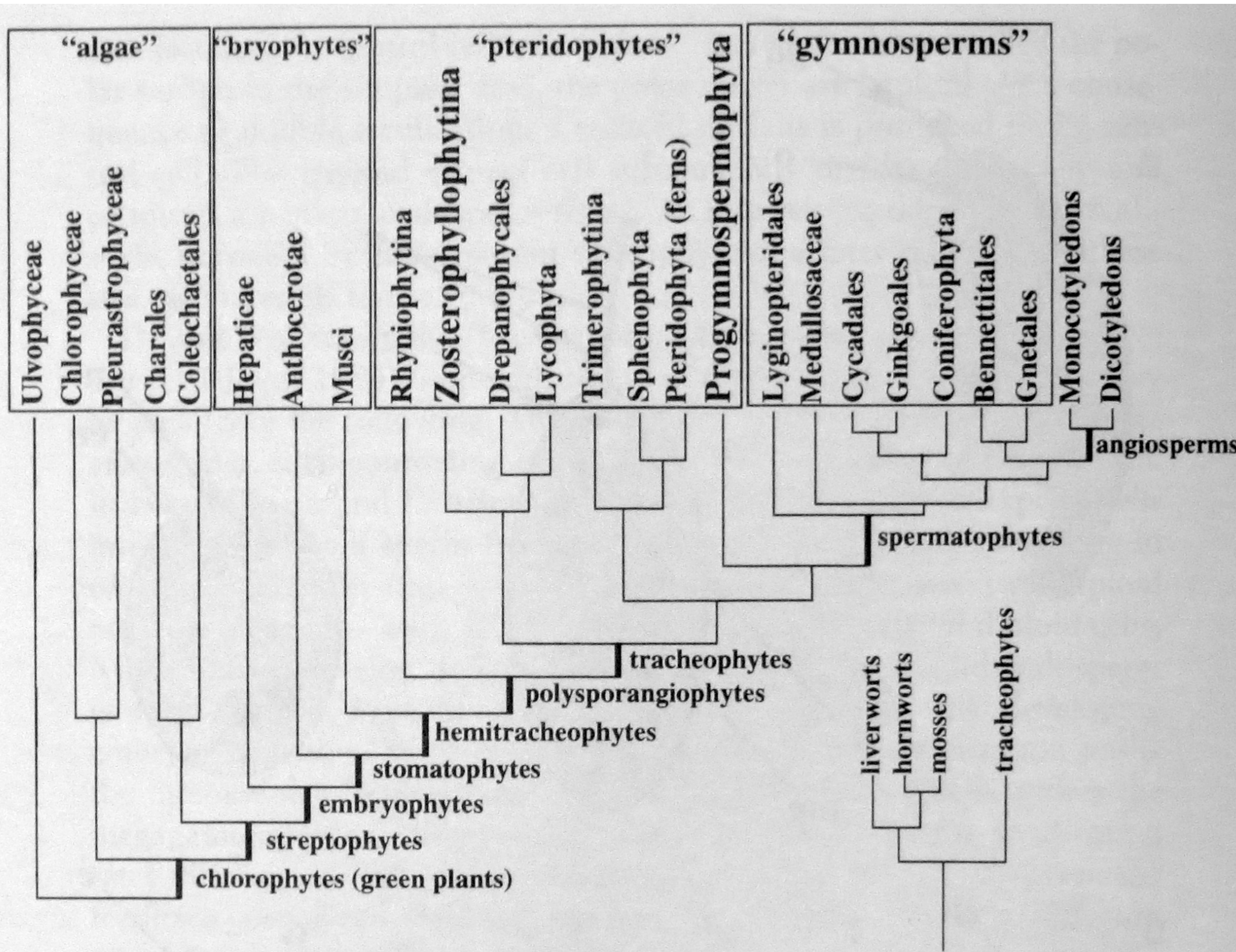


Figure 4.15. Simplified cladogram rendering a phyletic hypothesis for the embryophytes and evolutionarily related green algal lines. Different lineages sharing the same level of morphological or reproductive organization (i.e., evolutionary grades) are grouped in boxes. The informal names for these grades are given in parentheses (e.g., "algae"); formal taxonomic designations are given in boxes (e.g.., Ulvophyceae). Plant groups sharing the same ancestor are indicated by dark vertical links (e.g., chlorophytes). Note that not all the formal taxa are of equal taxonomic rank (e.g., "aceae" designates family rank, "ales" indicates an order, and "phyta" indicates division). According to this cladogram, "bryophytes" are a paraphyletic group (an assembly of organisms that excludes some species that share the same common ancestor with species included in the group). The small cladogram (bottom right) depicts the more traditional view that the bryophytes (Hepaticae = "liverworts," Anthocerotae = "hornworts"; Musci = "mosses") are monophyletic (i.e., Bryophyta) and shared a last common ancestor with the vascular plants (tracheophytes). Adapted from Mishler et al. 1994; Nixon et al. 1994; and Rothwell and Serbet 1994.


**Figure 8.6.** *Encephalartos hildebrandtii.* **Habit of plant bearing female cone. (After Eichler, from Eichler, in Engler and Prantl. 1889.** *Die natürlichen Pflanzenfamilien,* 2:1. **Engelmann, Leipzig.)**

*Ginkgo biloba* relicts survived for millions of years. Rediscovered in the time of Linnaeus, *Ginkgo* crosses the borders of the ancient and the new, a link between the invasion of land and the appearence of flowering plants in evolutionary time.

*Learn about the evolution of plants*

**Plant Biology**
**SC/BIOL 2010**

GO Green

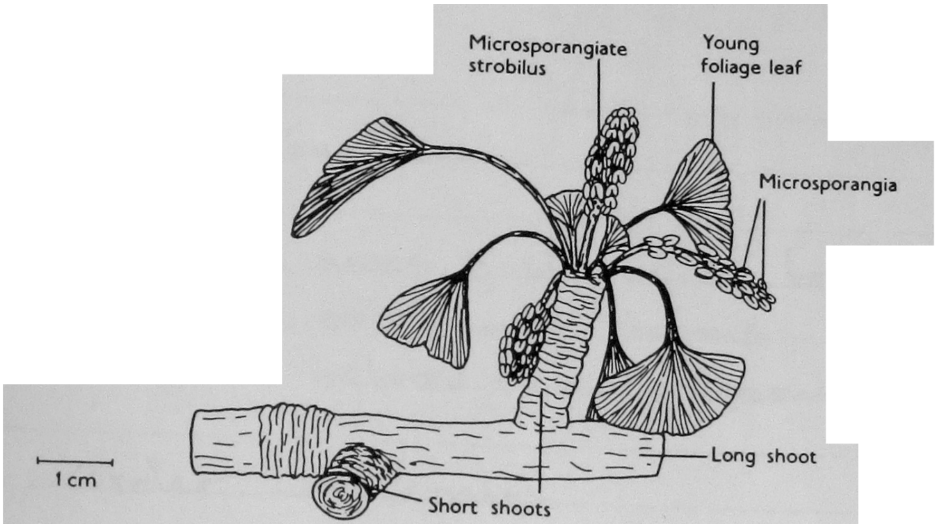


**Figure 8.36.** *Ginkgo biloba.* **Short shoot bearing male strobili. The leaves have not reached mature size.**

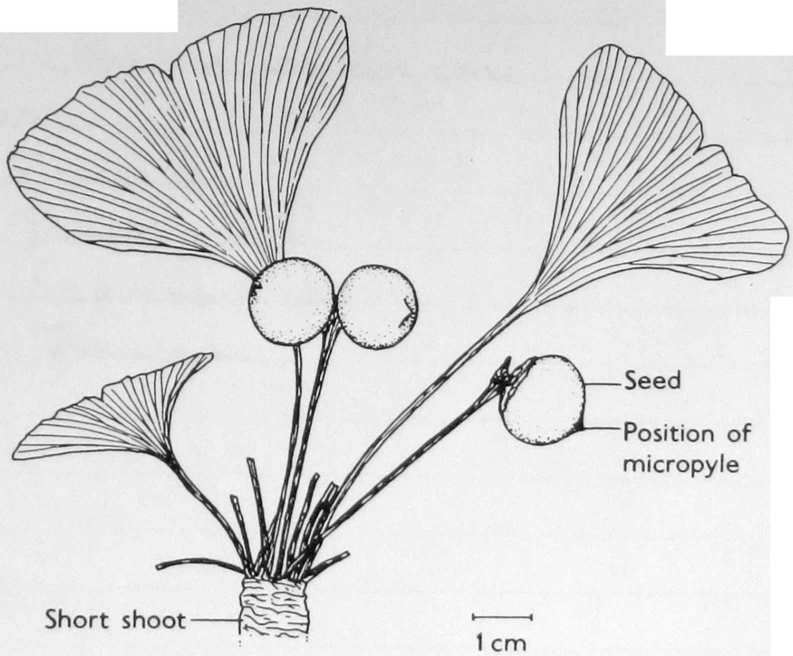


**Figure 8.38.** *Ginkgo biloba.* **Tip of short shoot bearing ripe seeds.**

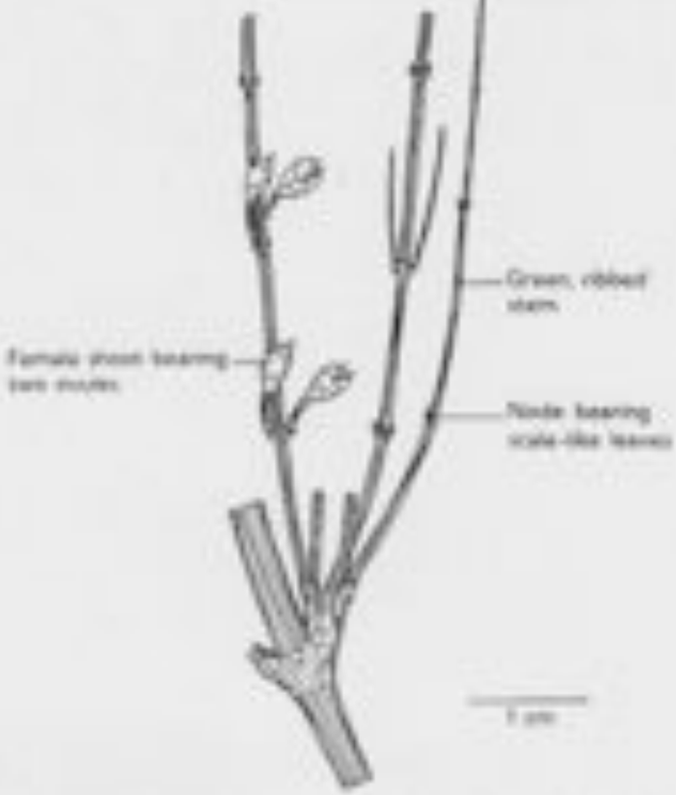


**Figure 8.38.** *Ephedra* sp. **Portion of shoot system showing the articulated stem, reduced leaves, and female reproductive structures.**


**Figure 8.43.** *Gnetum gnemon.* **Portion of shoot bearing female strobili. (After Madhulata, from Maheshwari and Vasil. 1961.** *Gnetum.* **CSIR, Delhi.)**

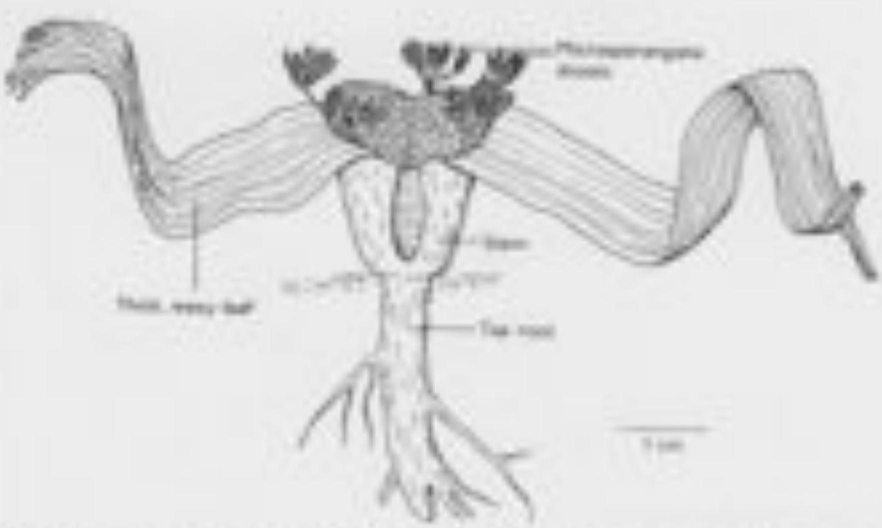


**Figure 8.46.** *Welwitschia mirabilis.* **Habit of the male plant. (After J. D. Hooker. 1863.** *Transaction of the Linnean Society* **[London] 24.)**

The ancient *Metasequoia glyptostroboides* survived in isolated regions of China for millions of years. Commonly called the Dawn Redwood, its closest relatives (the *Sequoia* spp.) are the amongst the tallest trees in the world.

*Learn about the Conifers*

**Plant Biology**
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GOreen

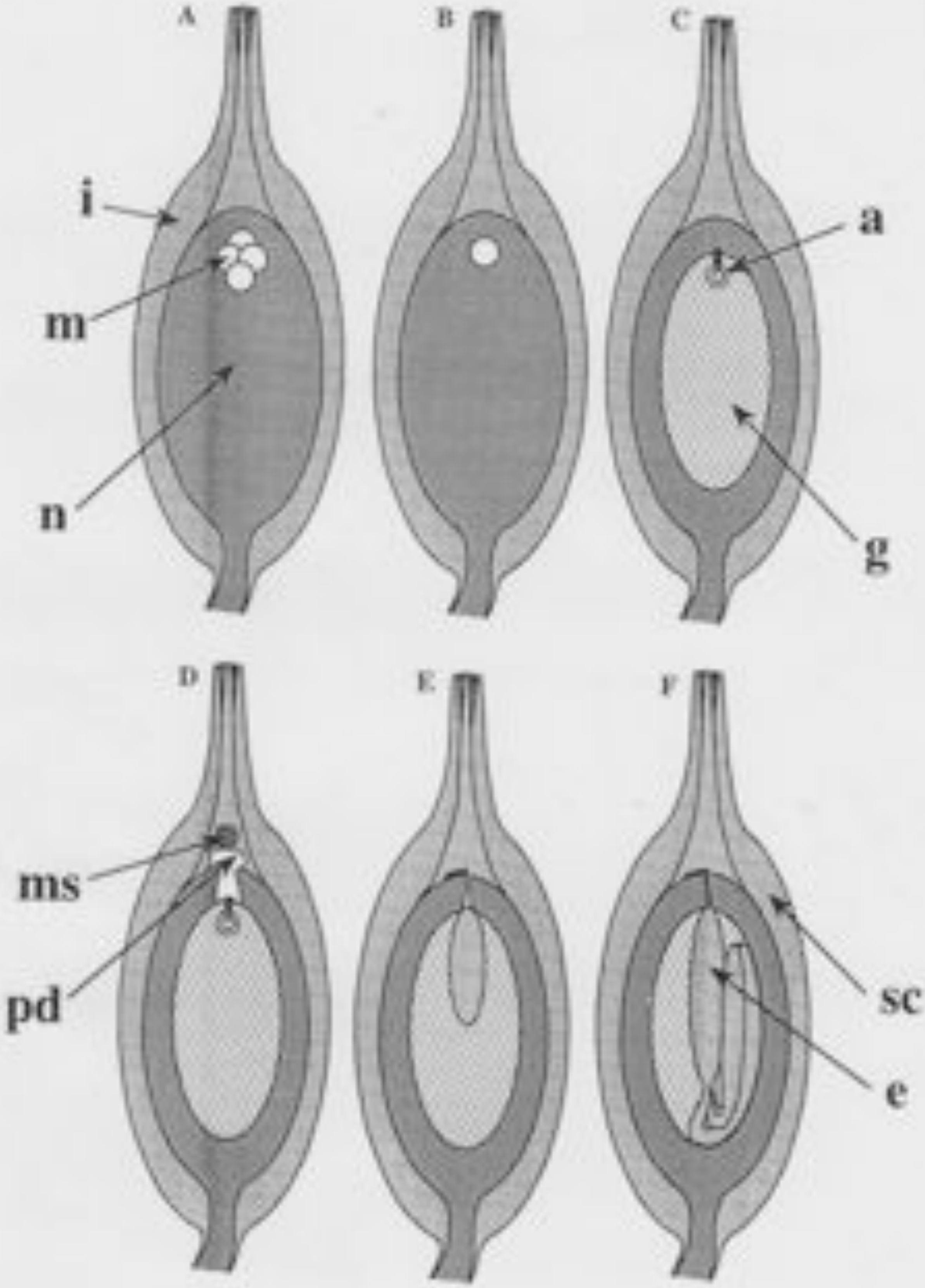



Figure 4.11. Diagrams rendering the stages in the development of an ovule (A) into a gymnosperm seed (F). (A–B) Three of the four megaspores (m) that develop within the nucellus (n) abort. (C) The surviving megaspore develops into a megagametophyte (g) that produces one or more archegonia (a). (D–F). A microspore (ms) attached to a pollination droplet (pd) fertilizes an egg within an archegonium, the resulting zygote develops within gametophytic tissues into a sporophyte embryo (e), and the integument (i, see A) develops into the seed coat (sc). Compare with fig. 4.12.

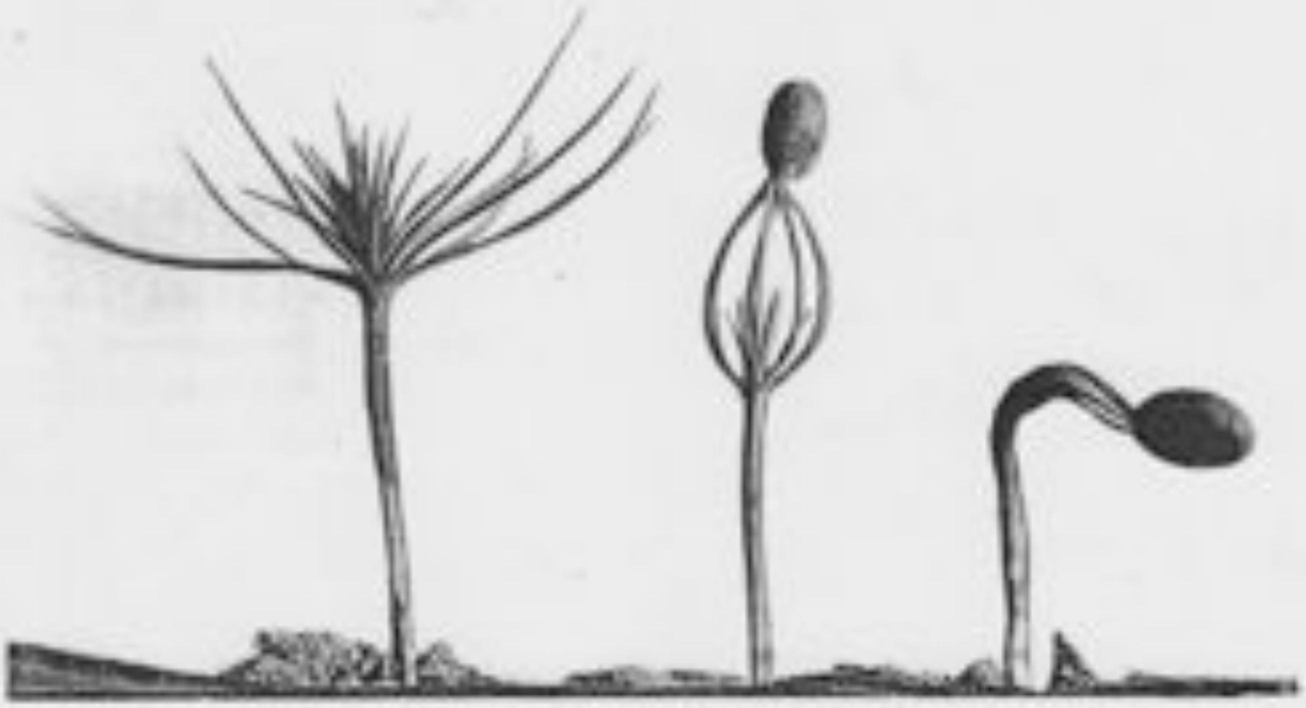
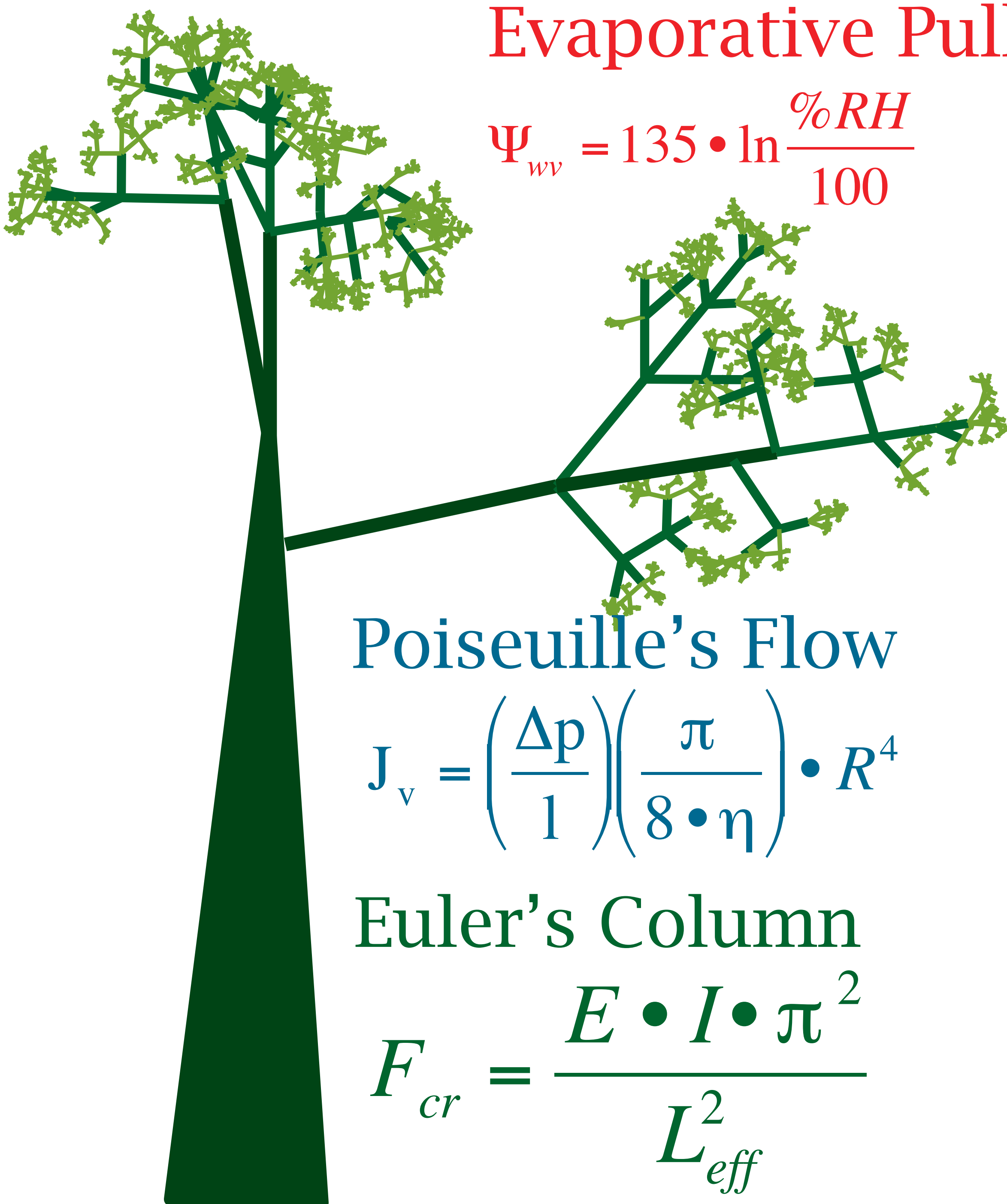


Fig. 16. Three stages in the development of a pine seedling, showing cotyledons and first juvenile leaves. (*Photograph by B. O. Longyear.*)

# How High Can a Tree Grow?

# Tensile Water



## Evaporative Pull

$$\Psi_{wv} = 135 \bullet \ln \frac{\%RH}{100}$$

## Poiseuille's Flow

$$J_v = \left(\frac{\Delta p}{l}\right)\left(\frac{\pi}{8 \bullet \eta}\right) \bullet R^4$$

## Euler's Column

$$F_{cr} = \frac{E \bullet I \bullet \pi^2}{L_{eff}^2}$$

Current Topics in Biophysics
(SC/BPHS 2090 2.0)

Biophysical Currents

# How High Can a Tree Grow?

## Biological Problem

Evolution and adaptation

- Colonization of land
- Competition for light

Physical aspects

- Pumping water
- Water piping
- Structural support

## Biological Structure

Leaves

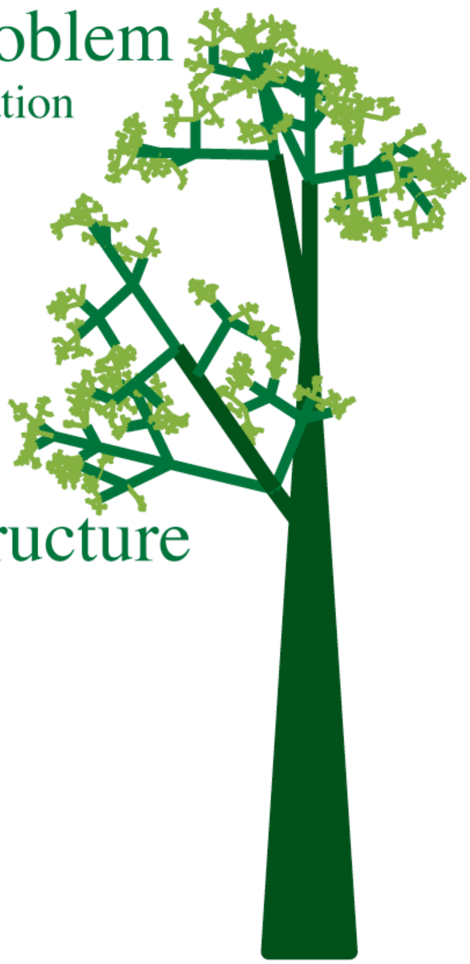
- Photosynthesis

Woody stem

- Xylem vessels
- Colomnar structure

Woody roots

- Water uptake
- Structure foundation



## Physical Approach

Evaporative pump
(thermodynamics)

$$\Psi_{wv} = 135 \times \ln \frac{\%RH}{100}$$

Poiseuille flow
(fluid dynamics)

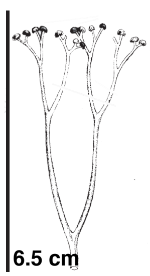
$$J_v = \left(\frac{\Delta p}{l}\right)\left(\frac{\pi}{8\eta}\right) R^4$$

Euler's column
(mechanics)

$$F_{critical} = \frac{EI\pi^2}{L_{eff}^2}$$

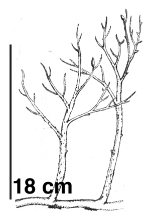
Tensile strength of water
(condensed matter)

In the context of evolutionary time, the invasion of land by plants is relatively recent, only 500 million years ago. Plants had to evolve many adaptive properties to allow them to survive in a dry environment. Their life cycles were modified to protect their offspring from dessication, they developed root systems to *drink* water from the newly developed soils, they evolved an increasingly complex vasculature to move both water and nutrients long distances. And, they grew to greater and greater heights.

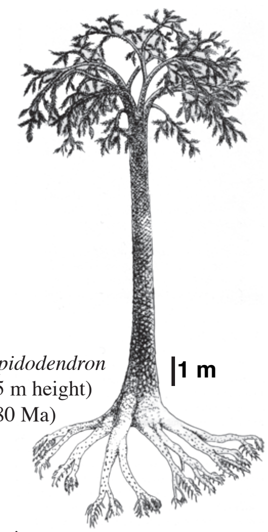



*Cooksonia* is one of the first land invaders known from the fossil record. It appeared about 428 million years ago (Ma), and grew to a height of about 6.5 cm.


*Aglaophyton major* grew upwards from horizontal rhizomes, attaining a height of about 20 cm. It appeared about 400 Ma.

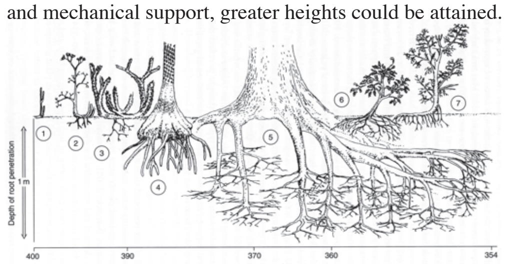



*Rhynian* appeared at the same time (400 Ma), and attained a height of about 18 cm.



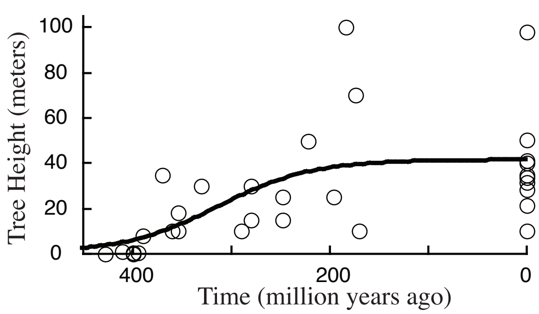

*Lepidodendron*
(35 m height)
(380 Ma)

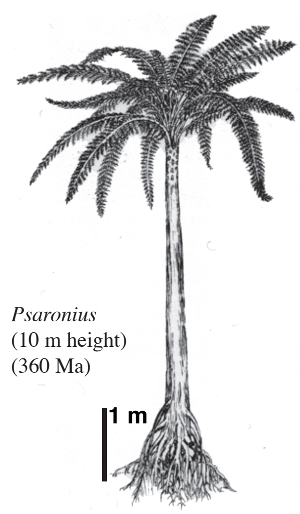
With the development of roots, providing a source of water and mechanical support, greater heights could be attained.





*Calamites*
(18 m height)
(354 Ma)

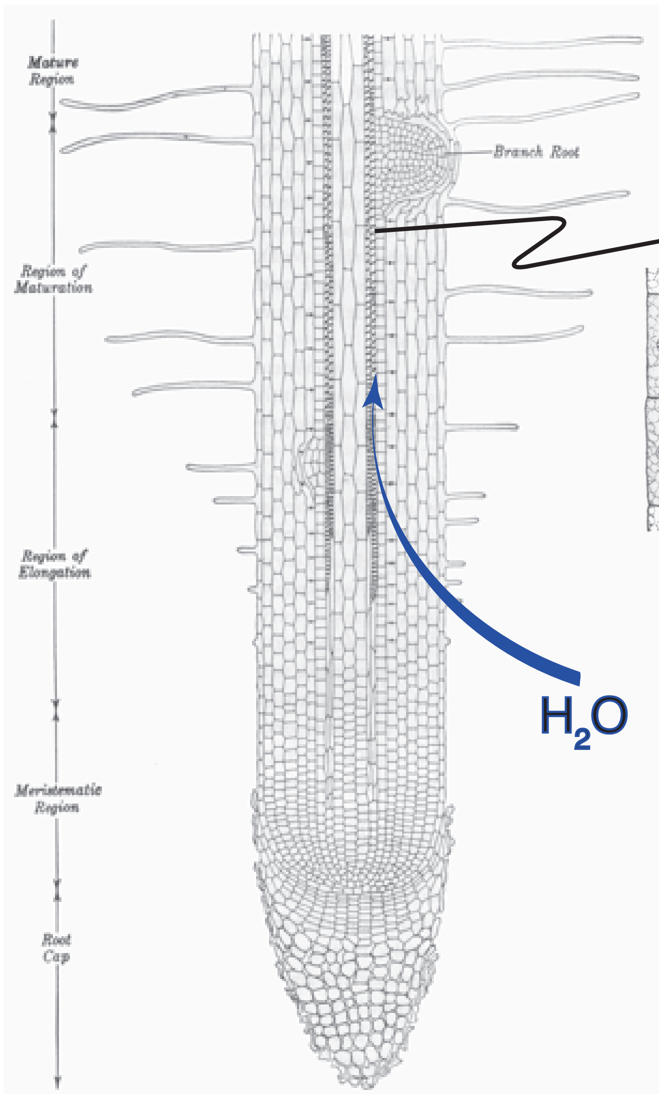


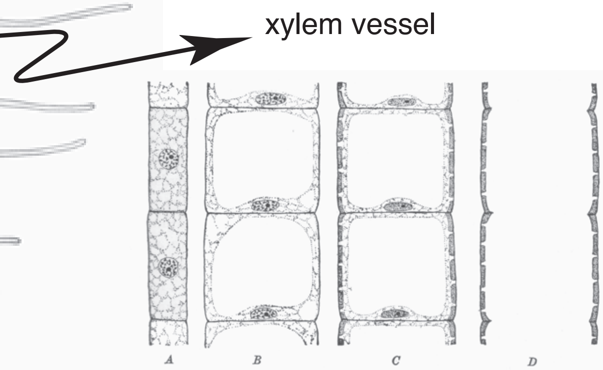

*Psaronius*
(10 m height)
(360 Ma)

[1]Source: Willis, K.J. and J.C. McElwain 2002. The Evolution of Plants. Oxford University Press.

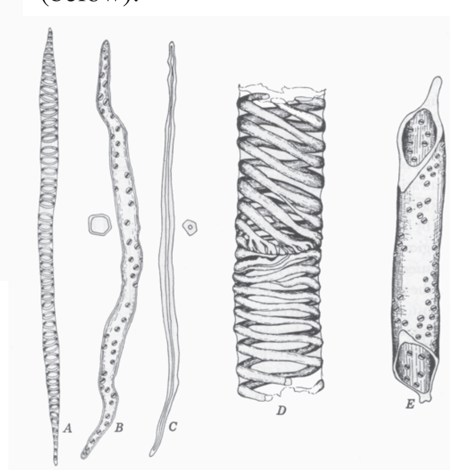
Water is essential for biological life, which is why the ability to draw water to the maximal height of the tree is crucial for survival and may constrain the height of a tree. To explore the physical limits on elevating water, we must first explore the structure and function of the water transport system in a tree (or other vascular plant)[1].



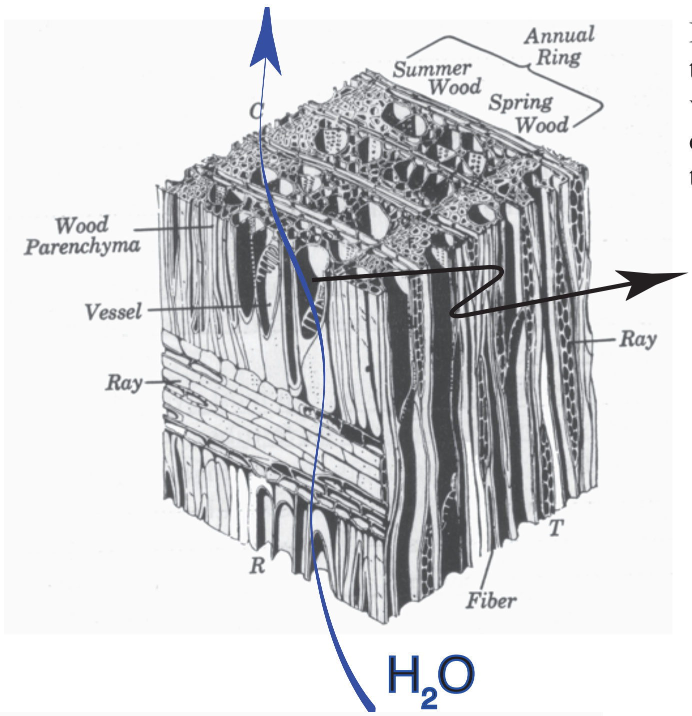

Water enters the plant roots from the soil matrix. It passes between and through the cells until it enters the xylem vessels.




Xylem vessels are constructed from individual cells, arranged end-to-end, which differentiate into a single pipe structure (above, a-d), non-vital (dead) in its final varied mature form (below).



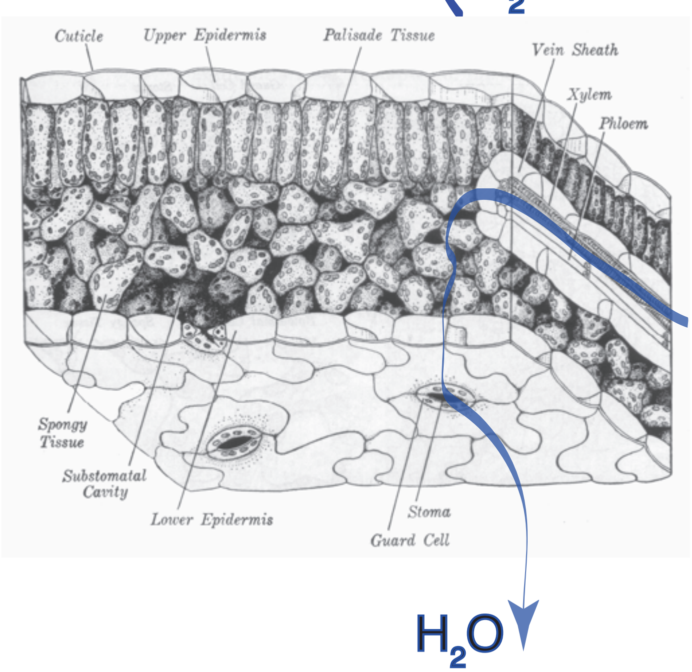

[1]Source: Smith, GM, EM Gilbert, GS Bryan, RI Evans, JF Stauffer (1953) A Textbook of General Botany. 5th ed. Macmillan Co.

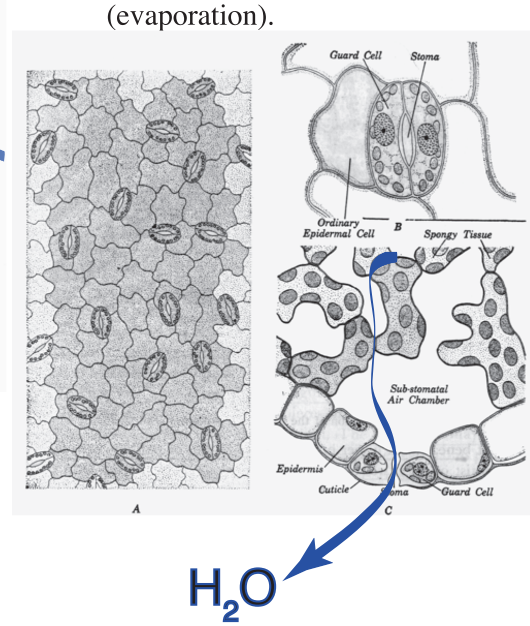



In the stem of a tree, the architecture of the vasculature can be very complex, with numerous cell types including the water-transporting xylem vessels[1].

The size of the xylem vessels varies, some can be quite large, about 150 $\mu$m in diameter (range 20–300 $\mu$m in dicotyledonous trees, about 50 $\mu$m in conifers). Nevertheless, this is still a small tube in the context of hydrodynamics. In fact, microfluidic.

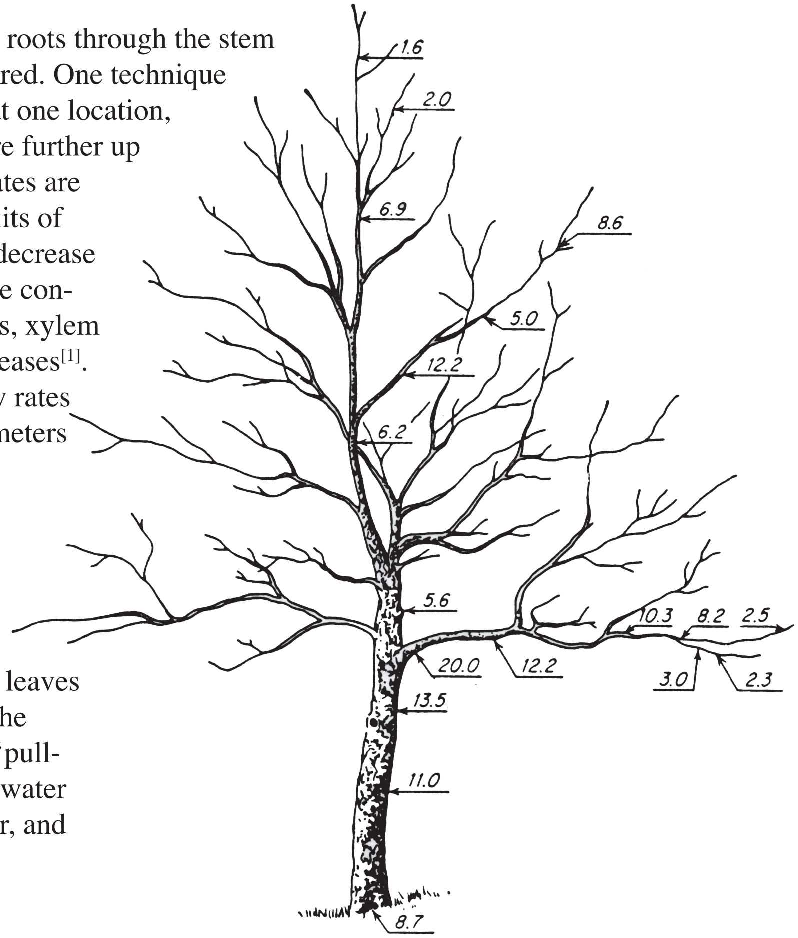
In the leaves, water continues to be transported through the xylem, but then passes through and between cells for a final exit from the plant through the stomata, via transpiration (evaporation).




[1]Source: Smith, GM, EM Gilbert, GS Bryan, RI Evans, JF Stauffer (1953) A Textbook of General Botany. 5th ed. Macmillan Co.

The flow of water from the roots through the stem and branches can be measured. One technique is to apply a pulse of heat at one location, and monitor the temperature further up the stem or branch. Flow rates are shown for an oak tree in units of meters per hour. The rates decrease towards the top, because the conducting surface ratio (that is, xylem cross area to leaf area) increases[1]. In a variety of species, flow rates vary from about 0.1 to 60 meters per hour.




The rates of flow are strongly affected by the atmospheric relative humidity, since it is evaporation of water at the leaves that 'pulls' water up from the soil. The energetics of the 'pulling' force are given by the water potential of the water vapor, and its dependence on relative humidity[2]:

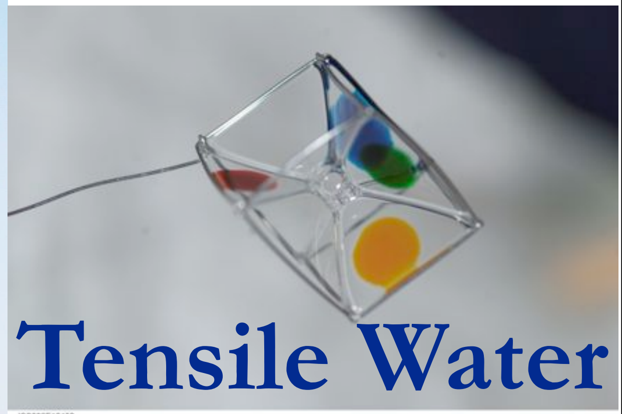
$$\Psi_{wv} = \frac{RT}{\overline{V}_w} \ln\left(\frac{\%\ \text{relative humidity}}{100}\right) + \rho_w g h$$

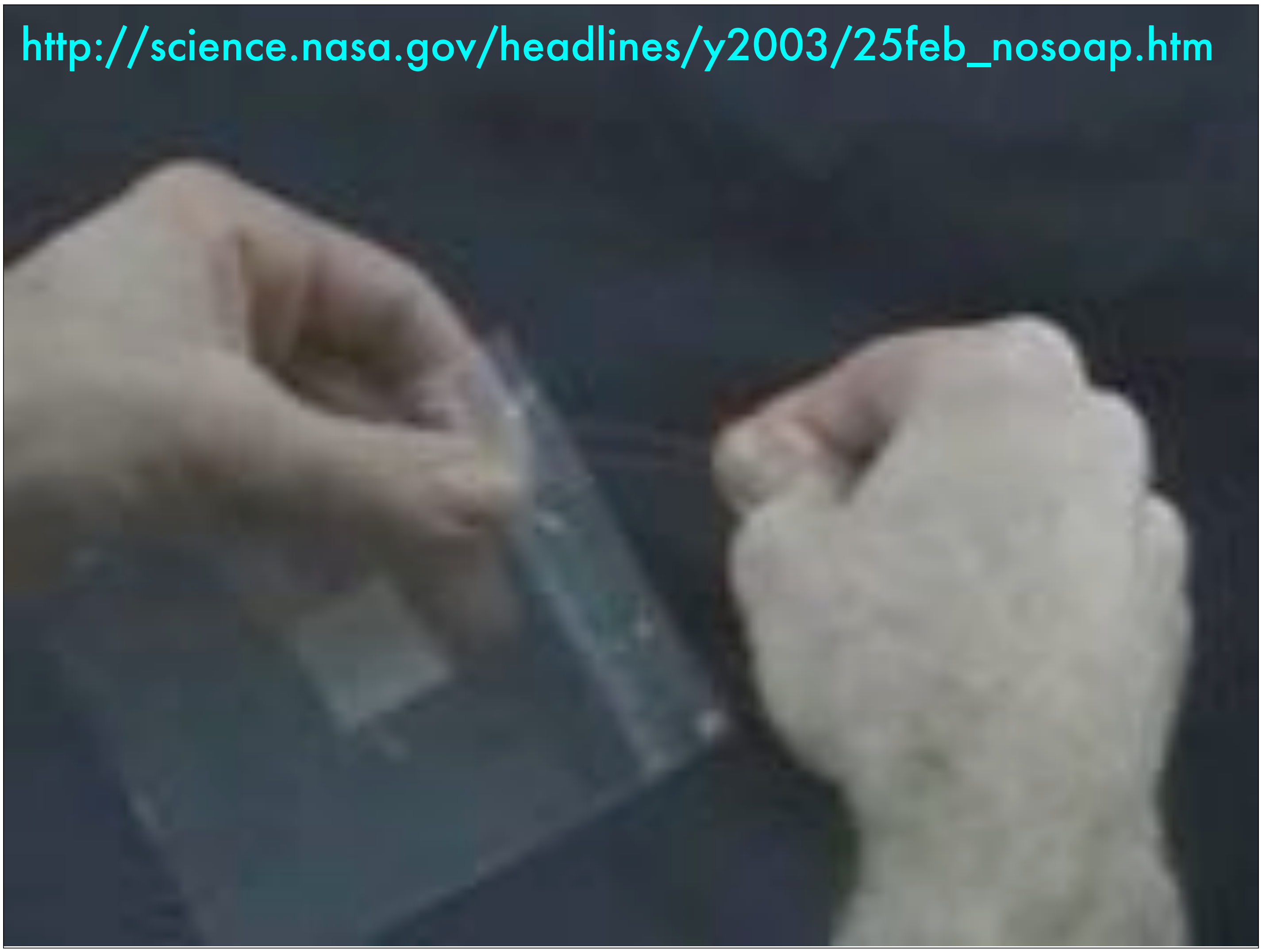
where R is the gas constant (8.314 $m^3$ Pa $mol^{-1}$ $^oK^{-1}$), T is the temperature ($^o$K), $V_w$ is the partial molal volume of water ($1.805 \bullet 10^{-5}$ $m^3$ $mol^{-1}$ at 20ºC [293ºK]). At 20ºC, the term $RT/V_w$ is 135 MPa. The second term is the gravitational potential: $\rho_w$ is the density of water (998.2 kg $m^{-3}$ at 20ºC), g is the gravitational constant (9.807 m $sec^{-2}$) and h is the height. For a tree 100 m high, $\rho_w gh$ is 978 kPa. Even at a relatively high relative humidity (95%), the water potential is about –6 MPa, more than sufficient to 'pull' water from the soil, providing the flow through the xylem vessels (the hydraulic tubes of the tree) is not limiting.

[1]Source: Kramer, PJ (1983) Water Relations of Plants. Academic Press. pp. 274-275

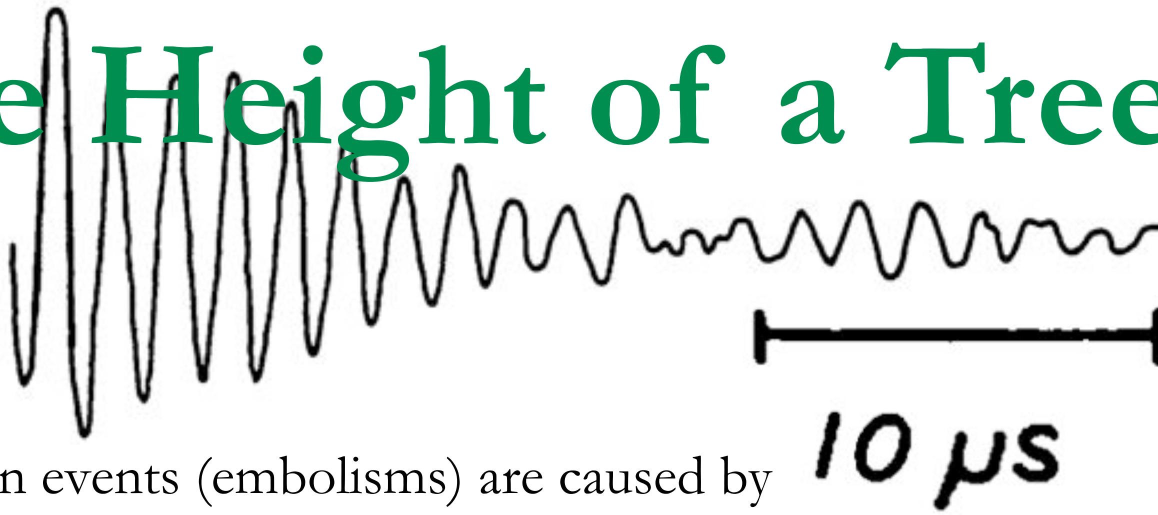
[2]Source: Nobel, PS (1991) Physicochemical and Environmental Plant Physiology. Academic Press. pp. 91–95.

# The Height of a Tree





http://science.nasa.gov/headlines/y2003/25feb_nosoap.htm

# The Height of a Tree




Cavitation events (embolisms) are caused by breakage of water capillaries in the xylem vessels.

www.expressnews.ualberta.ca/article.cfm?id=7390
Melvin Tyree at the University of Alberta

# Tensile Water


The Height of a Tree
Tensile Water
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