BIOMECHANICS OF TREE AND VINE STEMS

Steven K. Rice
Dept. of Biological Sciences
Union College
Schenectady, NY

Stems have multiple functions in plants. They simultaneously support the shoot and transport water, sucrose and other nutrients. Demands for each of these roles influenced the course of evolution and resulted in structures that we observe in the present. In some cases, the demands on structural features are clearly at odds. For example, energy and matter expended on thickened cell walls may enhance the rigidity of stems, but also reduce the diameter of transport vessels and limit the investment in height required to display leaves and flowers. Situations where the possible direction of evolution has been limited by physical, chemical or biological conditions are referred to as evolutionary constraints. Given that plant stems are under selection to carry out diverse functions, they are good models to investigate the nature of these constraints.

Of all the general trends observed in the evolution of embryophytes, one of the most dramatic is the enlargement of the sporophyte. In mosses, it is rare that the sporophyte is greater than 0.1 m, whereas the tallest redwood trees (the sporophyte) can be upwards of 100 m. With height, plants may gain an advantage in attracting pollinators, dispersing seed, and of course, intercepting light. However, larger stature creates an additional burden on supporting tissues that have to resist greater forces of bending and compression. But, why are the sporophytes of trees not merely enlarged versions of those of mosses? Why do they differ in the relative size of diameter to height (Figure 1)? What are some of the tradeoffs associated with increased size? In lab today, you will investigate the relationship between stem diameter and material properties of self-supporting tree and vine stems to gain a better understanding of how the evolutionary process operates within the constraints of the physical world. First, you need an introduction to common techniques of assessing stem mechanical and functional properties.

Figure 1. A moss and a tree sporophyte shown on a similar scale (from Gray, A. 1887. The Elements of Botany. The American Book Company, New York).

MATERIAL PROPERTIES OF STEMS

In order to understand more about the relationship among size, shape and function in plant stems, it is essential to characterize the stem biomechanical properties. Flexural stiffness measures the resistance of a stem to bending, and is intuitively what we think of as "stiffness." Flexural stiffness is the product of two variables: Material stiffness (E), which reflects the material properties of the object (e.g., steel versus plastic); and the second moment of area (I), which varies as a function of shape. The product flexural stiffness (EI), is easily measured using a three point bending technique (Figure 2 and 3) from the following formula:

$$EI = FL^3/12\ y$$

where, F is the force applied (in Newtons, you will use a spring balance to measure), L is the distance between supports, and y is the deflection (both in m). This technique is appropriate for conditions where the deflection $y < 0.1$ L. The units of EI are Nm^2. Material stiffness (units of gigapascals, GPa) can be estimated by dividing flexural stiffness by the second moment of area (I). For a stem with a circular cross-sectional area, $I = \pi r^4/4$, where r represents the radius if it is assumed that the stem is composed of homogeneous material.

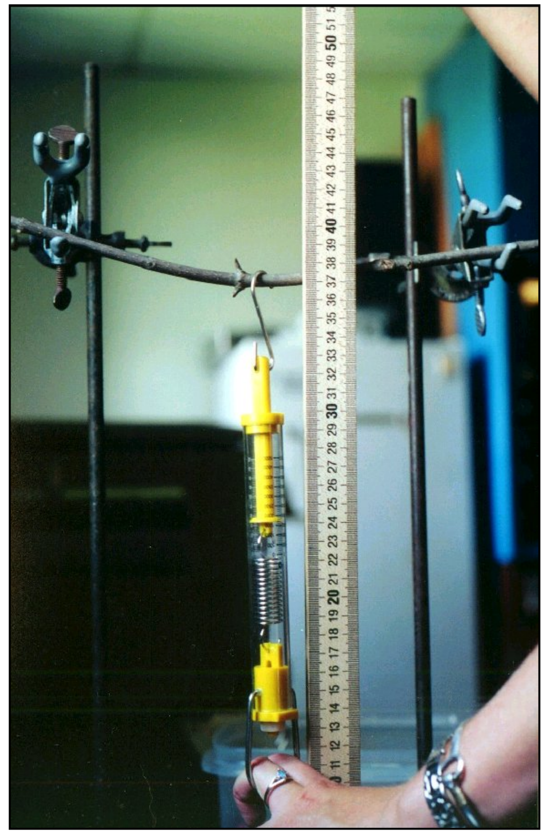


Figure 2. Apparatus to measure flexural stiffness

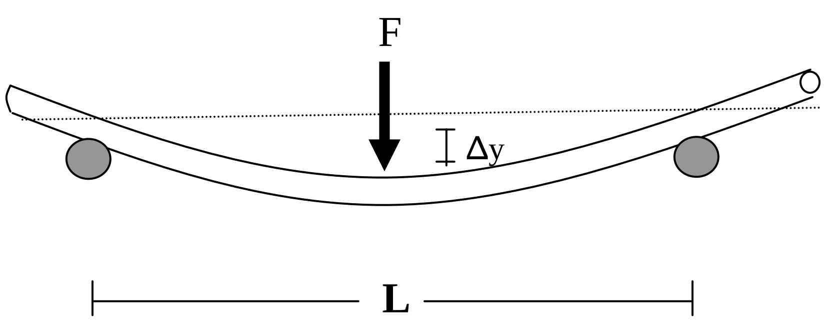
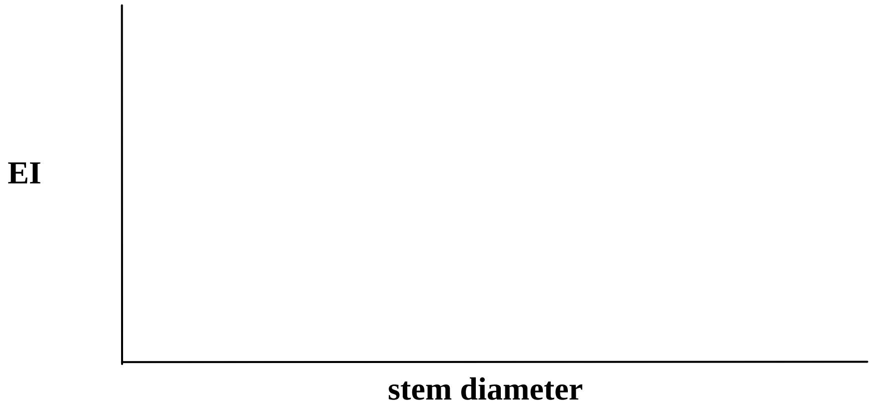


Figure 3. Calculating flexural stiffness (EI) from the force (F), the deflection (Δy) and the distance (L).

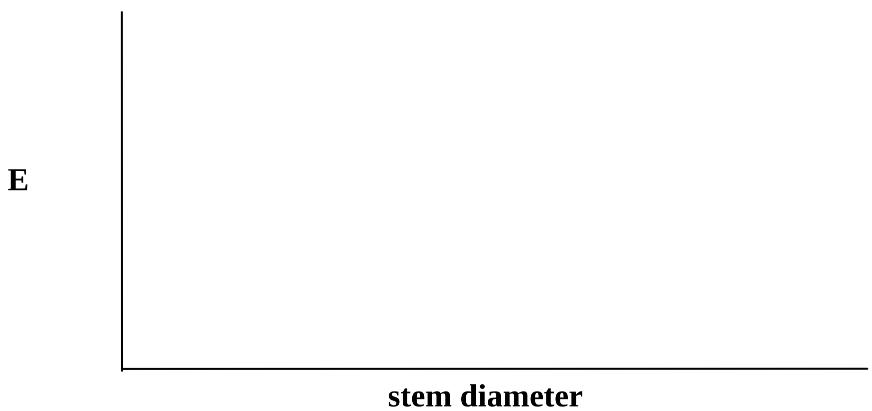
EXERCISE

In lab today, you will compare the relationship between stem diameter, and material properties of woody vines and tree stems. On the graph below, draw two lines that predict the general form of the relationship between stem diameter and flexural stiffness (EI) for woody vine and tree stems:



Justify your prediction:

Do the same showing the relationship between material stiffness (E) and stem diameter:



Justify your prediction:

TESTING YOUR PREDICTIONS

As a class, we will collect tree (sugar maple, *Acer saccharum*) and vine (wild grape, *Vitis sp*.; Figure 4) stems of different diameters and measure material properties using the technique described above. Use the spring balances provided to measure forces. Record your results in the table below:

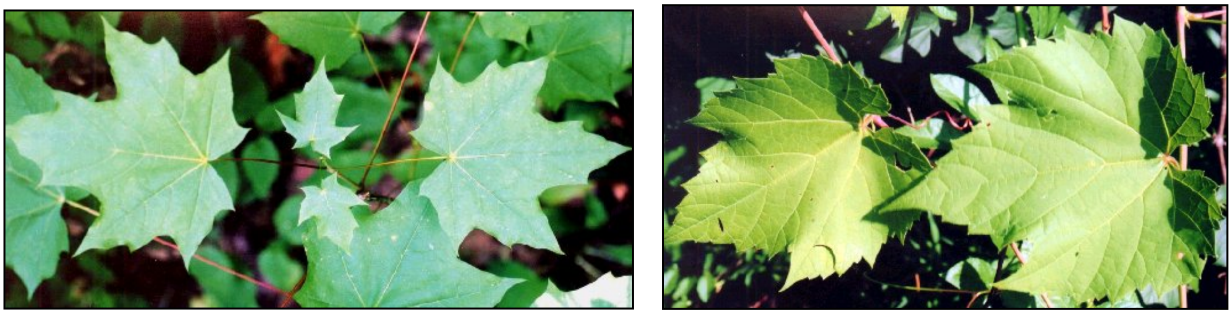


Figure 4. Leaves of sugar maple (left) and wild grape (right) on a similar scale.

species	diameter	EI	E

DATA ANALYSIS

1. Compile and use data from the entire class.

2. Generate graphs of the following relationships. Make sure to give each a title, label the axes, and write a figure legend for each. See the Gartner 1991 paper for help in determining what goes into a figure legend. For grape and maple stems (you may put these together on one graph, or make a graph for each), graph the following:
    a. log diameter versus log EI
    b. log diameter versus log E

3. Use regression analysis to estimate the power function (slope of log-log relationship) that relates EI and E (y axis) to diameter (x axis). To do this in EXCEL, choose the <Tools—data analysis—regression> menu option. Then add in the appropriate x and y values. The slope is indicated by the "X Variable" in the results.

OBSERVATIONS OF ANATOMY

Use a single edge razor to trim a small section of each wood type. CAREFULLY use the razor to shave a small transverse (i.e., cross) section of each stem type and place it in a drop of water on a microscope slide. Place a cover slip over the samples and view under the compound microscope. Compare your images to those below (Figure 5). Can you identify the xylem vessels? Use your observations to help you interpret differences in material properties.

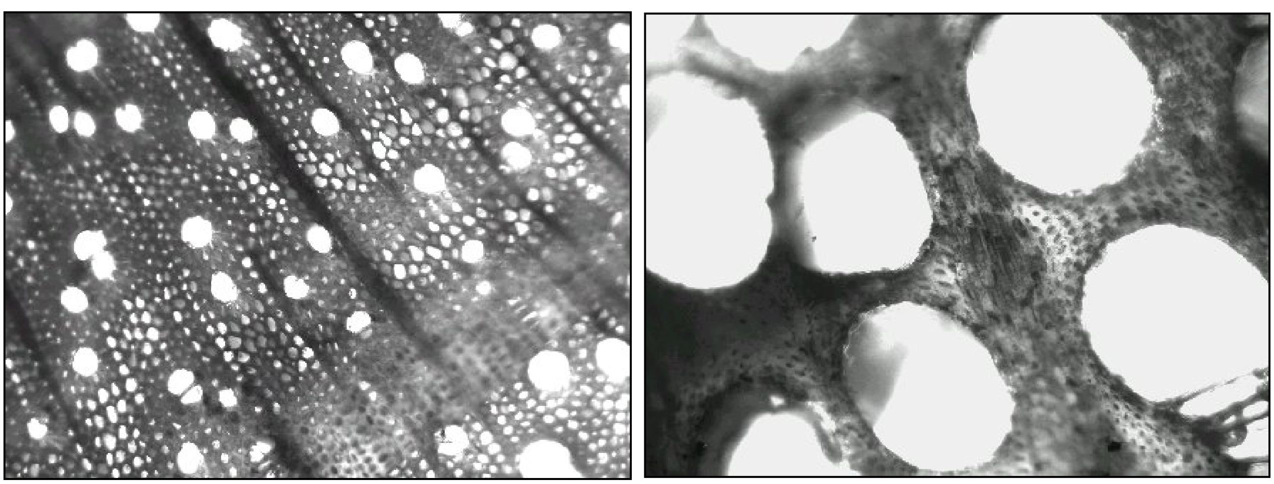


Figure 5. Images of sugar maple (left) and wild grape (right) wood taken at 400x magnification.

ASSIGNMENT

1. Present the figures you generated (with informative figure legends).

2. Explain why the relationship between log diameter and log EI has a positive slope.

3. Why is the relationship described in #2 important for the survival of plants?

4. Describe two differences between grape and maple stems in the relationship described in #2.

5. Properties like increased flexural stiffness does not come without a physiological cost. Consider the species with the higher EI. What function or process may have been compromised to allow it to generate such high EI? Use your observations and/or previous knowledge to answer this question.

6. Explain what causes the differences you described in #4 (at least 1-3 thorough paragraphs for each). Use evidence from your data analysis and observations to support your answer. For example, you may want to use information about the material stiffness (E) shown in your graphs. The best answers will also use support from supplemental readings and the Gartner 1991 paper (available on JSTOR in the library's electronic resources) in addition to other information from the course or readings.

7. Compare the results we obtained with those presented in the Gartner 1991 paper. This is intended to be an open-ended question. Your task is to demonstrate that you can relate the results and interpretation of our experiment to the results and interpretation in her paper. You may choose any subset of results to compare that is appropriate for a 2-3 paragraph response.

USEFUL REFERENCES

Gartner, B.L. 1991. Structrual stability and architecture of vines vs. shrubs of poison oak, *Toxicodendron diversilobum*. Ecology 72: 2005-2015.

Putz, F.E. and H.A. Mooney 1991. The biology of vines. Cambridge University Press, New York.

Niklas, K.J. 1992. Plant biomechanics: an engineering approach to plant form and function. The University of Chicago Press, Chicago.