

PHYSICAL MODELS AS AN AID FOR TEACHING WOOD ANATOMY

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SUMMARY

Student activities and instructor-made models are described to facilitate and encourage other instructors to develop their own appropriate activities and models for teaching the three-dimensional structure of wood. The teaching activities include making several annual rings with straws pushed into clay, drawing wood's structure onto a piece of paper that is folded to resemble a wedge, and assigning students to make an anatomical model to present in class. Plans are given for instructor-made models (1:500 scale) of tracheids, vessel elements, and a hardwood 'fiber' to demonstrate their relative dimensions and geometries. These models also include a set of outerwood and corewood tracheids onto which the microfibril angle is traced, and one tracheid on which bordered and cross-field pitting are shown. Plans are then given for a bordered pit pair with its membrane (1:6300 scale). The last model demonstrates the Hagen-Poiseuille equation with an array of 16 conduits that together have the same potential flow as one conduit of two times their diameter. The use of these models has enlivened the classroom and helped students to more readily grasp wood anatomy and function.

Key words: Teaching wood anatomy; physical models; classroom.

INTRODUCTION

In 2003, I asked subscribers to the online discussion group IAWA Forum (<http://bio.kuleuven.be/sys/iawa/>) for advice on how to engage undergraduate students more fully when teaching wood anatomy. One of the foremost suggestions (summarized in Anonymous 2003) was to use physical models of wood structure in the teaching. Following are some of the suggestions from the posting:

“Create exercises that make sure they understand the 3D nature of wood. Require them to construct a three-dimensional anatomical drawing of a block of wood (e.g., oak, pine, beech).”

“Use colored clay for modeling cells and tissues as they are looking in the microscope. Then have students exchange their work and discover what their classmates made.”

“Put students into the 3D structure as much as possible with whatever tricks you can come up with, and play down the microscopes/hand sections part.”

“Visualization of wood structure does not click for some people until they build their own model.”

“Give each student a small block of a softwood. ... Have them label the surfaces with TS, TLS, and RLS, and any features they can see on each surface. Then, working in pairs, have them construct a 3D model of a softwood as seen at a higher magnification, using drinking straws.”

“As a teaching aid, make a large-scale model of a softwood out of wooden tomato stakes. ... Draw the various types of pits on to the tracheids and rays, so they could be seen to correspond.”

“Then have students draw cells on paper at higher magnification, and glue them onto a wood block, so all the tissues are linked together correctly.”

This advice has been incorporated into instruction in two ways: with student exercises that involve their making models, and with the use of scale models that I made. The purpose of this paper is to describe the processes and outcomes for both of these approaches, and to encourage others to incorporate the use of simple models in instruction.

The motivation for the 2003 posting was that in spite of earnest efforts to make the Wood and Fiber Anatomy class interesting and relevant, I felt that students were not learning the material adequately. The class is small, averaging 10 students per year from 1994 to 2010. Students are in their third or fourth year at the university, and many of them have already had short careers in the wood industries. The class has three 50-minute periods and a 3-hour laboratory period per week for a 10-week term. At the end of each course, OSU administers course evaluation questionnaires, but they do not demonstrate a change in student learning. The class was rated highly by students both before and after introduction of the models, and the questionnaire was changed the same year that models were introduced. Student responses to my early supplemental questionnaires, however, reinforced my feeling that they were not learning anatomy adequately. Responses from the 1999 class included the following: “[I would have liked] more detail on learning cell types, although I got better under the microscope. I still need to learn a lot more and wasn’t sure about a lot of what I did,” and “Learning cellular features in lab was fairly difficult for me.” I had the feeling that about one-third of the students in any of the classes was very challenged to learn the three-dimensional relationships in wood. By 2003, many learning activities had been tried, included field trips to the forest for samples to analyze for within-tree variability; weekly quizzes and homework as well as changes in the textbook; guest lecturers in allied fields; demonstrations and/or labs on areas such as wood permeability or the expansion or shrinkage of juvenile (core) wood relative to mature (outer) wood; special lectures relating wood anatomy to topical areas with more immediate relevance to students such as mechanical properties, pulp and paper, and wood deterioration; use of a projecting system for a microscope; addition of a writing assignment on the structure/property relationship in a species of their choice; and so on. I believe the models have been the single most important teaching innovation in the class. In 2009, when asked for comments on the models, students responded with statements such as “Models were fun” and “I liked the models,” and even “You are fun.” Although there are no hard data to support this opinion, my strong sense is that the models were associated with an improvement in student enjoyment of the class and understanding of structure.

ASSIGNMENTS IN WHICH STUDENTS MAKE OR MANIPULATE MODELS

Observing major macroscopic and microscopic features

The first laboratory period comes after students have had one or two classroom lectures. Activities in this lab aim to familiarize students with the basics of softwood anatomy at macroscopic and microscopic scales. Students also are introduced to the use of microscopes, the technique of making usable hand-sections with a razor blade, and the importance of adhering to proper technique for safety. An unwritten goal of this lab is to establish a learning environment in which students reset their learning expectations: 1) in this class, much of their learning is achieved through their active involvement in seeking answers, 2) this learning can be fun, and 3) working in a team with fellow students improves their learning outcomes. This latter achievement will become important later in the class, in our curriculum, and in the workplace.

Each student starts with a wood wedge (including bark and pith) and a hand lens. They find the three major planes, and label them with masking tape (background, Fig. 1A). They then show a partner the major macroscopic features (pith, annual rings, earlywood, latewood, cambial region, inner bark, and outer bark). Still in pairs, they then use a com-

compound microscope to look at prepared sections of a Douglas-fir (*Pseudotsuga menziesii*) or a pine to see the major features in all three planes (in cross section (X): annual ring, earlywood, latewood, tracheid, resin canal, ray; in radial section (R): tracheid, ray, earlywood, latewood; in tangential section (T): tracheid, uniseriate ray, fusiform ray, resin canal). Next, they use a razor blade to make sections of a wetted piece of low density, easy-to-section softwood such as western redcedar (*Thuja plicata*) or redwood (*Sequoia sempervirens*). They make sections of all three planes, arrange them on a microscope slide, and look for the same features as in the prepared sections (except for resin canals).

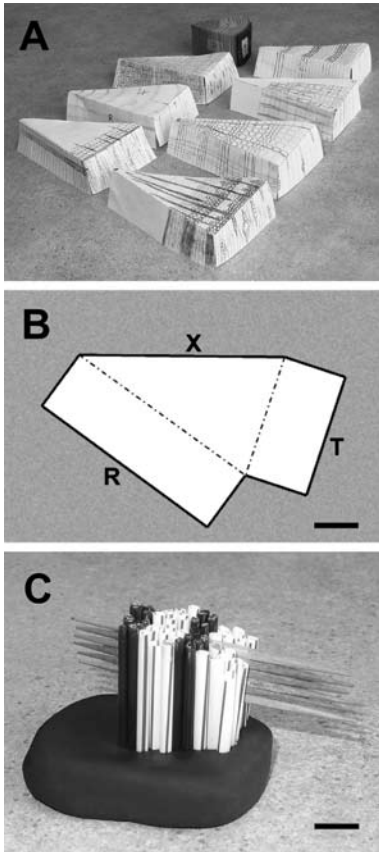


Figure 1. Models made by students during the first laboratory period. — A: Wedge of paper onto which students draw softwood features, with labeled wood wedge in the background. — B: Silhouette of wood wedge (to cut on the solid lines). Students label the planes, draw the wood features making sure that features in one plane connect properly to the same feature in the next plane, then fold on the dashed lines and tape at the RT corner. — C: Two conifer growth rings with earlywood (wide straws), latewood (coffee stirrers), and a ray (flat toothpicks, different colors at top and bottom to represent ray tracheids). — Scale bar in B & C = 10 mm.

Model of several annual rings and a ray

After students have finished looking at their hand-sections (above), they make a physical model of several growth rings (Fig. 1C) in order to improve their understanding of wood's cellular structure in three dimensions. They make a base with oil-based modeling clay (plasticine) and then insert into it earlywood cells (2-cm-long segments of drinking straws or round toothpicks) and latewood cells (2-cm-long segments of hollow plastic coffee stirrers or flat toothpicks) until they have made two annual rings. Next, they construct a ray with a ray tracheid at the top and bottom (flat toothpicks of one color) and ray parenchyma cells in between (three flat toothpicks of a second color). They hold the ray together with clear tape. They then insert the ray into the two annual rings that they have already finished.

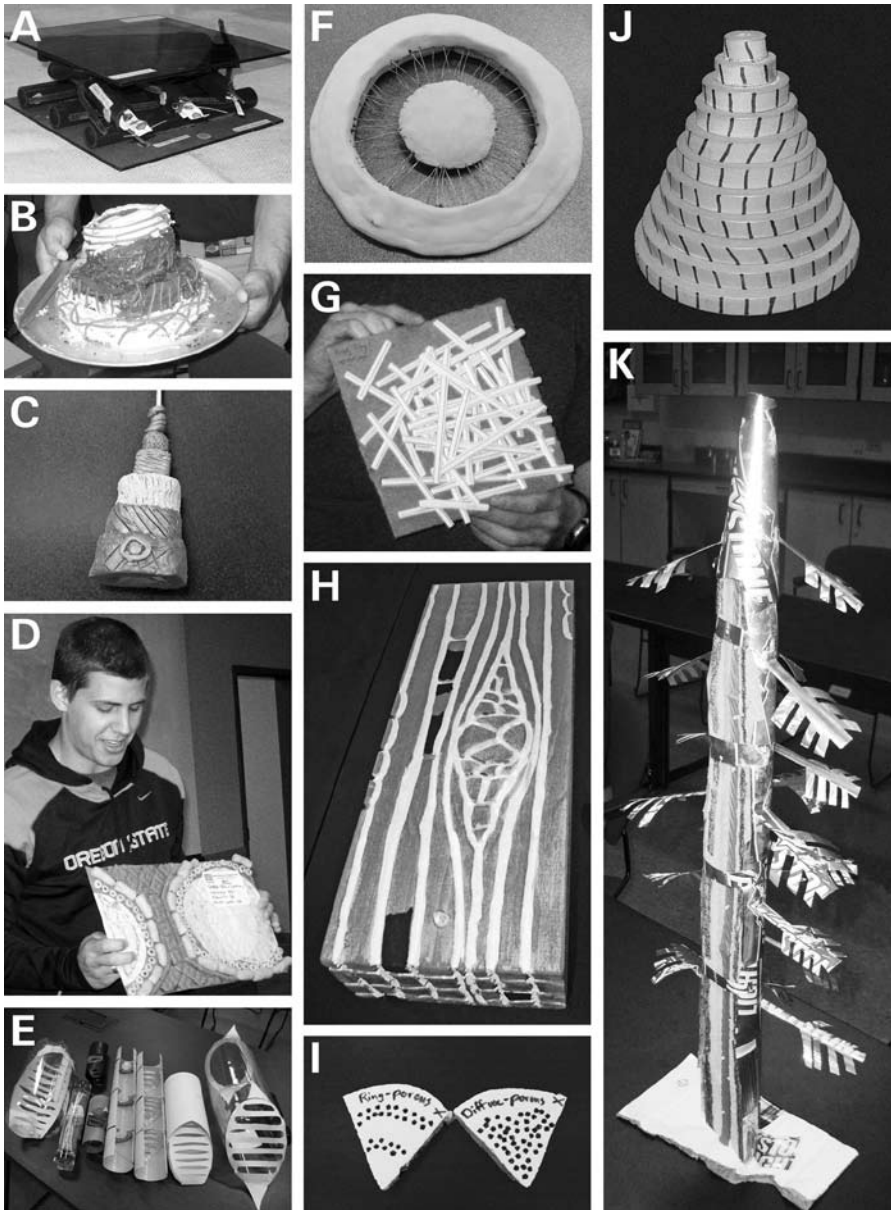
Drawing wood structure onto a wedge-shaped folded paper

As a final exercise in this first laboratory period, students draw anatomical features onto a paper representation of a wedge of wood (Fig. 1A). They are given a piece of paper that can be folded into a wedge and secured with one piece of tape; it is pre-cut for them (Fig. 1B). They are asked to fold it, but not to tape it yet. They are not shown a finished model because I want them to determine relationships for themselves. They are asked to label the three planes (X, R, and T) and then to draw the following. In X, they draw pith, tracheids (about 5–10 across the wider edge), rays, and earlywood and latewood for several growth rings. In R, they draw earlywood and latewood tracheids such that the cells connect properly to the cells in the X plane. They also draw a ray but it is not expected to show proper cellular structure. In T, they draw tracheids and rays, again connecting properly to the other planes. They use a length of tape to give the model its three-dimensional appearance, and then they set it alongside their labeled wood wedge and their model of several growth rings (with clay and toothpicks) at the back of the classroom for consultation during the rest of the term. Once or twice this exercise has re-appeared on an exam.

As I had been advised by the respondents on the IAWA Forum, students have benefited from touching, rotating, sectioning, and envisioning wood. This exercise has also been useful to me by indicating which of the students may need more help in the future.

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Figure 2. Examples of models of anatomical features made by students. – A: Cell wall showing microfibrils (PVC pipe) encrusted with hemicelluloses (pipe cleaners) sandwiched between clear plastic sheets (air-space depicting the lignin matrix); cellulose chains (hand-drawn onto strips of paper) inside the microfibrils. – B & C: Three-dimensional depiction of cell wall layers (layers of cake or modeling clay) and microfibril angle (licorice that is embedded in frosting, or grooves carved in the clay). – D: Two-dimensional depiction of cell wall layers (crackers, dry pasta, packing material, and breakfast cereal glued onto cardboard). – E: Simple and scalariform perforations (paper or cardboard) inside vessels (clear plastic soda bottles, shot glasses, cardboard tubes). – F: Pit membrane (wire spokes embedded in molded foam) and a torus (molded foam). – G: Cellular structure of paper (flattened soda straws of various lengths glued at random angles



across one another and to cardboard backing). – H: Wood block showing tracheids, longitudinal parenchyma with inclusions, pitting, a fusiform ray and a uniseriate ray (solid board that had been routed and marked to show features). – I: Hardwood vessel distribution patterns in the cross section (Styrofoam and marking pen). – J: Interlocked grain (cardboard disks of graduated cambial age, their tangential surface marked with grain angle). – K: Longitudinal section through conifer showing branch whorls and bark (fashioned from cut-open beer cans), phloem, sapwood, and heartwood (a longitudinally cut foam ‘noodle’ designed as a flotation device in the swimming pool, colored with marker), surrounding pith (licorice).

Take-home assignment to make a model of an anatomical structure

Each student is asked to make a model of an anatomical feature to share with the class (Fig. 2). The three goals are to have students get a better feel for the physical structure of wood, to provide a non-verbal way of expressing themselves (especially useful for some types of students), and to keep some levity in the class to engender better attitudes toward learning. I had also hoped this exercise would provide me with durable, visible models. Unfortunately, the articles are usually more fun than they are useful to me in teaching in future years.

It has been heartening, however, to see how much energy and creativity students put into the models, and how engaged most of them are with this exercise. Many students seem to appreciate an opportunity to use materials (such as wood and PVC, polyvinyl chloride) and tools with which they are already familiar from former jobs or hobbies. They also put much more energy into these models than to my other assignments. For example, one student, a former tree feller, was on academic probation and was struggling with study skills. He proudly unveiled his project from beneath a black cloth, that at first looked like an aluminum rocket with fringes (Fig. 2K): it was an elaborate tree made from a series of beer cans that he had cut (with a pocket knife) into sheets with little branches at their bottoms. It had pith (red licorice), xylem and phloem (a foam 'noodle' used for floating in a swimming pool), outer bark (the cans), and branch whorls. Other students have expressed creativity by using ordinary materials from the grocery store (cereals, crackers, noodles, candies, cake mixes and icing); one student arrived late and extremely proud, with a sagging undercooked cake with melted icing, announcing that this was the first cake he had ever made (Fig. 2B). On the less appetizing side, another student made an excellent model of cell wall with gelatin for the lignin matrix and different candies for the cellulose and hemicellulose. Other students go to craft stores for modeling clay, oven-bake clay, or moldable foam, or to the recycle bin for items like toilet paper rolls, packing material, Styrofoam sheets, cardboard, cans, or bags.

The students are warned early in the quarter that this assignment is coming, so they can start thinking about options. Two or three weeks before the due date, they receive the assignment that lists the learning goals, asks them to make a physical model of a structure that is somewhat anatomically correct (with the appropriate parts and in the appropriate orders but not necessarily to scale), that is inexpensive and takes them less than four hours to construct; and to prepare a simple presentation. To prohibit their making vessel perforations or any of the other several favorite features, they are told to make a model of a structure on the list unless they get permission to make a different feature. In 2010, the list included a microfibril, a tracheid showing layers and microfibril orientations, wood with figure on it (birdseye, flatsawn, quarter sawn, blister, *etc.*), or a model of paper.

They give a short presentation of the model, telling what it represents and how the structure contributes to properties of the wood or the tree. The audience includes the class and students who have already taken the class (mostly seniors and a few graduate students). The presence of the more advanced students helps lighten the atmosphere, and also promotes connections among the student cohorts. Students are given full credit for any viable model and accurate oral presentation. Figure 2 shows a selection of the models received and the materials from which they were made.

SCALE MODELS MADE BY INSTRUCTOR

Few of the student-made items have provided the durable, visible models that could be used later in my teaching, so I constructed several models myself. They are useful not only with undergraduate and graduate students but also with visitors to the university, from kiln operators and wood importers to potential donors.

Vessel elements, tracheids, and libriform fiber at the same scale

These models show the wide range of dimensions among these cell types. They are constructed at a scale of 1:500 (1 mm represented by 50 cm, and 10 mm representing 200 μm) in three sets of materials, depending on the purpose (Table 1, Fig. 3A). The first set used PVC pipes to represent earlywood and latewood vessel elements of white oak (*Quercus alba*), and a vessel element of the diffuse porous species red alder (*Alnus rubra*) (Fig. 3A). The available diameters of pipe are close to the desired sizes (Table 1). After pipes were cut to length, they were covered with a suitable spray-paint. Several duplicate vessel elements of each group were made to enable the stacking of vessel elements to represent a vessel.

The second set of materials used hemlock stakes, square in cross section and of appropriate dimensions to represent a tracheid from the outerwood (mature wood) of Douglas-fir (Table 1, Fig. 3A and inset). Numerous data suggest that tracheids are about 100 times longer than they are wide (*i.e.*, 32 μm diameter and 3.2 mm long, or 33 μm diameter and 3.5 mm long, Dunham *et al.* 2007). The OSU carpenter bevelled the final 2.5 cm at the two ends of the stake into a point. From inspection of Panshin and deZeeuw's (1980) tangential section of Douglas-fir, ray crossings were estimated to occupy 12–25% of the tracheid's length, and ray height to be about 4–7 times the tracheid diameter. Bordered pits were represented with gummed reinforcements (the doughnut-shaped reinforcers used to reinforce the holes in notebook paper), but note that they were slightly larger than desirable for the scale model. Cross-field pits and tracheid-to-ray tracheid pits were made from trimmed bits of the gummed reinforcements (see Fig. 4A inset). Two coats of urethane were then applied in order to seal the pits on and to increase the models' durability. Not shown here is a part of another tracheid with bordered pits, used to demonstrate that the pit pairs coincide on adjacent tracheids.

Another outerwood stake was paired with a smaller stake for corewood (juvenile wood) to represent their mean microfibril angles of the S_2 wall (MfA) (Table 1, Fig. 3A). To draw the spirals, the following technique was used. Twine was wrapped onto the stakes, secured at both ends with rubber (elastic) bands, and then adjusted until the scent angle was correct. The spiral then was drawn with a permanent marker about mid-way between the strings. Again, models were coated with urethane for protection. These stakes are useful for discussion of strength, shrinkage, within-plant variability in xylem structure, and outerwood vs. corewood.

The third set of materials used wooden dowels of appropriate diameter and length (coated with urethane) to represent an outerwood Douglas-fir tracheid and a 'typical' hardwood fiber (using red alder as the model) (Fig. 3A). These dowels are particularly useful when talking about paper composition and properties.

Table 1. Dimensions of physical models of vessel elements, tracheids and a fiber including the measure of the feature being modeled, the target size of the model at the scale of 1:500, the actual size of the feature in the model, and notes regarding the feature being modeled. Ages refer to cambial age of the sample (number of growth rings from the pith). PVC refers to polyvinyl chloride (plastic) pipes. MfA refers to microfibril angle in the S₂ layer.

Feature	Anatomical measure	Model's target size	Actual model size	Model notes
Earlywood vessel element, white oak (ring-porous)				
Length	340 μm	17 cm	17 cm PVC pipe	Estimated from photo (plate 40, Côté 1980)
Diameter	300 μm	15 cm	15.2 cm (6 in) inner diam.	Estimated from photo (p. 35, Hoadley 1990)
Latewood vessel element, white oak (ring-porous)				
Length	640 μm	32 cm	32 cm PVC pipe	After latewood vessel diameter was estimated (below), found vessel element of similar diam. in photo and estimated length (plate 40, Côté 1980)
Diameter	40 μm	2 cm	2.2 cm (7/8 in) inner diam.	Estimated from photo (p. 104, Hoadley 1990)
Vessel element, red alder (diffuse porous)				
Length	680 μm	34 cm	34 cm PVC pipe	Estimated from photo (plate 37, Côté 1980)
Diameter	70 μm	3.5 cm	4.1 cm (1 ⁵ / ₈ in) inner diam.	35 years old (Gartner <i>et al.</i> 1997)
Outerwood tracheid with pits, Douglas-fir				
Length	3.74 mm	187 cm	183 cm (6 ft) wooden stake	Averaged values (table 4-4, Panshin & deZeeuw 1980)
Diameter	37 μm	1.9 cm	1.9 cm (3/4 in) square	Used the relationship that earlywood tracheids are ~100 times longer than wide
Bordered pit width	22 μm	1.1 cm	1.4 cm	110-year-old tree (Domec <i>et al.</i> 2006)
Ray height	150–250 μm	7.5–13 cm	Various, used the range	4–7 times tracheid diameter (from slides of macerations)
Amount of tracheid length that is ray	470–940 μm	23–47 cm	Various, used the range	1/8 to 1/4 the length of the cell is covered with ray (from slides of macerations)
Pits on each R face (no.)	45		45	25 years old (Dunham <i>et al.</i> 2007), consistent with photo (Côté 1980)

(Table 1 continued)

Feature	Anatomical measure	Model's target size	Actual model size	Model notes
Outerwood tracheid with MfA, Douglas-fir				
Length	3.74 mm	187 cm	183 cm (6 ft) wooden stake	As in outerwood tracheids, above
Diameter	37 μ m	1.9 cm	1.9 cm ($3/4$ in) square	As in outerwood tracheids, above
MfA	14.6°		15°	29-year-old trees (Lachenbruch <i>et al.</i> 2010)
Corewood tracheid with MfA, Douglas-fir				
Length	1.76 mm	88 cm	wooden stake	4-year-old tracheid (Megraw 1986; Peterson <i>et al.</i> 2007)
Diameter	24 μ m	1.2 cm	1.3 cm ($1/2$ in) square	4-year-old tracheid (Spicer & Gartner 2001)
MfA	26°		26°	4-year-old tracheid (Erickson & Arima 1974)
Softwood 'fiber' (outerwood of Douglas-fir)				
Length	3.74 mm	187 cm	183 cm wooden dowel	As in outerwood tracheids, above
Diameter	37 μ m	1.9 cm	1.9 cm ($3/4$ in) round	As in outerwood tracheids, above
Hardwood 'fiber' (outerwood of red alder)				
Length	1.2 mm	60 cm	60 cm wooden dowel	35 years old (Gartner <i>et al.</i> 1997)
Diameter	28 μ m	1.4 cm	1.3 cm ($1/2$ in) round	Estimated from photo (p. 556, Panshin & deZeeuw 1980)

Bordered pits

The models of earlywood bordered pits of Douglas-fir (Table 2, Fig. 3B) were made at a scale of 1:6300 (1 μ m is represented by 6300 μ m (6.3 cm), and 1 cm represents 1.6 μ m). The size was dictated by the need for paper bowls and embroidery hoops of similar diameter. The pit aperture was made by cutting a circular hole in the bottom of each bowl. The margo was made by stretching 30 narrow rubber bands (to produce 60 strands) around the inner of the two hoops of the embroidery hoop; the outer hoop was then placed over the inner hoop and tightened to secure the rubber bands in place. The rubber bands (about 0.16 cm wide, rather the 0.10 cm desired) produced a rather rigid margo that cannot aspirate, although one can demonstrate the principle: it may, therefore, be preferable to use elasticized thread rather than rubber bands. The torus was made with two disks (cut from the lids of disposable plastic containers), one on each side of the membrane and held together with brads. The three pieces (the two

Table 2. Model dimensions for an earlywood bordered pit from the base of a 110-year-old Douglas-fir tree (Domec *et al.* 2006) at a scale of 1:6300.

Pit feature	Measure	Target size	Model notes
Border diameter	21.5 μm	13.5 cm	Paper bowl, inner diameter 13.5 cm, outer diameter 16 cm
Aperture diameter	6.7 μm	4.2 cm	Hole in bottom of bowl cut with scissors
Membrane diameter	21.5 μm	13.5 cm	Outer diameter of embroidery hoop, 13.5 cm
Torus diameter	9.7 μm	6.1 cm	Plastic disks, attached with brads
Strand width	0.16 μm	0.10 cm	Rubber bands, size no. 19, 8.9 \times 0.16 cm (3.5 \times 1/16 inch) unstretched
Number of strands	60		Use 30 rubber bands

borders and the membrane) are left separate for demonstration of where water and gas can move. These models help with instruction on bordered pit anatomy, pit aspiration, water movement between tracheids, and the concept that pits are actually pit pairs.

Flow is proportional to radius to the fourth power

A two-piece model was made to demonstrate the concept that flow through a cell is proportional to its radius (r) to the fourth power (as shown by the Hagen-Poiseuille equation) (Fig. 3C). One pipe has a potential flow that is proportional to r^4 , so a larger pipe with a radius of $2r$ has a potential flow proportional to $(2r)^4$, or $16r^4$. Therefore, 16 of the small pipes have the same potential flow as one pipe of two times the radius.

These models were constructed with PVC pipe with inner diameters that differed by a factor of two (1.9 and 3.8 cm; $\frac{3}{4}$ and $1\frac{1}{2}$ in). The narrow pipe was cut into 16 sections of 2 cm length, and glued into a 4 by 4 array. One 2-cm-long section of the wider pipe was then cut, and the array and the single pipe were then spray-painted. These models are used when teaching that with the same pressure gradient, the array and the single conduit will have the same flow. The array requires more carbon investment but it provides redundancy, and so if one conduit in the array were to become embolized or otherwise dysfunctional, there would still be some flow; if the single larger conduit became dysfunctional, flow would cease.

CONCLUSIONS

I believe that the incorporation of model-making and models into my teaching has had the desired effects of adding excitement and improving student learning. Unlike some of my teaching innovations, this one has not increased my workload once the prototypes were developed. Moreover, the models have also become popular with some of my colleagues, graduate students and post-doctoral students for use in their presentations. The exercises and models are presented a) to demonstrate the use of simple materi-

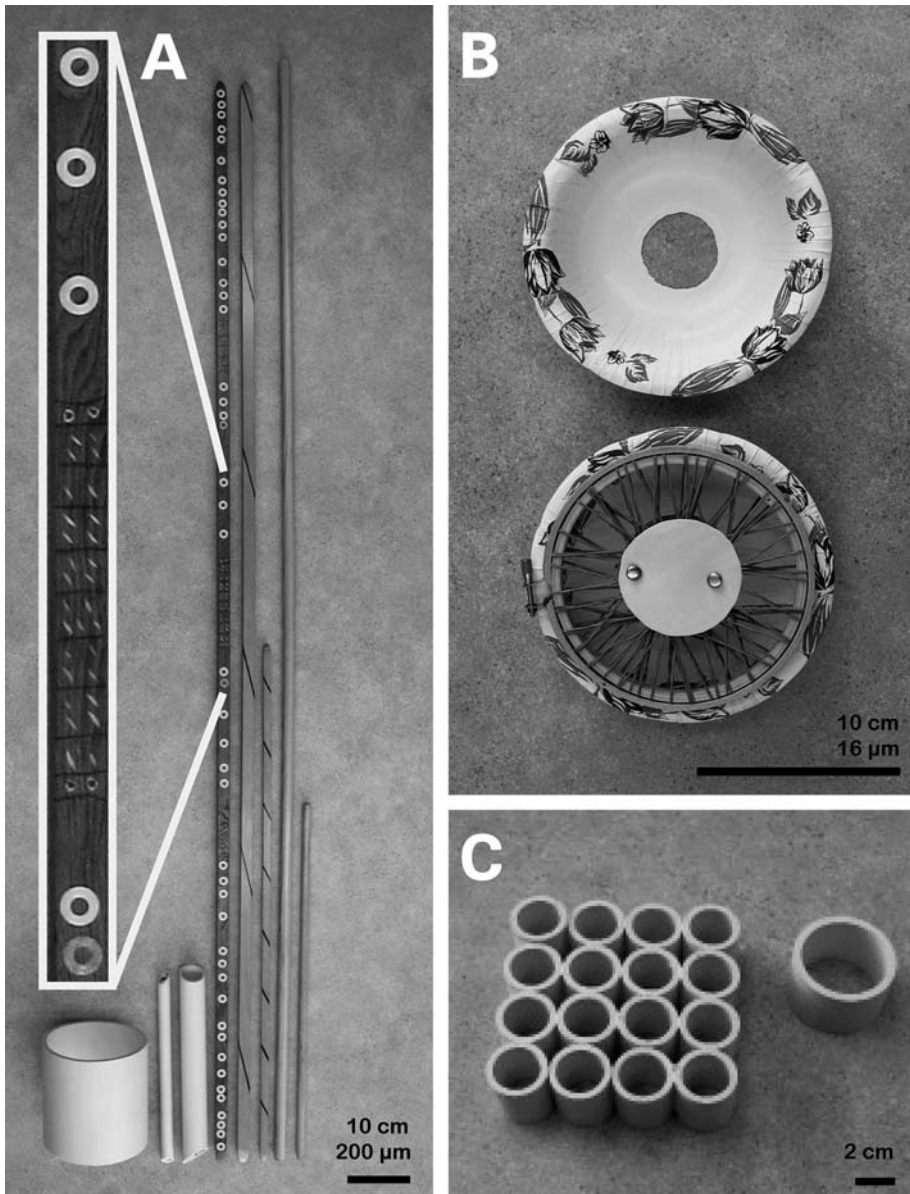


Figure 3. Models made by the instructor. – A: Vessel elements (white oak earlywood and latewood, red alder), tracheids (outerwood of Douglas-fir with pits, same with MfA, corewood of Douglas-fir with MfA), and ‘fibers’ (outerwood of Douglas-fir, fiber of red alder); scale bar shows actual size (10 cm) that represents size of structure (200 μm). Inset is close-up of inter-tracheid, tracheid-to-ray tracheid, and cross-field pitting. – B: Earlywood bordered pit of Douglas-fir; scale bar shows actual size (10 cm) that represents size of structure (16 μm). – C: Model of conduits showing two strategies of biomass investment that have the same potential flow; scale bar shows actual size.

als for improving instruction, and b) in the hopes that the models will inspire others to make use of these models, or better yet, design their own models targeted to their instructional needs.

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REFERENCES

- Anonymous. 2003. Teaching wood anatomy – tips to make your teaching more lively and engaging. *IAWA J.* 24: 452–455.
- Côté, W.A. 1980. Papermaking fibers: A photomicrographic atlas. Renewable Materials Institute of the State University of New York, College of Environmental Science and Forestry, and Syracuse University Press.
- Domec, J.-C., B. Lachenbruch & F.C. Meinzer. 2006. Bordered pit structure and function determine spatial patterns of air-seeding thresholds in xylem of Douglas-fir (*Pseudotsuga menziesii*; Pinaceae) trees. *Amer. J. Bot.* 93: 1588–1600.
- Dunham, S.M., B. Lachenbruch & L.M. Ganio. 2007. Bayesian analysis of Douglas-fir hydraulic architecture at multiple scales. *Trees* 21: 65–78.
- Erickson, H.D. & T. Arima. 1974. Douglas-fir wood quality studies. Part II: Effects of age and stimulated growth on fibril angle and chemical constituents. *Wood Sci. Technol.* 8: 255–265.
- Gartner, B.L., H. Lei & M.R. Milota. 1997. Variation in the anatomy and specific gravity of wood within and between trees of red alder (*Alnus rubra* Bong.). *Wood Fiber Sci.* 29: 10–20.
- Hoadley, R.B. 1990. Identifying wood: accurate results with simple tools. The Taunton Press, Newtown, CT.
- Lachenbruch, B., G.R. Johnson, G. Downes & R. Evans. 2010. Relationships of density, microfibril angle, and sound velocity with stiffness and strength in mature wood of Douglas-fir. *Can. J. For. Res.* 40: 55–64.
- Megraw, R.A. 1986. Douglas-fir wood properties. In: R.A. Megraw (ed.), Douglas-fir: stand management for the future: 81–96. University of Washington, Institute of Forest Resources, Contribution No. 55, Seattle, WA.
- Panshin, A.J. & C. deZeeuw. 1980. Textbook of wood technology. McGraw-Hill, New York.
- Peterson, M.G., H. R. Dietterich & B. Lachenbruch. 2007. Do Douglas-fir branches and roots have juvenile wood? *Wood Fiber Sci.* 39: 651–660.
- Spicer, R. & B.L. Gartner. 2001. The effects of cambial age and position within the stem on specific conductivity in Douglas-fir (*Pseudotsuga menziesii*) sapwood. *Trees* 15: 222–229.