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WOOD FORMATION AND PROPERTIES

Contents

Formation and Structure of Wood

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Introduction

Close examination of a piece of wood with a microscope reveals a minute cell structure that usually escapes casual observation. Remarkably, it is this minute cell structure that is responsible for many of the physical properties and characteristics of a piece of wood. All materials exhibit some degree of dependence on the fine structure of their components; however, this tendency is very pronounced with wood. An understanding of the appearance, properties, and potential of wood for use requires complete comprehension of both the physical properties and the fine structure. Knowledge of the formation processes is also required for complete awareness because wood is produced in a biological environment and the tree is subject to varying growth conditions. The formation of wood and its anatomical structure on the micro- and macroscopic scale are described in this section. Chemical and physical properties are described elsewhere (*see* **Wood Formation and Properties**: Physical Properties of Wood; Mechanical Properties of Wood).

Tree Growth and Wood Formation

Features of Woody Plants

Woody tissue is formed in a variety of plants, but it is the wood in trees that is of interest here. Characteristics of all woody plants include the following:

- possess vascular tissue that is specialized conducting tissue consisting of xylem (wood) and phloem (inner bark)
- are perennial and live for a number of years

- have a persistent stem that endures from year to year and does not die back
- have a means of secondary thickening of the stem by subsequent growth in diameter.

The basic structural and physiological unit of plants is the cell. Wood is a collection of various kinds of cells that are typically elongated and consist of an outer cell wall encompassing a hollow cell cavity. Wood cells are the result of secondary diameter thickening of tree stems. They exhibit an orderly arrangement that is characteristic of tree species, and each type of cell has a specific function.

Basic Processes in Tree Growth

Tree growth parallels the seasons in many parts of the world. It begins in the spring, slows in midsummer, and usually stops entirely in the autumn. A well-defined sequence of activities takes place during each growth season. Growth is activated when temperatures warm to an average of about 6° or 7°C and growth hormones are produced in the buds. At about the same time, water and dissolved minerals begin to move up the stem from the roots to the buds, then the buds swell due to formation and growth of cells, and soon thereafter, leaves emerge from the buds. The process of photosynthesis now begins in the leaves. During photosynthesis, water and carbon dioxide from the atmosphere are combined in the presence of chlorophyll and sunlight to make several different types of sugar.

Products of photosynthesis include oxygen that is released to the air and basic sugars, such as glucose, mannose, galactose, xylose, arabinose, and other five- and six-carbon sugars. The glucose units produced during photosynthesis are used to form cellulose, a linear, long-chain polymer with a degree of polymerization ranging as high as 30 000 monomer units. Glucose and the other five- and six-carbon sugars and sugar derivatives are used in synthesizing lower molecular weight hemicelluloses. These are branched polymers, with degrees of polymerization only in the hundreds. The tree transports the sugars to growth regions at branch and root tips and to the growth region that sheaths the main stem where they will be used to fuel cell formation and development.

New cells are formed in trees in growth areas called meristematic regions. There are two meristems involved in height and diameter growth, the apical meristem and the vascular cambium. Apical meristems are responsible for growth in height. They are composed of specialized dividing cells found at branch tips. As new cells are formed at the branch tips, the apical meristems are pushed outward, where they continue to divide and form new cells. In this manner, branches lengthen, the crown expands, and the tree gets taller and broader. Height growth begins just after the leaves emerge and is rapid at first, but slows as the growth nutrients are diverted to other regions in the tree.

Trees expand in diameter through cell enlargement and repeated cell division in the vascular cambium. This meristematic region is a thin layer of cells that lies just underneath the inner bark. It completely sheaths the entire tree and consists of specialized cells that divide to form new phloem (inner bark) to the outside and new xylem (wood) cells to the inside. Each growing season, the vascular cambium forms new layers of wood and inner bark over the entire surface of the stem and the branches. The result is an increase in stem and branch diameter (**Figure 1**).

Diameter growth in trees found in temperate zones occurs in two stages. This in turn results in two growth zones familiar to us as annual tree rings. These two growth zones are the earlywood and latewood portions of a tree ring. Cell formation during the early spring is rapid and focused on quantity. As a result, the earlywood cells form a large portion of an individual growth ring, and the cells themselves are often thin-walled and large in diameter. Toward the late summer, cell formation slows and a different scheme is used to produce new cells. Cells formed late in the growing season make up the latewood portion of tree rings. Usually there are fewer latewood cells produced per ring than earlywood, and they are thicker walled and smaller in diameter.

Growth rings or annual rings are characteristic of all temperate zone trees but this is not the case in trees growing in tropical regions where growth can be continuous year round. In this case, the wood may

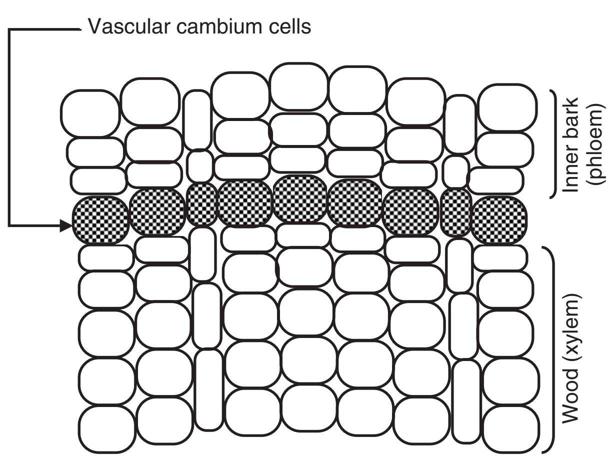

Figure 1 Diagram of a cross-section through the vascular cambium of a tree. Division of the cambial cells results in diameter expansion of the tree stem.

appear not to have any growth rings at all. Some notable exceptions are teak (*Tectona grandis*), padauk (*Pterocarpus* spp.), Honduras rosewood (*Dalbergia stevensonii*), Brazilian tulipwood (*Dalbergia fructescens* var. *tomentosa*), and sapele (*Entandrophragma cylindricum*), among others. In these woods, growth rings appear distinct due to specialized cell types and cell structure rather than two stages of growth annually.

Growth in trees is rapid in early spring but starts to decline as the end of the growing season draws near (approximately mid-July to October in the northern hemisphere). Eventually all growth stops when the meristem regions become dormant. The exact mechanisms that trigger initiation of dormancy are unknown, but there are common processes that occur. Production of growth hormones decreases and growth inhibitors accumulate. This combination results in a reduction in growth rate and eventually halting of growth. The factor that is thought to lead most reliably to dormancy is reduction in the photoperiod (length of day).

Formation and Development of Wood Cells

As mentioned earlier, wood cells in the stems of trees originate through division of the vascular cambium cells. This division can occur in one of two directions – parallel to the cambial ring or perpendicular to it. Division parallel to the ring is called periclinal and results in formation of a pair of cells – a new cambium cell and either a new xylem or phloem cell. Anticlinal division is division perpendicular to the ring and creates a pair of vascular cambium cells that provide for increasing the circumference of the cambium as the tree stem enlarges. The two types of division can take place in the same cambium cell, but do not occur simultaneously. **Figure 2** illustrates a highly idealized vascular cambium dividing periclinally to form two new cells. One of the cells becomes a new cambium cell and the other begins to mature into a new wood or bark cell. If the newly formed cell is to the outside of the cambium, it will become a bark cell, and if it is toward the inside, a wood cell.

Within a few days of formation, the new wood cell undergoes a sequence of changes involved in the maturation process. The shape of the cell changes, it increases in diameter, most cells elongate, and all cells enlarge. A newly formed wood cell consists of a thin, membrane-like wall called a primary wall and a fluid-filled center. A secondary wall is added to the inner surface of the delicate primary wall once the new cell reaches full size and shape. The secondary wall is constructed using macromolecules (cellulose, hemicelluloses, and lignin) that are synthesized from

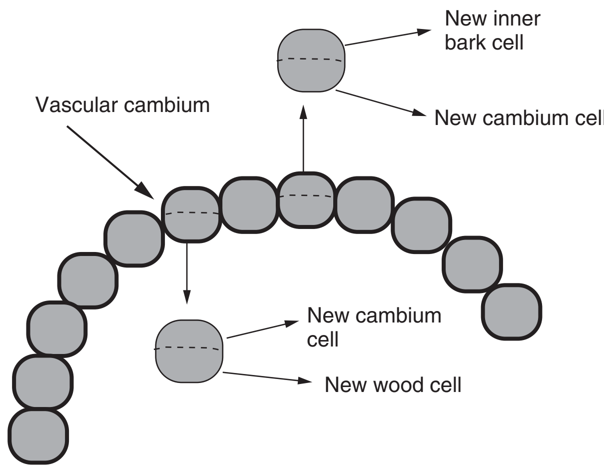

Figure 2 A highly simplified diagram of the vascular cambium dividing periclinally to form new cambial cells and new wood or bark cells.

biopolymers found in the fluid-filled center of the developing cell. Progressive layers are added to the cell wall from the inside. Eventually the fluid filling is expended and the cell has a thickened, rigid wall and a hollow center. Cell formation and maturation continues during the growing season, with the vascular cambium producing new wood and bark cells as rapidly as the conditions allow. Earlywood cells are formed first in the early spring, and those formed later are the latewood cells. Cell formation and maturation continues until growth is terminated at the end of the growing period.

Microscopic Structure

Chemical Structure

At the chemical element level, wood cell walls are made of carbon, hydrogen, and oxygen. Percentages vary with species, but average carbon content is 49%, hydrogen is about 6%, and oxygen is 44%, based on dry wood weight. There are other chemical elements found in wood but in very minor quantities. As mentioned above, carbon, hydrogen, and oxygen are combined in the fluid-filled center of a developing cell to synthesize macromolecules of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose together make up the polysaccharide fraction of wood substance. Cellulose accounts for roughly half the dry weight of wood substance. Cellulose is a high molecular weight, linear polymer synthesized from the glucose produced during photosynthesis. Cellulose is present in all the higher plants, many of the algae, and some of the fungi. In a wood cell wall, cellulose occurs in both a crystalline and a noncrystalline (amorphous) form. Hemicelluloses are also formed using sugars produced during photosynthesis. In general, hemicelluloses are branched carbohydrate polymers that constitute from 35% to 50% of the total dry weight of wood substance. Lignin is not a polysaccharide but rather a complex, high molecular weight amorphous polymer built upon phenylpropane units. Lignin content varies from 15% to 35% of the dry weight. Percentages of the various chemical components differ with tree species and growth conditions.

The three macromolecule groups – cellulose, hemicelluloses, and lignin – are incorporated together to assemble the cell walls. An extremely efficient incorporation scheme is employed by wood cells for fabrication of their walls that is sometimes referred to as the 'reinforced matrix process.' Molecular chains of crystalline cellulose aligned lengthwise are encased in a shell of hemicellulose to construct a long filament. This core of cellulose and hemicelluloses is then surrounded in an amorphous matrix of lignin. In this manner, the lignin matrix is reinforced with cellulose and hemicellulose filaments. These filaments are usually called microfibrils, but just fibrils by some.

Cell Wall Structure

Microfibrils The basic building-block of wood cell walls is the cellulose microfibril. As mentioned above, the core of a microfibril is composed of groups of cellulose crystallites encased in hemicelluloses. During cell wall formation, microfibrils are encased in an amorphous matrix of lignin. Individual microfibrils are approximately 10–12 nm wide and about 5–6 nm thick. A typical wood cell wall consists of several layers of microfibrils in parallel aggregates. As seen in the next section, orientation of the microfibril aggregates varies within and across layers. Microfibrillar orientation greatly affects the properties of wood on all scales of structure and properties, however mechanical properties and the relationship between wood and water are most significantly impacted.

Cell wall layers A wood cell wall is not homogeneous in structure or chemical content. It is a rather complex, layered composite consisting of an outer primary wall and from one to three secondary inner layers. All wall layers, however, are composed of cellulose microfibrils embedded in the lignin matrix. The layers are continuous, but when a wood cell wall is viewed on the cross section with an electron microscope, it is possible to distinguish discrete layers within the cell wall. **Figure 3** is a drawing of a wood cell and the cell wall in cross-section. The outermost layer, the primary wall, is the first formed layer; it is high in lignin and pectin, it is very thin – on the order of 0.1 μm in thickness, and it has a random, netlike microfibril orientation. Once the cell reaches full, mature size, the secondary cell wall layer develops. Thickness of the secondary wall is highly variable, it is dense and rigid, and it consists of highly ordered layers of microfibrils aligned in nearly parallel aggregates. The number of secondary wall layers depends on cell type and to some extent, growing conditions. Cell walls that have the most advanced layer structure have three secondary layers, designated S_1, S_2, and S_3 (**Figure 3**).

Orientation of the microfibril aggregates varies from layer to layer in a cross laminate pattern (**Figure 4**). Microfibrils in the S_1 layer are oriented in parallel clusters that are roughly perpendicular to the cell axis. The S_2 layer microfibrils are nearly parallel to the cell axis, and the orientation in the S_3 is again nearly perpendicular to the cell axis. As mentioned, the cell wall is a continuum but discrete layers can be

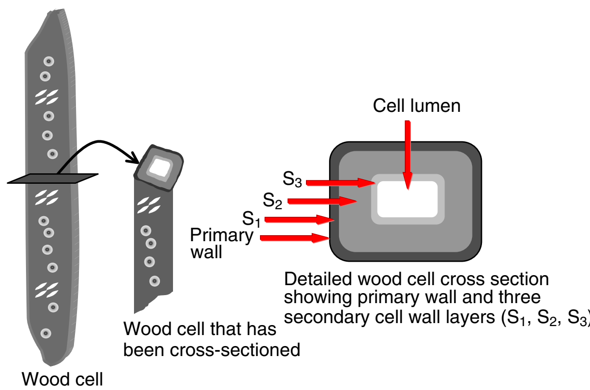

Figure 3 Diagram of a wood cell and the cell wall in cross-section.

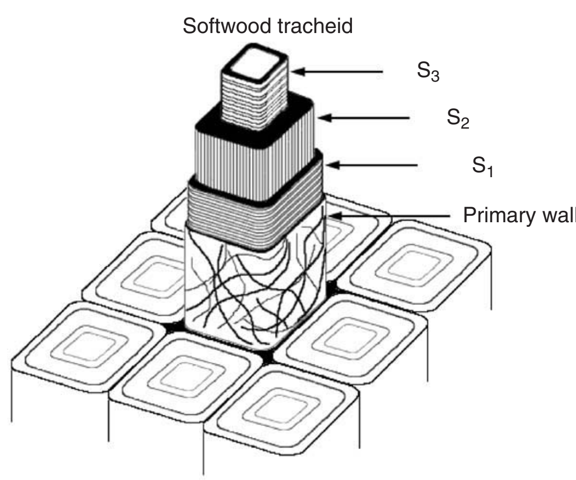

Figure 4 Diagram of cell wall layers and microfibrillar orientation within the layers.

identified in microscopic images. This wall structure is typical of almost all wood cells found in the needle-bearing trees (gymnosperms) and many of the cells found in the wood of the broadleaf trees (angiosperms).

Cell Types and Features

Due to the way in which wood cells are formed in the cambium and performance requirements of the tree, stem wood cells resemble tapered, rigid tubes in function and appearance. They are systematically assembled in tree stems in patterns that are reflective of tree type. Their cross-sectional shape varies from round to hexagonal, and their length varies from less than 1 mm to as long as 7 mm in certain trees. The majority have their long axis parallel to the tree stem, but up to 30% are oriented radially in the stem.

Trees are found in two botanical classifications based on seed type, the angiosperms and the gymnosperms. Angiosperms have seeds encapsulated inside an outer fruit, and gymnosperms have exposed seeds. In practice however, angiosperms are more commonly called hardwoods and gymnosperms, softwoods. While in general there are many similarities between the two groups, the fine structure and features are significantly different. The differences are found in the amount of cell diversity and in the arrangement schemes. **Figure 5** reveals these differences in fine cell structure. In the softwood (**Figure 5a**) the microstructure is fairly uniform and one cell type dominates the cross-section, the softwood tracheid. Tracheids occupy over 90% of softwood volume and are formed in uniform radial alignments. They average 3–5 mm in length and vary from 0.03 mm to 0.45 mm in diameter. Tracheids are rectangular to hexagonal in cross-section and are tapered at their ends. The ribbons of cells running vertically in **Figure 5a** are called wood rays. They are composed of a group of radially oriented cells called ray cells and are responsible for radial transport of fluids in the tree stem. Wood rays in softwoods are practically indistinguishable because they are almost always one cell wide, i.e. uniseriate. They occupy approximately 7% of the volume of softwood stems. Aside from the two cell types visible in **Figure 5a** (tracheids and ray cells), there is really only two other noticeable differences in cell structure: tracheid diameter and wall thickness. Tracheids formed early in the growing season in softwood trees found in temperate zones, i.e., the earlywood, are larger in diameter and have a thinner cell wall than those formed later in the growing season.

Pines (*Pinus* spp.), Douglas-fir (*Pseudotsuga* spp.), larches (*Larix* spp.), and spruces (*Picea* spp.) genera have a specialized feature called resin canals. These are basically a space between cell corners that has been surrounded by specialized resin-secreting cells, as seen at the arrows in **Figure 5b**. Resin canals are oriented both longitudinally and radially in those genera that normally exhibit them. They can be found also in other softwood trees that have been injured in some way. Resin canals that result from injury are called traumatic resin canals and are almost exclusively longitudinal in orientation.

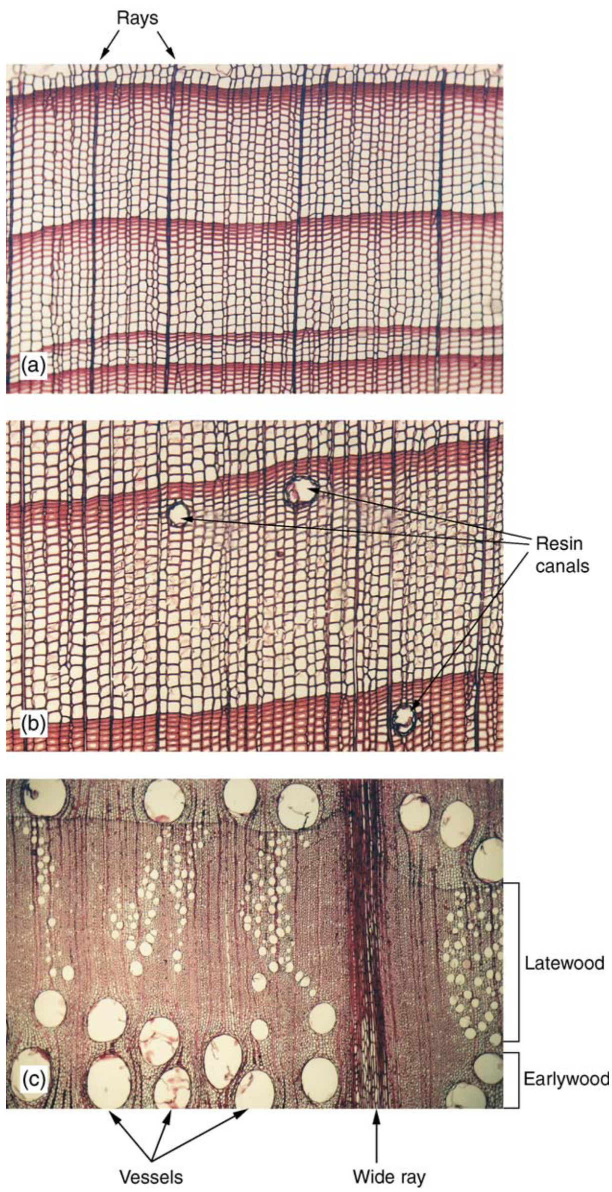

Figure 5 Differences in fine structure of cross-sections of wood as seen with a light microscope. (a) Nonresinous softwood, redwood (*Sequoia sempervirens*) (magnification × 80); (b) resinous softwood, red spruce (*Picea rubens*) (magnification × 100); (c) hardwood, white oak (*Quercus alba*) (magnification × 80).

Figure 5c illustrates the increased complexity of a hardwood in cross-section. Cell structure, features, and arrangements are considerably more diverse.

The uniform radial alignment found in softwoods is absent and there are very large-diameter cells mixed with smaller, thicker walled cells, and multiseriate rays mixed with uniseriate rays. The ray on the right of the micrograph is an example of the very wide rays found in oak (*Quercus*). Not all hardwoods exhibit these extremely wide rays, but almost all have rays that are many cells wide. The very large diameter, round cells on the bottom of **Figure 5c** are specialized transport cells called vessels. There are two groups of vessels visible in **Figure 5c** indicating the earlywood and latewood portion of the growth ring. Vessels are unique to the hardwoods and function as vertical fluid passageways for the trees. They are perforated at the ends with a variety of perforation types that vary from a simple opening to intricate, lacey patterns. Vessels occupy from 5% to 60% of total cell volume of hardwoods. Several other longitudinal cell types surround the vessels and rays in hardwoods. They are fibers, parenchyma cells, and hardwood tracheids. Tracheids and fibers serve as vertical transport and support for the tree and parenchyma serve primarily as nutrient storage. Fibers account for 20–70% of total hardwood cell volume, parenchyma from 1% to 33%, and hardwood tracheids from 27% to 70%. Each type of tree is characterized by a fine structure specific to it, so the actual percentages of any one cell type are almost entirely dependent on tree type.

Vessels in cross-section are sometimes referred to as pores. The difference in pore diameter within a growth ring is used to further classify hardwoods into ring porous, semi-ring porous, or diffuse porous subgroups. **Figure 6** illustrates the subclassification scheme based on porosity within a growth ring. Vessels within a growth ring of a ring porous wood exhibit very large differences in diameter in the earlywood versus the latewood portion of the ring (**Figure 6a**). Semi-ring porous woods exhibit earlywood vessels that are just slightly larger than the latewood vessels (**Figure 6b**). **Figure 6c** illustrates a diffuse porous wood in which the difference in vessel diameter is barely noticeable. Diffuse porous wood is the predominate growth pattern in the world and ring porous woods are usually found only in the temperate zone. Of course, there are a few notable exceptions; for example, teak and Brazilian tulipwood are ring porous woods that grow in tropical regions.

All cell elements regardless of tree or cell type display openings in the side walls, called pits, that allow for passage of fluids and water vapor between individual cells as well as radially in the tree stem. Pits possess microscopic features specific to tree and cell type. For example, the shape and pattern of pits between hardwood vessel elements, called intervessel pitting, can sometimes be used to distinguish one tree from another, and the pitting that occurs where wood rays cross and connect to softwood tracheids is indicative of genus. Pits vary from simple openings in the cell wall to an intricate valved structure in softwood tracheids.

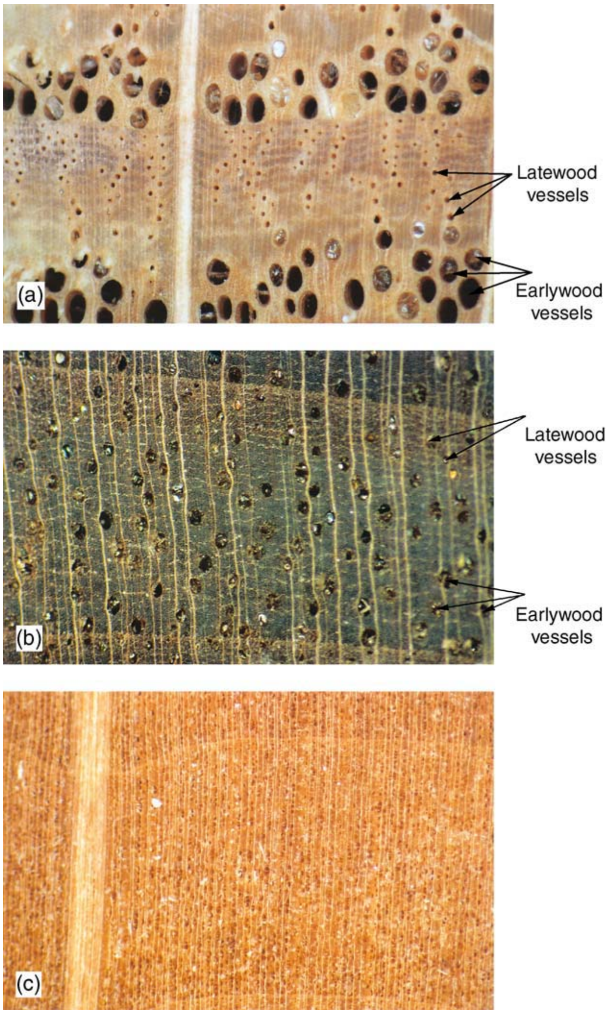

Figure 6 Classification scheme based on variation of vessel size across a growth ring. Magnification $\times$ 10. (a) Ring porous hardwood, red oak (*Quercus rubra*); (b) semi-ring porous hardwood, black walnut (*Juglans nigra*); (c) diffuse porous hardwood, red alder (*Alnus rubra*).

Three Surfaces to Microscopic Structure

Microscopic observation of slices or thin sections taken from a piece of wood reveals different anatomical structure depending on the direction of the original sectioning. An example of a section taken across the tree stem axis is a cross-section and, when viewed in a microscope, appears as in **Figure 7a**. A slice taken parallel to the tree axis and the wood rays is a radial–longitudinal slice (**Figure 7b**); observe the many pit openings along the tracheids.

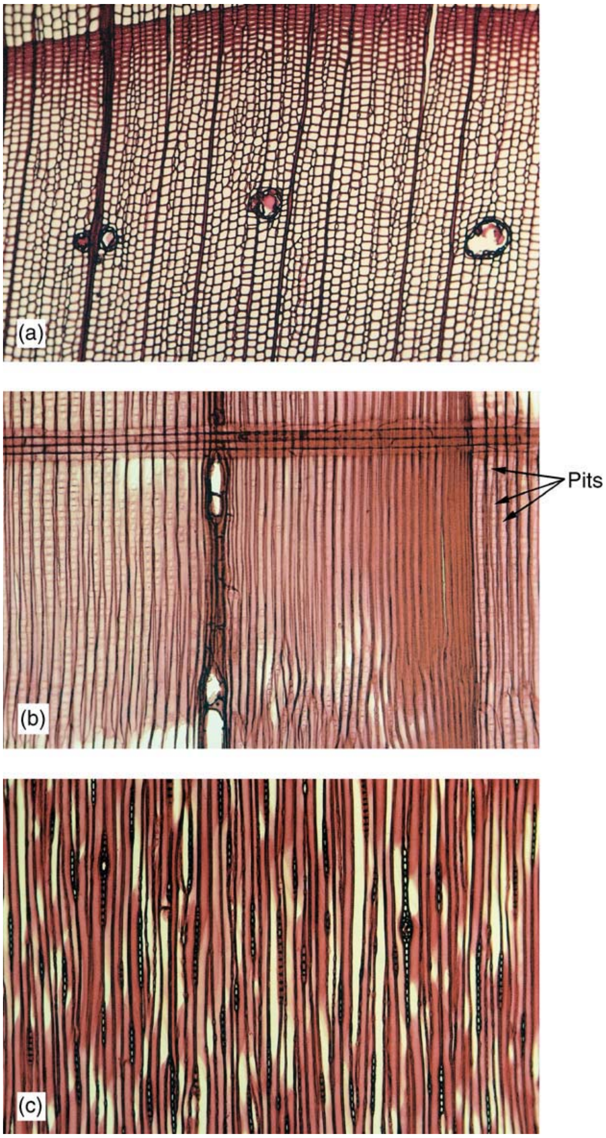

Figure 7 Microscopic images of the three surfaces of a softwood cube, southern yellow pine (*Pinus* sp.). Magnification × 100. (a) Cross-section; (b) radial surface; (c) tangential surface.

Figure 7c is the tangential section made from a cut parallel to the tree axis and a growth ring. Notice how the same piece of wood appears considerably different depending on which surface is being viewed. These differences have arisen from directional differentiation and the way in which the cells were created. Cell formation by the tree's vascular cambium results in elongated, pseudocircular cells that are arranged in a more or less radial ordering within rings around a central axis. Formation and elongation of radial cells perpendicular to the tree's axis further adds to patterning within a wood block.

There are many other, even finer structures and features in wood cells that are not described here. With an electron microscope and a great deal of time it has been possible to observe the extremely fine microscopic features of wood cells. Space simply does not allow a thorough description of the microscopic features (more information may be found in the books listed in the Further Reading section).

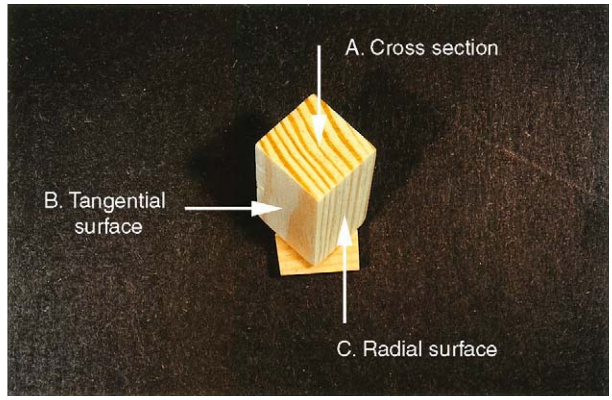

Figure 8 Photomacrograph of a southern pine cube illustrating the different macroscopic features of the three surfaces.

Macroscopic Structure

Anatomical structure visible without the aid of a microscope or hand lens can be thought of as macroscopic structure. Cell formation and directional differentiation have resulted in fine structure differences that translate into macroscopic structure and property differences as well. Examples are structural directions, growth rings, heartwood and sapwood, and ray patterns, among others.

Three Structural and Property Directions

Informal observation of a piece of solid wood reveals different surface characteristics depending on the surface being viewed. Microscopic cell structure is responsible for the three images visible in that single piece of wood. **Figure 8** illustrates surface features of each of the three faces of a wood block that has been cut parallel to both the rays and the growth rings. The surface on the top of the cube is the cross-section, the left face is the tangential surface, and the right face is the radial surface. Not only are the visual features different, the physical properties differ with, and are dependent on, the fine cell structure directions. Lumber grading, processing parameters, wood identification, physical property characterization, and dimensional stability are but a few of the areas in which knowledge of the surface and wood anatomy direction is important.

Growth Ring Structure

Growth rings are more or less distinct in trees depending on the degree of cell differentiation within an individual growth ring. **Figure 9a** indicates that growth rings are more easily distinguished in softwoods due to the usually marked difference in cell diameter and cell wall thickness in the earlywood and latewood growth regions. Ring porous hardwoods also exhibit distinct growth rings (**Figure 9b**), but growth rings are less easy to determine in the diffuse porous woods (**Figure 9c**). Physical and mechanical properties also differ within growth rings due to the cell structure differences. In general the latewood regions exhibit superior mechanical properties, higher density, more shrinkage, and darker color than the earlywood regions.

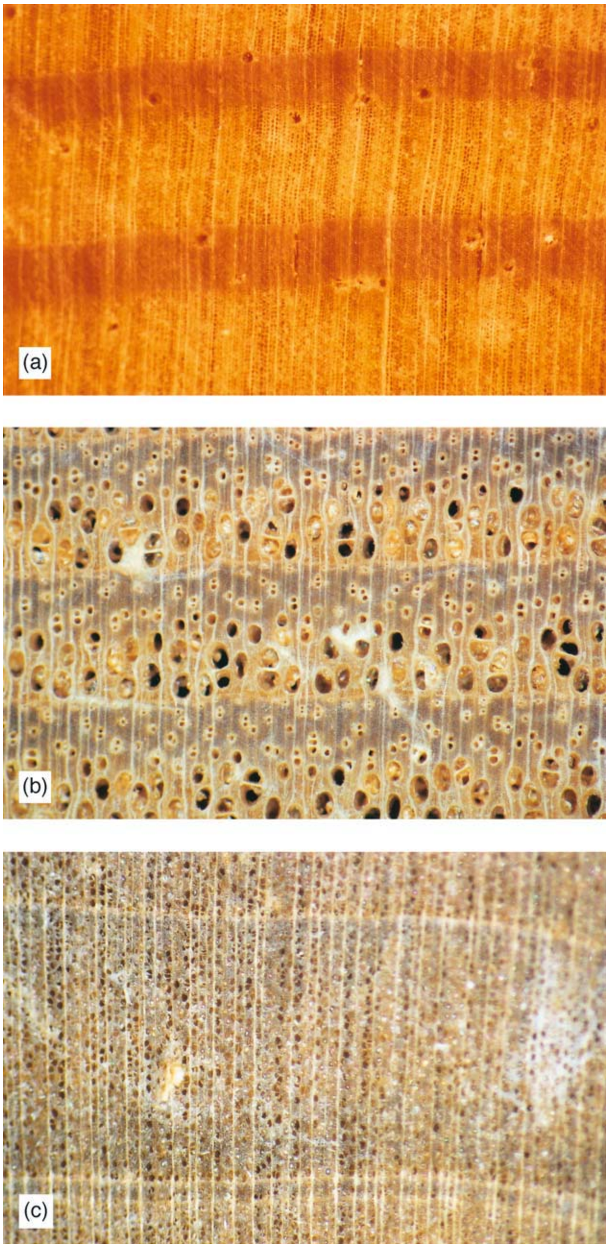

Figure 9 Photomacrographs showing distinct versus indistinct growth rings. Magnification × 10. (a) Softwood with distinct growth rings, southern yellow pine (*Pinus* spp.); (b) ring porous hardwood with distinct growth rings, black ash (*Fraxinus nigra*); (c) diffuse porous hardwood with indistinct growth rings, yellow-poplar (*Liriodendron tulipifera*).

Heartwood and Sapwood

Figure 10 illustrates two visibly different regions in a tree stem disk. The outer rim is lighter in color and is called the sapwood, and the inner, darker region is called heartwood. In twigs and very small, young trees, the entire xylem (wood) portion is involved in sap conduction upward and this wood portion is fittingly named 'sapwood.' As the tree ages, the entire sapwood portion is not needed to transport fluids to the leaves, so at the center of the tree, the cells cease to conduct, lose their nutrients, and eventually die. This transformation from living, conducting cell tissue to empty, dead cells is responsible for cells being converted into 'heartwood.' The transformation is accompanied by production of chemical compounds in the cell wall called extractives, disappearance of living nuclei, and reduction in nitrogen, starch, and sugar content. Notice however, there is no change in cell structure, i.e., cell structure in sapwood and heartwood is essentially the same, it is the chemical content that has been altered. Heartwood is usually darker in color than sapwood because some extractives in the cell walls of heartwood are usually, but not always, dark in color. In addition, extractives give heartwood increased durability, odor, and taste.

Rays

Also visible in **Figure 10** are wood rays extending from the vascular cambium inward toward the pith of the tree. As mentioned, wood rays in

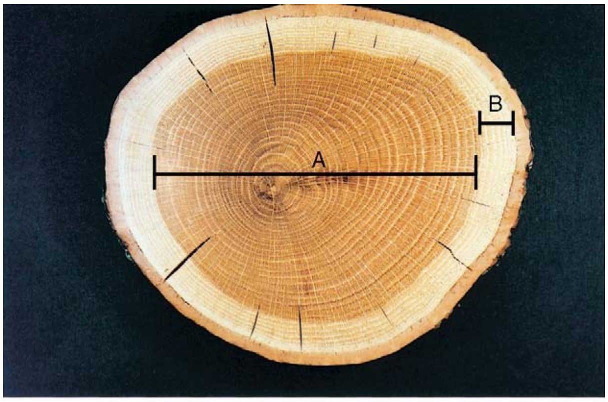

Figure 10 Photograph of a tree disk showing heartwood, sapwood, and rays of oak (*Quercus* sp.).

softwoods are very fine and essentially nondistinct macroscopically, but the rays in many hardwoods are very distinct and make dramatic patterns in finished products. Because the cells in wood rays have their long axis oriented perpendicular to the longitudinal cells, they reflect light differently and can also make unusual patterns on radially cut surfaces. The wood rays tend to form a plane of weakness within the otherwise longitudinally aligned cell structure, but at the same time, are thought to reduce radial shrinkage.

Juvenile and Reaction Wood

Juvenile Wood Features

Wood formed at the apical meristem (branch tips) and later incorporated into the main tree stem by diameter growth in the vascular cambium is significantly different from the outer stem wood. Because this wood is formed at growth shoots and at very early stages of stemwood formation, it is called 'juvenile wood.' It is also known as core, pith, or crown wood. It is formed in a cylindrical column around the pith and depending on species, is the first 5–20 growth increments in the tree stem. **Figure 11** illustrates the location of juvenile wood at the center of the tree stem disk. All trees have some portion of juvenile wood, but it is especially prevalent in plantation grown softwoods and where fast growth has occurred. Cell structure, chemistry, and wood properties all differ in juvenile wood when compared to mature wood. Cell length, cell wall thickness, and percentage of latewood per ring are lower in juvenile wood. This combination of structural features results in lower density. The S_2 microfibril angle is increased (more horizontal) over mature wood as is the percent of lignin in the cell walls.

A-Juvenile wood

Figure 11 Photograph of a tree disk with juvenile wood, Table-mountain pine (*Pinus pungens*).

In general, juvenile wood is considered inferior to mature wood in terms of mechanical and physical properties. It is weaker, less stiff, more prone to warp, and is more problematic to process into paper and fiber products. Differences in the cell structure and chemistry of juvenile wood are again responsible for macroscopic features. There are select circumstances or situations in which juvenile wood is considered acceptable, and perhaps even, preferable. Low-density wood-based composites and some paper products would be examples of products in which juvenile wood performs acceptably and with consistency.

Reaction Wood

Wood formed in leaning stems is also significantly different from wood formed in nonleaning stems. Collectively this wood is called 'reaction wood.' When found in leaning softwood stems, it is called compression wood, and tension wood in leaning hardwoods. Compression wood is formed on the lower side of leaning softwood stems or branches and tension wood is usually on the upper side of

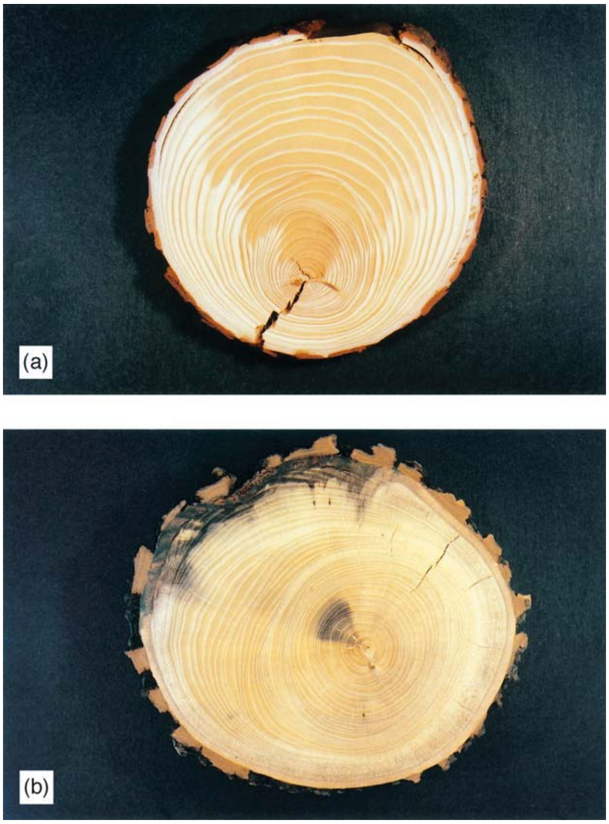

Figure 12 Photographs of cross-sections of reaction wood found in leaning tree stems. (a) Eccentric rings and discoloration of compression wood in spruce (*Picea* sp.); (b) eccentric rings of tension wood cross-section in ash (*Fraxinus* sp.).

leaning hardwood stems or branches. Characteristics of compression wood include eccentric growth rings, a high percent of latewood per ring, higher density, intercellular spaces, helical checking of the cell walls, a large microfibril angle in the S_2, and a higher lignin content. It is often 'dull' looking or darker in color. **Figure 12a** illustrates the eccentric rings and darkening of compression wood. Tension wood has eccentric growth increments, fuzzy cut surfaces, a gelatinous almost pure cellulose layer that may replace part of the cell wall, a higher percent of thick-walled fibers, and an increased cellulose content. Macroscopic features such as eccentric rings of tension wood of ash are shown in **Figure 12b**. Wood on the opposing side of the reaction wood is also 'unusual' in that it does not possess the same features of wood in the nonleaning stem portion. As with juvenile wood, the physical properties of reaction wood are reflective of the fine structure and chemistry and are considered inferior to those of mature wood.

See also: **Tree Breeding, Practices**: Biological Improvement of Wood Properties; Genetics and Improvement of Wood Properties. **Wood Formation and Properties**: Chemical Properties of Wood; Mechanical Properties of Wood; Physical Properties of Wood; Wood Quality. **Wood Use and Trade**: History and Overview of Wood Use.

Further Reading

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Mechanical Properties of Wood

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Introduction

This article covers mechanical properties of wood and wood-based materials. Wood is a nonisotropic material with directionally dependent elastic and mechanical properties. Rules governing wood as an anisotropic, orthotropic, and transverse isotropic material are outlined. Wood materials are classified into groups based on their structure. The relationship between mechanical properties of wood and moisture, temperature, and time are also covered.

Elastic Properties

Wood is an anisotropic nonhomogeneous material. Anisotropic means that the physical properties (including mechanical) are directionally dependent. Its nonhomogeneous character is related to wood being a porous material that is not continuous but contains voids. The anisotropy is cylindrical anisotropy (**Figure 1**) but it is often, for purpose of modeling, replaced by the orthogonal anisotropy (orthotropy). This is done to achieve simplicity and to avoid coordinate transformation from a cylindrical to Cartesian system. A cylindrical coordinate system can be superimposed on the tree cross section such that the longitudinal axis is oriented along the tree axis and the radius, R, is oriented in a radial direction. Angle φ will rotate counterclockwise and mechanical properties will be a function of R and φ. Strictly speaking, wood will only loosely follow anisotropy and transformation rules due to its natural variability. If we remove a block of finite dimensions (such as cutting a board from a log) and

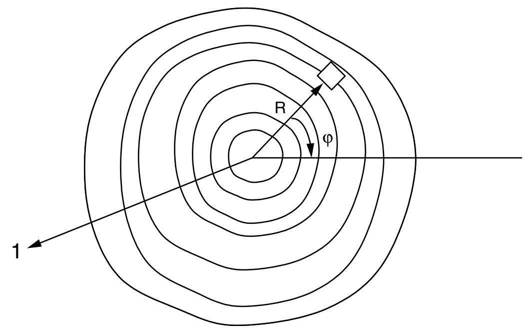

Figure 1 Cylindrical coordinate system superimposed on the tree cross-section.