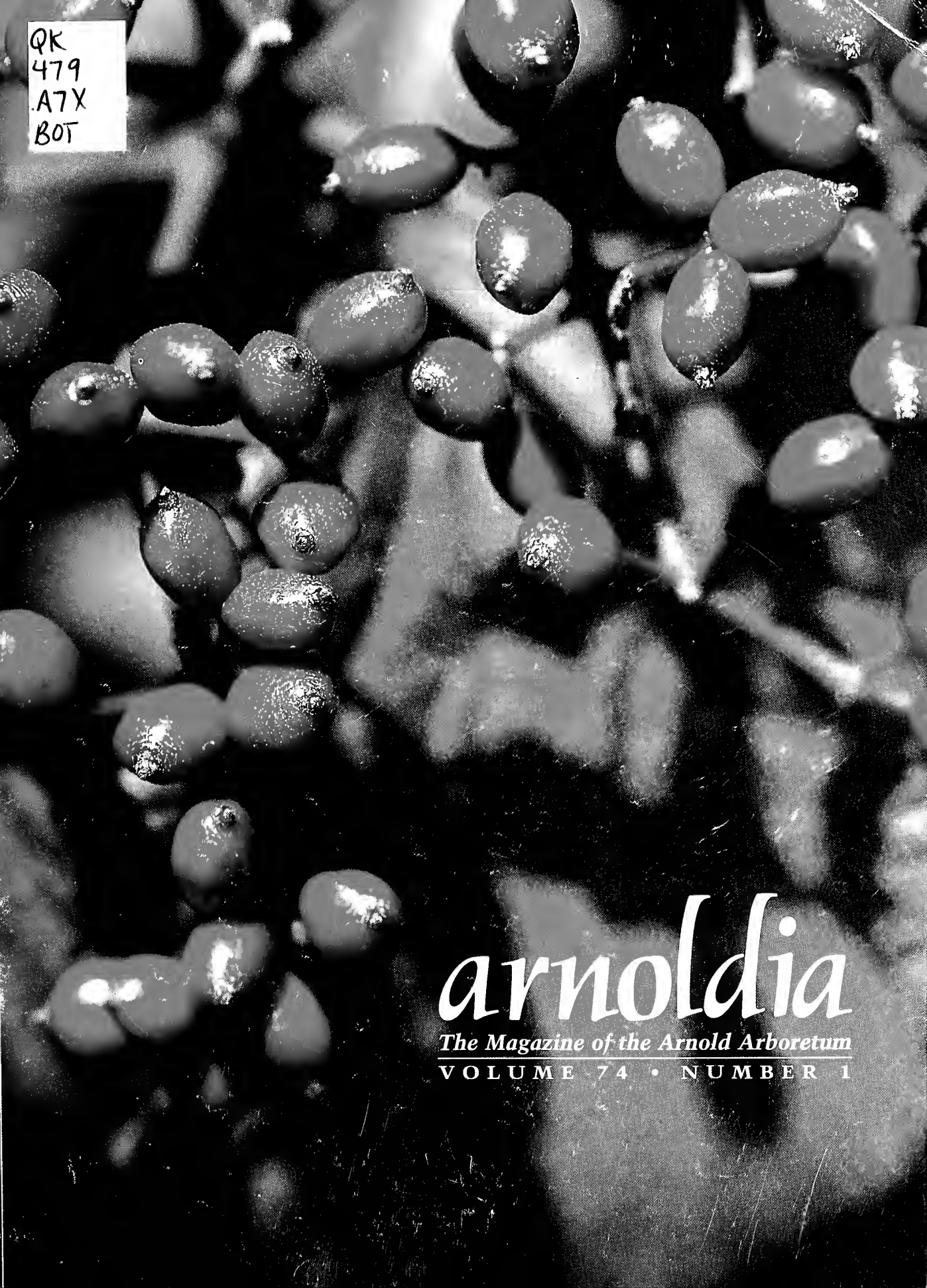

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The ARNOLD ARBORETUM of HARVARD UNIVERSITY

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Inside front cover: View of a section of the Dana Greenhouses in 1978. Archives of the Arnold Arboretum.

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Back cover: This specimen of Henry maple (*Acer henryi*, 164-83-A), a Chinese species that bears drooping clusters of winged fruits (samaras), was grown from seeds received from the Hangzhou Botanic Garden in China. Photo by Nancy Rose.

The ARNOLD ARBORETUM of HARVARD UNIVERSITY
CAMPAIGN FOR THE LIVING COLLECTIONS

The Campaign for the Living Collections kicked off last fall with plant collecting trips to China and Idaho, which Curator of Living Collections Michael Dosmann and Manager of Plant Records Kyle Port wrote about in the last issue of* Arnoldia. *Once newly acquired fruits, seeds, cuttings, divisions, and plants arrive at the Arboretum, the production staff at the Dana Greenhouses takes over. In this issue, Manager of Plant Production Tiffany Enzenbacher and Plant Propagator John H. Alexander III describe the process of shepherding new accessions from the greenhouse bench to final production nurseries, the last step before plants move to a permanent location on the Arboretum grounds.

A Concise Chronicle of Propagation

Tiffany Enzenbacher and John H. Alexander III

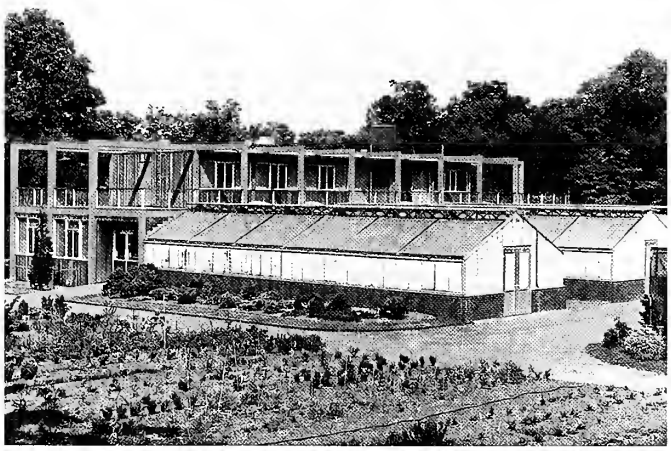
Plant propagation historically has been recognized as an integral component of the Arnold Arboretum's mission. In fact, the Arboretum's second employee (inaugural director Charles S. Sargent was the first) was plant propagator Jackson Dawson, hired in 1873, the year after the Arboretum was established. Since Dawson was Sargent's only employee, he served not only as the propagator but also the superintendent (Geary and Hutchinson 1980) and remained with the Arboretum until his death in 1916. The Arboretum's other long-term and influential propagators—William H. Judd (employed from 1913 to 1946), Alfred J. Fordham (1929 to 1977), and John H. Alexander III (1976 to 2016)—and shorter-term propagators followed suit after Dawson. Through horticultural expertise, experience, and old-fashioned trial and error, they coaxed seeds to germinate and cuttings to grow roots, successfully propagating taxa novel to New England and North America. The propagation facilities have moved five times over almost a century and a half and have seen many exciting horticultural accomplishments by Arboretum propagators and production staff.

In 1873, the Arboretum shared growing space with the Bussey Institution, then relocated in 1886 to a small land plot and 20-foot by 50-foot greenhouse on the property at 1090 Centre Street, where Dawson then resided (Geary and Hutchinson 1980). These modest accommodations were soon outgrown and a new greenhouse was constructed on Orchard Street across from the Arboretum (off of the Arborway) in 1917 (Howard 1962). With intensified Arborway traffic and road widening, production was moved back to land adjacent to the Bussey Institution in 1928. As additional space needs arose, along with the desire for a more up-to-date building, ground broke to construct the Charles Stratton Dana Greenhouses in 1961. The donation for the Greenhouses was provided by Mrs. William R. Mercer (née Martha Dana), and was named in honor of her father, Charles S. Dana (Howard 1962). This complex houses the present facilities, including specialized equipment and environments for seed, cutting, and grafting propagation, greenhouse and outdoor bench space for containers, an evaluation

ARCHIVES OF THE ARNOLD ARBORETUM

The Arnold Arboretum's greenhouse at the Bussey Institution was built in 1928. This view is of the greenhouse interior in 1949, photographed by Heman Howard.

TIFFANY ENZENBACHER



ARCHIVES OF THE ARNOLD ARBORETUM

Views of the Dana Greenhouses in spring 1966 by Heman Howard (above) and again in fall 1974 by Alfred J. Fordham (below).

Recent renovations to the Dana Greenhouses increase efficiency and save water and energy. The seed propagation house is now equipped with an improved mist system that features hanging mist assemblies, which allows for maximum use of bench space. Other revamped features include sectioning the house into three irrigation zones with as many isolation valves in each zone, which allows for the flexibility to tailor water needs to specific taxa. Mist frequency can be controlled to come on at intervals of 2 to 180 minutes, with the duration of a mist event ranging from 2 to 60 seconds. LED (light-emitting diode) lighting was installed in fall 2015. The LumiGrow Pro 325 LEDs utilize 70% less energy than our previous HID (high intensity discharge) lamps and produce 70% less heat. Lights are used to extend the day length during short days.

nursery, three longer-term nurseries, a cold storage building for overwintering containers, and the Bonsai and Penjing Pavilion.

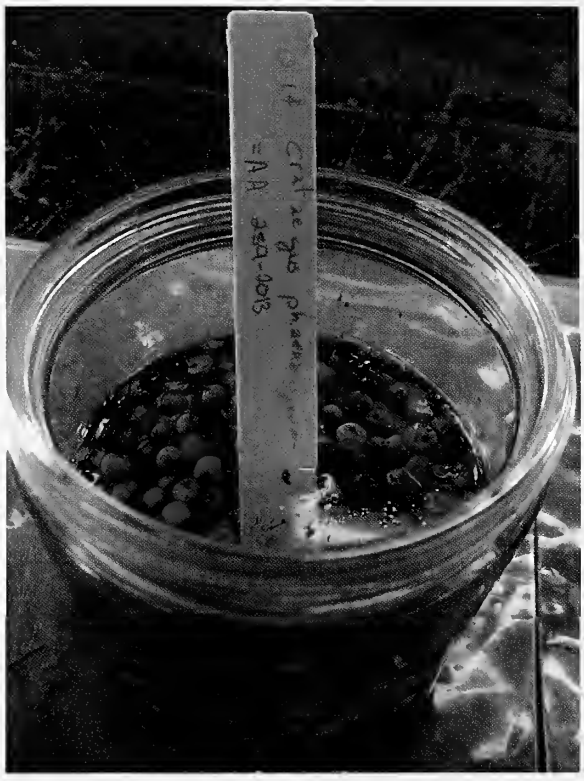
Through facility relocations and many staff changes in the years since the Arboretum's inception, plant propagation and production have remained center stage. The current ten-year Campaign for the Living Collections (Friedman et al. 2016), which focuses on acquiring nearly 400 wild-collected plant taxa, will assuredly keep propagation in the limelight well into the future. The Campaign's list of desiderata features taxa selected because they increase the phylogenetic and biological breadth of Arboretum collections, belong to geographically disjunct clades, are marginally hardy or threatened in the wild, or can be used to create a "living type specimen" in genomic research.

Last September, the Dana Greenhouses staff received 100 new accessions (seeds, cuttings, plants) from expeditions related to the Campaign. Seeds from many accessions have already germinated, and others such as paperbark maple (*Acer griseum*) may take several cycles of warm and cold stratification to germinate uniformly. We look forward to transitioning individuals through the phases of production here at the Dana Greenhouses, with the end goal of having plants in their permanent locations in the living collections for researchers to study, children to learn from, and the public to enjoy.

PROPAGATION MATERIAL ARRIVES

In autumn, as plants in the living collections are slowing in growth and their foliage begins to abscise, the "growing season" in the Dana Greenhouses is just commencing. Production staff is overwhelmed with anticipation about what seeds, fruit, cuttings, and plants we will be receiving from foreign and domestic expeditions. However, once the highly sought-after fruit or cutting has been harvested from its parent and is now at long last in the hands of an Arnold Arboretum explorer, its trip to the Arboretum's greenhouses is nowhere near complete.

As Curator of Living Collections Michael Dosmann and Plant Records Manager Kyle Port (2016) explained in the last issue of *Arnoldia*, the United States Department of Agriculture's Animal and Plant Health Inspection Service



KYLE PORT

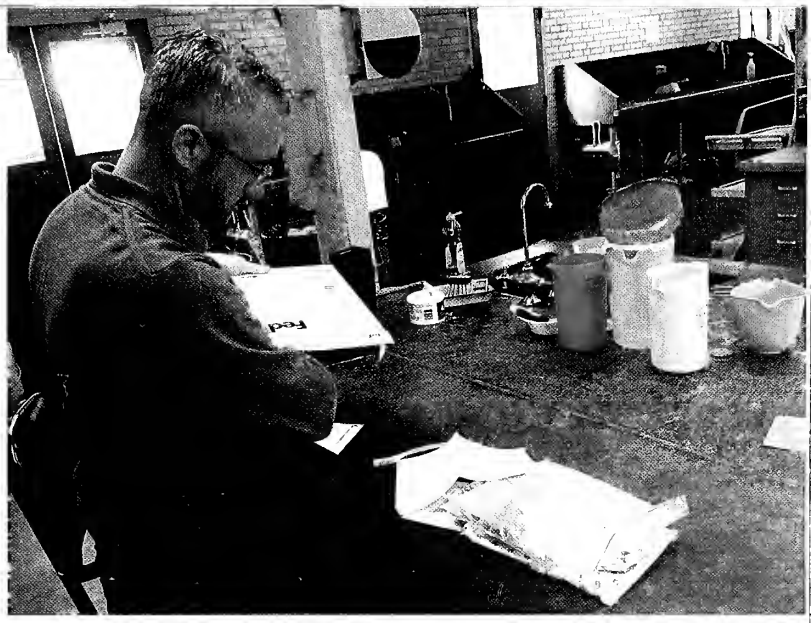
Fleshy fruits like these from wild-collected Washington hawthorn (*Crataegus phaenopyrum*) are soaked, rubbed, and sieved to separate the pulp from the seeds.

(APHIS) requires a specialized permit to import foreign seeds into the United States. This permit allows for the importation of a small quantity of seeds, pending a successful evaluation for hitchhikers—noxious weed or parasitic plant seeds, insect pests, or pathogens of concern. The Arboretum typically has seeds routed to the APHIS Plant Protection and Quarantine inspection station at John F. Kennedy International Airport in Jamaica, New York. Because the several day to weeklong inspection process is so complex and vital, foreign seeds have to be clean (removal of fruit surrounding seeds), properly labeled, and limited to only 50 seeds (or 10 grams [0.35 ounces]) per package. Should the scrutinizing agent discover any unwanted travelers on the coveted soon-to-be Arboretum seeds, the entire content of the package fails to pass the test, and the voyage for that seed lot ends there.

Because much time is spent to meticulously clean the seeds and package them correctly in the foreign country, the majority pass through inspection and are then shipped on to the Arboretum, where the true journey through

Clockwise from upper right:

Curator of Living Collections Michael Dosmann opens a shipment of seeds from the APHIS Plant Protection and Quarantine inspection station at John F. Kennedy International Airport in Jamaica, New York. The seeds were acquired during the North America-China Plant Exploration Consortium (NACPEC) expedition in September 2015 and were sent directly from China to the inspection station.



Jack Alexander prepares to sow *Quercus rehderiana* acorns in individual containers. These acorns were shipped directly to the Arboretum from collaborators in China. We then sent them to APHIS for inspection, and, after passing examination, they were returned to the Arboretum where they were cold stratified to break dormancy.

Kyle Port collected this bunchberry accession (*Cornus canadensis* 209-2015) as a whole plant during his expedition to northern Idaho in September 2015.

This paperbark filbert (*Corylus fargesii*) seedling is identified with accession number, form received as (SD = seed), and collection information on both hand-written and thermal-printed labels. Sixteen seeds were acquired during the 2015 NACPEC expedition and so far three have germinated.

ALL PAGE 5 PHOTOS BY TIFFANY ENZENBACHER

Seed Propagation

Seeds from our own staff collectors, collaborators, and other gardens never arrive in those colorful packets seen on garden center display racks. Our seeds may arrive in small, resealable polyethlene bags, coin envelopes labelled in beautiful cursive writing, or sheets of paper neatly folded into packets. All will be carefully handled as they enter the propagation process.

The first step is examination, since occasionally those packets contain more than seeds. Fruit remnants, cones, and chaff may arrive with the seeds, plus the occasional weevil or other insect. Collections made in foreign countries are thoroughly cleaned before being shipped since they will have to pass an inspection by APHIS (see page 4). Collections made within the United States by our own staff are seldom cleaned before being shipped back to the Arboretum, so at the greenhouse we often get to unpack boxes full of polyethylene bags containing rotting and fermenting fruits. Seeds from other arboreta and botanic gardens, be it foreign or domestic, are usually neatly cleaned and packaged.

Not every seed in every packet will germinate, though. We once obtained a half kilogram (about a pound) of wild-collected Chinese sweetgum (*Liquidambar acalycina*) seeds, but ended up with only a tablespoon of viable seeds while the rest were undeveloped. Anyone unfamiliar with sweetgum seeds could easily make this mistake since sweetgum fruits often hold more undeveloped seeds than sound seeds. Careful visual inspection may help determine sound from unsound seeds, but not always. For example, bald cypress (*Taxodium distichum*) seeds are not uniform and could easily be tossed out with the cones.

Before sowing, plant propagators routinely remove all that is not seed (e.g., fruit pulp, capsules, cones) because it is likely to host fungi, attract insects or rodents, or, in the case of fruit pulp, inhibit seed germination. Cleaning may involve soaking, drying, sieving, or a combination of these and other techniques. Sometimes seeds and chaff are all so tiny, and separating the two so difficult, that it only makes sense to clean reasonably well and sow it all.

Freshly collected seeds generally germinate in higher percentages than stored seeds so we go to work quickly once seeds arrive. Before sowing the cleaned seeds we need to know the best protocol for germination for that particular species. For many plants, past experience or a search of seed propagation reference materials provides well-established protocols for germination variables such as soil temperature, day length, or light/dark requirements. Seeds of most temperate zone species require cold stratification, which simulates winter conditions, and will germinate in higher percentages if they first experience 30 to 120 days at temperatures just above freezing. We routinely place seeds into polyethylene bags containing a moist, well-drained medium and refrigerate at 40°F for 90 days.

The seeds of some species need both warm and cold stratification periods. Examples include paperbark maple (*Acer griseum*) and related trifoliate maples, the dove tree (*Davidia involucrata*), and most viburnums (*Viburnum* spp.). And there are also many species whose seeds don't strictly require cold stratification (heath family [Ericaceae] members, for example) but they germinate more uniformly and in higher percentages if first given a one month cold stratification so we often opt for that treatment.

Another obstacle for germination in some seeds is the presence of an impermeable seed coat. Plants in Fabaceae, the pea family, often have impermeable seed coats, so we typically scarify seeds of any fabaceous species, whether known or new to us, by rubbing on sandpaper or a file. Scarified seeds are then soaked in water; if they "imbibe" and swell to about twice their size, they are ready to be sown or stratified. For all seeds, imbibition is the first step in germination (and why garden seed packets always exhort gardeners to "keep soil moist after sowing").

Keeping records is an essential part of plant propagation. To track germination percentages and successful protocols, we count seeds (or make a close estimate) before they are sown. Once the number of seeds is known and a protocol has been determined, we begin the specified treatment. With species that haven't been grown before at the Arboretum or for which no established protocol can be found, we may experiment and try a variety of treatments if there are plenty of seeds. If there are only a few seeds, we rely on experience and best judgement to pick a treatment.

Once stratifications (if needed) are complete, seeds are sown in flats and placed in a warm, humid greenhouse with the option of supplemental lighting. The best time to sow seeds is in the early spring but that timing isn't always possible, so supplemental lighting allows us to lengthen the photoperiod to simulate the longer days of spring and summer. When seedlings reach sufficient size they are potted up in individual containers, ready to continue through our production system. Modern technology has changed many greenhouse peripherals—we now use LED lights, thermostats, soil heating mats, and precise irrigation—but nature's requirements for seed germination haven't changed, and we accomplish that in much the same way as did the Arboretum's earliest propagators.

KYLE PORT

Many accessions of fruits and seeds are processed at the Dana Greenhouses.

the production system begins. On occasion, this step is skipped and seeds are shipped directly to the Arboretum from a foreign country. Since the inspection process is required by law and is essential in mitigating the introduction of invasive and/or threating agents to agriculture and the environment, greenhouse staff sends the material to APHIS to be inspected prior to any germination treatment.

If domestic fruits (berries, capsules, samaras, etc.), cuttings, or plants are acquired, such as materials that Kyle Port collected on his expedition to Northern Idaho last fall, they are shipped directly to the greenhouse. It should be noted that obtaining material from expeditions is not the sole means by which the greenhouse procures plants. Propagules and plants are also obtained by several other methods: through *Index Seminum* (seed list) exchanges offered by botanical institutions, from other gardens or arboreta, or by purchasing from nurseries (particularly when acquiring cultivars). However, upon receiving any new seed, cutting, or plant, no matter what it is or where it is from, the first step that production staff takes on is accessioning.

Similar to all museums, the Arboretum has a number classification system in place so that each plant can be treated as a specimen with a unique, recognized background. The accession number is composed of a number-year unit. For example, the number 274-2015 signifies the 274th plant material lot received in 2015. For every accession, abbreviations such as SD (seed), CT (cutting), PT (plant) denote the form of material received.

MOVING UP

After a seedling has rooted into its growing container, the next phase through the production system beckons. The Shade House, true to its name, is covered by woven polyethylene fabric that

TIFFANY ENZENBACHER

When it's large enough, this healthy *Rosa moyesii* seedling will be planted in the Shade House.

TIFFANY ENZENBACHER

Seedlings of *Acer oblongum*, a semi-evergreen maple native to the sub-Himalayan region, wait in the outdoor container area before being transplanted into the Shade House in 2016. The first Arboretum accession of this species in 1908 comprised seeds collected by Ernest H. Wilson in China. This most recent accession, 272-2015, represents the sixth accession of *A. oblongum* grown at the Arboretum.

A Rose Returns to the Arboretum

An illustration of *Rosa moyesii* from the October 21, 1916, issue of *The Garden*, a weekly gardening journal published in London from 1871 to 1927.

One accession in particular that we are eager about having the opportunity to move through the production system is Moyes rose (*Rosa moyesii*). First collected by Antwerp E. Pratt in 1893, *R. moyesii* was introduced from Western Sichuan in 1903 by Ernest H. Wilson, Arboretum plant explorer and botanist, and William Botting Hemsley. Wilson collected *R. moyesii* on the Tibetan frontier, near Tatien-lu, while on expedition for James Veitch and Sons Nurseries (Wilson 1906). Wilson noted that "the species is not uncommon in shrubberies on the mountains between Mt. Omi and Tatien-lu," and described the solitary flowers as "very dark red ... 5 to 6.5 cm across" and "singularly pleasing." Wilson wrote that *R. moyesii* was "named in compliment to the Rev. James Moyes, of the China Inland Mission, stationed at Tatien-lu, to whom I am much indebted for hospitality, assistance, and companionship on one long and interesting journey in Eastern Tibet." Sargent later commissioned Wilson to collect for the Arboretum, and in 1909 Wilson was successful in acquiring seeds—the Arboretum's second accession of *R. moyesii* (17091). The first accession (6827) was obtained two years prior, as a plant, directly from Veitch Nurseries.

The blossoms of *R. moyesii* are unique, an intense deep red. Wilson wrote in 1930, "few if any wild species of Rose have created so much interest as this native of the Chino-Thibetan borderland." However, he also noted that "unfortunately, in this climate the flowers bleach rapidly and New England gardens will never know the real beauty of this Rose," which prompted him to add that the "hips ... in this country are more attractive than its flowers." The showy orangish red hips have an elongated, bottle-like shape and can reach 2 inches (5 centimeters) long. *R. moyesii* is still a popular species rose today, but 'Geranium', a selection introduced to North America by the Arboretum, is more widely grown. 'Geranium' was written about in 1960 by Donald Wyman, Arboretum horticulturist from 1935 to 1970, as a plant of possible merit. It is more compact than the species, with larger hips. This selection originated at the Royal Horticultural Society's garden at Wisley in southern England.

JENNIFER RIOUX

Manager of Plant Production Tiffany Enzenbacher rearranges flats in the center alley to make room for *Cornus sericea* (accession 257-2015) and *Rosa moyesii* (accession 285-2015) seedlings. All seedlings transition from the greenhouse to the outdoor container area before being transplanted into the Shade House.

allows only 45% of the light to pass through. This keeps the vulnerable plants less stressed after transplant. Seedlings and small cuttings or plants are transplanted into the highly organic soil of this evaluation nursery in late spring to early summer and are well tended throughout the season. Plants are mulched in and hand watered until established. There is an overhead sprinkler system for irrigating the entire nursery when necessary. Rodents have been problematic, occasionally damaging all individuals within an accession, so caging plants that they appear to be most attracted to such as horse chestnut (*Aesculus*), hickory (*Carya*), and oak (*Quercus*) has become mandatory in recent years.

The Shade House also offers a first test of cold hardiness. Since the vast majority of Arboretum

TIFFANY ENZENBACHER

Former Isabella Welles Hunnewell 2014 Intern and Term Employee Olivia Fragale (left) and former Hunnewell 2015 Intern Carly Troncale (right) standing next to cages in the Shade House that they constructed to protect seedlings from possible rodent damage.

accessions funnel through here, and because the greenhouse area is in a recognized cooler microclimate of the Arboretum (Dosmann 2015), it provides a rudimentary assessment of hardiness. However, if a species is known to be marginally hardy, one to several individuals may be containerized instead of being planted in the Shade House. Those individuals would then subsequently be planted in a warmer microclimate of the Arboretum to increase their likelihood of survival during typical Zone 6 (average annual minimum temperatures -10 to 0°F [-23.3 to -17.8°C]) Boston winters. Along with hardiness, seedlings are also evaluated for form and vigor.

HEADING TO THE COLLECTIONS

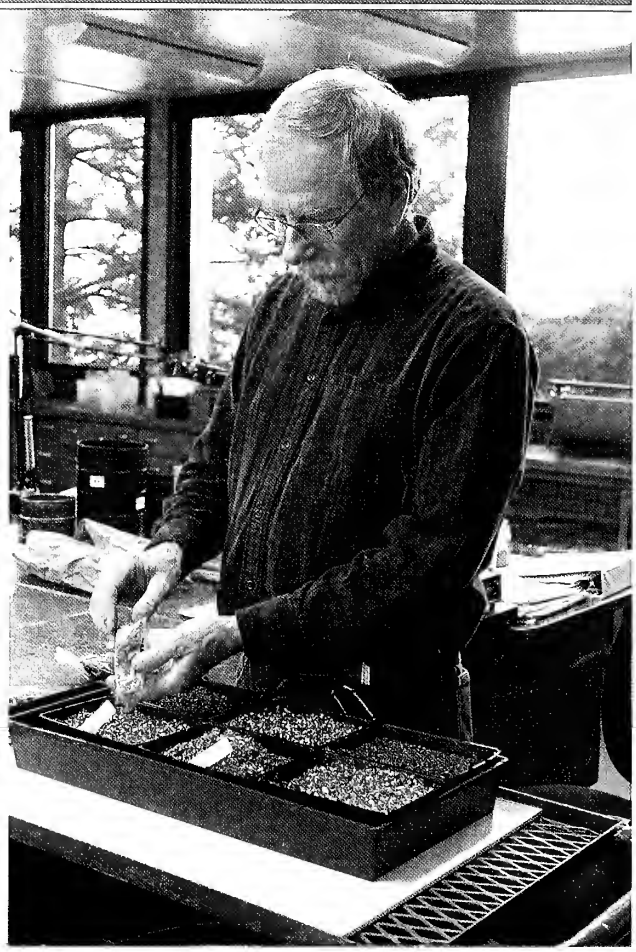
After the individuals in an accession are large enough to transplant, shrubs get containerized and trees continue their journeys through the facility into one of three longer term nurseries.

After entering the production facility as a propagule, trees take anywhere from five to seven years in the system before they are robust enough to be transplanted into the living collections. Shrubs are at the greenhouse for three to five years on average. The voyage of an accession through the Dana Greenhouses concludes when the individuals are planted into their sited location out on the grounds. Now a new, much longer passage of life begins.

KYLE PORT

Shrubs and trees gain size in the container area (foreground) and the East Nursery (beyond container area). Curator Michael Dosmann, Manager of Horticulture Andrew Gapinski, and Manager of Plant Production Tiffany Enzenbacher regularly walk through the nurseries and container areas and determine which individuals will be designated for upcoming plantings.

TIFFANY ENZENBACHER



TIFFANY ENZENBACHER

KYLE PORT

Young trees may grow for several years in the well-mulched East Nursery adjacent to the Dana Greenhouses. Once they attain sufficient size, they will be transplanted to permanent locations on the Arboretum grounds.

Long-time Arboretum plant propagator Jack Alexander was sowing seeds in the Dana Greenhouses earlier this year.

Divisions of twinflower (*Linnaea borealis,* 198-2015) collected by Kyle Port during last year's North Idaho Expedition take root under mist. This trailing, semi-woody evergreen has a wide circumboreal distribution and was named in honor of famed Swedish botanist Carl Linnaeus.

TIFFANY ENZENBACHER

The cold storage building provides a controlled climate during winter for dormant seedlings, rooted cuttings, containerized plants, and the bonsai and penjing collection.

The Campaign for the Living Collections is now in its second year and it is already providing greenhouse staff with exciting and challenging opportunities to germinate seeds, root cuttings, and grow-on wild-collected species that are new to the Arboretum as well as previously attempted taxa. The Campaign has reinforced the importance of horticultural research and reasserts that propagation is very much center stage, even as we near our 2022 sesquicentennial. As autumn is fast approaching and new collecting expeditions will soon start, we are once again awaiting the propagules that will be beginning their journey through the production system. We can only imagine that this is how Dawson felt during Wilson's 1907 to 1909 expedition to China, eager to receive the 2,262 seed collections and 1,473 collections of live plants or cuttings that resulted from the trip.

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Tiffany Enzenbacher is Manager of Plant Production at the Arnold Arboretum. Plant Propagator John H. Alexander III recently retired from the Arboretum after 40 years of service.

Unlocking Ancient Environmental Change with the Help of Living Trees

John M. Marston

With both human societies and ecosystems worldwide now facing ongoing, and even accelerating, environmental change, both scholars and policy makers are increasingly concerned with predicting the future implications of climate change. Where will our coastlines, tree lines, and urban boundaries lie in 50 or 100 years? How will changes in the seasonality and intensity of precipitation, frosts, and heat waves affect the plants and animals on which we rely for food? And, most important, what are the consequences for us?

One avenue for understanding human responses to dramatic environmental and climatic change is to look to the past when societies faced similar periods of rapid change. Paleoclimatologists and paleoecologists have developed numerous methods to identify ancient environmental change, creating rich records from glacial ice at the poles and on mountaintops, as well as cores drilled deep into seabeds and lakes that preserve hundreds or thousands of years of annually deposited sediments. Archaeologists who study the deep history of human-environmental relationships draw on these datasets, as well as archaeological records of social and economic change, to explore human adaptation to environmental change in the past.

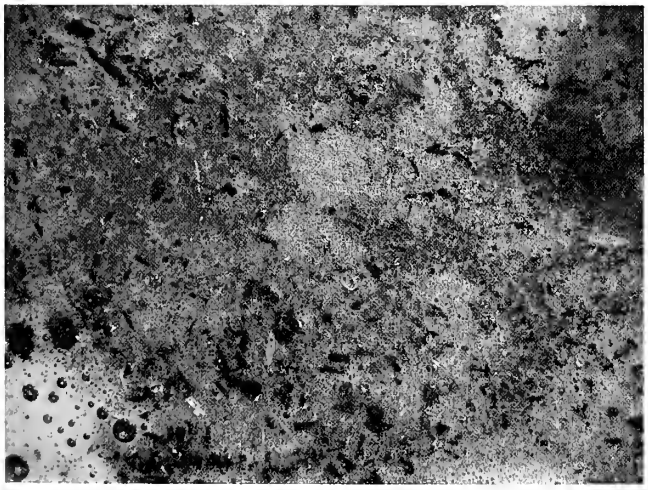
A variety of archaeological finds are useful in identifying climatic change, from mammal and fish bones to microscopic starch grains found on tools used in plant food processing. One material commonly found in archaeological sites from many different periods of the human past, nearly worldwide, is wood charcoal. Incompletely burned wood from fireplaces, ovens, kilns, and accidently (or deliberately) burned buildings becomes inorganic charcoal, which is resistant to degradation from soil microbes and fungi and thus can survive for thousands of years within the soil. It is frequently possible to identify the type of tree that produced these charcoal remains and thus reconstruct patterns of wood use and forest change, both as a result of climatic change and deliberate or inadvertent human reconfiguration of woodlands. Scholars have developed methods for systematically recovering, identifying, and interpreting these remains to identify patterns of climate and environmental change in the past.

Recently, Boston University and the Arnold Arboretum have begun a partnership to draw on the vast living collections of the Arboretum to improve the resolution of archaeological charcoal studies in the Environmental Archaeology Laboratory in the Department of Archaeology at Boston University. In this article, I describe how archaeologists study charcoal from archaeological sites and use it to reconstruct the human role in environmental change, highlighting how resources of the Arnold Arboretum enhance our teaching and research mission at Boston University.

Recovering and Identifying Archaeological Plant Remains

Wood charcoal fragments from archaeological sites have been studied since the 1940s to address multiple questions about human wood use in the past. The first step in archaeological charcoal analysis is systematic recovery of charcoal remains from archaeological sites. Although not a universal practice, the recovery of plant remains is increasingly ubiquitous among archaeologists worldwide, even in remote areas of developing countries. We recover soil samples, generally 10 to 20 liters (2.6 to 5.3 gallons) in volume (equivalent to one or two buckets full), from every archaeological level and distinct feature (e.g., a pit or a hearth) identified during excavation.

Archaeologists most commonly use a water flotation method to recover charred plant

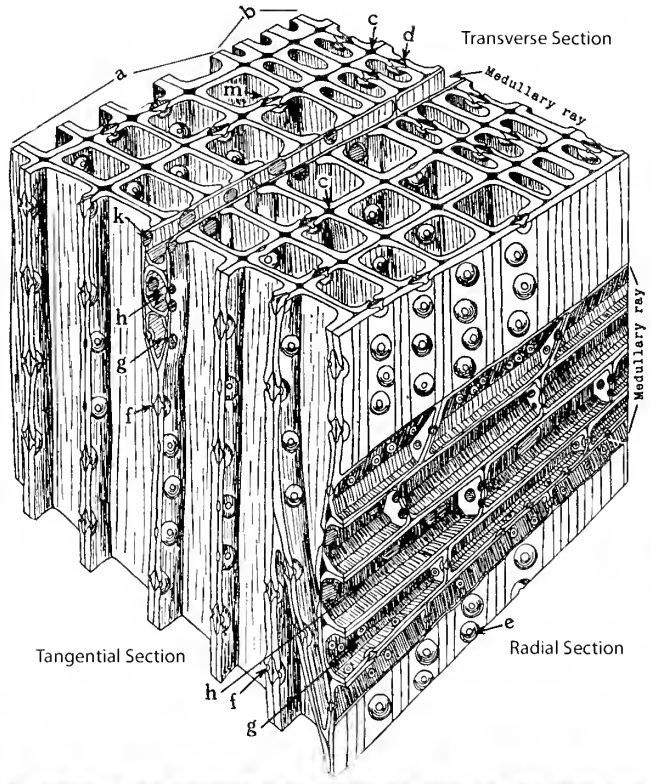


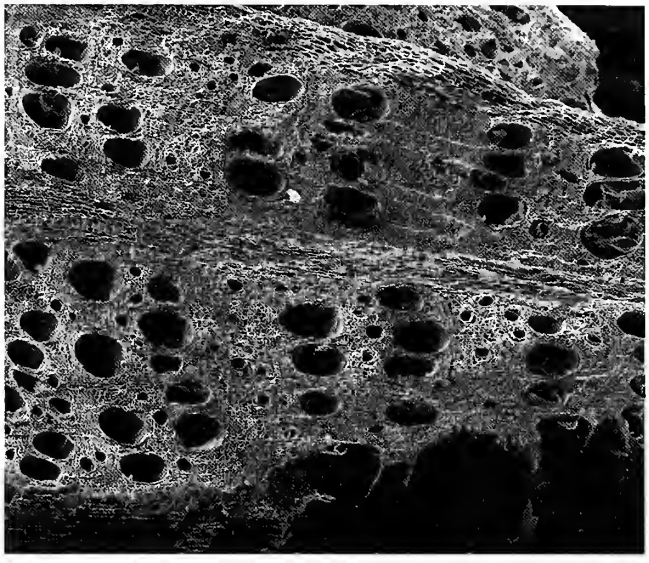
The author operating a flotation tank on site in Turkey, and charred plant remains floating to the surface within the tank.

remains, including wood charcoal as well as carbonized seeds and other plant structures, from soil samples. Although flotation can be accomplished using only a pair of buckets and a fine mesh strainer, more common are systems that pump large volumes of water to process even large samples quickly. Clean water is pumped into the tank of the machine where the soil sample is held in a plastic window screen mesh. The water dissolves the soil, freeing carbonized plant remains, which float, and rinsing away sediment in the dirty effluent that is released from the bottom of the tank. Heavy components of the soil, including bone and pottery fragments as well as occasional heavy pieces of charcoal, are caught in the window screen and later dried and analyzed. The floating, or light, fraction consists of wood charcoal and carbonized plant remains, but also soil components lighter than water, including tiny roots and fine clay particles. The light fraction is allowed to overflow into a very fine polyester mesh, with holes less than 0.1 millimeter (0.004 inch) to catch even the smallest seeds. This fraction is then carefully air dried and brought to the laboratory for identification and analysis.

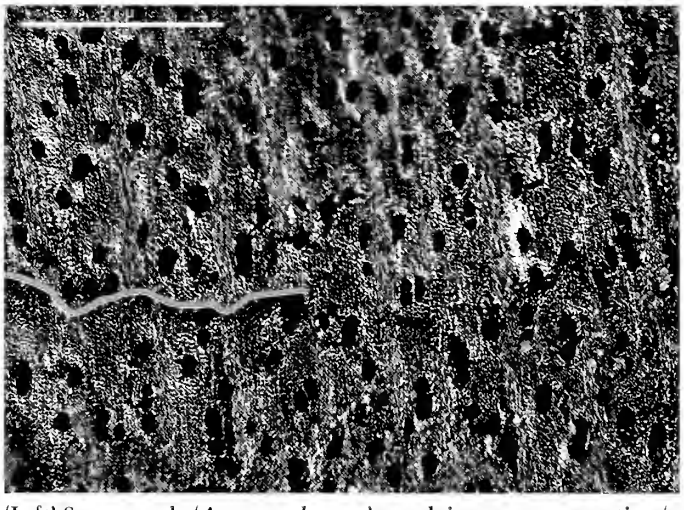
We then pour the light fraction through a series of nested sieves, creating several size classes of material that can be sorted differently. In general, only wood charcoal fragments larger than 2 millimeters (0.08 inch) are analyzed, as smaller fragments are unlikely to be identifiable. Systematically sorting each size class under low-power stereomicroscopes, we remove each type of plant remain for subsequent identification and measurement, with wood charcoal, carbonized seeds and seed fragments, and nutshell distinguished and separated. Wood charcoal fragments are then weighed in aggregate and a representative number of those fragments are identified.

The identification of wood charcoal can be challenging because fragments are often small and may be distorted by burning and subsequent deterioration in the soil. Fortunately, different species of woody plants vary considerably in their cellular anatomy, which allows wood (even charcoal) to be identified to varying levels of specificity depending on the wood





(Left) Diagram of pine wood, showing three planes of structure (image from *Plant Anatomy* by William Chase Stevens, 1916, Philadelphia: P. Blakiston. Courtesy of Florida Center for Instructional Technology, http://etc.usf.edu/clipart/). (Right) Scanning electron micrograph of Turkey oak (*Quercus cerris*) wood from the Environmental Archaeology Laboratory collection.



(Left) Sugar maple (*Acer saccharum*) wood, in transverse section (scale bar 500 µm = 0.5 mm); growth ring boundary is marked with red line. (Right) Black pine (*Pinus nigra*) wood, in transverse section (scale bar 500 µm = 0.5 mm); growth ring boundaries are marked with red lines.

type. Wood can be viewed from three planes, each of which presents a distinct set of anatomical structures for identification. All three are necessary for detailed identification, but the transverse, or cross section, is the most useful for charcoal identification and can be examined with a stereomicroscope at 20 to 100× magnification. Distinguishing hardwoods (angiosperms) and softwoods (gymnosperms) can be easily accomplished using just low-power magnification of the transverse section; many families within these large categories can also be distinguished based solely on the transverse section. Using a combination of basic reflected light microscopy, high-power incident light microscopy, and electron microscopy, we cata-

log features of archaeological wood fragments and assign them tentative identifications based on their anatomy. Confirmation of these identifications, however, typically requires a comprehensive comparative collection of modern wood taken from properly identified and fully vouchered trees. Assembling such a comparative collection has been an ongoing effort of the Environmental Archaeology Laboratory and is the origin of our collaboration with the Arnold Arboretum.

Using the Arboretum as a Research Collection

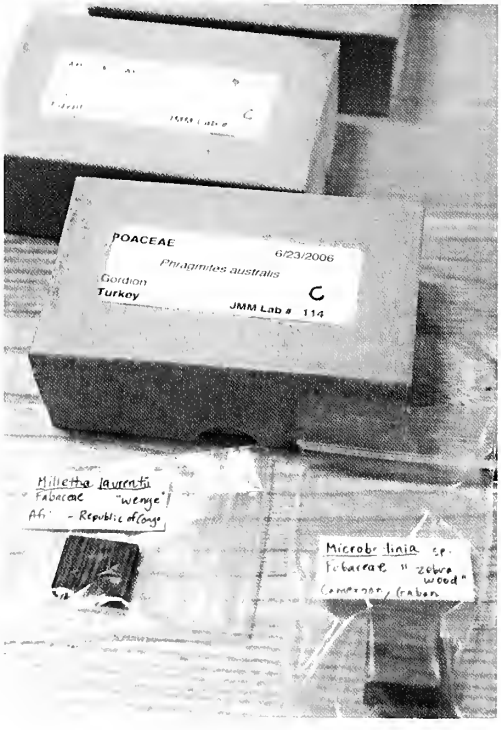
The Arnold Arboretum offers a tremendous opportunity to collect wood from a wide variety of temperate tree species from the Americas, Europe, and Asia. Each tree is properly identified and labeled, and considerable information regarding its life history is recorded in the Arboretum's living collections database. For our partnership, since most woody plants are identifiable at the genus level, we preferentially collect wood from species native to the areas in which members of the Environmental Archaeology Laboratory work (mainly southern Europe, the Middle East, East Asia, and northeastern North America). When the most relevant species are not available, we choose other species of those genera in order to obtain the most similar comparative specimens possible.

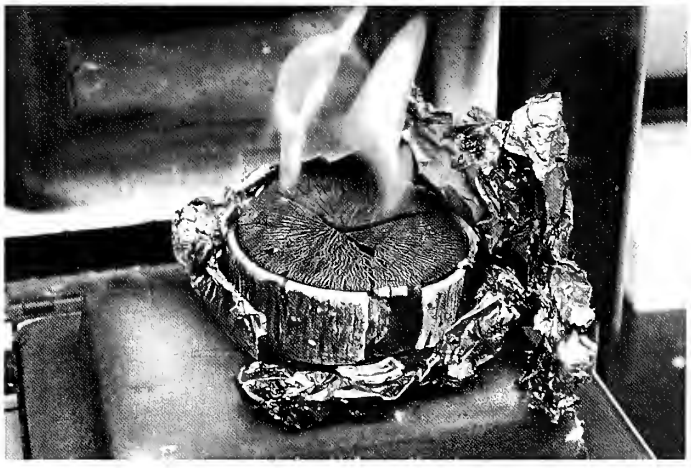
Wood anatomy can vary based on the diameter and age of the branch collected, between branch and trunk wood, and because of unique growth conditions such as bending or disease. As a result, we attempt to collect wood from multiple parts of a tree when possible. The Arboretum facilitates our collection by allowing us to gather dead branches that have fallen from trees as well as gathering samples from trees that are trimmed or cut down during the course of routine tree maintenance activities. Members of the Environmental Archaeology Laboratory compiled a "wish list" of trees in the living collections that Arboretum arborists can refer to when tree work is done. The arborists then collect specimens from trees of specific interest to us. We periodically stop by the Arboretum to collect these wood samples for further processing at Boston University.

Back in the Environmental Archaeology Laboratory, we interface with the Arboretum's database and use the Arboretum Explorer website (http://arboretum.harvard.edu/explorer/) to gather information about trees that have been sampled. We record much of that information into the Environmental Archaeology Laboratory Collections Database, which is also searchable online (http://sites.bu.edu/ealab/collections/database/). The wood sample is then divided between a wood specimen and a specimen to be converted into charcoal. Experimental carbonization of comparative wood samples is critical for two reasons. First, carbonization can modify the structure of the wood in predictable ways, leading perhaps to certain patterns of cracks that can be diagnostic when examining archaeological wood charcoal. Second, charcoal can be easily broken to expose any of the three planes, facilitating rapid examination, while wood needs to be cut with an ultrathin blade so as not to crush the exposed cell walls, requiring additional equipment and time to prepare comparative slides.

We carbonize wood using a muffle furnace capable of reaching temperatures of 1000°C (1832°F), although we typically carbonize wood around 400°C (752°F) to maximize speed of carbonization without incinerating the wood. It is critical that wood heat in an oxygen-poor reducing atmosphere because that promotes charcoal formation, while an abundance of oxygen would lead to ashing and destruction of the sample. We carefully wrap samples twice in heavy-duty aluminum foil to minimize contact with oxygen and pack them tightly in the muffle furnace. At 400°C, wood carbonizes in 10 to 40 minutes, depending on the thickness of the pieces.

Finally, both charcoal and wood specimens are stored in labeled boxes within a specialized shelving system in the lab. The boxes include basic information on the wood and its location of origin, together with an identifier code that corresponds to its record in our database. A future project for the laboratory is to take microscopic images of the wood anatomy of all woods in the collection and to make them available online, both through the laboratory website and as a contribution to Inside Wood





Clockwise from top left:

Collected wood specimens to be accessioned into comparative collection. Larger pieces were provided by the Arnold Arboretum.

Preparation of wood for experimental carbonization: sawing a sample for carbonization; packing the muffle furnace; a fully carbonized specimen, just out of the furnace.

Samples housed and labeled for comparative collection.

(http://insidewood.lib.ncsu.edu), a free, public, wood anatomy database created at North Carolina State University. Although extensive comparative collections of wood samples are preserved at other arboreta and herbaria worldwide, very few of these have been digitized to make them publically accessible. Because our collection includes specimens from many countries of the Middle East and Central Asia, as well as specimens from several arboreta in the United States, we aim to publicize our records as widely as possible as a research tool for archaeologists worldwide.

Reconstructing Past Woodland Ecology and Wood Use, with Implications for the Future

Once it is possible to identify wood fragments reliably, we work to identify a statistically robust subsample of all wood charcoal fragments present in our archaeological samples. Recording both count and weight of these fragments, we are able to create diagrams that represent change in the prevalence and context of use for woods over time. For example, in my ongoing research at the ancient city of Gordion, in central Turkey, which was inhabited from the Early Bronze Age (3000 to 2000 BC) through the medieval period (fourteenth century AD), I was able to document changes in wood use practices and forest ecology over a span of 3,000 years. Gordion became a large city around 800 BC as the capital of the Phrygian kingdom, which grew from Gordion to control most of central Turkey. At that time the Phrygians began to construct monumental temples, massive city walls, and huge earthen burial mounds (the largest over 170 feet [52 meters] in height) containing royal burials inside elaborate wooden structures, including the oldest standing wooden building in the world.

This amazing structure was fashioned from juniper (*Juniperus* spp.) wood, which was widely used within the city in roofing large public buildings. Juniper is a slow-growing tree, however, and the inhabitants of Gordion appear to have quickly exhausted their supply of easily cut large juniper trees. In later periods of occupation, charcoal samples from burned buildings indicate that oak (*Quercus* spp.) and pine (*Pinus*

KYLE PORT

Wood samples from this yellow birch (*Betula alleghaniensis*, accession 629-83-F) were carbonized for the Boston University Environmental Archaeology Laboratory charcoal collection.

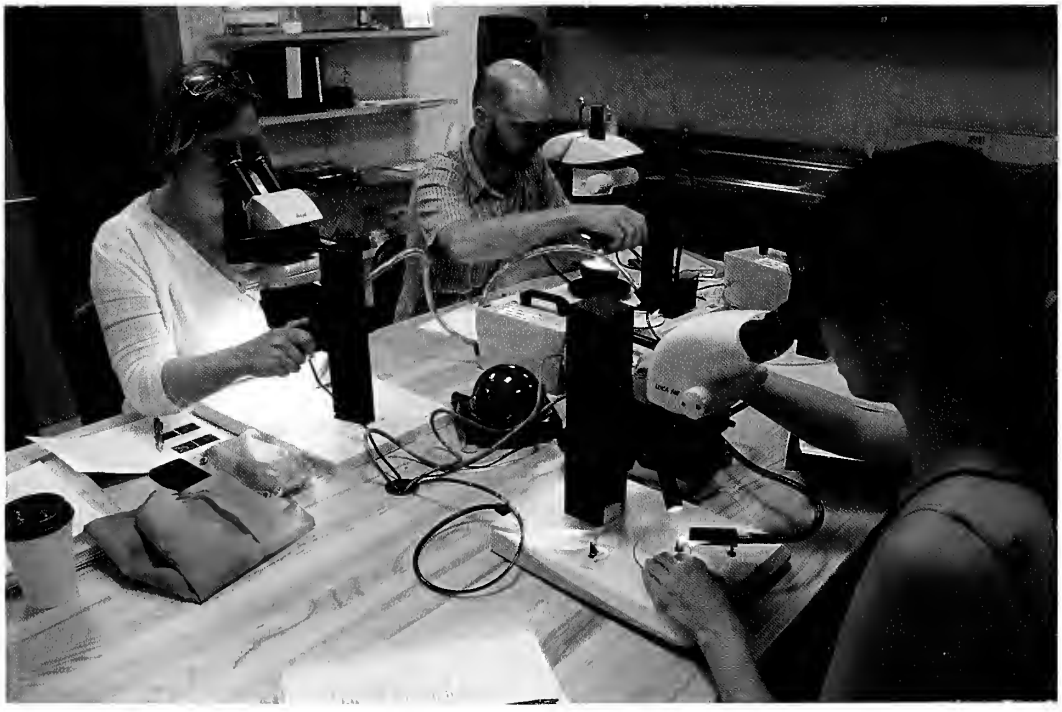
KYLE PORT

Wood samples from this hybrid tuliptree (*Liriodendron tulipifera* × *chinense*, accession 584-81-A) growing near the Arboretum's Hunnewell Visitor Center were provided to the Boston University Environmental Archaeology Laboratory.

Using the Arboretum as a Teaching Collection

Every summer I teach a weeklong intensive workshop on wood anatomy and wood charcoal identification for archaeologists. Participants come to Boston from universities nationwide, from Santa Barbara to Chapel Hill, and a few even join us from across the river in Cambridge. Participants are mainly doctoral students, but we have a number of faculty participants and even an occasional undergraduate. During the week we cover wood anatomy from initial concepts (e.g., the three planes of wood) to advanced structural variation (e.g., ray cell margin shape in gymnosperms). We also read and discuss a number of articles that illustrate best practices for sampling and recovery of wood charcoal from archaeological sediments, methods for quantifying and presenting results, and the challenges of changes brought about by both the initial burning of wood and its preservation in soils for hundreds or thousands of years. Students spend the last few days analyzing their own wood charcoal assemblages and learning how to identify the woods common to their areas of expertise, which have ranged from southwest China to Jordan, the California Channel Islands, the Yucatan, and the Andes.

One highlight of the week is our field trip to the Arnold Arboretum. The group receives an orientation and tour led by Michael Dosmann, Curator of Living Collections. During the tour, workshop participants learn about the unique collections of the Arnold Arboretum and about the life history of particular trees on the property. Following an orientation to the Arboretum Explorer web application, participants are able to use their smartphones to find particular trees of interest to them and spend the next two hours visiting those trees. We collect a few samples of dead wood from the ground under selected trees to bring back to the laboratory, where we then experimentally carbonize wood samples and study their microscopic structure. Participants then split their newly collected specimens, with a portion joining the permanent collection of the Environmental Archaeology Laboratory and the rest returning home with each participant. As a result, every participant returns to their home lab with the beginning of a personal comparative charcoal collection and the experience needed to expand their collection through fieldwork and collaborative ventures with local botanical gardens and arboreta.



Participants in the 2014 wood charcoal workshop analyzing samples in the Boston University Environmental Archaeology Laboratory.

Clockwise from top:

The funerary chamber within the largest burial mound at Gordion, dated to 743–741 BC, showing the outer casing of roughly finished juniper logs.

Juniper logs used as support ties within a stone wall at Gordion.

A Greek juniper (*Juniperus excelsa*) of a size similar to that of the logs in the funerary chamber; trees of this size are rare in the landscape around Gordion today.

spp.) were the primary woods used in construction, both of which have the advantage of being fast-growing trees that often take over in sites where older juniper trees have been cut. Oak and pine, however, have inferior strength and rot resistance compared to juniper. Archaeological wood charcoal assemblages show a dramatic human impact on the landscape that led to considerable forest reorganization during the early history of the city. Later inhabitants of the region had to contend with a different landscape, and different availability of natural resources, than their ancestors.

Examples such as the case of Gordion parallel more recent human history, both in central Turkey and worldwide, in which human activity transforms a landscape for future inhabitants. When viewed from the perspective of later populations, we term these impacts "legacy effects," and the implications of such changes are many. It has been argued by several scholars, including Jared Diamond, that the deforestation of Easter Island pushed its ecosystem beyond a tipping point that led to severely reduced resources and impoverishment of the isolated inhabitants. In contrast, legacy effects may also have been deliberate outcomes, designed to boost productivity and resource availability. The use of fire to maintain prairie habitats in the American Great Plains prior to European contact is an example of such "niche construction," in which people modify their environment to boost productivity of desired resources to suit their cultural needs.

Archaeologists have explored these environmental histories using wood charcoal analysis, and continue to search for a deeper understanding of not only when and how, but also why human groups manipulate their landscape in specific ways. These detailed studies offer cases of environmental disaster and social collapse, but also resilience and survival in even the most uninviting landscapes. As contemporary society faces environmental change on an unprecedented scale, archaeologists offer both cautionary and inspiring stories of human-environmental relationships that provide novel, proven effective tools for continued survival in a changing world.

Additional Reading

These include sources that outline the practice of archaeological wood charcoal analysis (Asouti and Austin 2005, Marston 2009); wood anatomy and identification (Panshin and de Zeeuw 1970, Schweingruber 1990, Schweingruber et al. 2006); frameworks for studying human-environmental interactions (Cumming et al. 2006, Marston 2015, Redman 1999, Smith 2007); and more about our team's recent work at Gordion (Marston in press, Miller 2010, Rose 2012).

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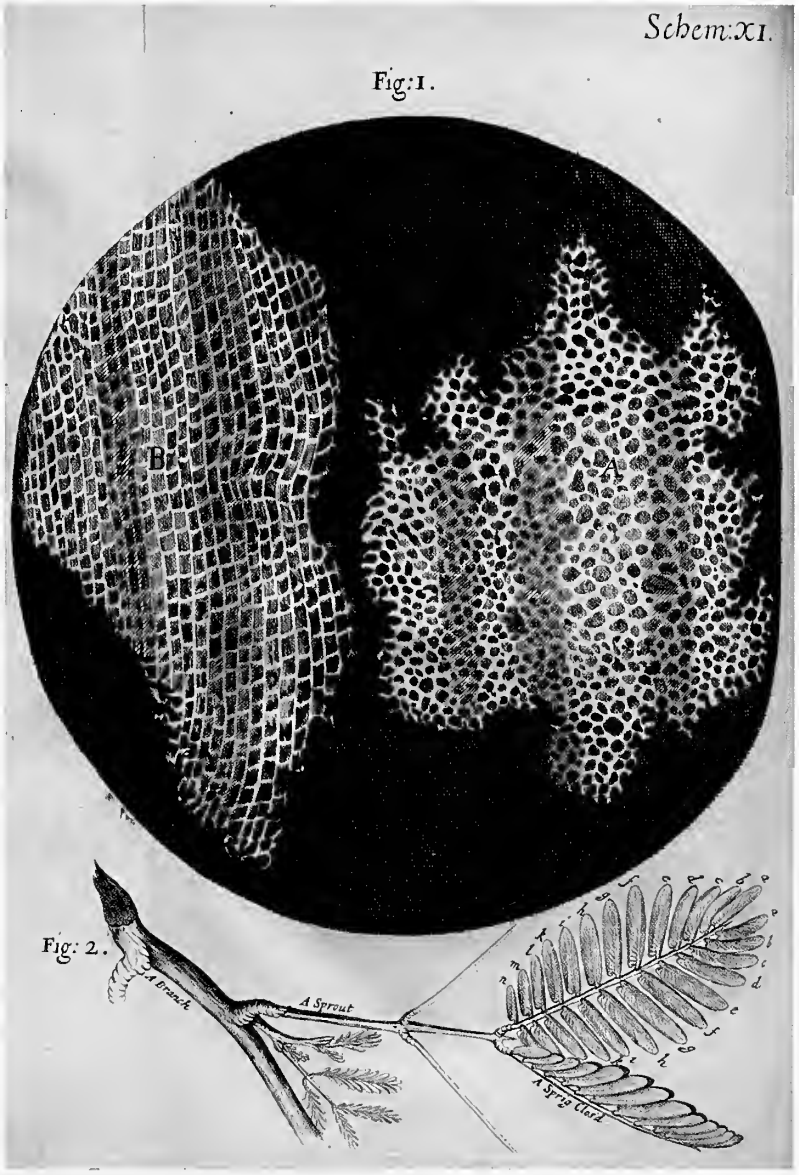
Cork: Structure, Properties, Applications

Lorna J. Gibson

Ever since people have cared about wine, they have cared about cork to keep it sealed in bottles. *"Corticum abstrictum pice demovebit amphorae ..."* (Pull the cork, set in pitch, from the bottle) sang the Roman poet Horace in 27 B.C., to celebrate the anniversary of his miraculous escape from death from a falling tree. In Roman times, corks used to seal bottles were covered in pitch; it was not until the 1600s that a method for stoppering bottles with clean corks was perfected by Benedictine monks at Hautvillers in France. Cork's elasticity, impermeability, and chemical stability means that it seals the bottle without contaminating the wine, even when it must mature for many years. The Romans also used cork for the soles of shoes and for floats for fishing nets. According to Plutarch (A.D. 100), when Rome was besieged by the Gauls in 400 B.C., messengers crossing the Tiber clung to cork for buoyancy.

Cork is the bark of the cork oak, *Quercus suber,* which grows in Mediterranean climates. Pliny, in his *Natural History* (A.D. 77), describes it: "The cork-oak is a small tree, and its acorns are bad in quality and few in number; its only useful product is its bark which is extremely thick and which, when cut, grows again." All trees have a thin layer of cork in their bark; *Quercus suber* is unusual in that, at maturity, the cork forms a layer many centimeters thick around the trunk of the tree. The cell walls of cork are covered with thin layers of unsaturated fatty



Robert Hooke's book *Micrographia* amazed readers with its detailed drawings such as this one of cork showing the roughly rectangular cell shape in one plane and the roughly circular cell shape in the perpendicular plane. The lower drawing is of sensitive plant (*Mimosa pudica*), whose touch-induced leaf movement Hooke studied. For more images and insight on *Micrographia* from this article's author, please view this YouTube video: https://www.youtube.com/watch?v=zFfVtziLhg4

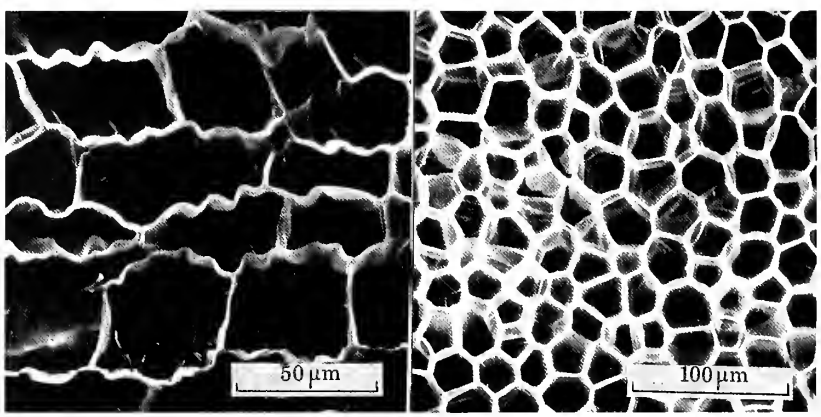
Cork is harvested from managed cork oak (*Quercus suber*) forests such as this one in Portugal.

acid (suberin) and waxes, which make them impervious to air and water, and resistant to attack by many acids.

Cork Under the Microscope

Cork occupies a special place in the history of microscopy and of plant anatomy. When English scientist Robert Hooke perfected his microscope, around 1660, one of the first materials he examined was cork. What he saw led him to identify the basic unit of plant and biological structure, which he called the "cell" (from *cella*, Latin for small chamber). His book, *Micrographia*, published in 1665, records his observations, including the comment that, "I no sooner descern'd these (which were indeed the first *microscopical* pores I ever saw, and perhaps, that were ever seen, for I had not met with any Writer or Person that had made any mention of them before this) but me thought I had with the discovery of them, presently hinted to me the true and intelligible reason of all the *Phenomena* of Cork." Hooke's detailed drawings of cork show the roughly rectangular cell shape in one plane and the roughly circular cell shape in the perpendicular plane. Hooke noted that the cell walls were arranged "as those thin films of Wax in a Honey-comb."

Modern scanning electron micrographs of cork show additional detail. In the plane in which the cells look rectangular, we see that the cell walls are wavy, rather than straight, and in the perpendicular plane, the cells are roughly hexagonal prisms, with the waviness in the cell walls along the length of the prism axis. The dimensions on the unit cell are microns, or micrometers (μm); for comparison, a human hair is roughly 50 microns in diameter.

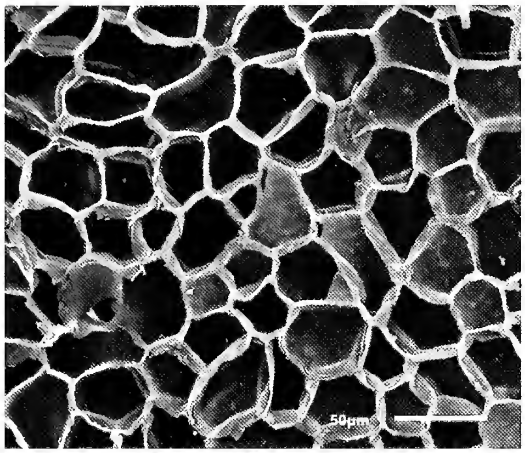


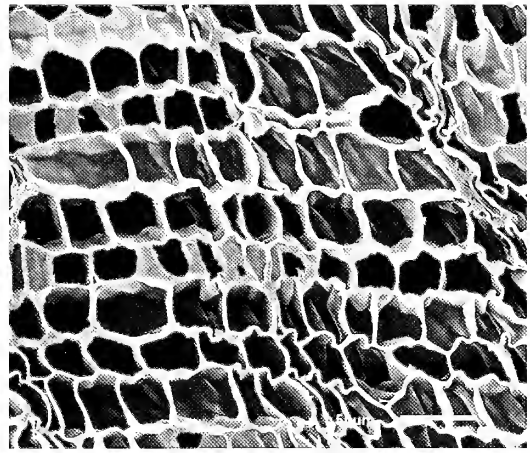
Scanning electron micrographs of cork cells in the same two perpendicular planes as in Hooke's drawings, showing the corrugations in the cell walls (from Gibson et al., 1981).

Cork Tree vs Cork Oak

The Arboretum's cork tree (*Phellodendron* spp.) collection lies south of the Hunnewell Visitor Center along Meadow Road, as seen in the photo below. There are 18 *Phellodendron* specimens comprising 5 taxa, all native to Asia, in the collection.

While the bark of cork trees has a similar compliant feel as that of the true cork oak (*Quercus suber*), it is not used as a source of cork. These scanning electron micrographs of two perpendicular planes in *Phellodendron* bark show more irregular cells compared with those of *Quercus suber* (seen on page 24). Cork oak is only cold hardy through USDA hardiness zone 8 (average annual minimum temperature 10 to 20°F [-12.2 to -6.7°C]) so there are no specimens at the Arboretum.





LESLIE J. MEHRHOFF, UCONN, BUGWOOD.ORG

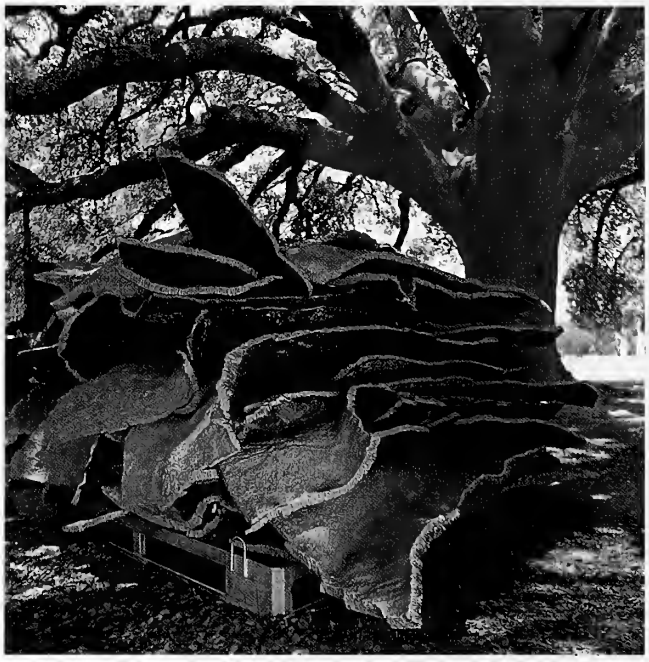
How Cork Works

Cork is roughly 15% solid and the rest is air. Its density is typically about 15% that of water: its low density, combined with the closed cells that do not allow water to enter, gives cork its great buoyancy. The low volume fraction of solid, along with the relatively compliant cell wall material, gives rise to its compressibility.

The waviness or corrugations in the cell walls of cork leads to an unusual behavior: if pulled along the prism axis, the corrugations in the cell walls straighten out, with little change in the transverse dimension (like the bellows of an accordion unfolding). In contrast, if you pull on most materials they get narrower in the transverse direction (think of pulling on a rubber band, for example). And if a cube of rubber is compressed some amount in one direction, it will expand out sideways by nearly half that amount in each of the other two transverse directions. When compressed along the prism axis, the corrugations in cork's cell walls simply fold up, again producing no change in the transverse dimension. It is this property, along with the compressibility of cork, that makes it easy to insert cork into a bottle and gives a good seal against the glass neck of the bottle.

Cork makes good gaskets for the same reason that it makes good bungs for bottles: it is compressible, accommodating deformation, and its closed cells are impervious to liquids. Thin sheets of cork are used, for instance, as gaskets between sections of woodwind instruments. The sheet of cork is always cut with the prism axis normal to its plane, so that when the two sections of the instrument are mated, the cork does not expand around the circumference of the section and will not wrinkle.

Cork makes an admirable flooring material because it is comfortable to walk on (thanks to its compressibility), it holds warmth, and it doesn't become slippery, even when wet. Cork holds warmth because it transfers heat poorly. In porous, cellular solids such as cork, heat transfer occurs by conduction (through the solid or gas), by convection (as gas on the warmer side of a cell rises and that on the cooler side falls, setting up convection currents), or by radiation. Gases have lower thermal conductivities than solids (by a factor of up to a thousand) so the high volume fraction of air within the cells reduces heat transfer by conduction through cork. Convection currents, carrying heat from one side of a cell to the other, are suppressed for cell sizes less than about 1 millimeter (for small cell sizes, the buoyancy force associated with hot air rising is counteracted by drag of the air against the walls of the cells). And heat flow by radiation also depends on cell size—the smaller the cells, the more times the heat has to be absorbed and reradiated, reducing the rate of heat flow. So the high volume fraction of air in cork and its small cells contribute to its ability to hold warmth.

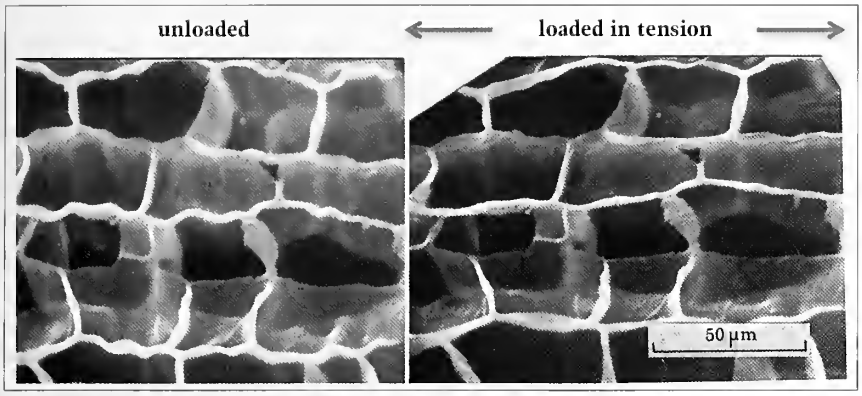


COURTESY OF AMORIM

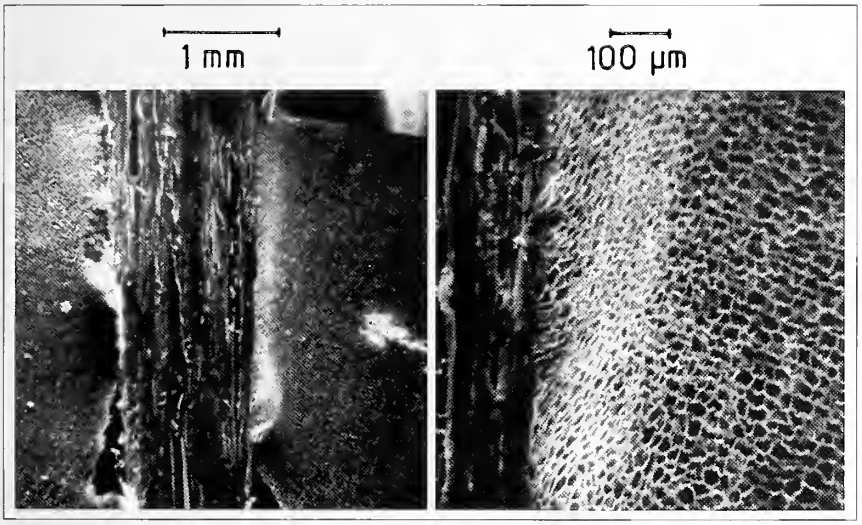
Sheets of cork oak bark rest in front of the tree they were harvested from.

KESSLER AND SONS MUSIC

Cork gaskets are used at the tenon joints of clarinet sections.



Micrographs showing (left) cork cells unloaded and (right) the progressive straightening of cell walls as cork is pulled along the prism axis (from Gibson et al., 1981).



A pin pushed into cork results in a narrow band of crushed cells next to the pin (left) but little deformation of the cork beyond that (right) (from Gibson et al., 1981).

Friction between a shoe and a cork floor has two origins. One is adhesion, in which atomic bonds form between the two contacting surfaces and work must be done to break them. Between a shoe and a tiled or stone floor, this is the only source of friction, and since it is a surface effect, it is completely destroyed by a film of water or soap, making the floor slippery. The other source of friction is due to energy losses associated with loading and unloading the floor (as a step is taken, for instance). In some materials, such as stone, these energy losses are small, but in cork, the energy losses are significant (it is said to have a high loss coefficient). Since the energy losses occur within the cork, and are not a surface effect, cork floors do not become slippery even when wet or soapy.

Cork is widely used for bulletin boards. When a pin is stuck into cork, the deformation is very localized around the pin. A narrow band of cork cells, occupying a thickness of only about a quarter of the diameter of the pin, collapses, crushing those cells nearly completely, to accommodate the diameter of the pin. The deformation in the cells beyond this highly deformed band is negligible in comparison. For this reason, the force needed to push the pin into a cork bulletin board is small. And cork recovers most of the deformation when it is unloaded, so that the hole nearly closes up after the pin is removed.

The cellular structure of cork is unique. It gives rise to a remarkable combination of properties that are exploited in everything from bottle stoppers and gaskets to the soles of shoes, flooring, and bulletin boards.

Acknowledgements

This article is based on the paper, *The structure and mechanics of cork*, co-authored with Ken Easterling and Mike Ashby, referenced below; it is a pleasure to acknowledge their contributions. Micrographs on pages 24 and 27 are from that paper.

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Ulmus thomasii: The Hard Elm That's Hard to Find

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If you hike Beech Path up the steep slope from Valley Road and continue to the point where a footpath branches off to the right, you will find a slender, stately tree next to the trail. It is a rock elm, *Ulmus thomasii*, one of only three elms native to northeastern North America. This particular specimen, accession number 444-88-A, is the only rock elm currently in the Arnold Arboretum's living collections. It is well worth seeing.

Rock elm was originally named *Ulmus racemosa* in 1831 by its discoverer, American civil engineer David Thomas of New York. It was renamed *Ulmus thomasii* in 1902 by Arboretum director Charles Sprague Sargent when he determined that another elm already had the name *Ulmus racemosa*. Rock elm is most common in the northeastern and north-central states, with the core of its range stretching from north-central Wisconsin to southern Michigan and southern Ontario. Populations exist as far south as Tennessee, but it is primarily a cold-weather tree, not often found in regions warmer than USDA Plant Hardiness Zone 5 (average annual minimum temperature -10 to -20°F [-23.3 to -28.9°C]). Rock elm is rarely encountered in New England, likely because it has a strong preference for limestone substrates, which are not common here.

Back in the 1910s to 1930s there were as many as twelve rock elms growing on the Arboretum grounds, all procured from well known plant nurseries of the era. Most of these trees eventually died of Dutch elm disease (DED), a devastating fungal vascular wilt. Four succumbed to Boston's first big DED epidemic in 1946. Two died of DED in 1987, another three in 1989. Specimen 17925-B was recorded as being in "excellent health" on May 5, 1989. It was cut down 75 days later, on July 19, dead from DED. Our current living specimen was propagated in 1988 as a cutting from a then 102-year-old tree (accession 17926-A) that was planted at the Arboretum in 1886.

One of the best traits for identifying a rock elm—not often listed in identification books—is its form. The species is typically tall and slender, with a single bole that gets remarkably tall before it splits into a narrow crown. Rock elms growing in crowded forest situations also usually have small corky branches that droop downward from the middle third of the main bole. The Arboretum's specimen has grown out in the open all its life and does not have drooping branches at mid-bole, though it does have a strikingly straight main trunk and currently measures 44.24 feet (13.48 meters) tall with a dbh (diameter at breast height) of 18.31 inches (46.5 centimeters).

Rock elm leaves can look much like American elm leaves. Tree identification books generally list three identifier traits for rock elm: *branches* with 3 to 5 irregular corky wings; *inflorescences* of 7 to 13 flowers arranged in a long, pendulous raceme; and *fruits* (samaras) covered with tiny hairs and an inflated paper wing that is not distinct from the seed case. Unfortunately those unique traits are not always present. Some rock elms, including our specimen, lack corky twigs. Rock elms don't reproduce until about age 20, don't produce full seed crops until age 45, and produce bountiful seed crops only once every 3 to 4 years. Seeds drop from the tree as soon as they ripen, so from May to February there are no reproductive structures to aid identification.

The timber of rock elm is especially prized for its hardness. It has interlaced fibers that make it almost impossible to split, yet easy to bend. It is especially durable underwater. In past centuries, much rock elm was cut and shipped to Great Britain to build wooden battleships. Rock elm is also highly regarded for its beautiful gold fall foliage color, so consider a hike up Beech Path this autumn. A tall, handsome native elm is awaiting you.

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