connection with the idea of a teenage human; this is particularly effective if you currently have, or have had, a child of that age.

Planes of Section

I have reserved the discussion of the three planes of section in wood for this section of the paper, despite the fact that for an anatomist, it belongs back in the section on cells. For our purposes, the idea of the geometry and disposition of cells and features in wood at the microscopic level is not relevant, and a macrosopic understanding of the material is more appropriate. Therefore, we will explore the three planes of section, or three frames of reference, for wood, in the context of growth rings.

If you cut down a tree with a clean cut that is parallel to the ground and perpendicular to the trunk, you have prepared the first of the three planes of section in wood, the transverse plane, or cross section. When seen in cross section the growth rings run in a circle around the circumference of the tree. A quick review of terminology from rudimentary geometry along with a review of the axial and radial systems will help to establish the basic directions within wood. First, to describe something that runs along the grain, the word axial is used. To discuss directions across the grain, we make reference to basic geometry; if the movement is circular around the stem, parallel to the growth rings, it is tangential movement. If the movement is from the center of the tree out to the edge, it is radial movement. These derive from the definition of a radius (a straight line from the center of a circle out to the edge) and a tangent line (a line that

touches the edge of a circle at a single point only, and is at that point parallel to the edge of the circle and exactly perpendicular to the radius that strikes that point). This nomenclature is particularly apt, since the rays of the radial system do indeed run across the grain perpendicular to the growth rings. By extending the tangent line or a radius axially into a sheet or plane, we then define the tangential and radial planes, respectively **(Figure 2A, 100x section).** When referring either to the radial wall of a cell, or the radial face of a board, it would be the wall or face that is parallel to a radius of the circle (trunk) from which the piece of wood was cut.

This is important to the interaction between wood and coatings because wood changes dimension with changes in moisture content differentially in the radial, tangential, and axial directions. There is a basic assumption in this paper and in many others, that a given board will be straight grained and not diagonal grained when it is cut from the tree **(Figure 2A, 5x section, F, G).** This is a separate issue from the issues of grain angle discussed in more details in Williams 2007.

Wood composites

Inasmuch as wood itself is a composite at the chemical and cellular level, many of the issues and concerns for whole wood are similar for wood composites. The type of composite and the degree to which the wood components are comminuted are central to the types of problems to be found in finishing such products, as those aspects will affect how much resin or binder is used, the orientation of the individual wood particles, their interconnectedness in the composite, and the exposed chemistries for bonding with the coating. In some cases, composite products take coatings more readily and perform better than solid wood. For example, both high-grade plywood and engineered flooring products can, when made correctly, move less with changes in moisture content than solid wood of the same species, and therefore exhibit performance superior to the parent material, and thus require little in the way of special preparation, Composites with increasing proportions of plastic, binder, waxes, or other non-wood components can require special preparations for effective coating.

Nature of the wood-coating interface

With the basic structure of wood now familiar, the exploration of the wood-coating interface is comparatively simple, as there is only perhaps a 1mm layer of wood on the surface of a board that is engaged in any kind of interaction with the coating; all the wood subtending that 1mm layer is relevant only in larger-scale ways that are secondary to the actual wood-coating interface itself. That is not to say that the rest of the board is unimportant; indeed I will argue just the opposite. Rather, a failure in that 1mm surface layer will cause more or less immedate failure of a coating, whereas features deeper in the board will play roles in the long term success or failure of the coating. It is important to note that there is great similarity between wood-coating and wood-adhesive interactions, and that the concerns for one are more or less the same for the other, at least in the context of the interaction with and adhesion to the wood. The details of the wood surface is the subject of Williams 2007.

One important issue is the exposure of the grain and the types of cells that are on the surface to be coated. If one is painting the end-grain of a hardwood, it is reasonable to expect that the wood will take up a comparatively large amount of paint due to capillary action and bulk flow of

the paint into the vessels. Similarly, if one is painting the tangential face of a board, one might see greater penetration, again by bulk flow, of the paint into the earlywood portions of the growth ring. It is not uncommon to see reports on film thickness, evenness of coverage, and other issues that pertain to the finished coating when discussing wood coatings, without ever taking special note of the wood side of the equation. For example, it is fairly common to have better adhesion of paint on the earlywood of a softwood than the latewood, even when painting the bark side of a flat-grained piece of wood (for more on this see Williams 2007). To which property of earlywood should this be attributed? Lower density? Larger-lumined cells? Crushing (or lack thereof) during processing? Any combination of these may be part of the answer, but it is likely not simply one of these. There are numerous differences in wall thickness, number and size of pits, and other anatomical features that occur at the earlywood vs. latewood scale, and are also at a scale appropriate to affect coating adhesion. The larger lumina and greater degree of pitting in earlywood tends to result in greater penetration of the paint into the depth of the wood, by only perhaps 50µm -100µm or so, but that is 2-4 rows of cells. Surely there is no particular fundamental value in terms of pure adhesion to have a tracheid three layers beneath the surface filled with paint; the tiny threads of mechanically interlocked paint, if present at all, would provide negligible strength. If, however, the penetration of the paint results in a surface or an interface region that, by virtue of the presence of the paint, moves less in response to changes in environmental moisture, then additional penetration would damp (pun intended) the magnitude of dimensional changes in response to a given shift in environmental moisture. We at the Forest Products Laboratory (FPL) are in the initial phases of planning studies to examine such fine-scale anatomical effects on coatings and adhesives durability.

In the above discussion of the effect of anatomy on coating adhesion, some reference was made to structures and anatomical features that were made by the tree for the tree's purposes. This preceding discussion was a brief foray into the realm of anatomy and coatings interactions. Such interactions are mostly concerned with, at most, the surface 1mm of wood as mentioned before. The underlying wood beneath this veneer of interaction is only really relevant to the extent that it either moves or does not move, provides or does not provide for the growth of microorganisms, or does or does not store excess moisture. And indeed, it is in the context of the bulk of the wood as a vector for other agents that the rest of this paper will deal.

The Role of Biological Attack in Experimental Systems

An unfortunate truth of studies pertaining to the outdoor performance of wood coatings and wood adhesives is that compelling scientific design and statistical rigor are the exception rather than the rule. Much as was mentioned in the section on cell wall chemistry, other fields of wood science (including anatomy) are often almost xenophobically provincial in their purview, and as a result fail to apply the lessons learned in other fields to their own work. Such is certainly the case in outdoor exposure tests of wood finishes and wood adhesives. Studies regularly use coatings that were manufactured to a specificity or tolerance many times greater than the uniformity of the substrate on which they will be tested, with no consideration of the potentially dramatic effects of variability in the wood substrate on the results and interpretations of the study. Too many studies were carried out with no reference to or confirmation of: actual species of wood used; cut of boards used; uniformity of surfacing methods; presence or absence of heartwood; confirmation and standardization of moisture content at time of coating; method used

to bring experimental wood to initial moisture content (e.g. kiln dried, air died, etc); similarity of developmental age between boards (i.e. rings per inch, etc); presence ofjuvenile wood; pith or bark face in testing; and others.

Most of these flaws in experimental design could be dealt with statistically if the number of samples were large, but it is uncommon to have a sample size much larger than three to five specimens per treatment combination. Such a small number of specimens is only appropriate if all other components of the experimental system are carefully controlled. Controlling the wood substrate for these and other parameters requires some expertise in wood technology on the part of the experimental designer, and both personal and institutional commitments to find appropriate wood for testing. Once one goes to great lengths to have precisely controlled conditions, one has reduced the study to what may amount to an academically beautiful thing, but relevance to the real world application of the coating as a product for sale is generally lost. That is to say, scientific rigor and experimental robustness - applicability of the results to the real world - are often mutually exclusive, though they needn't necessarily be so. The uncomfortable truth of the matter is that this sort of testing, if it is to be done with scientific rigor, is expensive, time-consuming, and best done by interdisciplinary teams who will commit to the labor of a well-designed study.

The concerns enumerated above are commonly overlooked, but even more strikingly overlooked has been the role of biological attack on the wood substrate in outdoor exposure tests. In both the coatings and adhesives fields, there has been a once-explicit and now tacit assumption that specimens applied to a test fence in the correct configuration would not experience any appreciable biological attack, and instead would be affected only by physical forces (UV exposure, water exposure, etc). This assumption was based on visual inspection of specimens after various exposure durations. Unfortunately, only the most severe wood decay is obvious to the naked eye, and massive, systemic damage can be done to specimens with no outward signs of decay or obvious change in properties.

Preamble to the Five Phase Model of Wood Colonization and Degradation

To discuss the biological degradation of wood in this context we will restrict ourselves to fungi. For our purposes, therefore, there are two basic groups of fungi, the stain fungi and the decay fungi. We will look at them in terms of their lifestyle in wood, their nutritional needs, and the damage they do. We will organize these and other aspects of their biology in a framework I have developed for the colonization and early decay of wood. It is in this section, finally, that the trouble we have taken to learn wood structure will bear fruit.

I wish to state clearly that this organizational scheme for colonization is at this point a hypothetical framework, as yet untested by experimental work. It is something that I have compiled over twelve years based on the microscopic observation of hundreds of test specimens from ASTM soil bottles, thousands of specimens from my wood identification work, and many other specimens that have, for whatever reason, experienced varying degrees of decay hazard exposure. Until my hypotheses are tested and supported or refuted, this must be considered a conceptual framework rather than a rigorous model, and one in which the various phases are not altogether discrete in all cases, but rather represent general phases in the time course of colonization.

Basic Fungal Biology and Wood as a Nutrient Source

All living things ultimately experience a situation wherein their growth is threatened by a limiting requirement; oxygen, light, water, etc. For fungi in wood, that limiting thing is often water. Dry wood will not rot, nor permit the growth of decay fungi. As soon as wood is wet enough, however, the limit of moisture is lifted. Assuming the wood does not become too wet (which restricts oxygen diffusion, among other things) and is at a reasonable temperature, the main limiting factor that controls fungal growth in wood is wood's very low nitrogen content. Wood, by dry weight, is typically on the order of 0.1% to 0.3% nitrogen. Nitrogen is a critical element for all forms of life, but fungi are particularly nitrogen-demanding, as they build their thread-like cells (called hyphae - sing. hypha) in part from a polymer that has nitrogen as a component (Alexopoulos et al. 1996). Therefore, if a fungus is to grow without bound within wood as a substrate, it would ideally secure the maximum amount of nitrogen with the minimum possible effort. If nitrogen in wood were evenly distributed, a random attack of wood would be appropriate. The location of nitrogen in wood, much like wood itself, is not random, however. It is predictable and regular in both heartwood and sapwood, juvenile wood and mature wood, earlywood and latewood, softwood and hardwood.

Specifically it is found in the parenchyma cells; those cells that were alive at functional maturity in the tree and thus retained their protoplasts. Within each protoplast were many proteins, free amino acids, a cell nucleus rich with nitrogen from DNA, and many other cellular organelles, all of which are comparatively nitrogen rich. Recall that all woods have rays, and virtually all the cells of all rays are parenchyma cells, and further that rays always run in a pith-to-bark direction in the wood. This means that a reliable (in some woods, the only reliable) source of nitrogen, a limiting nutrient for fungal growth, is always found in the same place in any wood, topological1 speaking; in the radial system. This suggests that the fungi would do well to find and colonize the rays as soon as possible. In general, this cannot be the first step, however, as the fungi first must enter into the volume of wood. Therefore, in the quest to secure nitrogen, the first step is the conquest of continuous open spaces.

Phase I: Continuous Space Conquest

Continuous open spaces are those structures in wood where there are no cell walls blocking the path for long distances (e.g. millimeters at a time). In all woods such things can be cracks and checks, places where cells have separated from one another. In softwoods that have them (pines, spruces, larches, and Douglas-fir), resin canal complexes represent another such continuous open space **(Figure 9).** Resin canal complexes are structures in wood responsible for synthesizing and exuding pitch or resin in response to wounding. In a cellular sense, they are intercellular spaces or cavities, and they run in both the axial and radial system and are interconnected **(Figure 9C),** with the net result that a one inch cube of pine, for example, could in theory be threaded through with a few inches of microscopic thread without ever encountering a cell wall to block the way. An additional aspect of resin canal complexes is that, assuming the resin is not toxic to the fungus (sometimes it is), both the resin and the parenchyma cells that secrete it are rich food sources.

In hardwoods, the vessels (composed of stacks of perforated vessel elements) are such continuous open spaces **(Figure 10, black arrowheads).** A one inch cube of hardwood will

have orders of magnitude more vessels than a softwood will have resin canal complexes. In the case of both resin canal complexes and vessels, both of these spaces are intimately connected, in a regular and predictable fashion, to virtually every ray they touch.

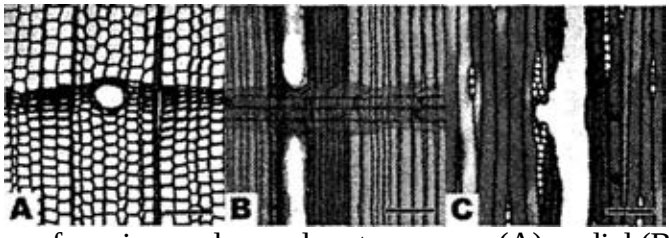

Figure 9. Three views of a resin canal complex; transverse (A), radial (B), and tangential (C). Note in C the anastomosis between the vertical canal complex and the one running out of the image toward the viewer. Scale bars = 100µm.

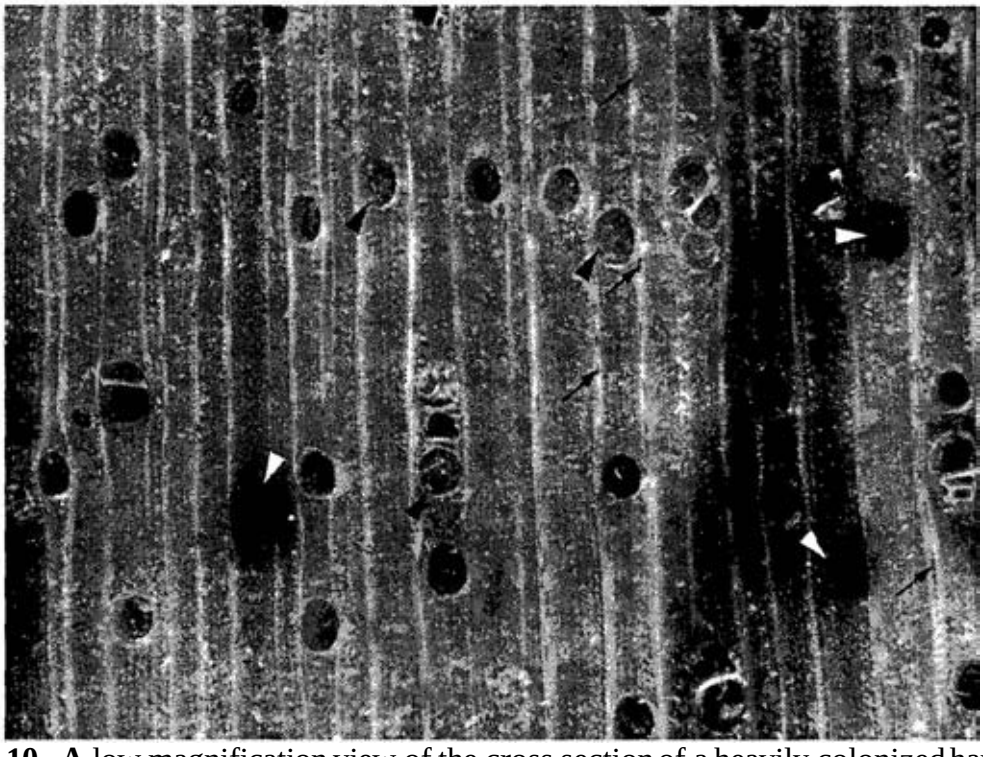

Figure 10. A low magnification view of the cross section of a heavily colonized hardwood showing several of the phases of colonization. Black arrowheads indicate vessels with fungi growing within; Phase I. Arrows indicated rays colonized by stain fungi; Phase II. White arrowheads indicate vessels filled with dark fungi and fungal spores; Phase V.

Phase 11: Parenchymatous Conquest

This means that if a fungus can enter a continuous open space, it will have almost immediate access to the radial system. This lends two advantages; one is that the radial system is the nitrogen and nutrient rich environment discussed before. The other is that the radial system allows rapid movement in the radial direction in the wood, with fewer cell walls to traverse per unit length than growing radially through the axial system **(Figure 10, arrows; Figure 11).** Furthermore, the same ray will be connected to the axial system along its entire length, thus allowing numerous, convenient exits from the radial system back into the axial system. Once a

fungus enters a ray, it tends to stay in the ray until the ray is well colonized, only leaving when it has secured sufficient nutrition to sponsor a trip into the axial system, either questing for a new ray or other parenchyma cell, or beginning the transition into bulk colonization of the axial system, and wood decay proper.

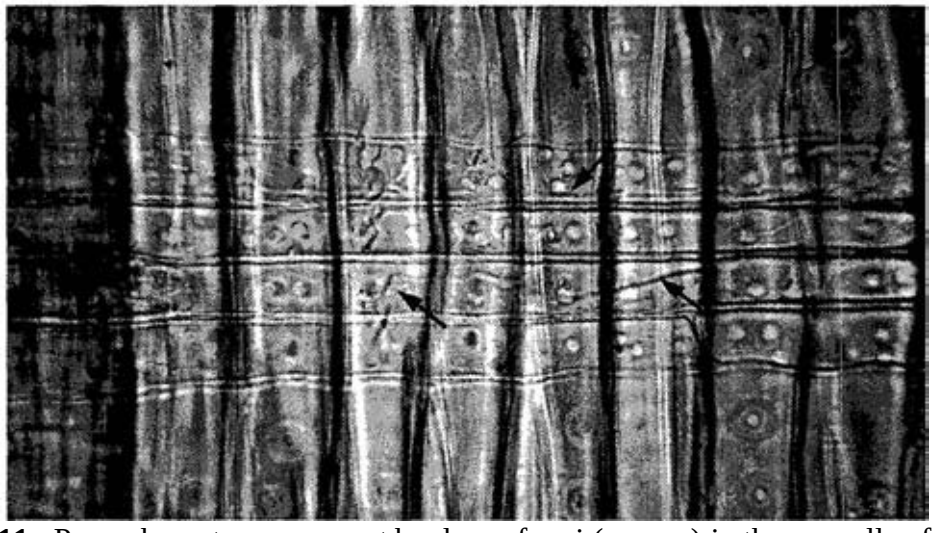

Figure 11. Parenchymatous conquest by decay fungi (arrows) in the ray cells of western redcedar; Phase II.

Stain Fungi Stop Here, Go Directly to Phase V: Escape to the Surface and Sporulation
Most of the colonization discussed to this point is the same for both stain and mold fungi and wood decay fungi. At this point, however, their paths diverge; stain and mold fungi lack the chemical arsenal necessary to circumvent the lignin in the cell wall, and therefore they cannot access the cellulose and hemicelluloses. Inasmuch as their growth has been mostly in the radial system, they have done no appreciable damage to the strength of the wood (ray cells are parenchyma, and parenchyma cells do not bear the mechanical function in wood). They have, however, "opened up" the wood by penetrating pits between rays cells. The explanation for this exceeds the purview of this paper; it is enough to say that wood colonized by stain fungi will often have much higher gas and liquid permeability, which means that liquid water in contact with the wood (from a wetting event) is more likely to be pulled into the depth of the wood, thus facilitating a moisture content sufficient for fungal growth. At this point, then, stain and mold fungi tend to progress directly to the fifth of the five phases; escape to the surface to form spores **(Figure 10, white arrowheads)** or fruiting bodies, sometimes causing difficulties with the wood-coating interface (see text below).

Phase III: Bulk Colonization of the Axial System (Wood Decay Proper)
Decay fungi, unlike their gentler cousins, have and readily employ a potent chemical arsenal to damage or remove the lignin in the cell wall and then degrade the cellulose and hemicelluloses. Wood decay is a cellularly local event; a fungus must be inside or adjacent to a cell to decay it, and if you recall, even a small piece of wood has a large number of cells: about 400 million in a one foot 2x4 of Douglas-fir, for example. In the macroscopic world, a rotten 2x4 is not uncommon or particularly amazing, but at the cellular level, in a nitrogen-limiting environment like wood, it represents a marvel of coordinated colonization and destruction of the substrate. This colonization is the bulk colonization of the axial system, and occurs when the fungi move

out from the rays and open spaces into the mechanical cells of the axial system; tracheids in softwoods **(Figure 12)** and fibers in hardwoods. It is in this phase that the transition from incipient decay to full decay takes place as the fungi now grow and degrade along the grain, and it is here that mechanical testing of rotting wood first begins to reveal strength losses even before there is appreciable weight loss in the wood. For a decay fungus with sufficient nitrogen, wood is a vast resource of carbohydrate energy to tap and degrade, and this phase of colonization is the longest-lived.

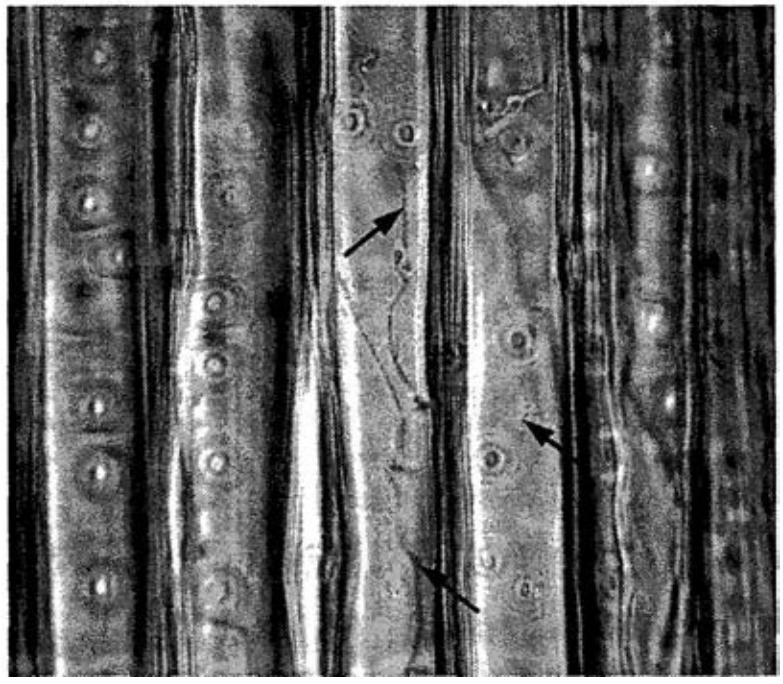

Figure 12. Bulk axial colonization by decay fungi (arrows) in western redcedar; Phase 111.

Phase IV: Recolonization by Brute Force

The fourth phase is one in which the fungi begin to explore less systematically, and due to the softened nature of the now degraded cell walls, with less consideration of the structure of the wood. Specifically, the fungi begin to grow across the grain, punching holes through the cell walls as they go, without recourse to pits or open spaces **(Figure 13; Figure 14C).** This phase is in effect an iteration of the third phase.

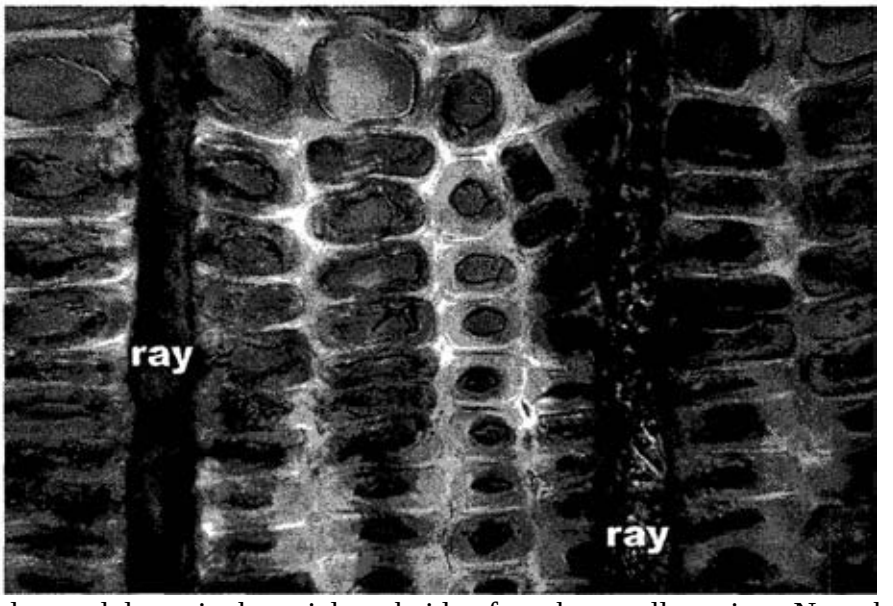

Figure 13. Advanced decay in the axial tracheids of southern yellow pine. Note that the middle row of cells is relatively unharmed, but all rows adjacent to rays are heavily damaged. Wood in this state of decomposition generally represents Phase IV or later.

Phase V: Revisited

The last phase, as mentioned with the stain and mold fungi, is the fungal escape to the surface, to produce spores or fruiting bodies in order to send propagules to colonize a fresh substrate. This is essentially the fungus "going to seed" when its environment is nutrient depleted or some other environmental cue signals the need for a hasty departure (e.g. the substrate beginning to dry below the point of active decay).

Brief Case Studies of Fungal Effects on Test Specimens

In an attempt to close the file on a study begun many years ago at FPL, a colleague decided to perform the final field inspections for a set of adhesive bond durability test specimens and then gather the laboratory data for the final time points and prepare a report. In the course of examining the specimens in the field, he observed tiny fungal fruiting bodies growing from some of the specimens **(Figure 14D).** In discussing this problem with him, we decided to examine all the specimens for microscopic evidence of fungal decay and colonization as well as estimate weight loss (Carll and Wiedenhoeft 2007). The full details of the study can be found in the citation, but in short, fungal colonization was significant and obvious at the microscopic level in all the specimens **(Figure 14A-C),** in all species, in inverse proportion to the decay resistance of the species. The presence of large numbers of decay and stain fungi and clear microscopic evidence of damage to the wood was more than enough to refute the study's tacit assumption of the action of only abiotic stresses on the specimens. Rather than test the residual strength in various types of composite products with exposure to weather and repeated moisture cycles, instead the relative natural decay resistance of different kinds of wood were tested, with results much as would be expected for a decay test. The net result is that the data produced by the study can no longer be considered moisture cycle or weathering data, and instead must be viewed as durability data. In many ways, this constitutes a profound failure of the original experimental design.

It is particularly important to note that these were small specimens, installed on a test fence in a special configuration intended specifically to minimize the risk of biological attack, and the were exposed in Madison, WI, not a notoriously favorable environment for the establishment and growth of wood decay. If major biologic contamination confounded the results of this particular study in a moderate decay hazard climate like southern Wisconsin, it should raise questions about previous studies that did not undertake microscopic evaluation of their specimens following field exposure. Between the effects of the biological variability of the wood substrate at the time of exposure and the additional compounding of biological effects during exposure, a prudent reader might consider carefully the full meaning of any coatings or adhesive field studies that do not explicitly address the issue of microbiological attack of their specimens.

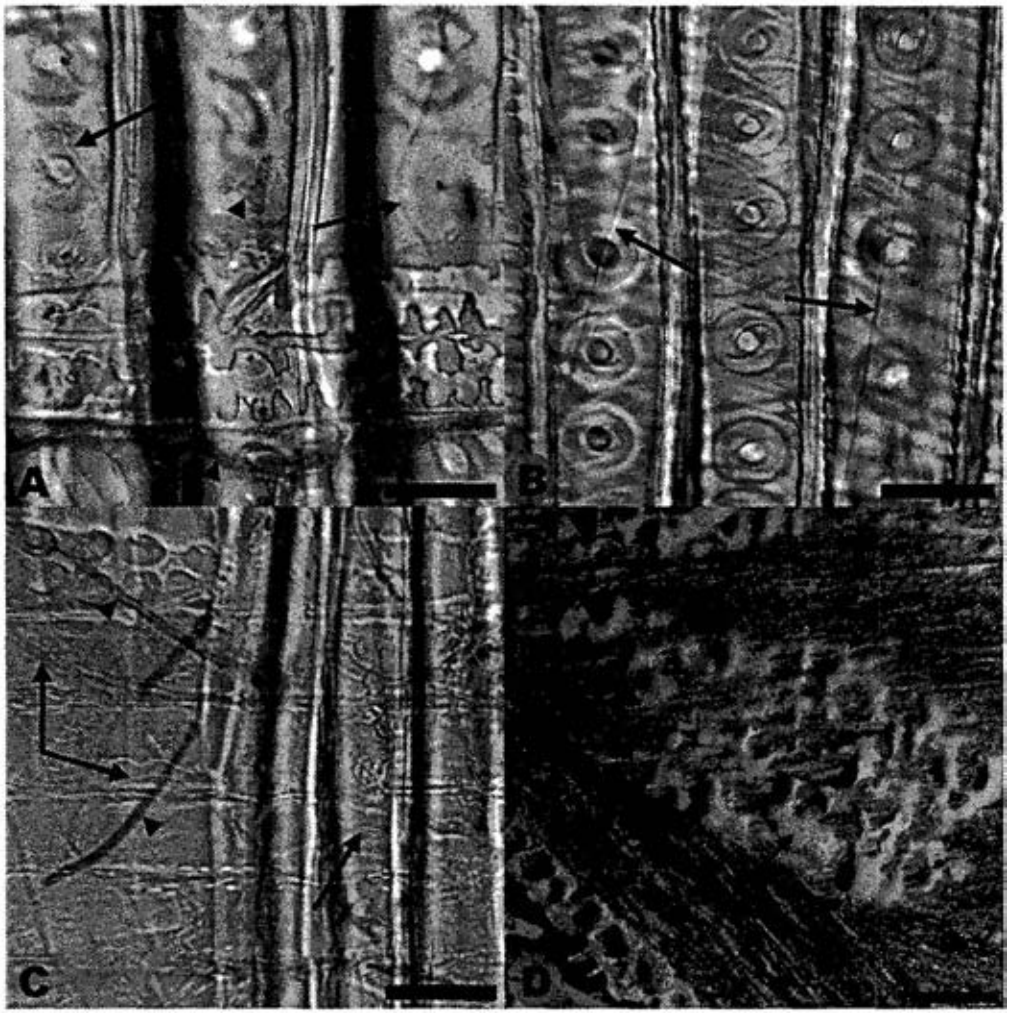

Figure 14. A-C: Transmitted light micrographs. Scale bars = 20µm. Arrows indicate decay type fungal hyphae. Arrowheads indicate stain type hyphae. A: Southern yellow pine plywood specimen. B: Douglas-fir plywood specimen. In both A and B, the fungi are representative of Phase 111. C: Aspen plywood specimen. There are many more decay type hyphae than can be conveniently labeled with arrows; this degree of degradation is typical of Phase IV. D: Stereophotomicrograph showing *Antrodia variiformis* growing on the surface of aspen OSB. Arrows indicate portions of the raised fruiting body of the fungus. Scale bar represents 2 mm.

In a recent consultation with a representative of a coatings company, FPL was called on to examine the nature of some coatings failures after outdoor exposure. In that case, there was an interesting phenomenon with mold fungi growing in the wood-coating interface region. As this was merely a brief phenomenological examination of the material after the fact, and not a study designed to look into the question of mold growth, many questions were left unanswered. Some interesting observations, however, were very much in concert with the hypothetical colonization and resource capture plan I have outlined above. In the bulk of the wood away from the wood-coating interface, the mold fungi, not having the biochemical wherewithal to take on the degradation of the cell walls themselves, were growing predominantly in the open spaces (in this case, resin canal complexes, **Figure 15)** and in the parenchymatous cells; those areas that can be accessed without lignin-degradative or wood-specific chemical attack, and those cells or domains in which free sugars and other nutritious and relatively chemically undefended materials could be found. In addition to the open space conquest, there was also an apparent (but statistically untested) relationship between the proprietary formulation of the coating with respect to nitrogen content, and the degree to which mold fungi could successfully growth in the interface region. In some boards, mold fungi were actually erupting, in shape and aspect very much like miniature volcanoes, up through the coating from the resin canal complexes. In some cases, the mold fungi grew between the wood and the finish, separating them **(Figure 16).** In other cases, the eruption formed blisters in the finish, and delamination of the finish in a halo or zone around the eruption was common. The delamination was greatest along the grain, but there was across the grain failure as well. Such areas of delamination in the vicinity of a breach in the coating are almost certain to fill with liquid water by capillary action during a rain event. That water would then have access to a large surface area, and would likely be pulled down into the drier bulk of the board, thus raising the moisture content. The length of exposure of these boards was only a few years; I have little doubt that had they been exposed another two or three years, actual decay of the substrate would have been significant.

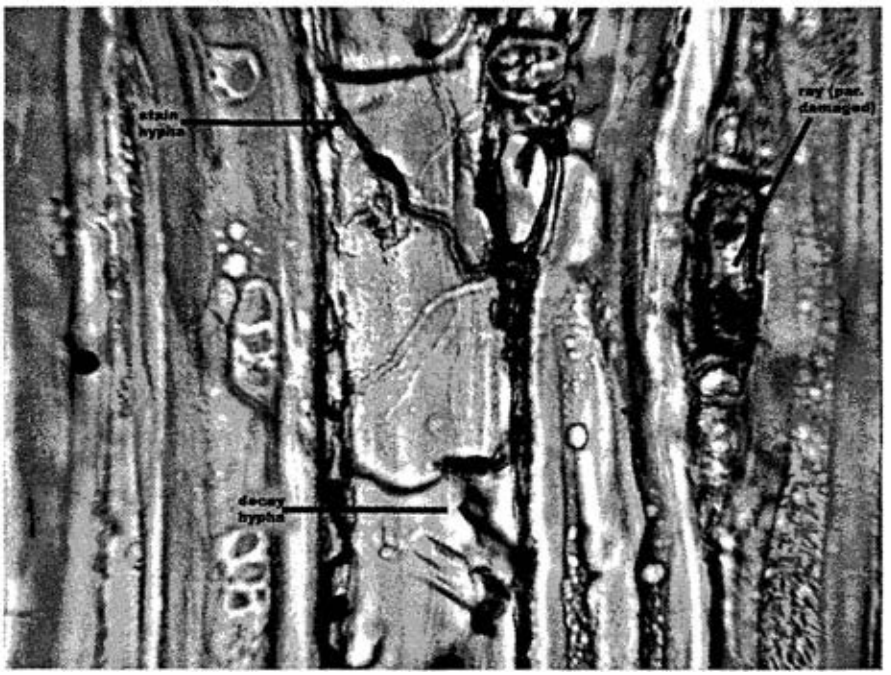

Figure 15. A microscopic view of Phase I colonization of the wood under a failing coating. The fungi are growing in a resin canal complex in a southern pine.

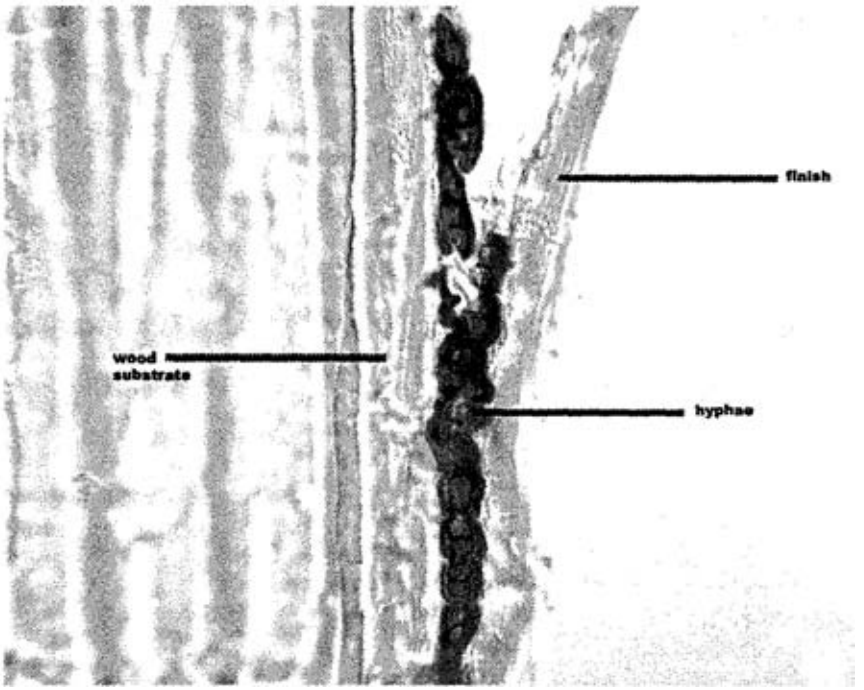

Figure 16. A microscopic section showing failure between the coating and the wood substrate, and the presence of stain or mold type hyphae in the wood-coating interface region. Based on the intimacy of the contact between the fungi and wood and finish in the lower part of the photograph, I speculate that the fungus was actually invading the wood-coating interface rather than merely crawling into an already open area.

Conclusions

As a biological material used for human products, wood exhibits strengths and weaknesses derived from its cellular nature. A basic understanding of the general structure and chemistry of wood allows a framework for understanding the ways in which wood can fail, particularly as a substrate for coatings. Research into wood-coating interactions has often been hampered by a paucity of wood technological knowledge, as reflected in poor experimental designs with insufficient documentation of pertinent wood properties, and too little replication for statistically sound interpretations. In addition to these issues of wood biology affecting coatings performance and research, there is a significant risk of biological attack on the wood during field testing, thus leading to faulty inferences about coatings performance. With a basic conceptual framework in hand for the events involved in the colonization of wood by stain, mold, and decay fungi, one can design studies that will truly test the wood-coating interface rather than the natural durability of the wood substrate or the suitability of the coating as a substrate for fungal nutrition.

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Coatings Wood and Wood Composites:
Designing for Durability

The Central Role of Wood Biology in Understanding the Durability of Wood – Coating Interactions

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