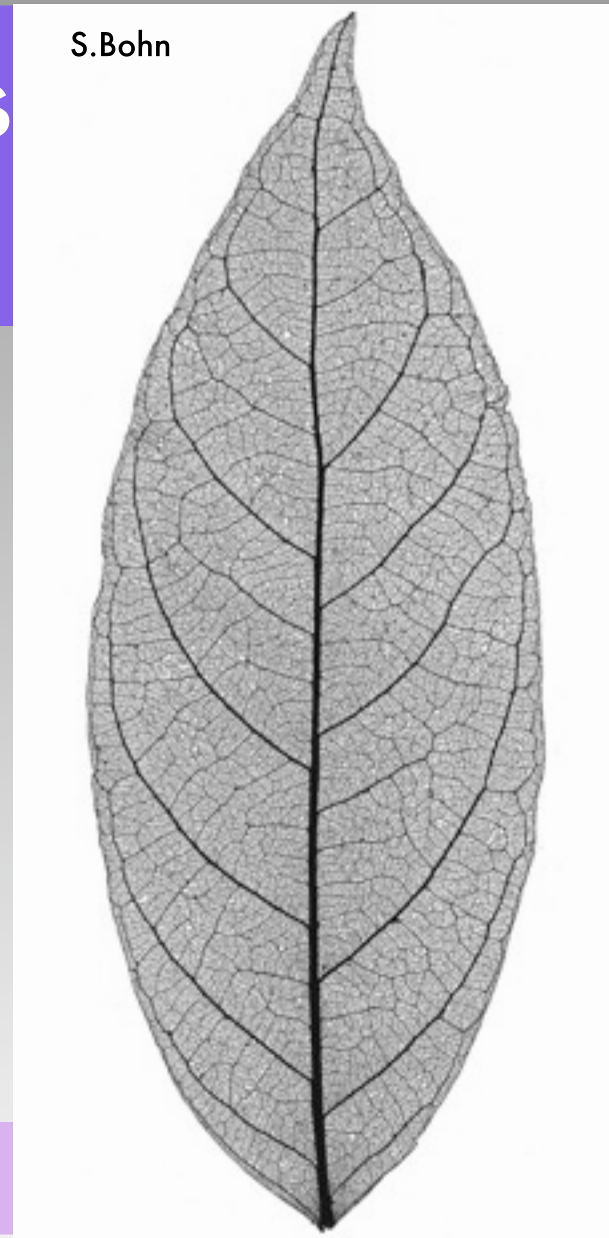
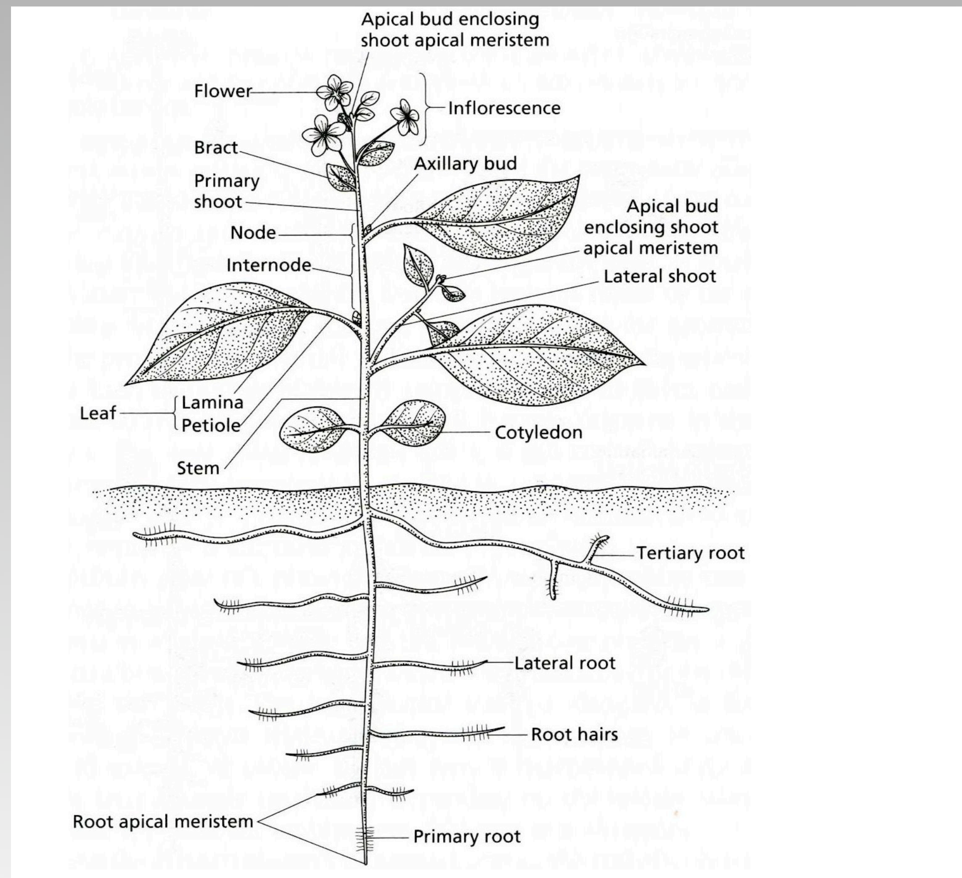
The geometry and mechanics of morphogensis in leaves



Arezki Boudaoud; LPS, ENS Paris

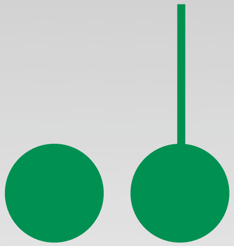
Introduction



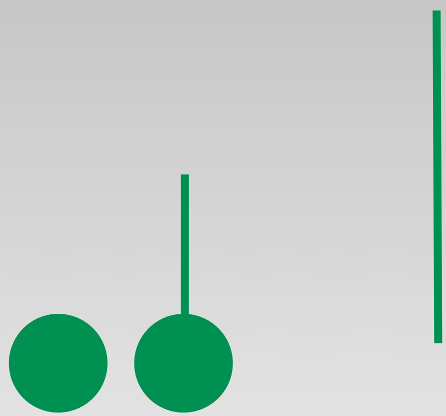
Leyser & Day, Mechanisms in Plant Development

Introduction

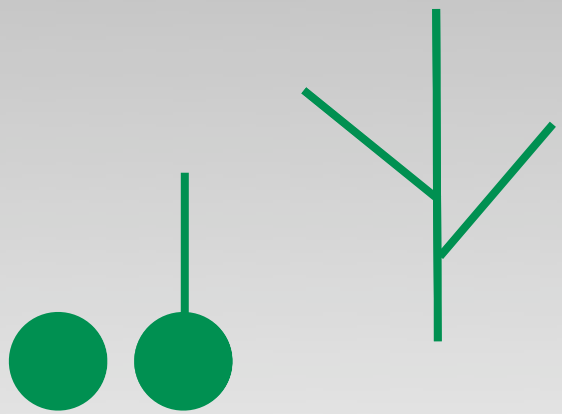
Introduction



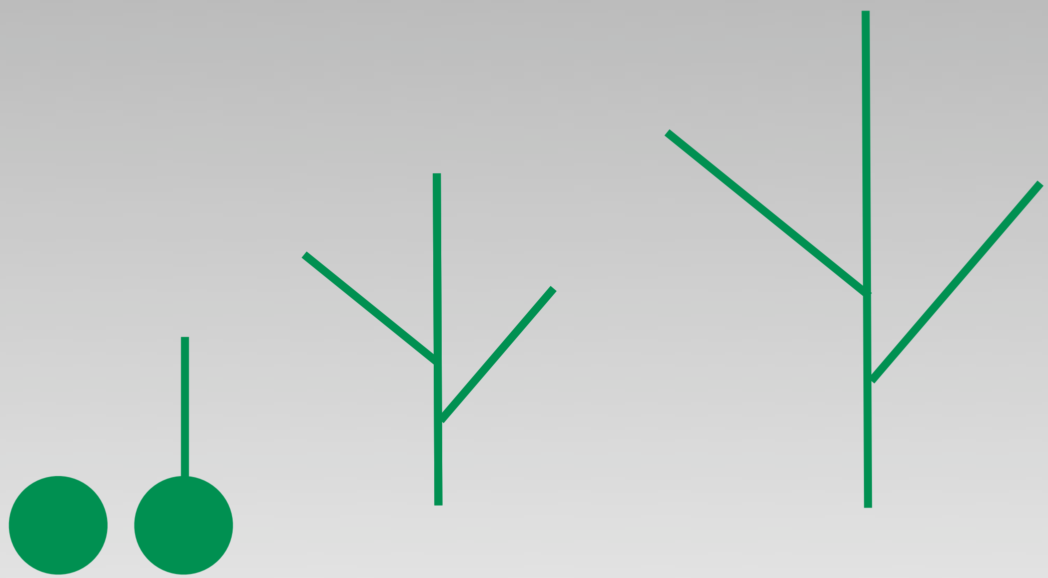
Introduction



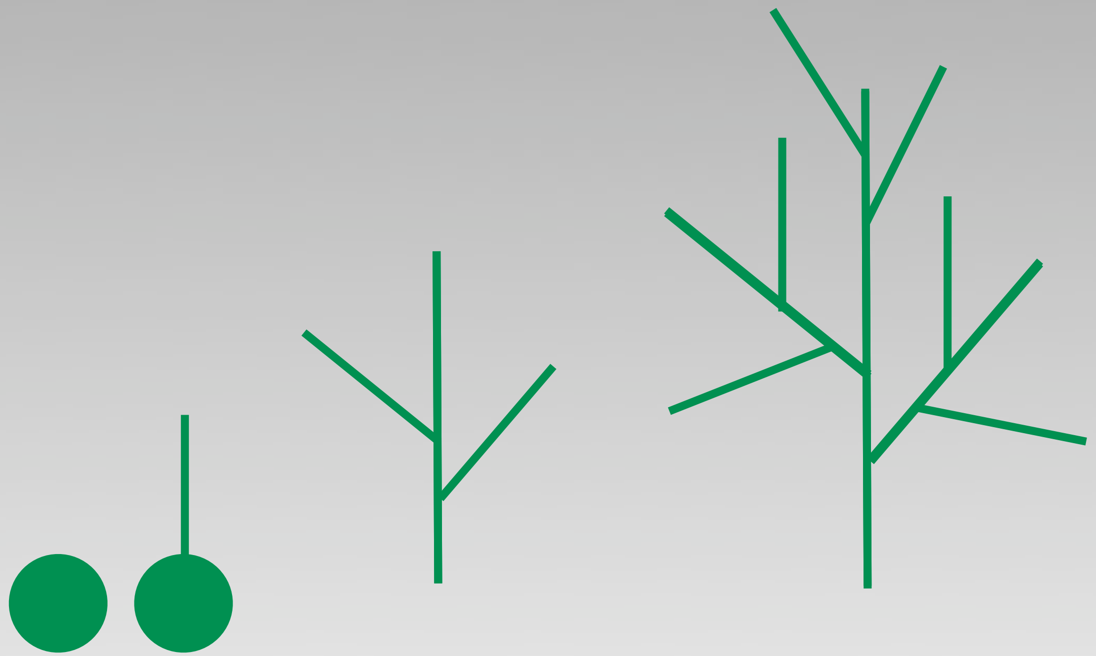
Introduction



Introduction



Introduction



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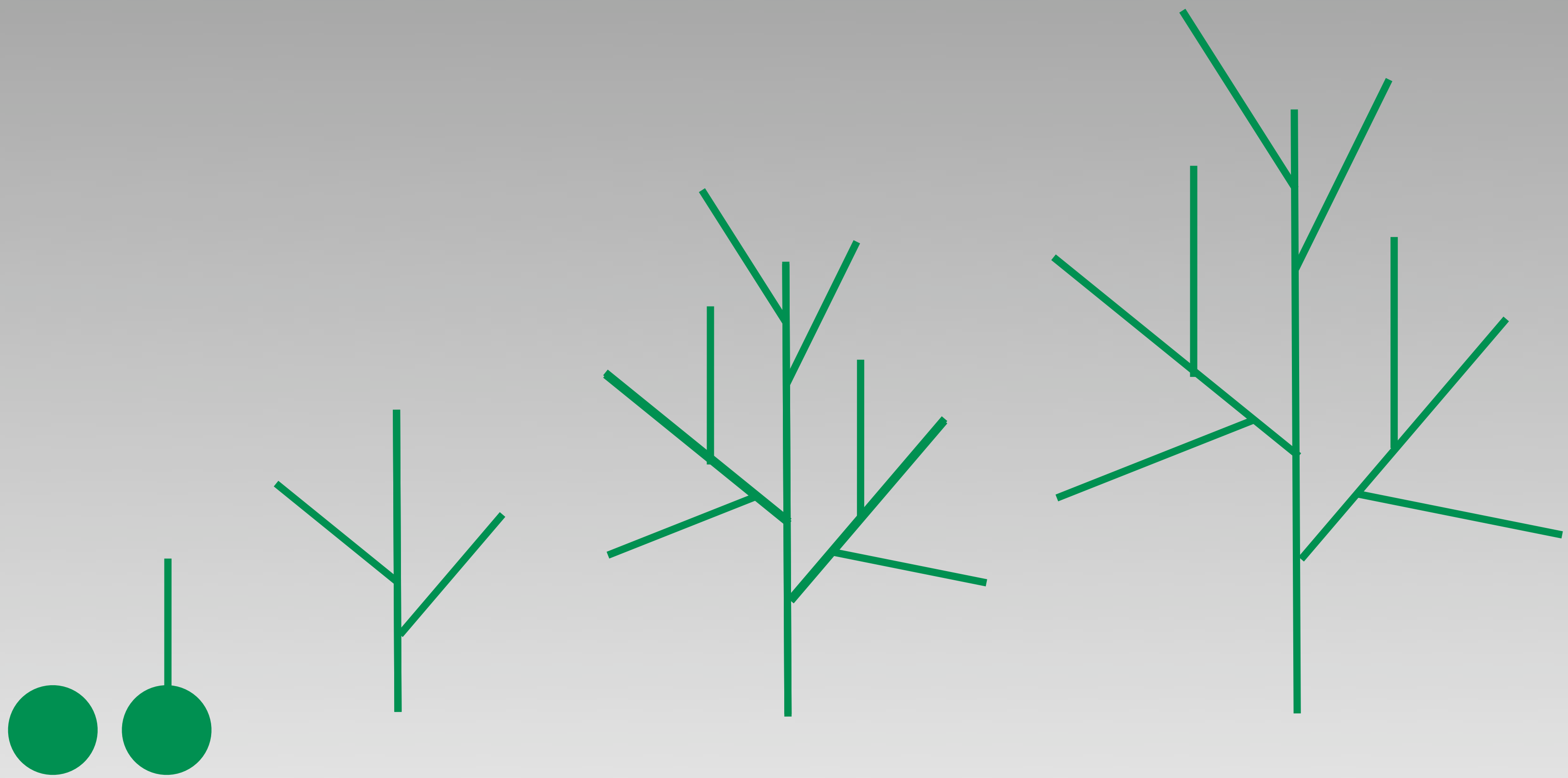

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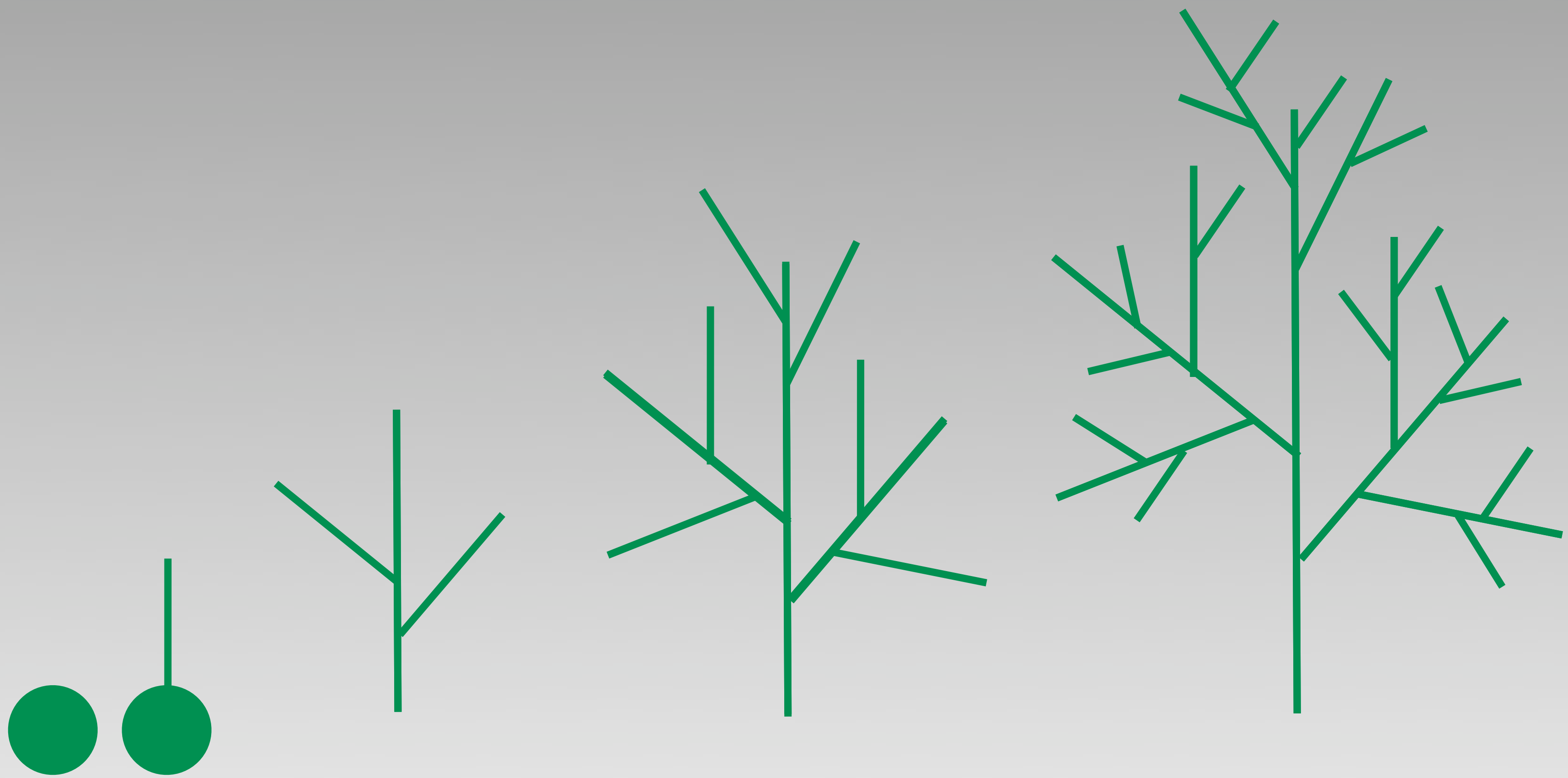
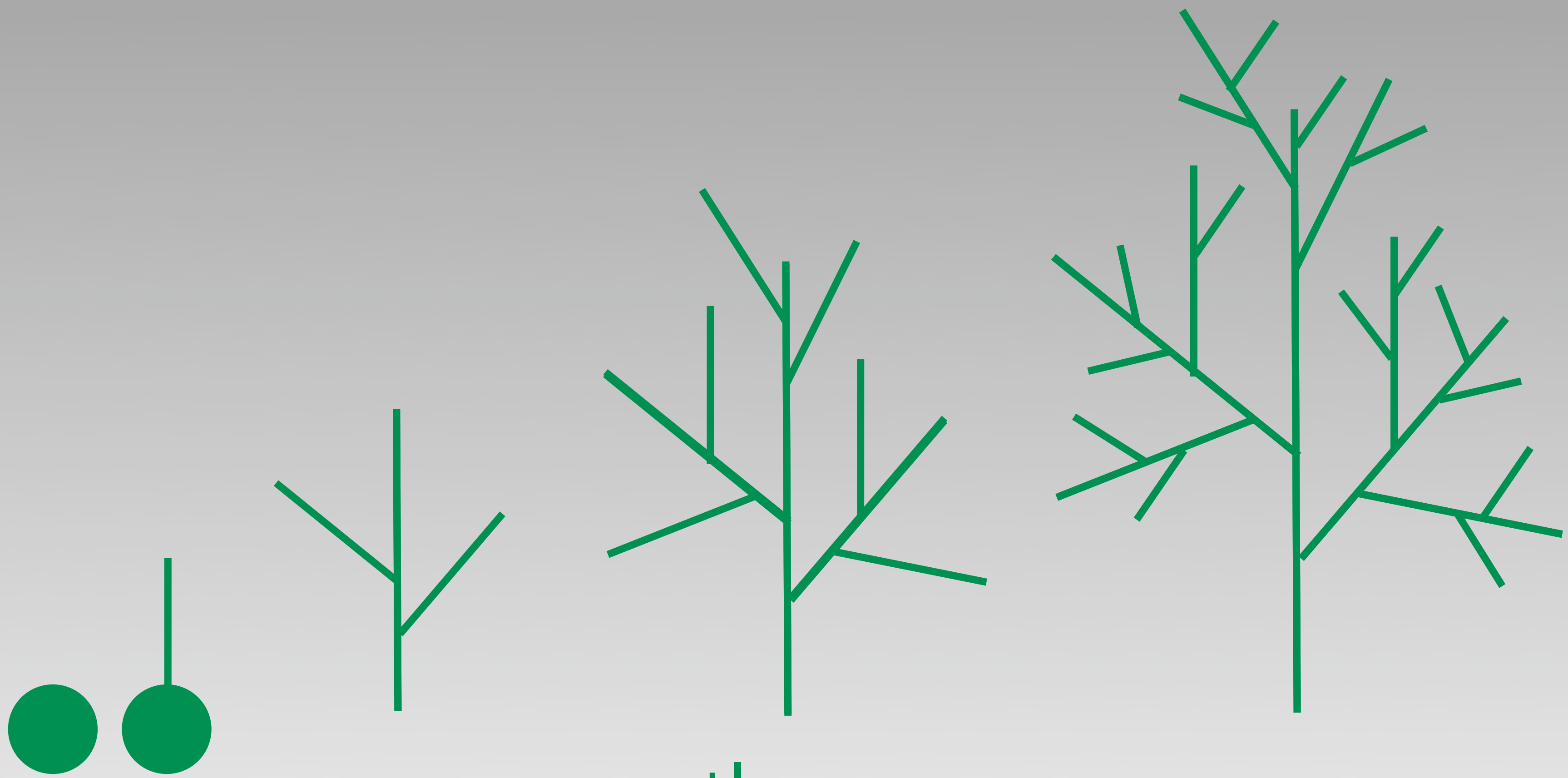
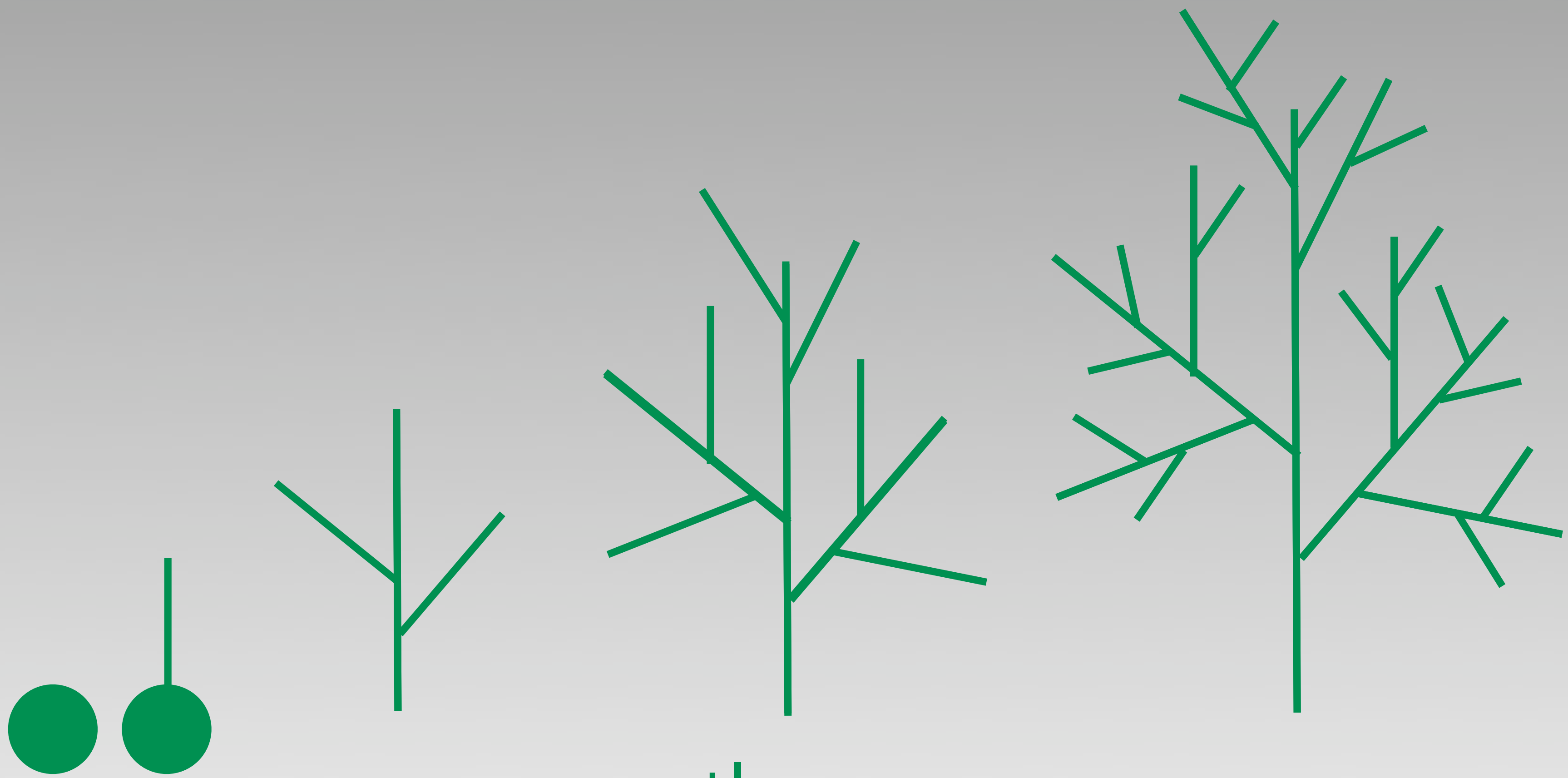


Introduction



+leaves

Introduction



+leaves

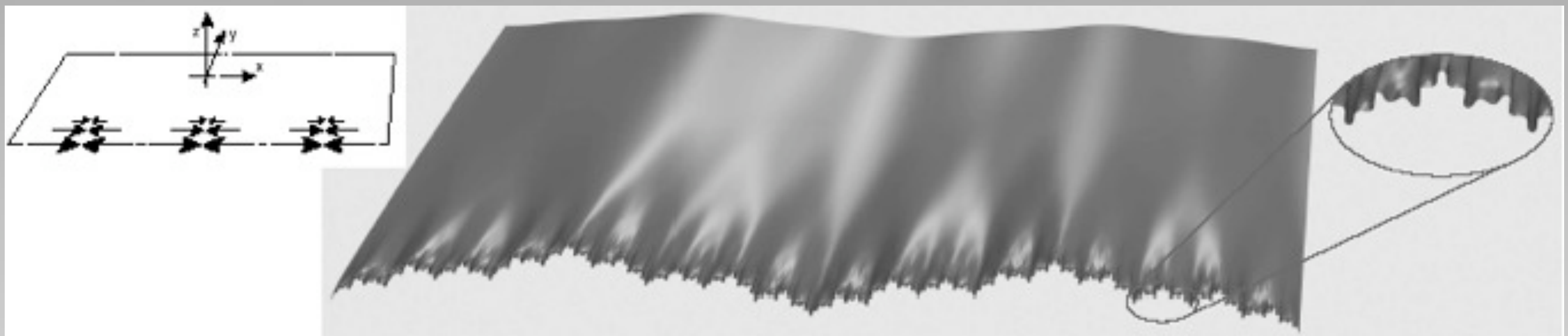
3D ⟶ 1D ⟶ 2D

How to build tapered or flat organs?

Outline

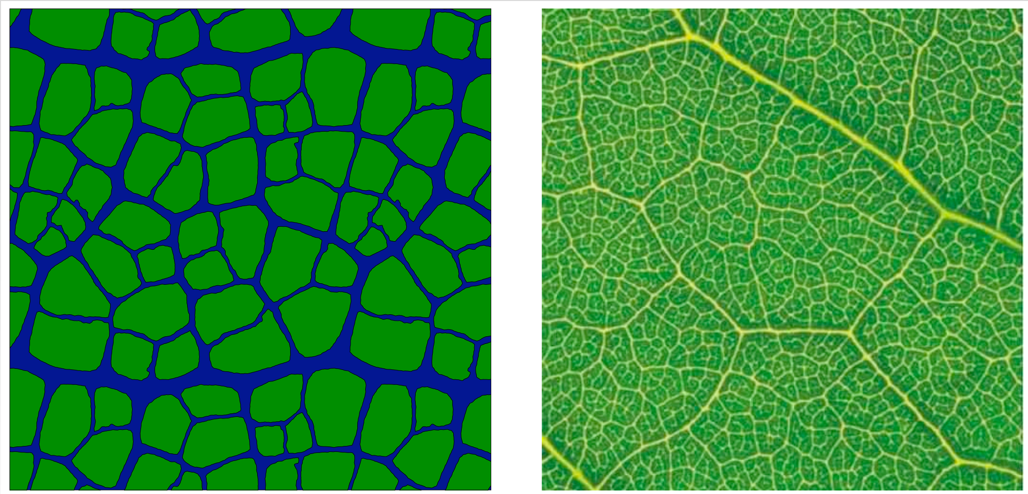
Ruffles in leaves

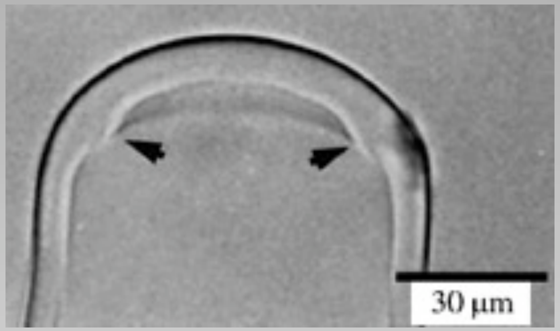
B. Audoly, A.B.



Leaf vasculature

F. Corson, M. Adda-Bedia, A.B.



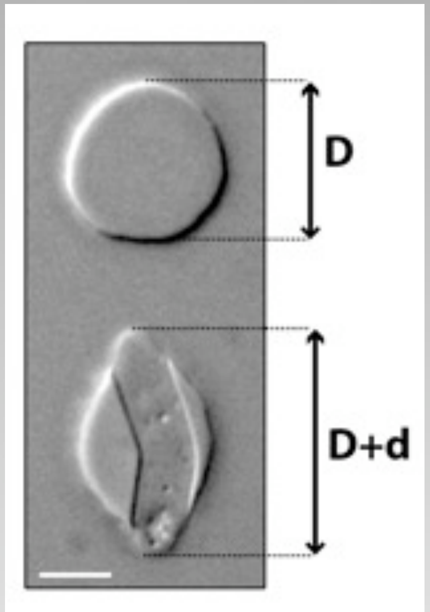


Walled cells:
plants, fungi, bacteria
mechanically `simple'

A.B.

Yeast growth mechanics

N. Minc, F. Chang, A.B.



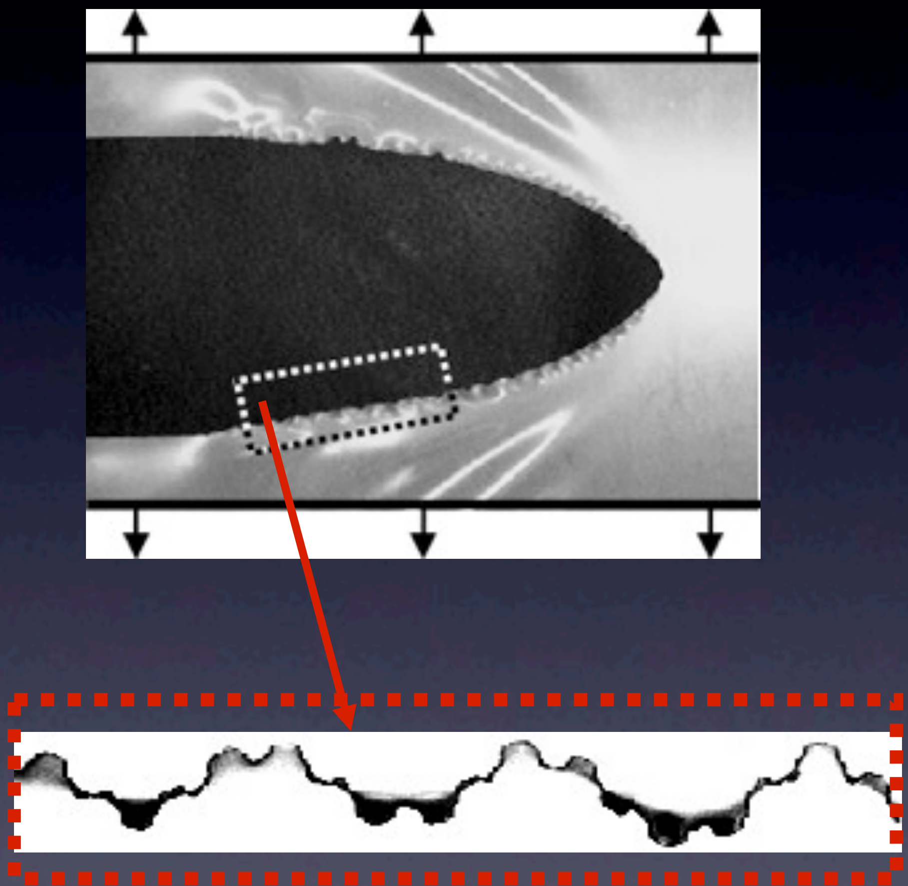
Ruffles in leaves, petals, and more

Ruffles in leaves

Ruffles in leaves

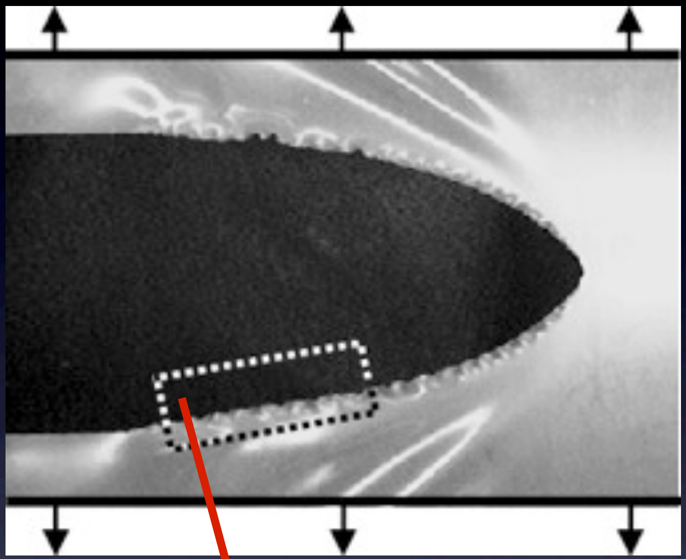
Eran Sharon

Ruffles in torn plastic sheets



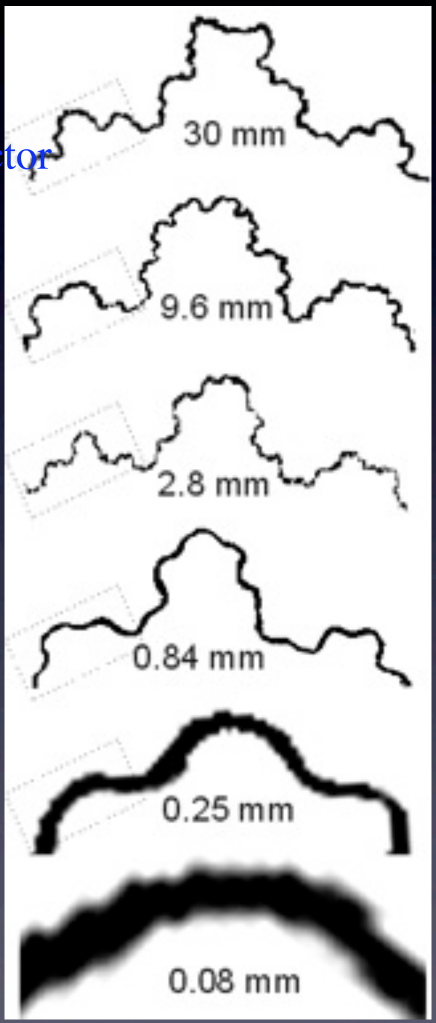
Eran Sharon et al 2002

Ruffles in torn plastic sheets



Eran Sharon et al 2002

Magnification factor
3.2

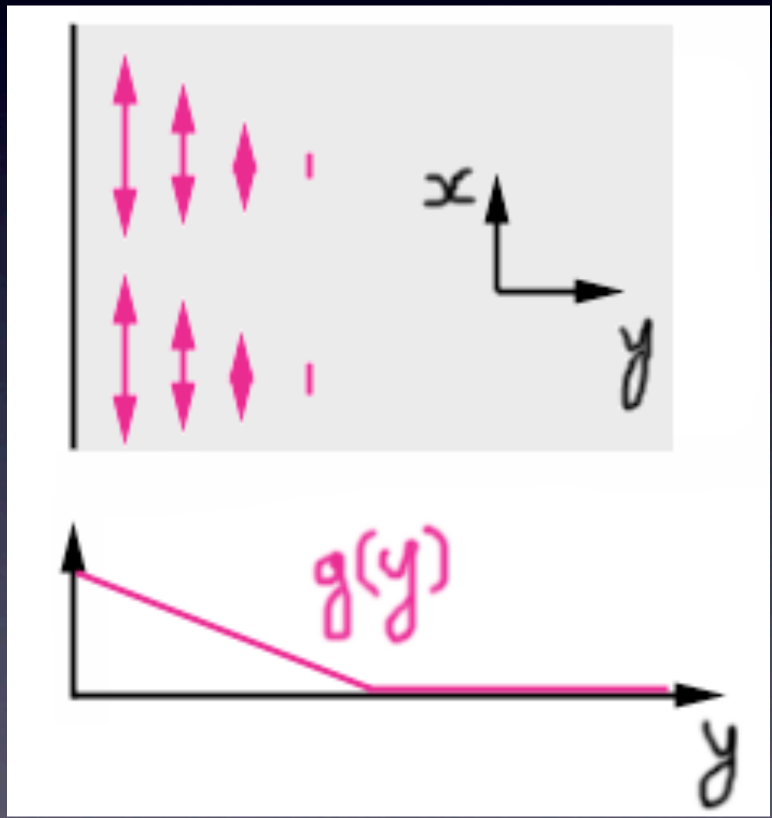


Ruffles

- Metric

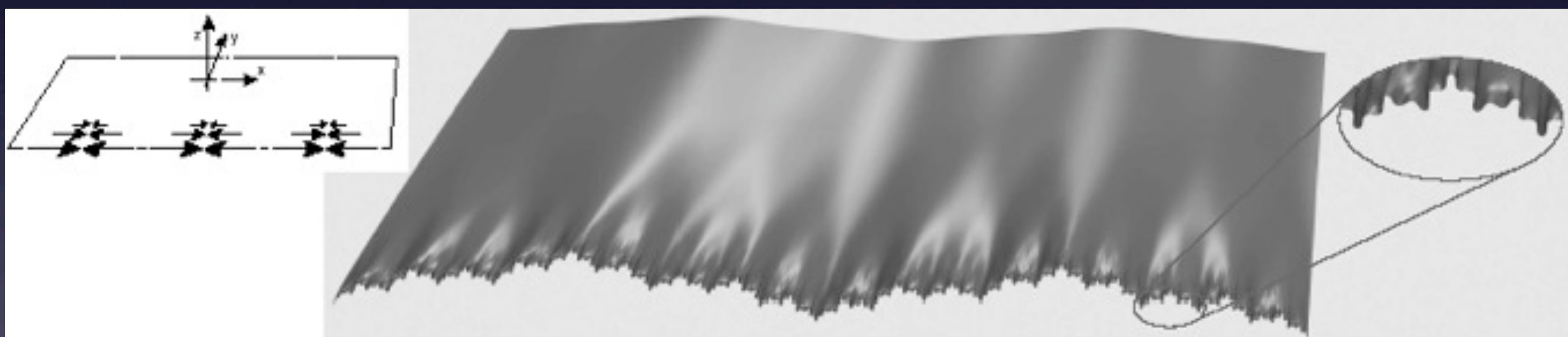
$$ds^2 = (1+g(y))^2\, dx^2 + dy^2$$

- $g(y)$: growth strain

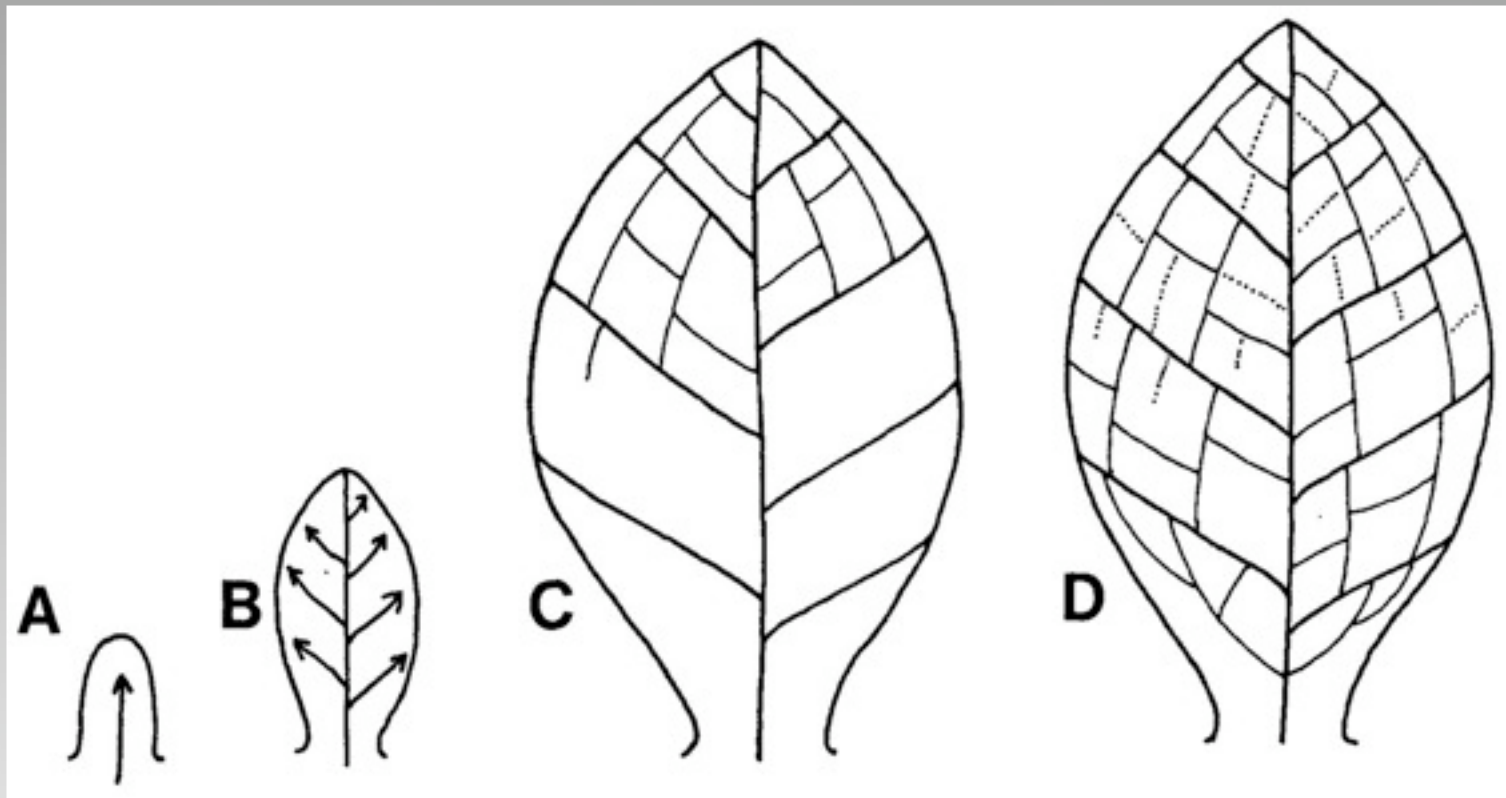


Ruffles

Up to 5 generations with wavelenghts λ, $\lambda/3$, $\lambda/9$, $\lambda/27$, $\lambda/81$.



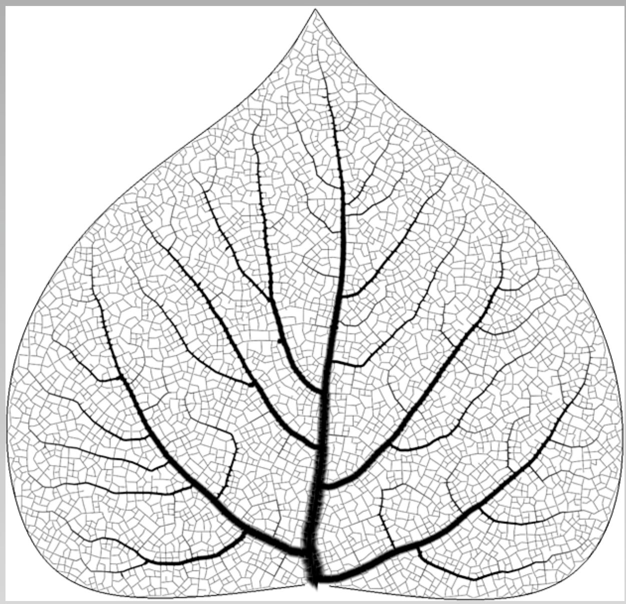
Venation networks



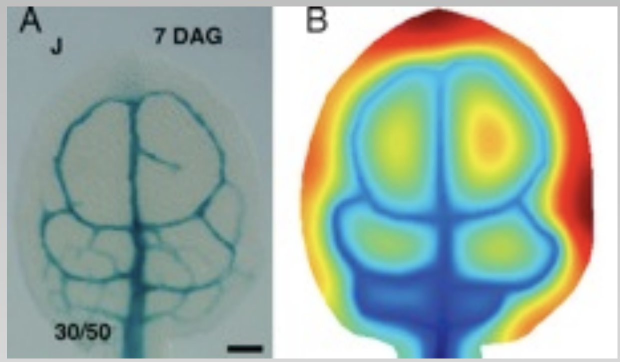
conserved: midvein, secondary veins
variable: higher order ... ; areoles

Venation networks

Sachs, Mitchison... 1980
Rolland-Lagan & Prusinkiewicz 2005
Feugier et al. 2005-2006



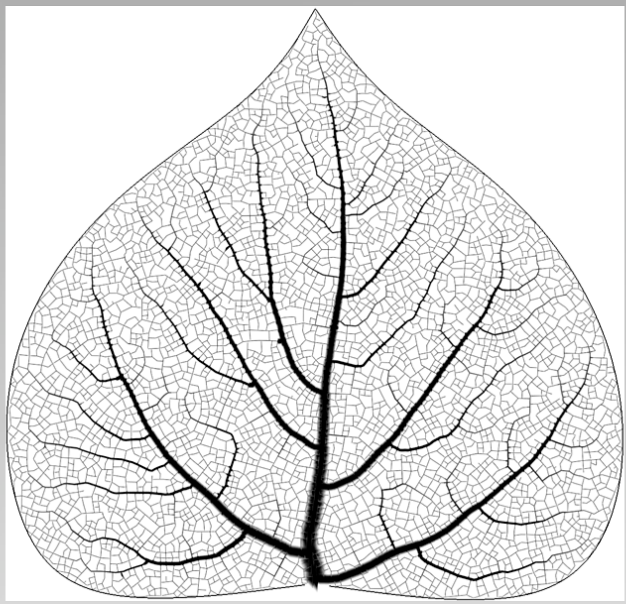
Runions et al. 2005



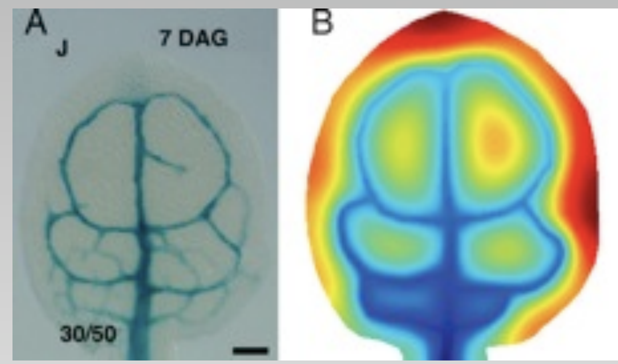
Dimitrov & Zucker 2006

Venation networks

Sachs, Mitchison... 1980
Rolland-Lagan & Prusinkiewicz 2005
Feugier et al. 2005-2006



Runions et al. 2005



Dimitrov & Zucker 2006

Couder et al 2002
Laguna et al 2008

Venation networks

Main motivations

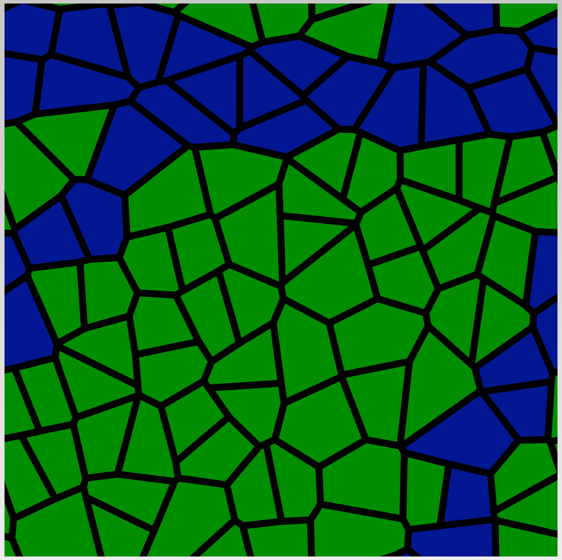
- Tissue with two cell types – a minimal system for 2D morphogensis

Goal:

- understand reorganisation of network as leaf grows
- compare with observations and suggest future experiments

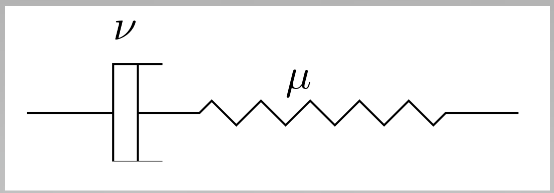
Model:

- cell based
- elastic walls slowly yielding to tension
- growth driven by
- cell division
- two cell types with different mechanical properties
- division of areoles



Venation networks

viscoelastic walls $T_i = \mu h \left(\frac{l_i}{l_i^0} - 1 \right) = \frac{\nu_i h}{l_i^0} \frac{\mathrm{d}l_i^0}{\mathrm{d}t}$

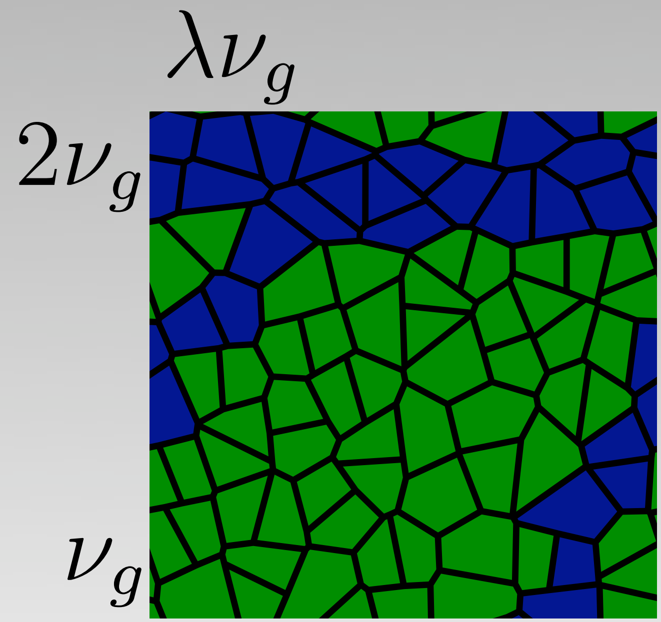


quasi-static, energy minimisation

$$\mathcal{E} = \sum \frac{\mu h}{2} \left(\frac{l_i}{l_i^0} - 1 \right)^2 - \sum P S_i$$

update l_i^0

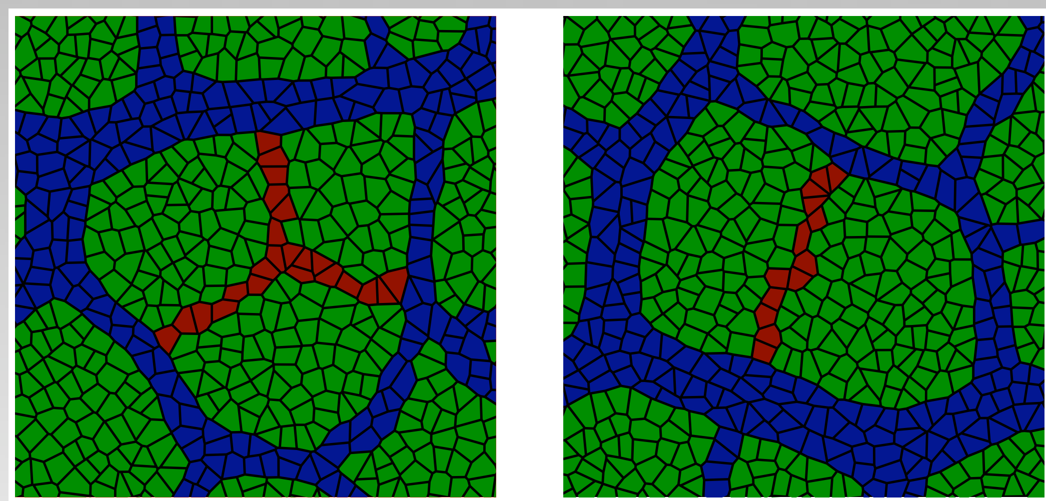
cell division: when $S = 1$
according to smallest axis of inertia



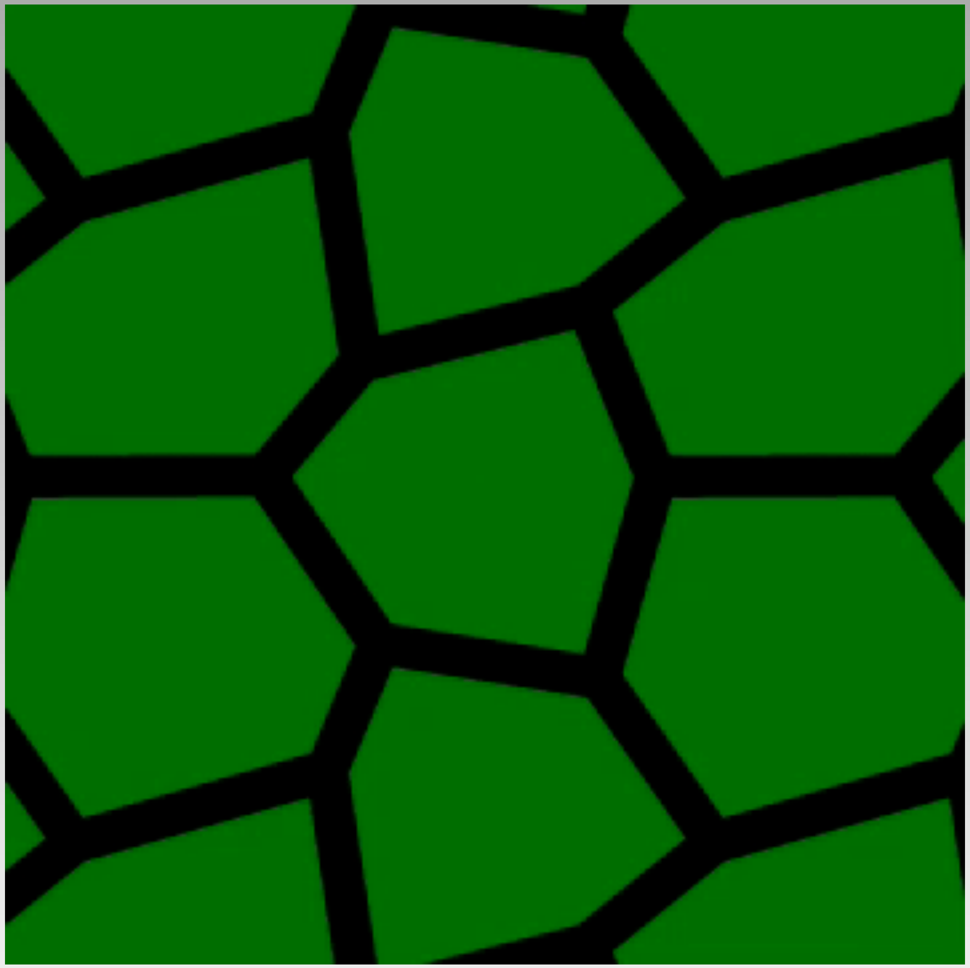
periodic boundary conditions

Venation networks

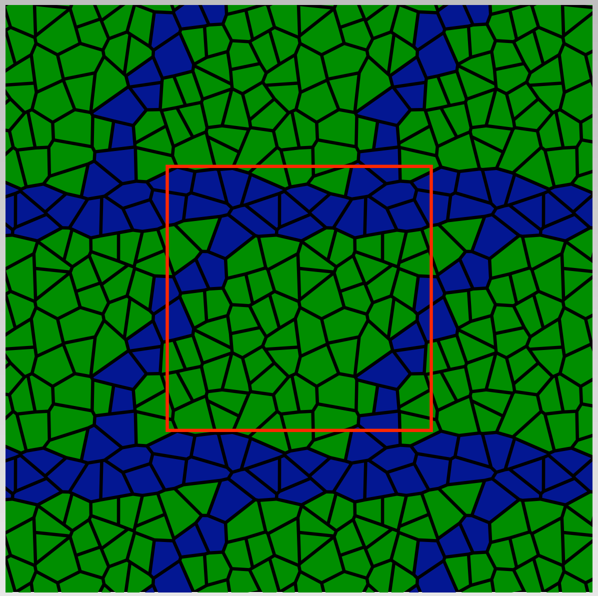
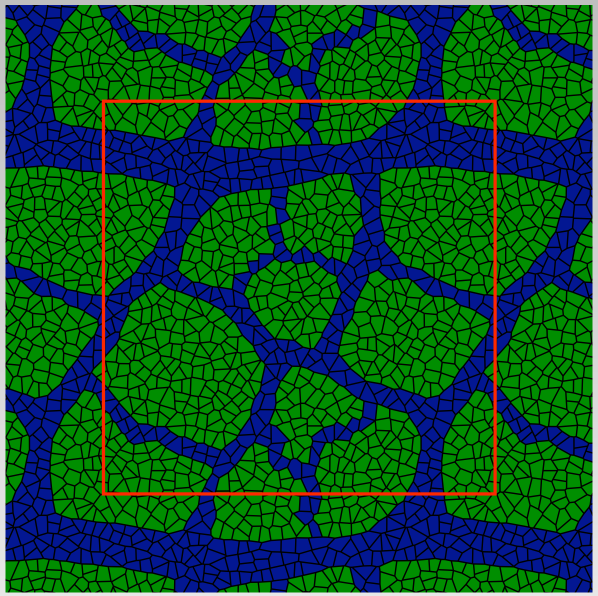
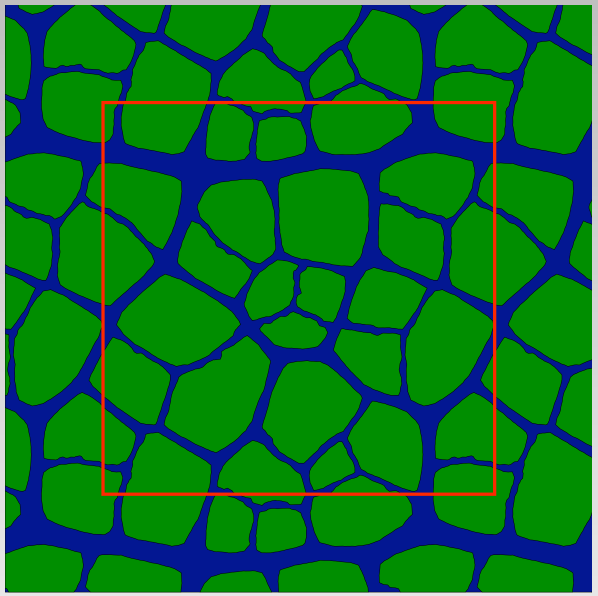
areole division: from sides to centroid
minima of distance to centroid
2 or 3 new veins according to areole shape



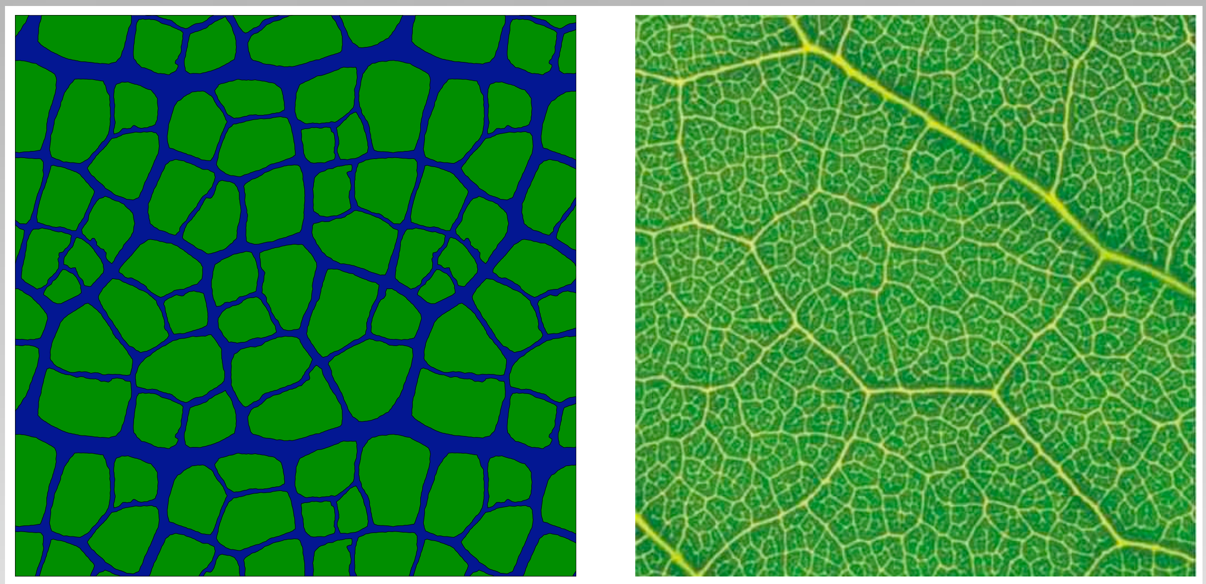
Venation networks



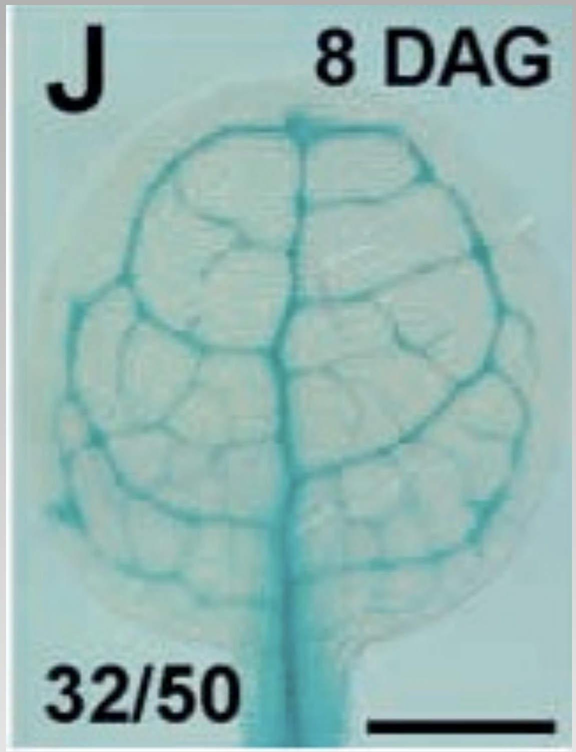
Venation networks

Venation networks

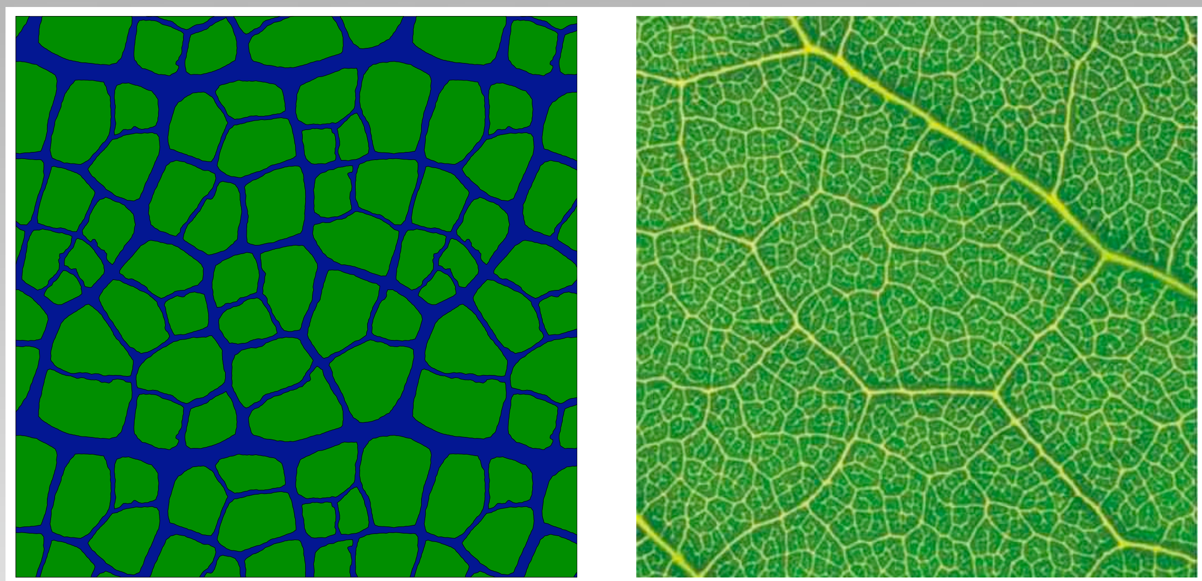


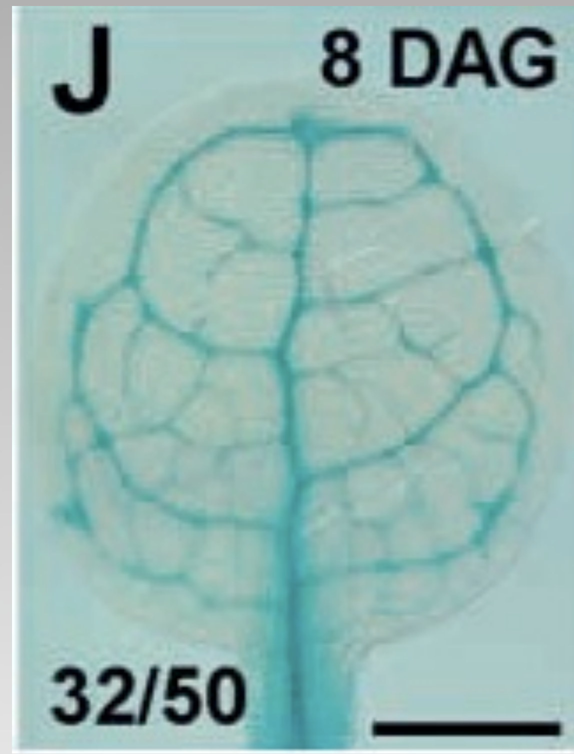
Scarpella, Francis & Berleth 2004



Venation networks

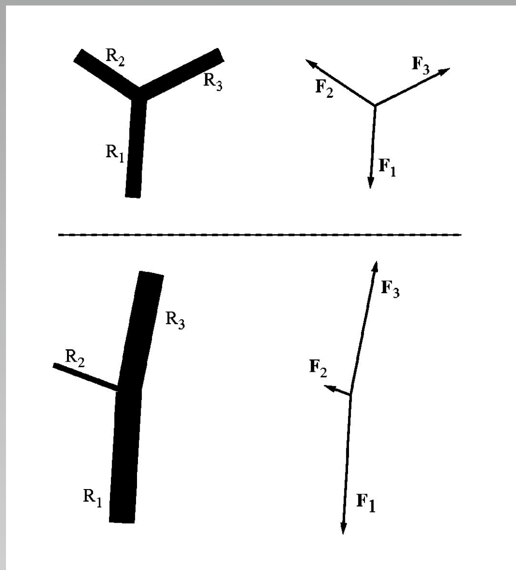
Scarpella, Francis & Berleth 2004



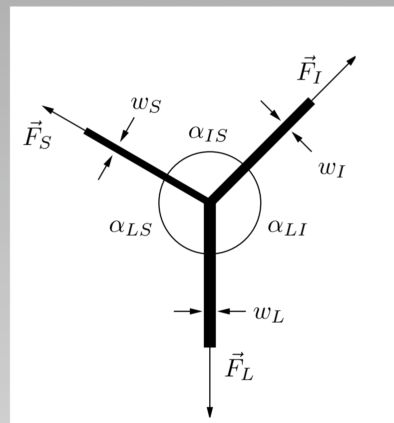


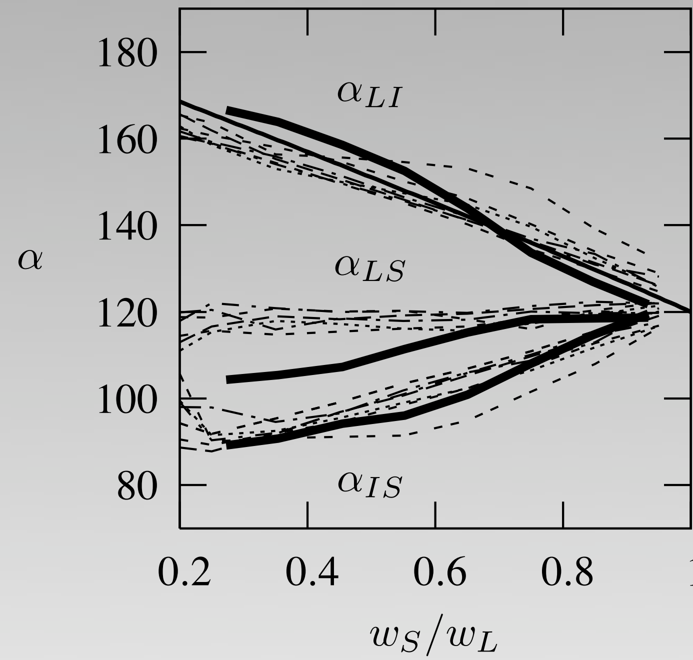
force balance at junctions

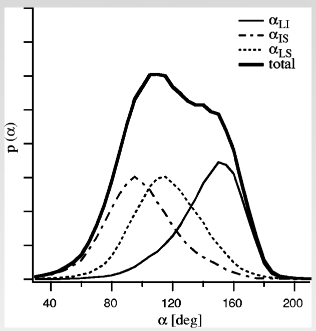
Venation networks

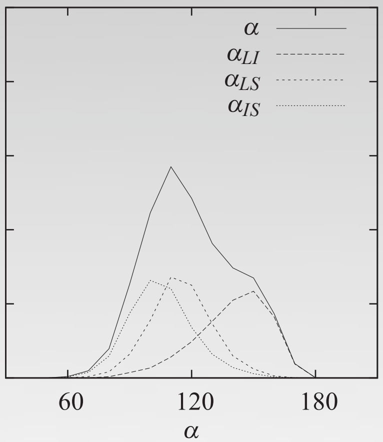


properties of junctions





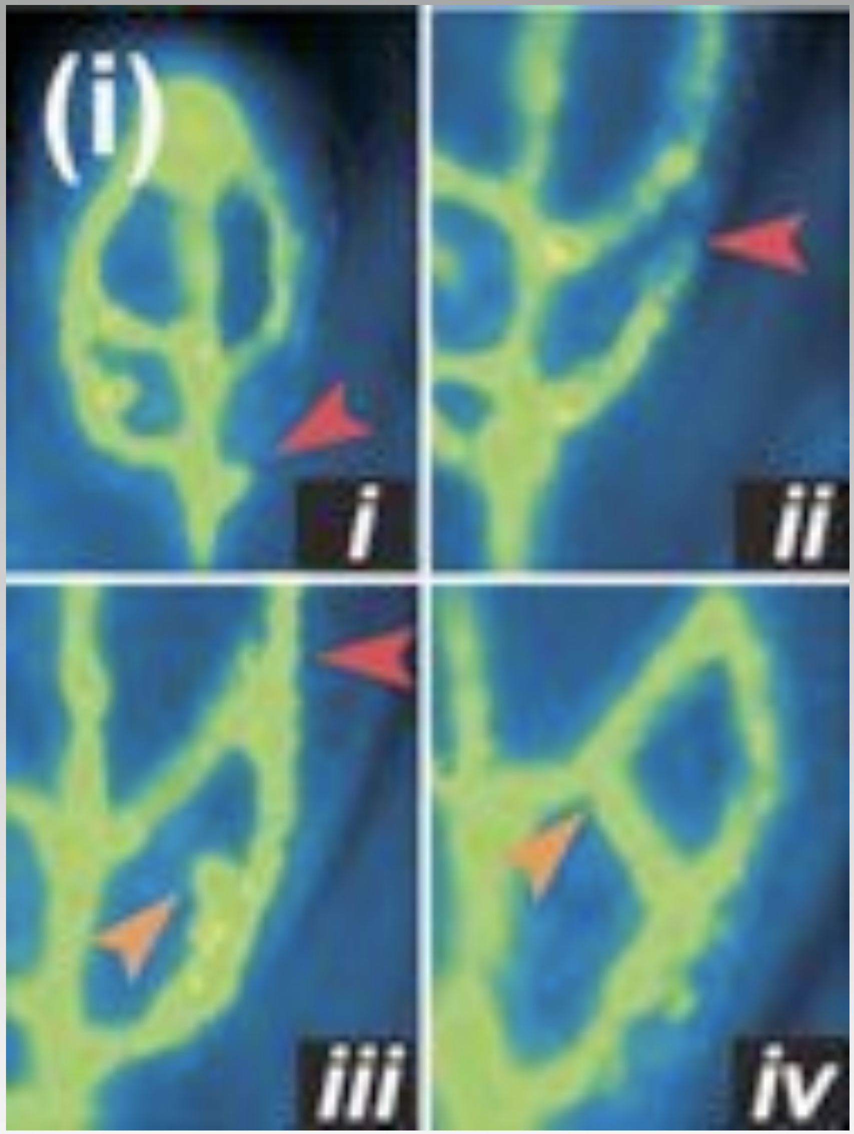




leaf data by Bohn, Andreotti, Douady, Muzinger & Couder 2002

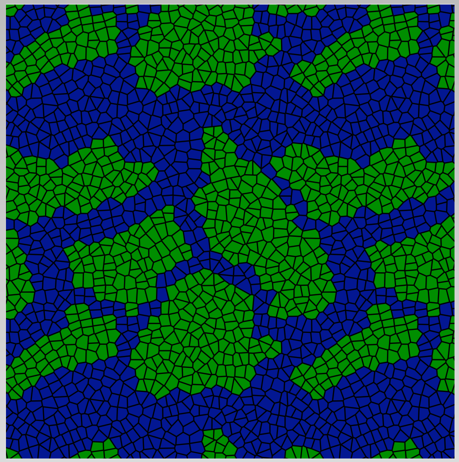
Venation networks

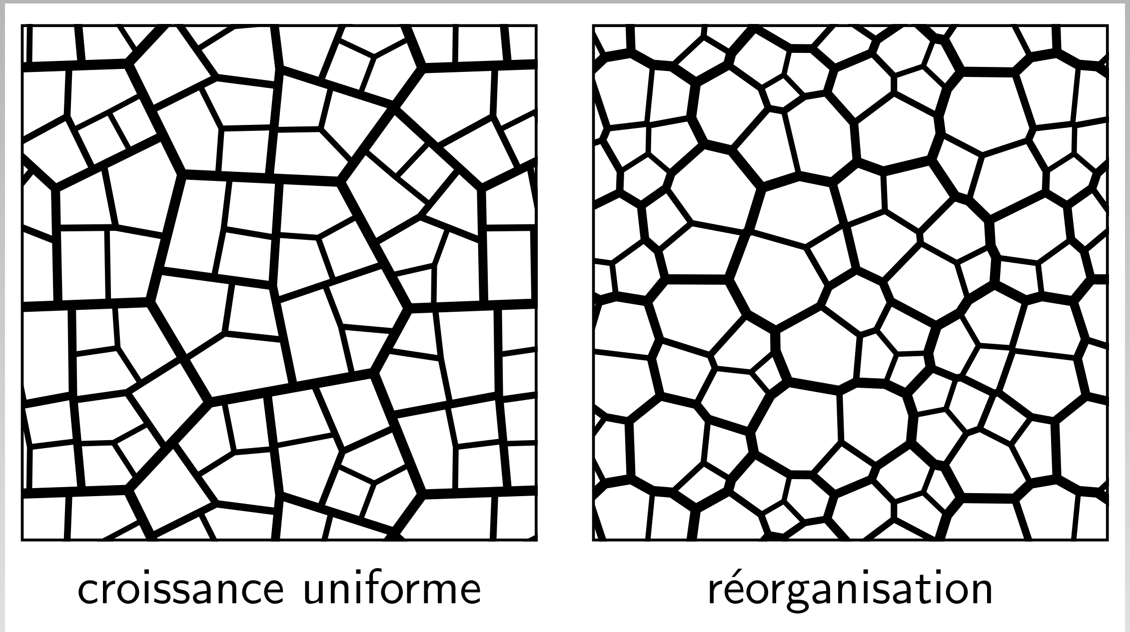
reorganisation in young leaves



Sawchuck et al. 2007

Venation networks





Conclusion

- A ‘simple’ growth program leads to complex forms

- venation networks growth and reorganisation seems to be driven by mechanical forces – assuming differences in stiffness

- experimental tests: A. Peaucelle ; N. Nakayama ; E. Sharon

- Future: integrate genetic & hormonal regulation

Ruffles

Basile Audoly
Paris 6 University

Venation

Mokhtar Adda-Bedia
ENS

Francis Corson
ENS, now Rockefeller University

Experimental collaborations

Eran Sharon
HUJI

Yohai Bar Sinai
HUJI, now ENS

Naomi Nakayama
Bern University

Alexis Peaucelle
INRA Versailles

Main entrance ENS Lyon

Old city of Lyon

Department of Biology, Ecole Normale Supérieure, Lyon

Come & join the adventure