Heartwood, Part I

Biology, Formation, Identification, and Importance

By Kevin T. Smith and Christopher J. Luley

Learning Objectives

- Understand the differences between sapwood, heartwood, and wound-initiated discoloration and how each is formed.
- Review the relative decay resistance of select North American tree species.
- Understand the importance of being able to distinguish between sapwood, heartwood, and wound-initiated discoloration for the purposes of arboricultural operations.

CEUs: A, U, M, T, L, Bs

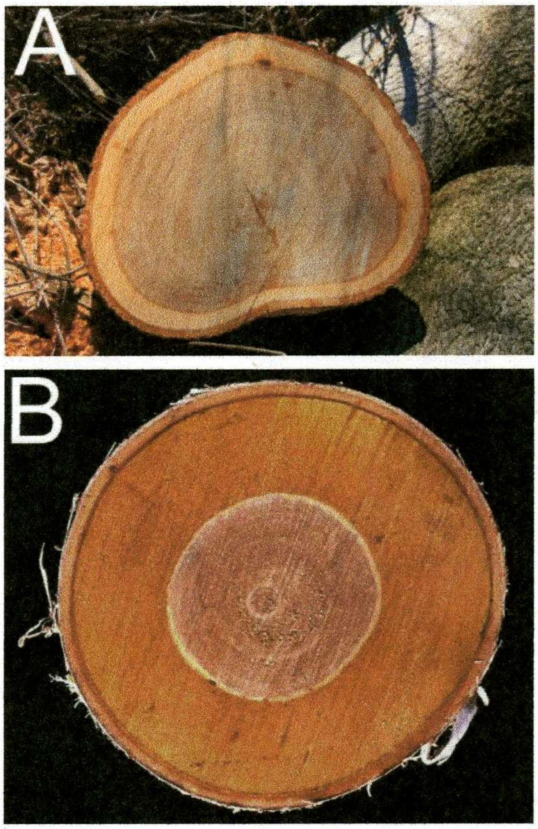

Figure 1. (A) Heartwood of pignut hickory (*Carya glabra*) surrounded by a thin band of lighter-colored sapwood. (B) Discolored wood from injury and infection in the core of paper birch (*Betula papyrifera*). Discolored wood is often misidentified as heartwood due to its central position in the stem and different or darker color. Photographs courtesy of Christopher Luley (A) and Kenneth R. Dudzik, USDA Forest Service (B).

Introduction

"Heartwood" and "heart rot" are terms frequently used by arborists to refer to distinctly different parts and processes in the living tree. Arborists recognize that the presence of heartwood and heart rot can significantly influence management decisions and risk assessment. Here in Part I, we define heartwood and discuss its biology, common characteristics, and importance in the management of urban trees. In Part II (to be published in 2025) we will examine the related topic of heart rot, which commonly is defined as fungal decay in the stem center of the living tree (Schwarze 2004; Boddy 2021).

Heartwood has been loosely defined by its color, position, and presumed decay resistance (Shigo and Hillis 1973)(Figure 1A). Arborists may be trained to adjust treatment practices based on the presence of heartwood. For example, pruning prescriptions may limit the diameter of target branches to minimize exposure of heartwood in the face of the pruning cut. The characteristics of wood at the center of a standing tree can be difficult to assess, and no single physical characteristic consistently defines heartwood. Previous researchers and management guides did not recognize that some tree species are slow to form heartwood or may not form heartwood at all (Spicer and Holbrook 2007). Here, our primary interest is to inform practitioners and help improve decision-making in practical arboriculture.

We propose that position in the stem, wood coloration, resistance to decay, or presence/absence of sap conduction do not define either heartwood or sapwood. We follow Shigo (1986) and define sapwood simply as wood that contains living tree cells, most frequently parenchyma in wood rays. We suggest that heartwood is defined by its formation in response to an inborn genetically pre-programmed shift in metabolism that transforms or converts sapwood into non-living, non-conducting heartwood. Note that this physiological definition includes heartwood with no apparent difference from sapwood with respect to wood color or decay resistance. In addition to sapwood and heartwood, we categorize the different wood types in the core of living trees as ripewood (a form of heartwood), inner sapwood, wound-initiated discoloration (WID), and decayed wood (Table 1).

Sapwood

All wood begins as sapwood, secondary xylem produced by seasonal divisions of the vascular cambium with the latter located between the most recently formed wood and the secondary phloem (inner bark). Living sapwood primarily contains two types of cells: (1) non-living vessels and tracheids (with the former found exclusively in broadleaved species) that conduct water from the roots through the stem and branches into the foliage, and (2) living parenchyma and fibers that store metabolic energy (usually in the form of starch). The metabolic energy is then available for cellular maintenance as well as to break seasonal dormancy and fuel growth early in the growing season and to dynamically respond to injury and infection. Essentially, all of the living cell contents in wood and in other plant parts are interconnected to form the tree symplast network. The genetically programmed death of the tree symplast is the hallmark of heartwood formation.

Heartwood (Including Ripewood)

Heartwood is "the inner layers of wood, that no longer contain living cells, and in which the reserve materials (e.g., starch) have been removed or converted into heartwood substances" (IAWA 1964) as the result of a genetically pre-programmed shift in metabolism. Heartwood also does not conduct sap as part of this definition.

In some familiar tree species, heartwood is commonly recognized in cross section as the comparatively dark core of the stem or branch surrounded by a band of light-colored sapwood (Figure 1A). After a period of years as sapwood, many tree species will convert inner sapwood rings into heartwood. Heartwood formation proceeds from the genetically programmed death of formerly living sapwood cells (parenchyma and in some cases wood fibers) together with the loss of sap conduction. For species that produce heartwood, sapwood function for water conduction, starch storage, and future defense is traded away to reduce overhead costs of metabolic energy as the stem increases in diameter (and volume).

Ripewood is heartwood that visually appears to be similar to sapwood (Figure 2). Historical guides frequently used the term ripewood to refer both to concolorous heartwood (heartwood the same color as sapwood) and inner sapwood with no distinction between them.

Ripewood species produce heartwood that is not darker in color or otherwise appreciably different in appearance than functional sapwood. In ripewood species, sapwood and ripewood can be differentiated in

Table 1. Wood types within the living tree.

Wood type	Color	Decay resistance	Representative genera	Implications
Heartwood	+++	+ to +++	*Quercus, Pinus, Carya, Ulmus, Robinia,* and many others.	Easy to see but color does not confer decay resistance.
Ripewood	0 to +	0 to +	*Picea, Fagus* (Boddy 2021), and *Fraxinus* (Frey-Wyssling and Bosshard 1959).	Hard to confirm visually, as it appears similar to sapwood.
Sapwood	0	0	All species	Decay resistance due to living cells that respond to invasion of healthy sapwood and maintain sapwood water conductance and high moisture content.
Inner sapwood	0	0	Mostly diffuse-porous species such as *Acer, Betula,* and *Populus*	Mostly non-conducting sapwood that retains living cells on non-heartwood forming species. Difficult to separate in the field from conducting sapwood.
Wound Initiated Discoloration (WID)	+ to +++	– to 0	All species	May be incorrectly interpreted as heartwood.
Decayed Wood	0 to +++	0	All species	Early stages may be difficult to distinguish visually from WID.

0 Denotes concolorous with normal sapwood
+ Denotes slight color different relative to normal sapwood
+++ Denotes distinct color difference relative to normal sapwood

freshly cut and sanded cross sections, in which the sapwood appears darker than ripewood due to water soaking. Upon drying, the ripewood becomes essentially indistinguishable from sapwood (Figure 2). European texts and guides frequently refer to ripewood (Büsgen and Munch 1929; Wilson 2020) while the term is mostly unused by North American arborists, perhaps because the tree species that form ripewood have not been clearly identified as such. This is due, at least in part, to the lack of a visible difference between ripewood and inner sapwood.

Inner Sapwood

Some trees retain older rings of sapwood that no longer conduct sap but still retain living cells that store starch and lipids and react to wounding or fungal invasion. In the heartwood-forming white oak group (*Quercus*), only the most recently formed ring or two conduct xylem sap. The non-conducting sapwood with living cells can be referred to as "inner sapwood". For diffuse-porous species such as maple (*Acer*) and birch (*Betula*), inner sapwood may extend to the pith (Figure 3A) and has similar wood strength properties as conducting sapwood.

Wound-Initiated Discoloration (Discolored Wood)

The dynamic compartmentalization response known to most arborists through the CODIT (Compartmentalization of Decay/Dysfunction in Trees) model resists the spread of lost function, infection, and disease in wounded sapwood (Smith 2020). The response includes the depletion of stored energy reserves from parenchyma and the formation and oxidation of chemicals that locally discolor the wood. Importantly, this discoloration that results from sapwood wounding may, but usually does not, increase decay resistance.

Wound-initiated discoloration (WID) is responsible for the dark-colored core of many broadleaved trees, particularly for species in diffuse-porous genera such as *Acer* and *Betula* (Figure 1B and Figure 3B). WID may resemble heartwood with respect to color, lack of sap conduction, and absence of living cells. Unlike heartwood, WID occurs due to the response to wounding and is not part of regular aging or maturation (Shigo and Hillis 1973). Due

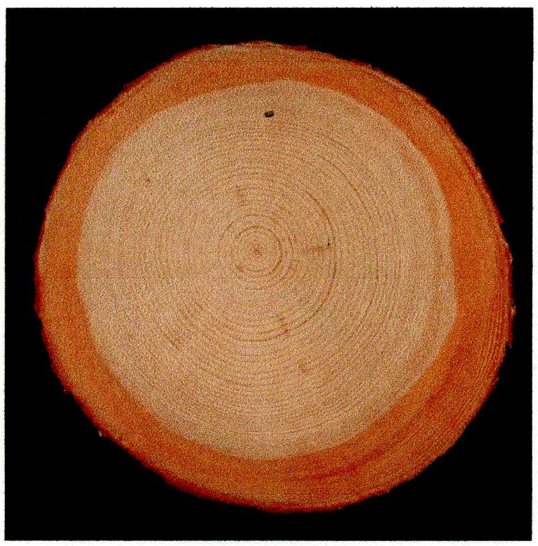

Figure 2. In a freshly cut and sanded disk of red spruce (*Picea rubens*), the sapwood is visible as an outer band of water-soaking. Upon drying, the sapwood becomes indistinguishable in appearance from the ripewood core. Photograph courtesy of Kenneth R. Dudzik, USDA Forest Service.

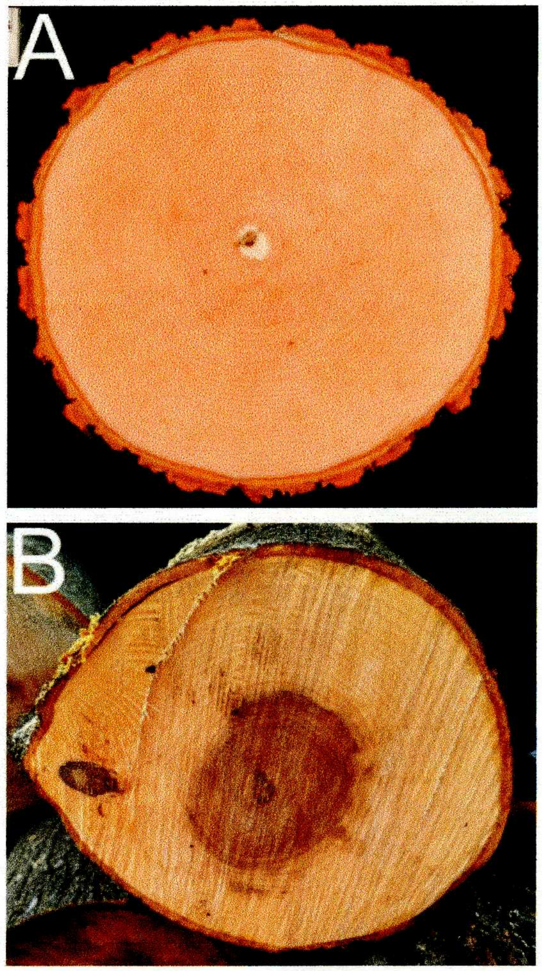

Figure 3. (A) Freshly cut sugar maple (*Acer saccharum*) cross section with some discoloration, a dry zone close to the pith, and a wide band of sapwood. (B) Wound-initiated discoloration or "dark heart" in the core of this sugar maple bolt. Photographs coutesy of Kenneth R. Dudzik, USDA Forest Service (A) and Christopher Luley (B).

to stem position and color, wound-initiated discoloration may be confused with heartwood and lead to unreasonable expectations of performance during tree treatment. We recommend that WID be referred to as such rather than "false heartwood," as the latter term adds no understanding of origin or significance. In practical arboriculture, the specific technical term is less important than to recognize that color and position within the stem alone does not indicate heartwood. Heartwood is not necessarily highly decay resistant. Most past and current published guides do not acknowledge these various types of wood at the center of trees.

Is it Heartwood?

This seemingly simple question becomes difficult to answer as the definition of heartwood becomes more stringent. The first step is to be able to identify trees to species and know their wood characteristics. Heartwood was recognized as a unique type of wood early in the study of tree biology because of the obvious difference in performance between light-colored sapwood and the inner, darker heartwood of some tree species (Hartig 1894; Büsgen and Munch 1929). Heartwood decay resistance varies among and within individual trees of the same species depending on heartwood age, tree health, genetics, and other factors. In most species, the outer rings of heartwood are the most resistant to decay (Taylor et al. 2002).

Folk wisdom correctly understood that some colored heartwood resisted decay, even in ground contact, as for black locust (*Robinia pseudoacacia*) and eastern red cedar (*Juniperus virginiana*). In most of these trees, the darker-colored heartwood is easily visible, and the width of surrounding sapwood is often small when compared to heartwood, especially in older stems (Wagener and Davidson 1954)(Figure 1A and Figure 4). However, some dark heartwood may not be appreciably more resistant to decay than sapwood of the same species, such as for the red oak group (*Quercus* section *Lobatae*), the hickories (*Carya*), and the horsechestnut/buckeyes (*Aesculus*)(Table 2). Even when freshly exposed, identification of ripewood, inner sapwood, or wound-initiated discoloration in an unfamiliar species may require microscopy with specialized staining to detect living wood cells.

Unfortunately, the past identification of heartwood based solely on stem position and coloration has added to the confusion. To further complicate matters in diffuse-porous trees, terminal parenchyma at the annual ring boundary may slowly die and begin to deposit secondary metabolites such as phenolic compounds that slowly discolor sapwood while ray parenchyma remain alive and functional as described for sugar maple (*Acer saccharum*) (Figure 3A)(Good et al. 1955). In other studies, the discolored wood (sometimes referred to as "mineral stain") was identified as the result of tree injury and infection rather than the inborn program of heartwood formation (Shigo and Hillis 1973; Kaminski et al. 2019)(Figure 3B).

Heartwood Formation

The genetically controlled physiological and physical processes that result in the formation of heartwood have been extensively studied but are mostly unseen by arborists and are only briefly summarized here. Heartwood formation in species with dark-colored heartwood begins in the oldest (first-formed) ring of sapwood and continues in a transition zone just outside a developing central core of heartwood. This transition zone, which is considered sapwood, as it still contains living cells, may be visible on the outer edge of darker heartwood (Figure 4). Heartwood formation is completed by the death of all wood cells and the loss of sap conduction.

The transition zone where sapwood is converted to heartwood has many physiological processes taking place. These processes are dominated by a shift in metabolism that converts stored starch and lipids into chemical extractives such as tannins, terpenes, flavonoids, lectins, and polyphenols (Hillis 1987; Taylor et al. 2002) that may inhibit decay fungi and other microorganisms and insects. Heartwood generally has elevated CO_2 and reduced O_2 compared to sapwood (Taylor et al. 2002), which also slows aerobic decay and the oxidative discoloration of phenols (Frey-Wyssling and Bosshard 1959).

The metabolic shift behind heartwood formation also results in the death of living sapwood cells and the

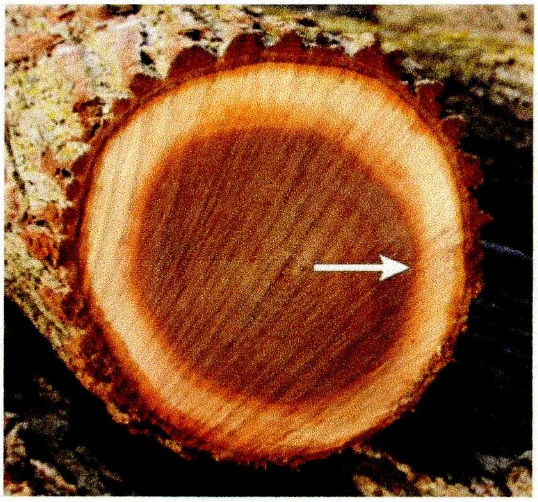

Figure 4. In many species, such as black walnut (*Juglans nigra*) shown here, a transition zone around the inner core of darker heartwood can be seen where heartwood formation is taking place. The transition zone is where an elevated level of physiologic activity occurs as parenchyma cells senesce and eventually die. Photograph courtesy of Christopher Luley.

Table 2. Relative decay resistance of heartwood in service for selected North American species. Note that some of the listed species may not form heartwood or have ripewood that is not appreciably different than sapwood in coloration (adapted from Ross 2021 and USDA 1967).

Very resistant	Resistant	Moderately resistant	Slightly or non-resistant
Black locust (*Robinia pseudoacacia*)	Baldcypress (*Taxodium distichum*, old growth)	Baldcypress (young growth)	Alder, red (*Alnus rubra*)
Mulberry, red (*Morus rubra*)	*Catalpa*	Cherry, black (*Prunus serotina*)	Ash (*Fraxinus*)**
Osage-orange (*Maclura pomifera*)	Cedars (Atlantic white [*Chamaecyparis thyoides*], Eastern red [*Juniperus virginiana*], Northern white [*Thuja occidentalis*], Port-Orford [*Chamaecyparis lawsoniana*], Western red [*Thuja plicata*], Yellow [*Cupressus nootkatensis*])	Fir, Douglas (*Pseudotsuga menziesii*)	Basswood (*Tilia americana*)
Yew, Pacific (*Taxus brevifolia*)	Chestnut, American (*Castanea dentata*)	Honey locust (*Gleditsia triacanthos*)	Beech (*Fagus*)**
	Cypress, Arizona (*Cypressus arizonica*)	Larch, western (*Larix occidentalis*)	Birch (*Betula*)
	Junipers (*Juniperus*)	Oak, swamp chestnut (*Quercus michauxii*)	Buckeye (*Aesculus*)
	Mesquite (*Prosopis*)	Pine (eastern white [*Pinus strobus*], longleaf [*P. palustris*], slash [*P. elliottii*], all old growth)	Butternut (*Juglans cinerea*)
	Oak (white oak group primarily, bur [*Quercus macrocarpa*], chestnut [*Q. montana*], Gambel [*Q. gambelii*], Oregon white [*Q. garryana*], post [*Q. stellata*], white [*Q. alba*])	Redwood, young growth	Elm (*Ulmus*) and Hackberry (*Celtis*)
	Redwood (*Sequoia*, old growth)	Tamarack (eastern larch [*Larix laricina*])	Firs, true (*Abies*)
	Sassafras		Hemlock (*Tsuga*)
	Walnut, black (*Juglans nigra*)		*Magnolia*
			Maple (*Acer*)
			Oak (*Quercus*, red oak group)*
			Pines (*Pinus*)*
			Poplars (*Populus*), including aspen and willow (*Salix*)
			Spruces (*Picea*)**
			Sweetgum (*Liquidambar*)
			Sycamore (*Platanus*)
			Tanoak (*Notholithocarpus densiflorus*)
			Yellow poplar (*Liriodendron tulipifera*)

*Heartwood may have elevated resistance compared to other species in the same column.

**Ripewood-forming species where heartwood is not appreciably different colored than sapwood.

formation of tyloses and other plugging materials. The plugging of water-conducting tissues is also an important process in heartwood formation for both broadleaved and conifer species. Tyloses form from the cell membranes of adjacent parenchyma that are drawn into vessels and are then encrusted with waterproofing lipids (Figures 5A and 5B). For species that do not form tyloses, sapwood is plugged by gums, resins, and emboli (air bubbles) during heartwood development. Loss of sap conduction occurs with heartwood formation in all species. Heartwood of conifers is typically lower in moisture content than sapwood (Taylor et al. 2002), while heartwood moisture content of hardwoods may be higher or lower depending on tree species (Taylor et al. 2002; Kampe and Magel 2013) and potential infection by wetwood bacteria.

Heartwood initiation and formation appear to occur primarily during the growing season (Kampe and Magel 2013), although evidence of heartwood formation during dormancy also exists (Taylor et al. 2002). Heartwood formation may not occur evenly around the stem, often giving heartwood an irregular outline in a cut cross section (Figure 6). Heartwood can be found in large-diameter branches (Figure 7), in the main trunk, and in buttress roots and large woody roots (Figure 8). A number of studies have shown that heartwood formation often proceeds at different rates depending on the location within the tree.

The boundary between sapwood and heartwood often does not follow a particular annual ring around the stem circumference nor along the stem axis (up and down the stem). The number of rings of sapwood varies among heartwood-forming trees and may be determined in part by the physical width of the sapwood band in cross section as well as the number of rings. Heartwood is considered a preformed or constitutive portion of Wall 2 in the CODIT model (Morris et al. 2020). Interestingly, heartwood may darken when wounded without further chemical deposition when previously formed heartwood extractives undergo enzymatic oxidation (Shigo and Shortle 1979). Heartwood may be further discolored (including apparent lightening in color or bleaching) by the invasion of decay fungi. These color changes can further complicate field identification (Figure 3B).

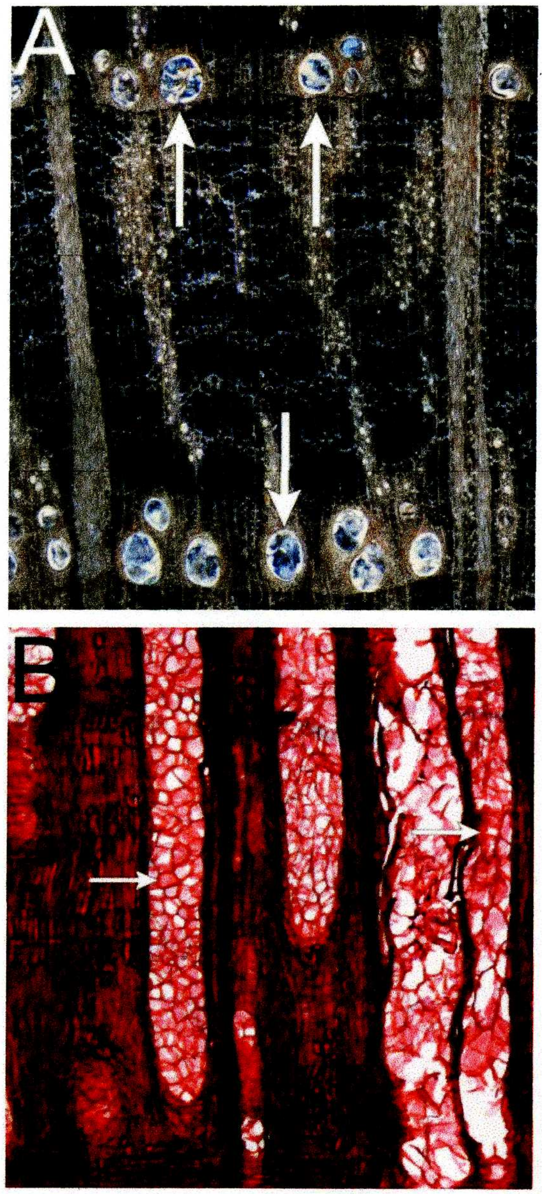

Figure 5. Microscopic view of wood vessels with several tyloses marked in a cross section of white oak (*Quercus alba*) (A) and a longitudinal section of black locust (*Robinia pseudoacacia*)(B). Photographs courtesy of Kenneth R. Dudzik, USDA Forest Service.

Figure 6. Heartwood may form unevenly around the stem, giving it an irregular shape, depending on the tree species and site conditions, as shown here for white pine (*Pinus strobus*). Photograph courtesy of Christopher Luley.

Figure 7. Heartwood in the branch and trunk of black walnut (*Juglans nigra*). Photograph courtesy of Christopher Luley.

Figure 8. Heartwood also forms in buttress roots and larger diameter woody roots as shown here for black locust (*Robinia pseudoacacia*). Photograph courtesy of Christopher Luley.

Figure 9. The elevated resistance of heartwood to decay in some tree species allows its use in service, as shown here for black locust fence posts and white oak rails. Photograph courtesy of Christopher Luley.

Heartwood in the Real World and Importance in Arboriculture

Long before the formal study of tree biology and the development of modern arboriculture, humans benefited as they still do today from the decay resistance of heartwood. People recognized that the heartwood of certain tree species (e.g., cedar, black locust [*Robinia pseudoacacia*], osage orange [*Maclura pomifera*], Pacific yew [*Taxus brevifolia*], redwood [*Sequoia*], and white oak [*Quercus alba*]) greatly resisted decay when used outdoors in contact with the environment or in contact with soil, such as for fence posts (Figure 9; Table 2). Anyone relying on the decay resistance of heartwood species should consider that only heartwood may be decay-resistant; sapwood of even the most decay-resistant tree species will decay quickly once exposed to weather and intermittent wetting and drying. Because heartwood formation may be accompanied by a dramatic change in wood color, such as for black walnut (*Juglans nigra*) and black cherry (*Prunus serotina*), it is often highly prized by furniture manufacturers and woodworkers. Extractives from heartwood have also been shown to have promise in use as wood preservatives and as anti-cancer and microbial agents in medicine (Kampe and Magel 2013).

Arboricultural Importance

Because heartwood formation is hidden from view, it would be easy to overlook how heartwood impacts urban tree management. However, there are several places where heartwood is important to arboriculture. Heartwood exposed by the pruning of large branches may become readily infected by decay pathogens. Consequently, pruning prescriptions can specify the use of heading or reduction cuts, as well as diameter limits to reduce or avoid heartwood exposure and to delay the spread of infection into the main trunk or larger branches (Figure 10 and Figure 11). Heartwood, ripewood, and wound-initiated discoloration may also have different hardware requirements for cabling than stems with no heartwood or undecayed sapwood (ANSI 2023). Proper assessment of discolored wood can also be important when notching and felling trees, as WID is a stage in the wood decay process and may indicate reduced wood strength that may impact safe tree care operations, especially during notching and felling (Figure 12).

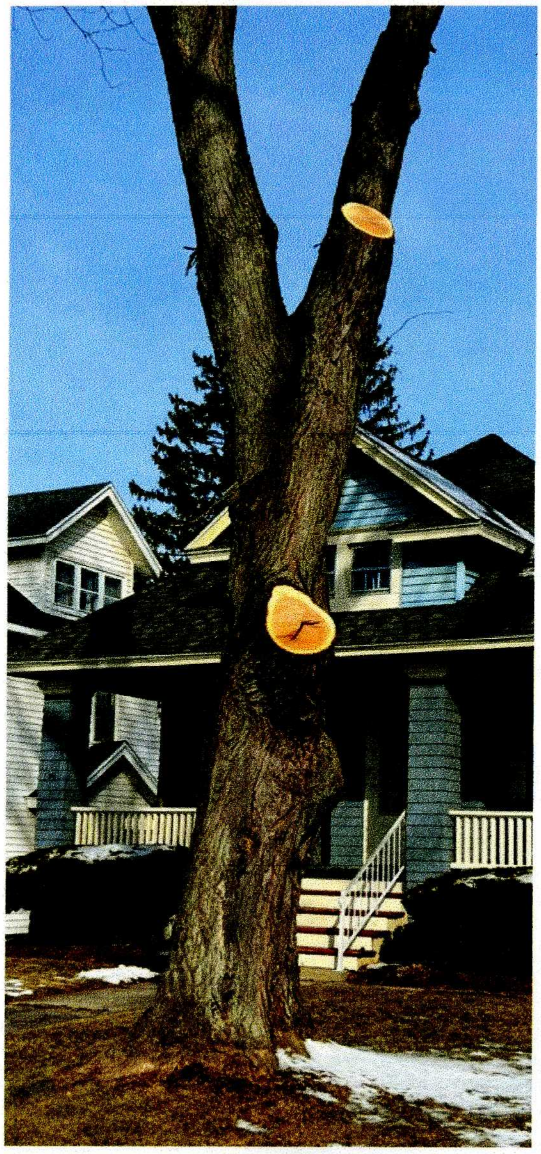

Figure 10. Avoid heartwood exposure on the trunk and main stems to delay heart rot decay. Heartwood exposed on this honey locust (*Gleditsia triacanthos*) will likely be infected by decay fungi. Photograph courtesy of Christopher Luley.

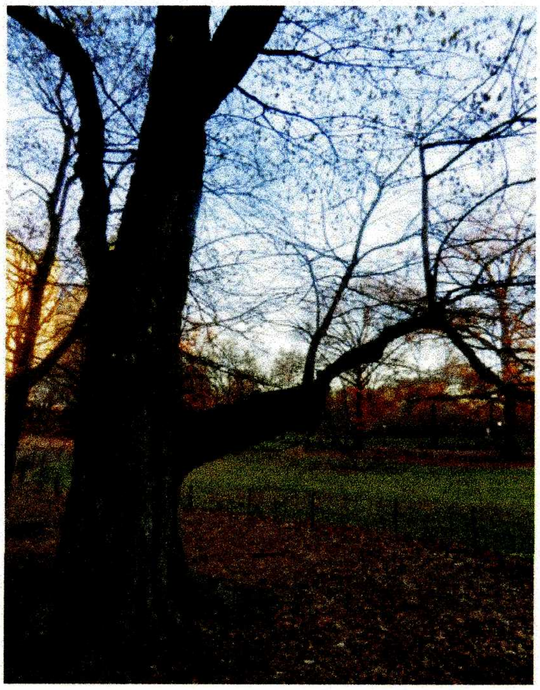

Figure 11. The use of heading cuts on larger diameter branches is a reasonable strategy to delay exposing heartwood on the main trunk to infection by decay fungi. Photograph courtesy of Josh Galiley.

Figure 12. Knowledge of the wood types at the center of different tree species can impact safe tree care operations. Decay in the center of this sugar maple (*Acer saccharum*) resulted in failure of the hinge wood that was relied on for directional felling. Healthy, undecayed heartwood or sapwood are equivalent in most measures of wood strength. Photograph courtesy of Nate Wright, National Grid.

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