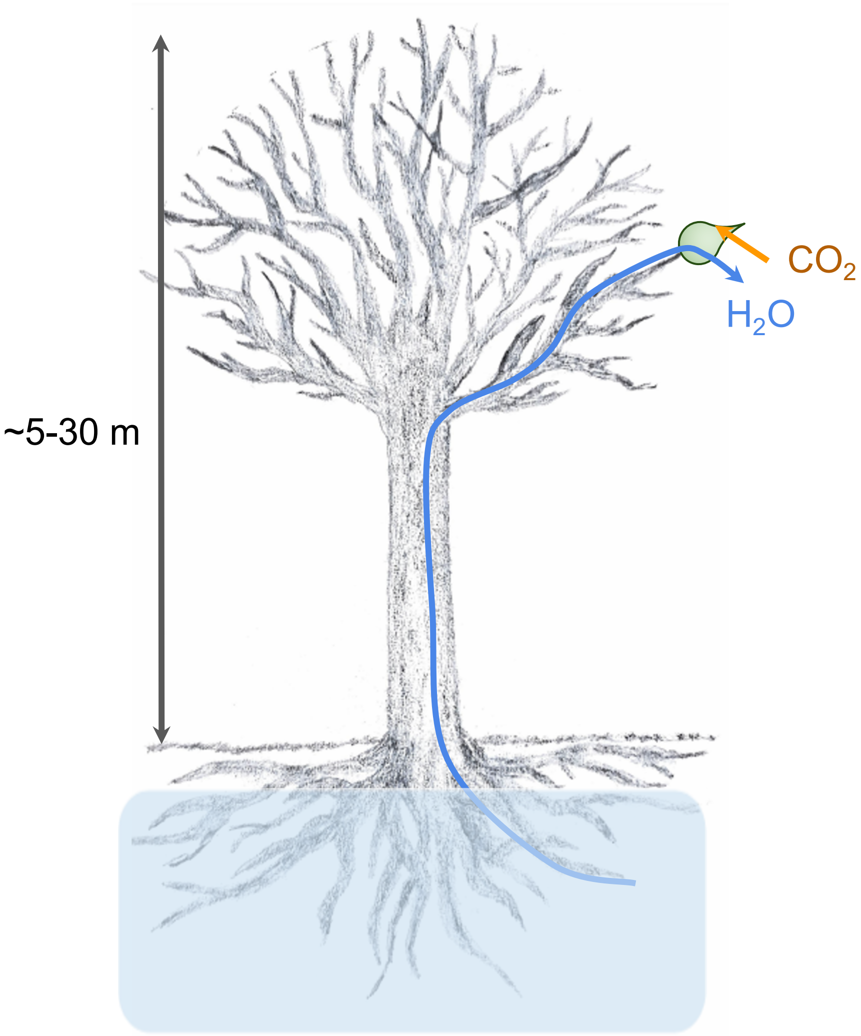
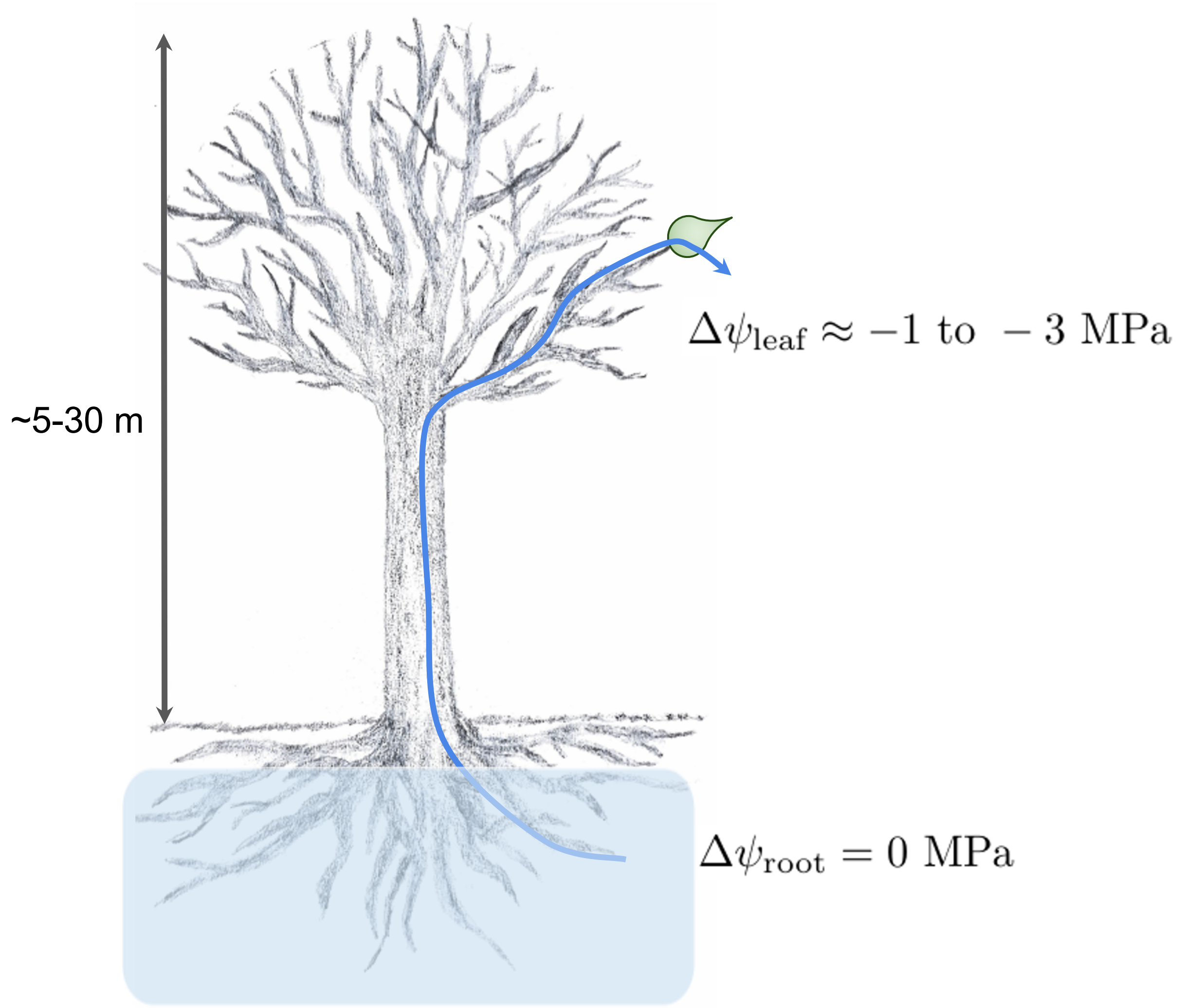
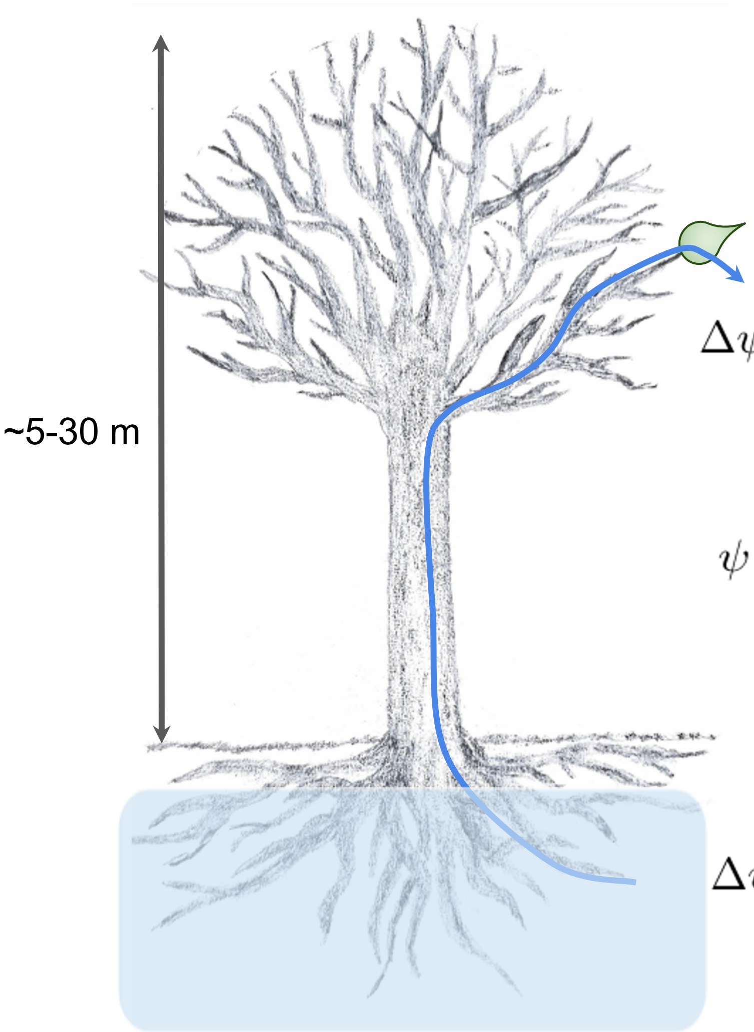
Hydraulic function of margo-torus pit membranes

Melissa Mai
2.29 Final Project
May 20, 2021



A mature tree can transpire up to ~300 to 400 L of water a day!

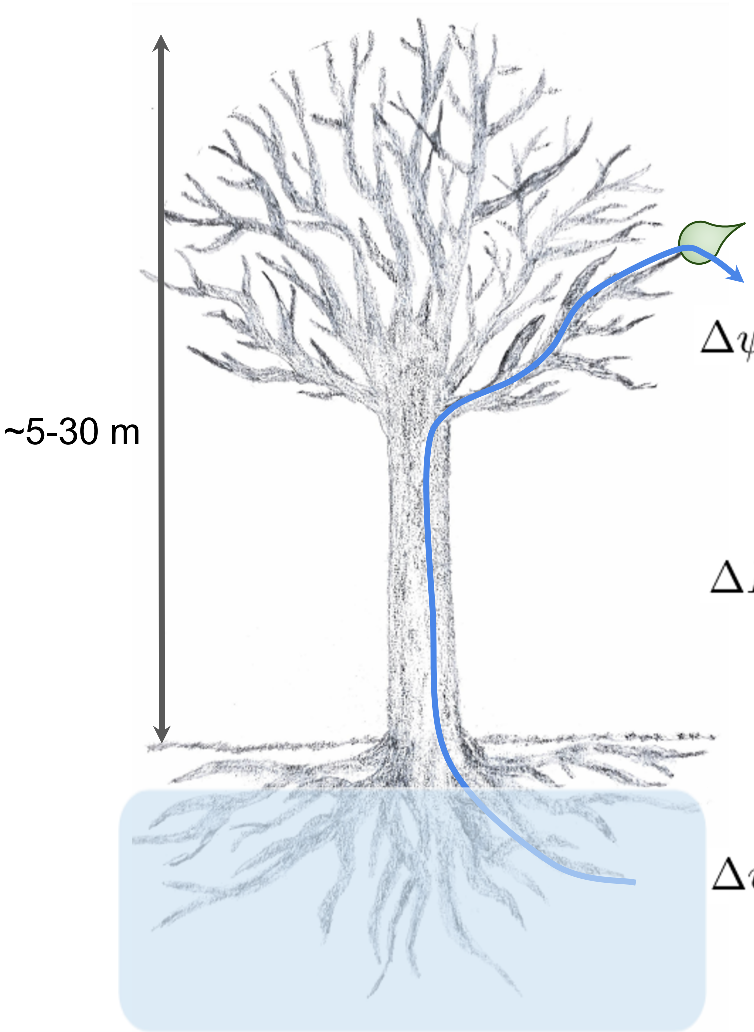

~5-30 m
$\Delta\psi_{\text{leaf}} \approx -1$ to -3 MPa
$\Delta\psi_{\text{root}} = 0$ MPa



$$\Delta\psi_{\text{leaf}} \approx -1 \text{ to } -3 \text{ MPa}$$

$$\psi = P - \overbrace{RTc}^{\text{osmotic potential}} + \underbrace{\rho g h}_{\leq 3 \text{ atm } (\approx 0.3 \text{ MPa})}$$

$$\Delta\psi_{\text{root}} = 0 \text{ MPa}$$



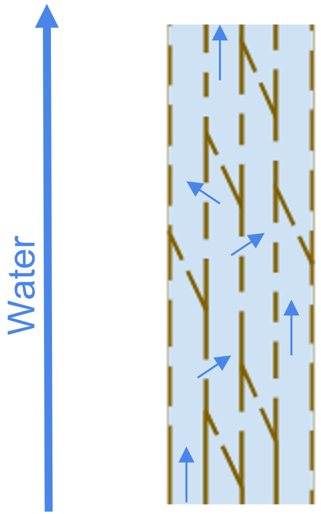
$$\Delta\psi_{\text{leaf}} \approx -1 \text{ to } -3 \text{ MPa}$$

$$\Delta P \approx -1 \text{ to } -3 \text{ MPa}$$

$$\Delta\psi_{\text{root}} = 0 \text{ MPa}$$

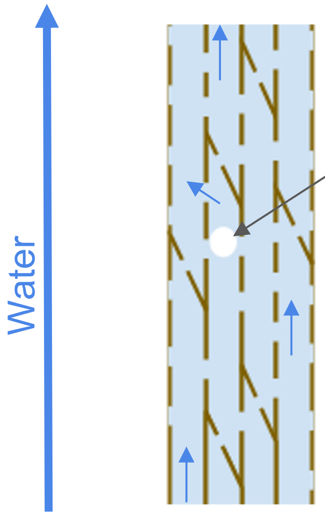
The water column is actually under tension and is susceptible to cavitation & embolism!

Typical flow in the xylem



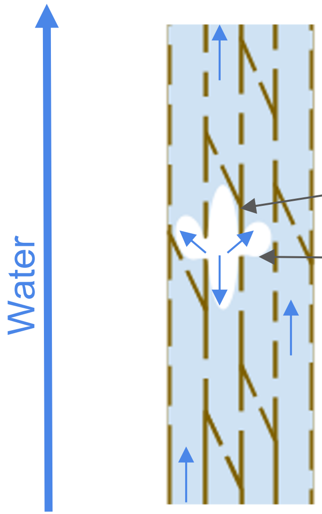
Water moves up the xylem through perforations (pits) between tracheids

Vulnerability to embolism



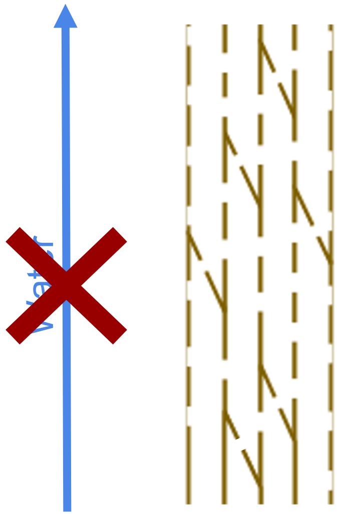
- An embolism (air bubble) is introduced

Vulnerability to embolism



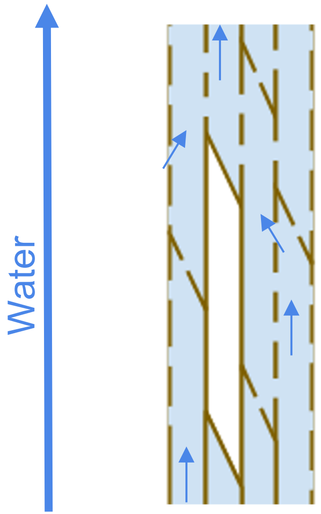
- An embolism (air bubble) is introduced
- Since the water is under tension, the embolism expands
- Air seeds through the perforations into neighboring tracheids

Vulnerability to embolism



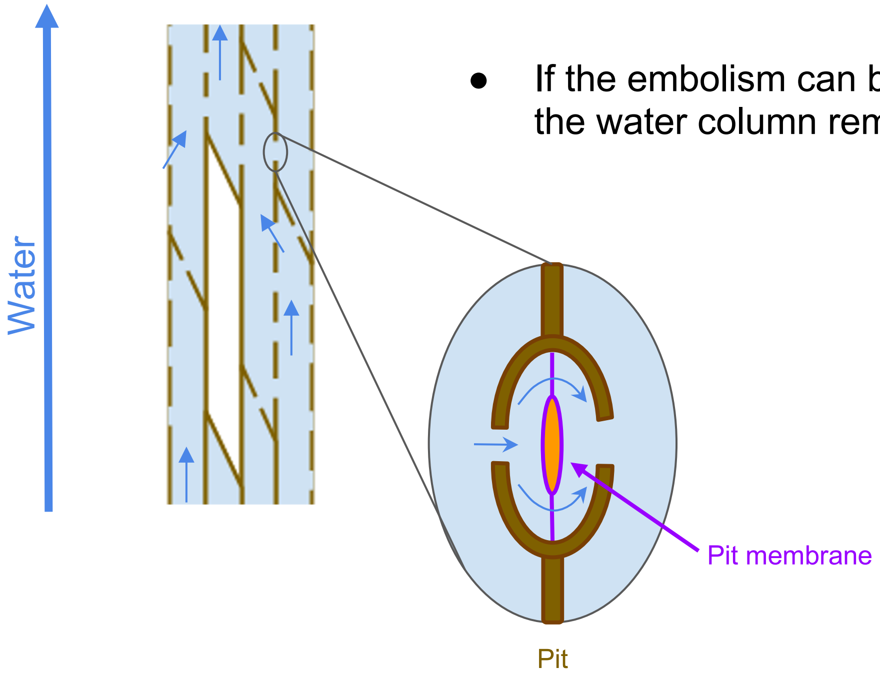
- An embolism (air bubble) is introduced
- Since the water is under tension, the embolism expands
- Air seeds through the perforations into neighboring tracheids
- The embolism spreads through the entire xylem network and leads to total loss of hydraulic conductivity

Protection against embolism



- If the embolism can be contained within a single tracheid, the water column remains intact

Protection against embolism



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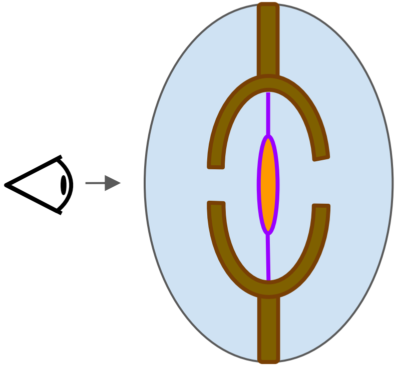
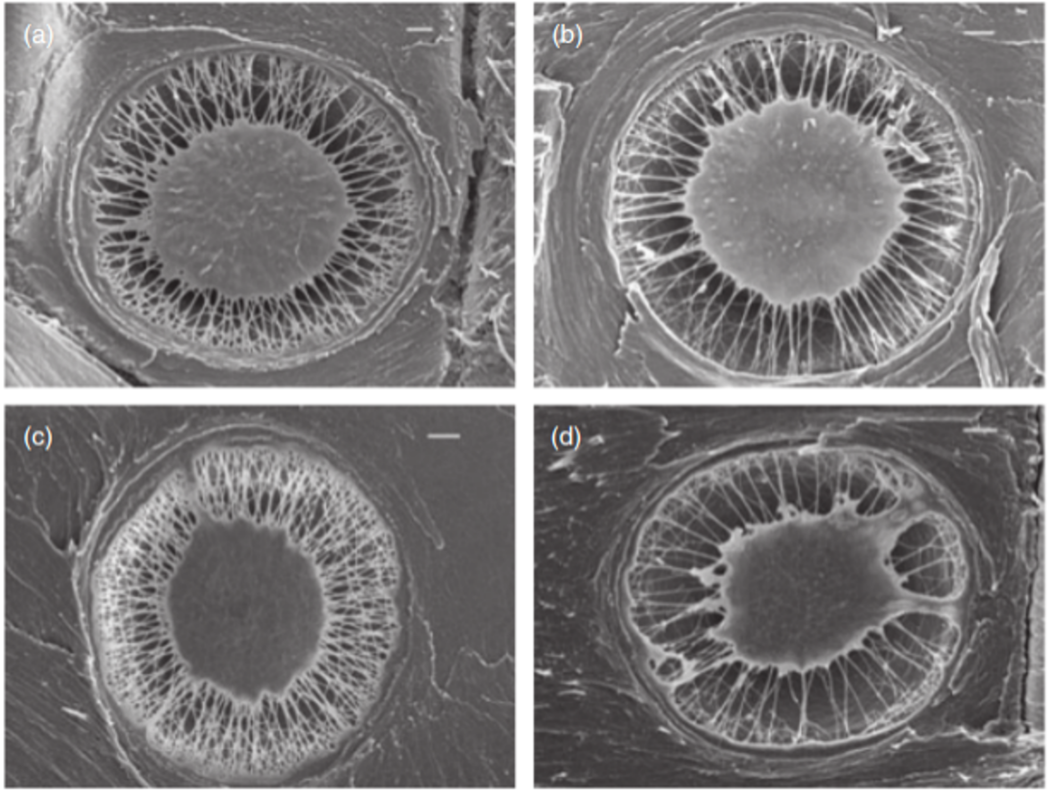
The margo-torus pit membrane



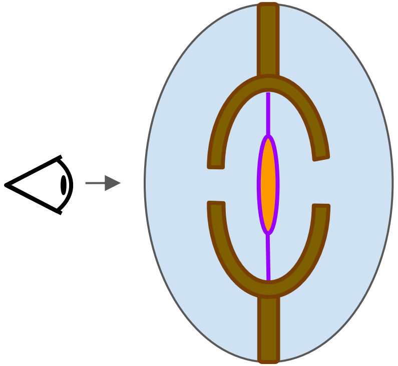


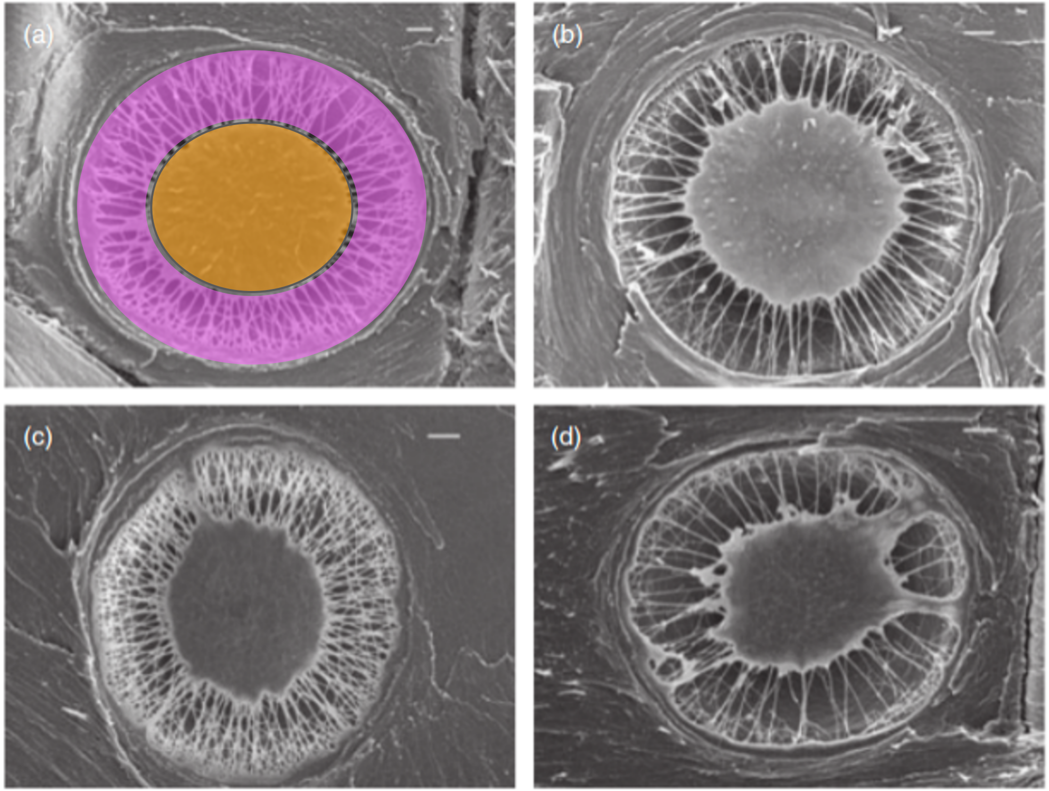
Schoonmaker et al. *Plant Cell Env.* (2010)
Scale bars: 1 µm

The margo-torus pit membrane

Flexible, highly permeable “margo”

Rigid, impermeable “torus”





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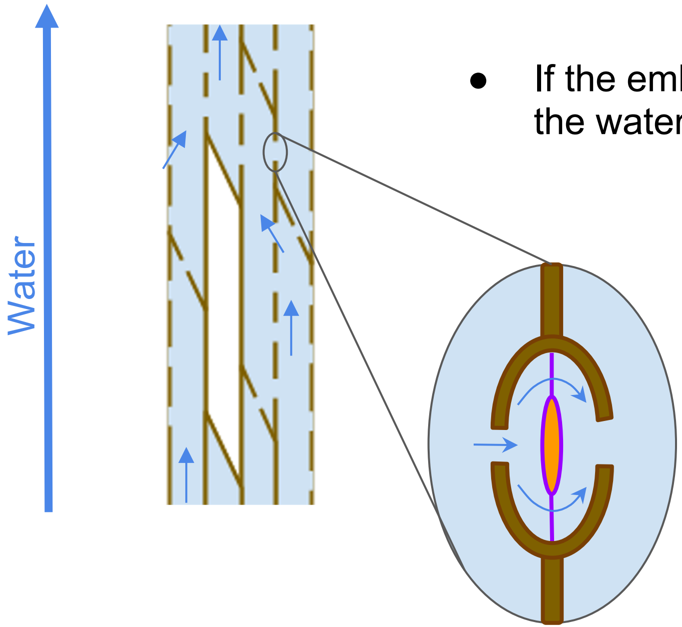
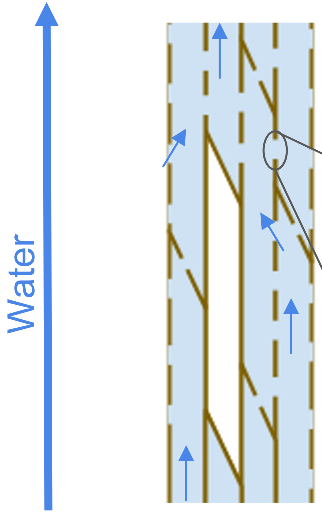
Protection against embolism

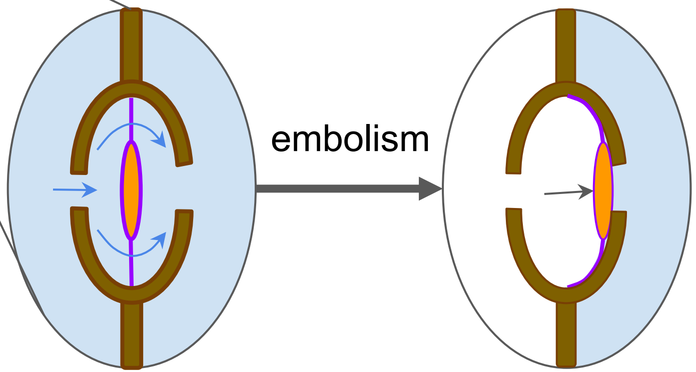


- If the embolism can be contained within a single tracheid, the water column remains intact

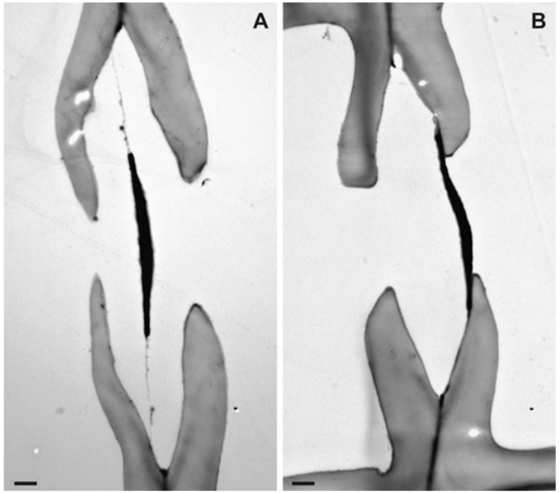
Protection against embolism

- If the embolism can be contained within a single tracheid, the water column remains intact
- ΔP causes the torus to plug the pit aperture





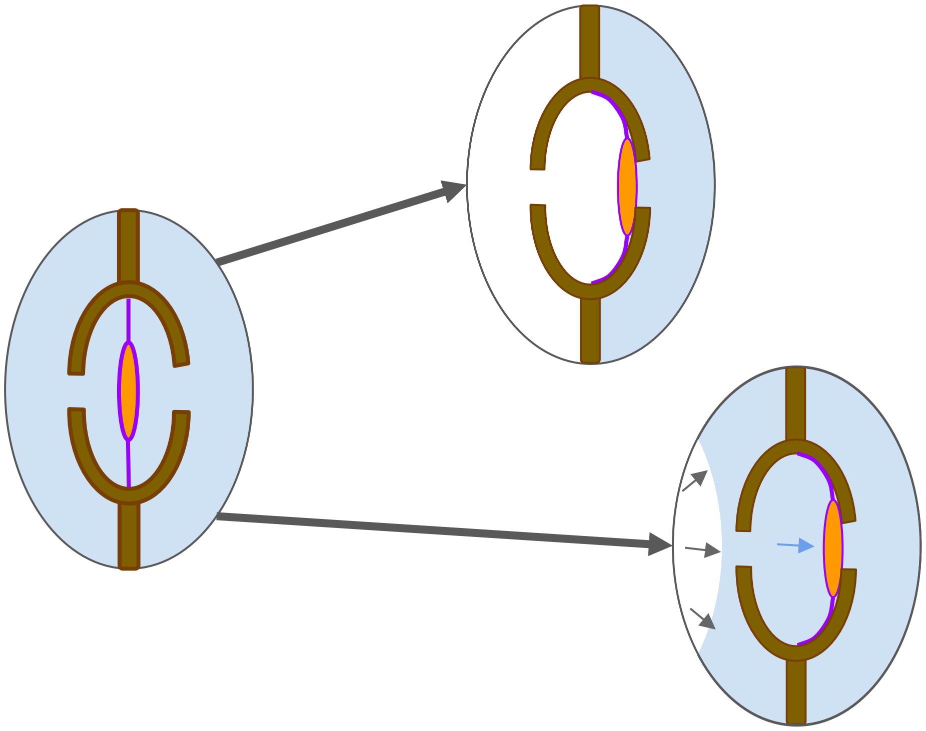
“Aspiration”



Hacke and Jansen. *New Phyt.* (2009)
Scale bars: 1 μm

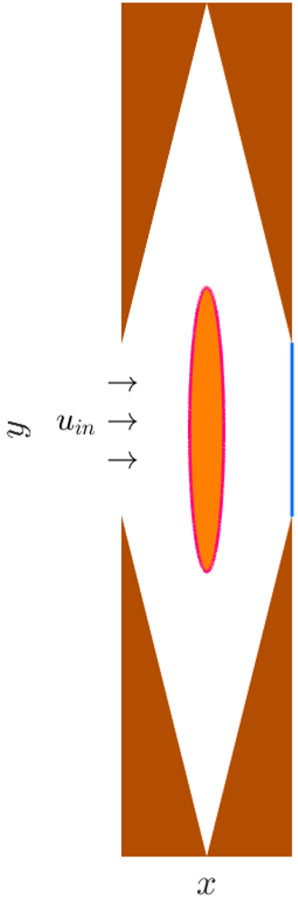
Objectives

1. Characterize typical flow through the pit + small membrane deflections
2. Examine mechanisms of aspiration



Simplified pit geometry

- 2D (radially symmetric in 3D)
- Explicitly defined torus boundary
- Thin, massless margo (including the margo's resistance would increase ΔP
- Set inlet velocity u_{in} ~ mm/s (ahead of expanding bubble front)
- Open outlet



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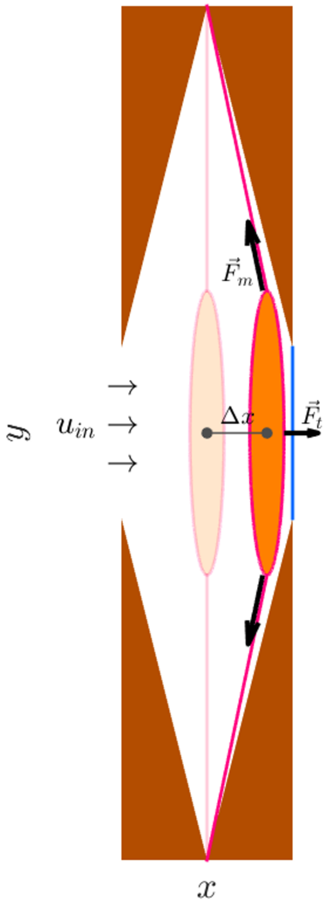
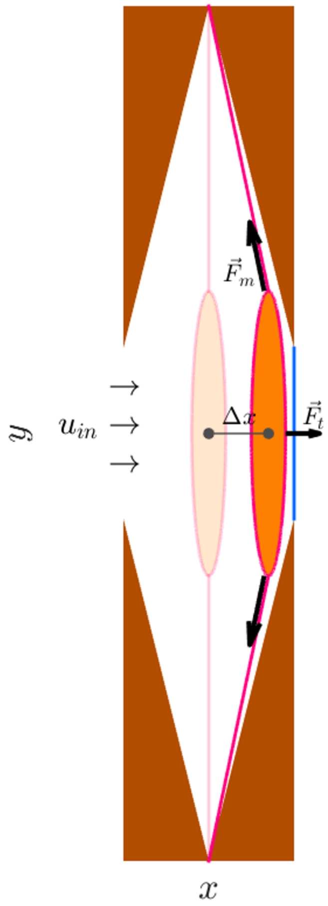


- F_m modeled as a spring force parametrized by the Young's modulus *E* (~50 GPa)
- F_t calculated through integration of pressure around the torus
- $F = F_t + F_m$
- Expect an equilibrium deflection *Δx* where the forces are balanced

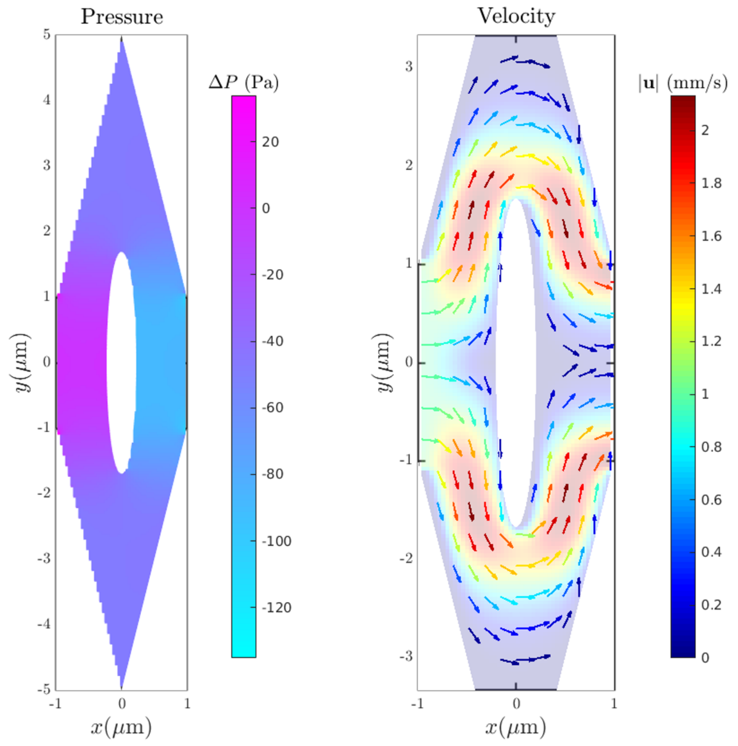
Flow & simulation properties

- Low Reynolds number
- Modified 2.29 FV code
- Torus deflection determined by $\boldsymbol{F_t} + \boldsymbol{F_m}$
- Mesh redefined after deflection update

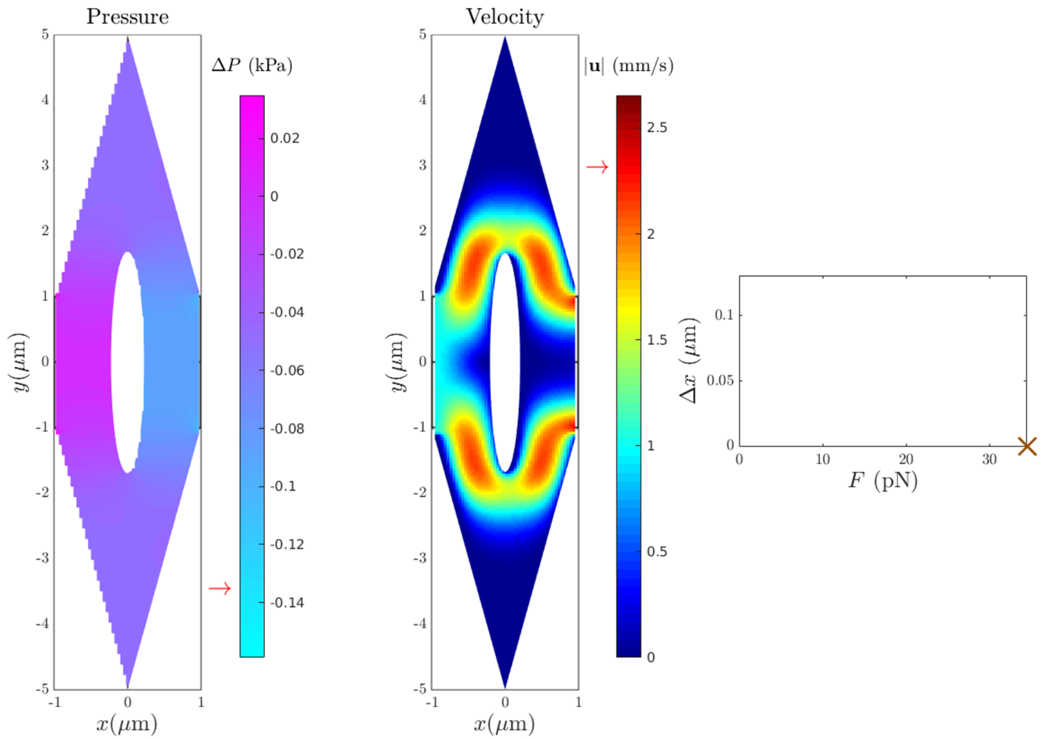


Typical flow through the pit

$$\Delta P = P - \bar{P}_{\text{in}}$$



Stability of deflection at low pressures



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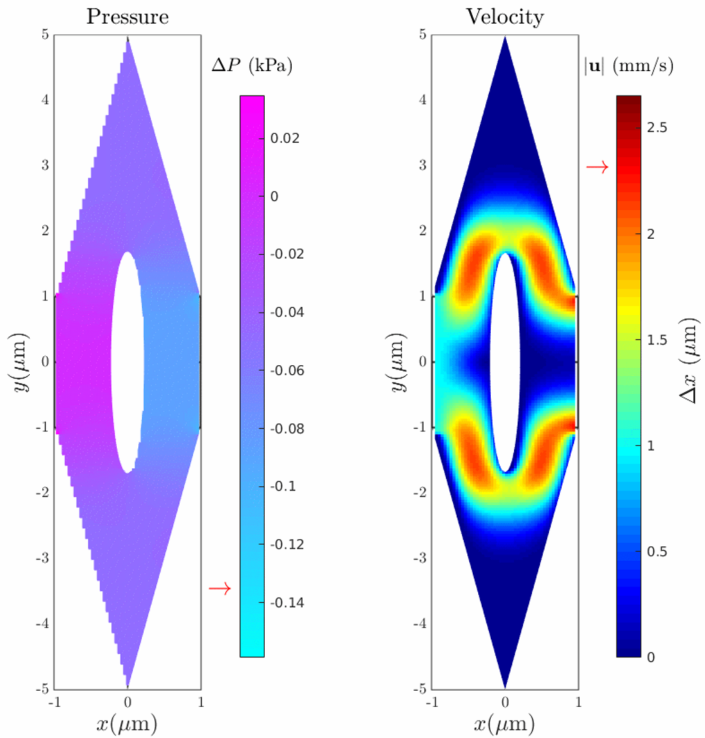
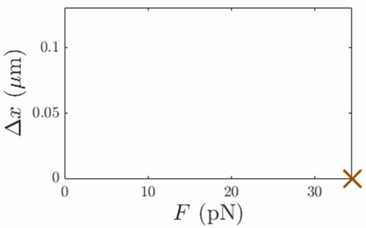
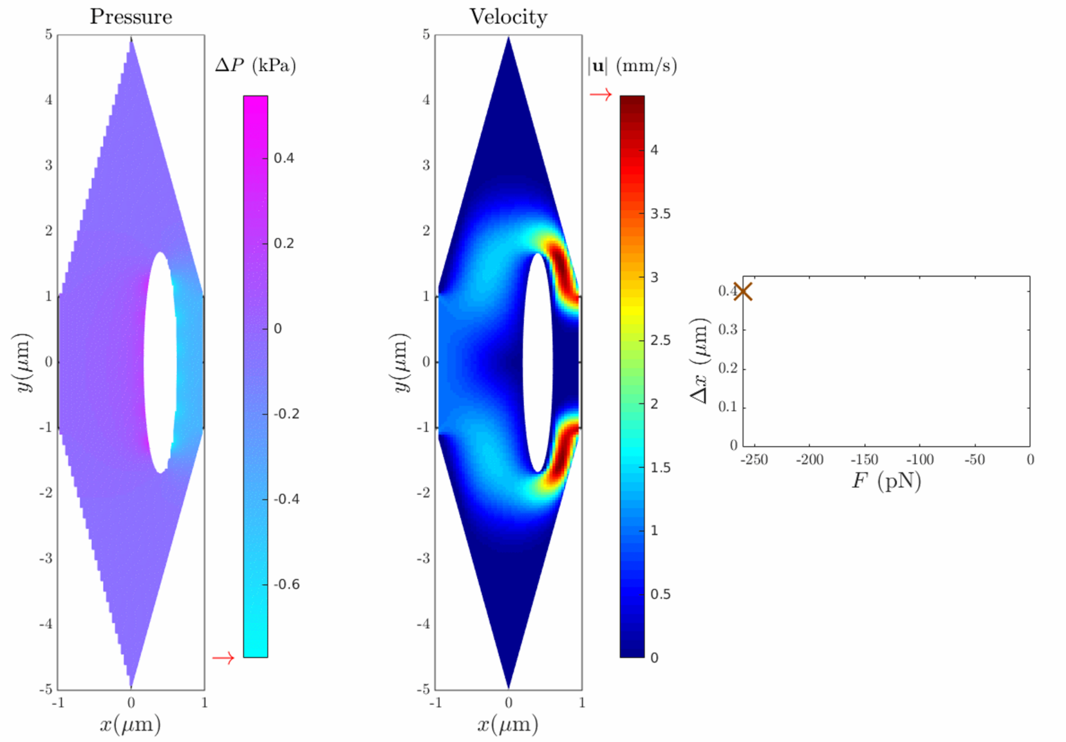


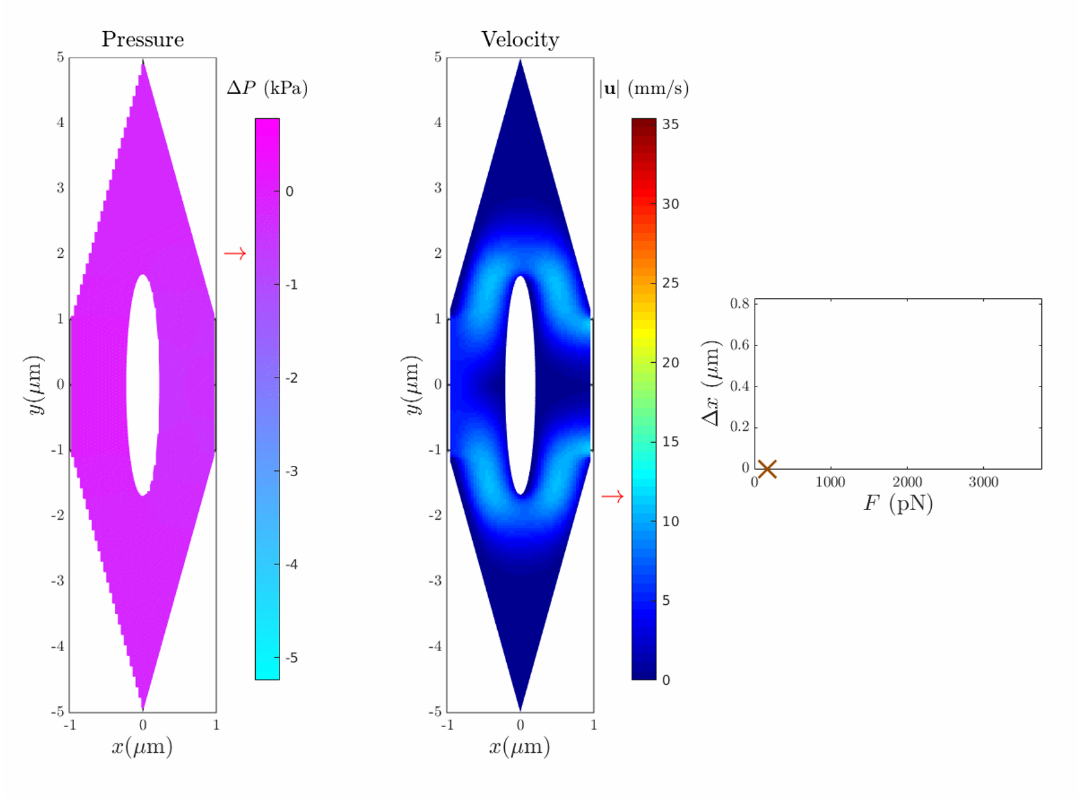
Balance between the deflecting fluid force and the restoring margo force



Stability of deflection at low pressures

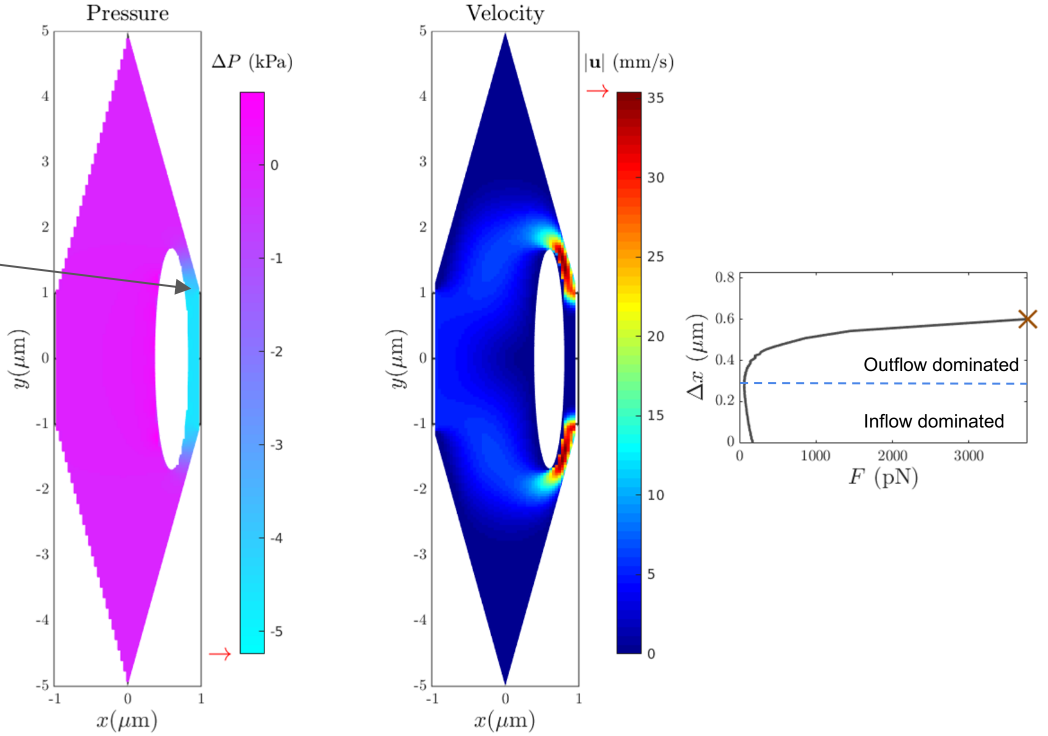


Aspiration is a biphasic process



Aspiration is a biphasic process

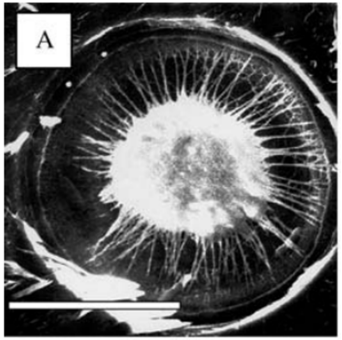
Outgoing flow pulls the torus towards the aperture



Comments

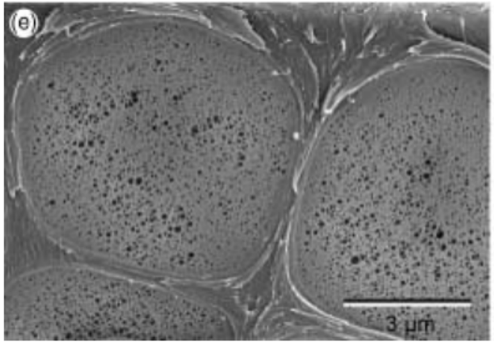
Aspiration (ie closure) can precede the air-water interface, in contrast with angiosperm “simple” pit membranes, which function by capillarity

Gymnosperm
“Margo-torus”



Domec et al. *Am. J. Bot.* (2006)
Scale bars: 10 μm

Angiosperm
“Simple”



Choat et al. *New Phyt.* (2008)