Patterns and form: from physical systems to living systems

Arezki BOUDAOUD
Reproduction et Développement des Plantes
ENS de Lyon / UCB Lyon 1/ CNRS / INRA

PhD; postdoc
Paris, Boston
Physics

CR, CNRS
Paris
Physics

PR, ENS de Lyon
Biology

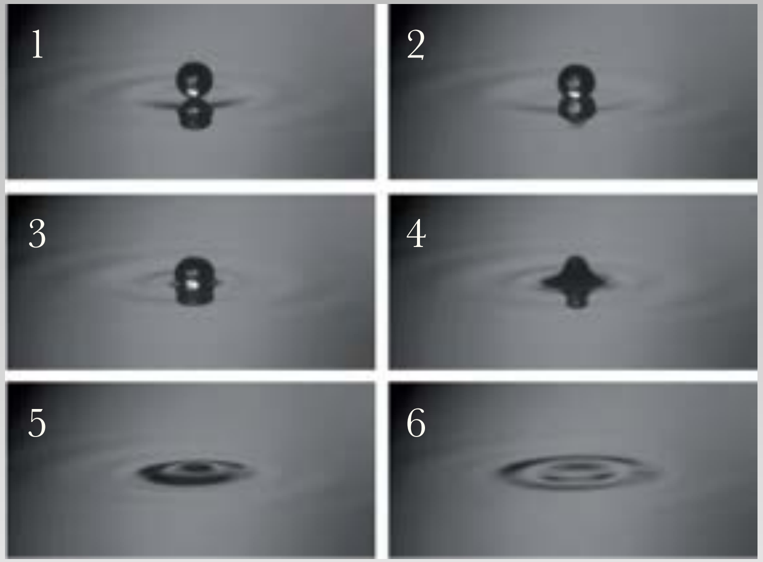
1997 2002 2009 2017

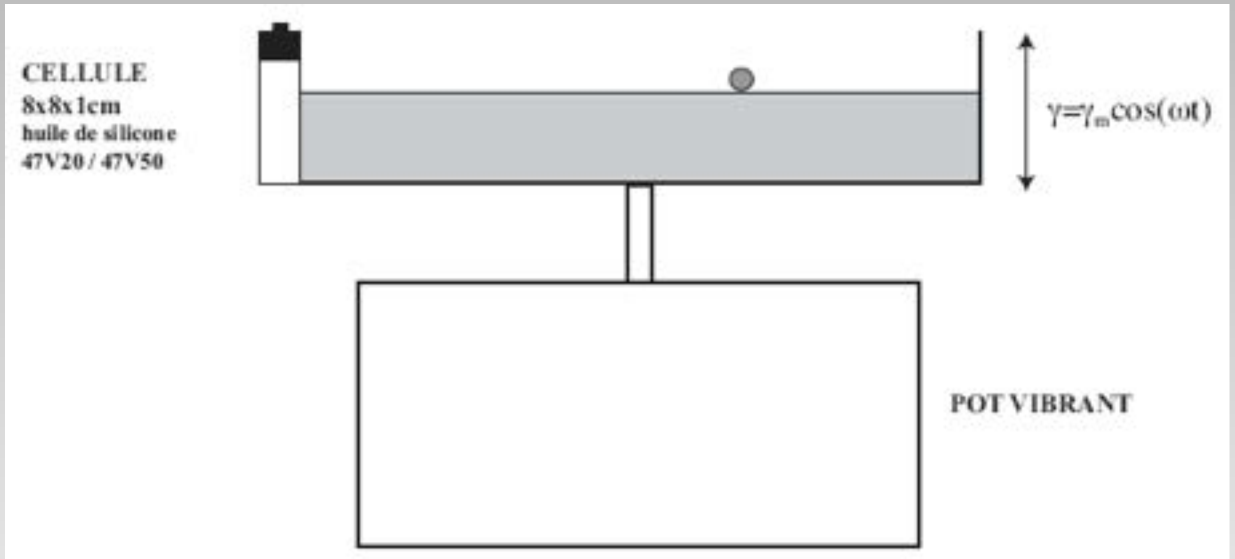
Physical questions

Biological questions

- Questions in nonlinear/statistical physics
- Questions in physics inspired by living systems
- Questions in cell and developmental biology

Self-organisation of droplets



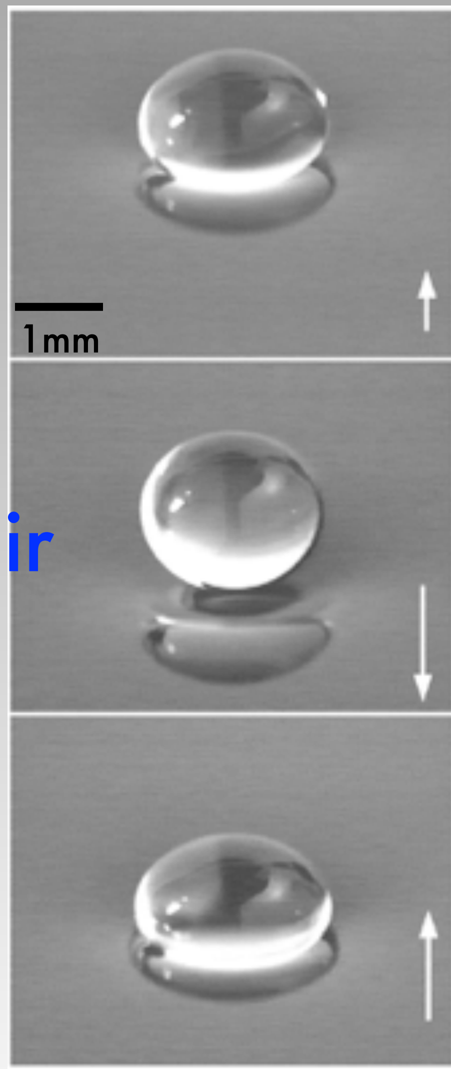


Self-organisation of droplets

Silicon oil

Frequency
50 Hz

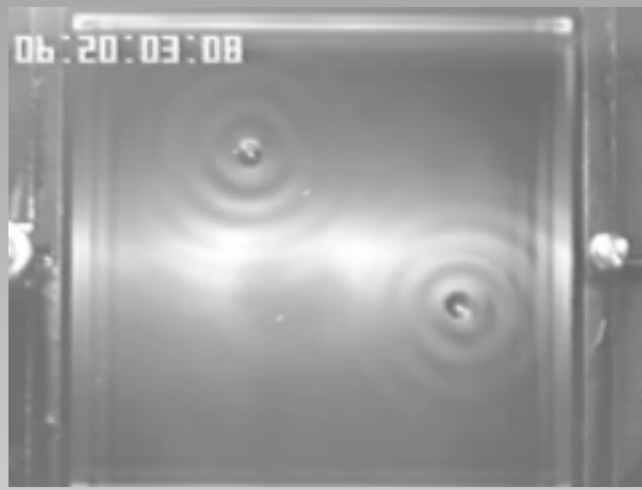
Film of air

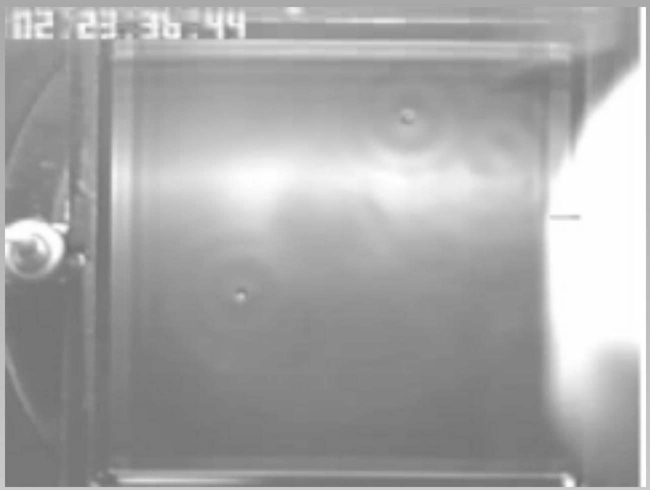


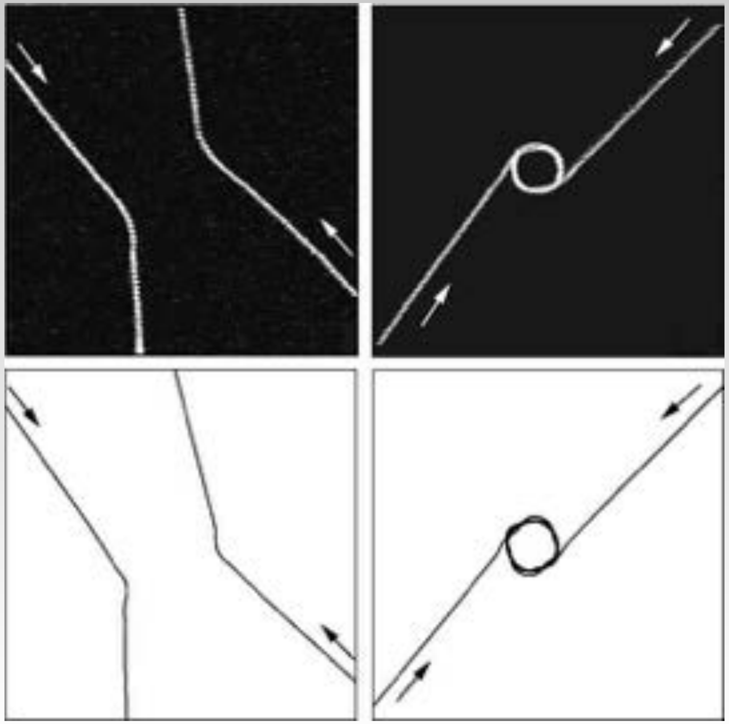
Couder et al. Phys. Rev. Lett. 2005

Couder et al. Nature. 2005

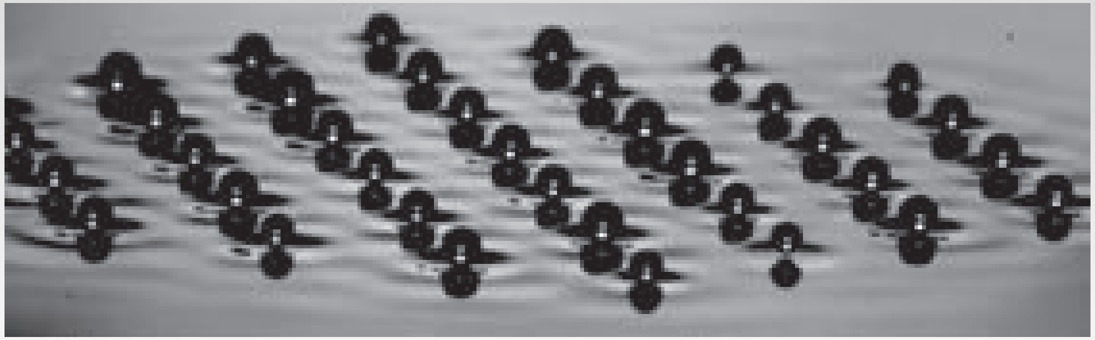
Self-organisation of droplets





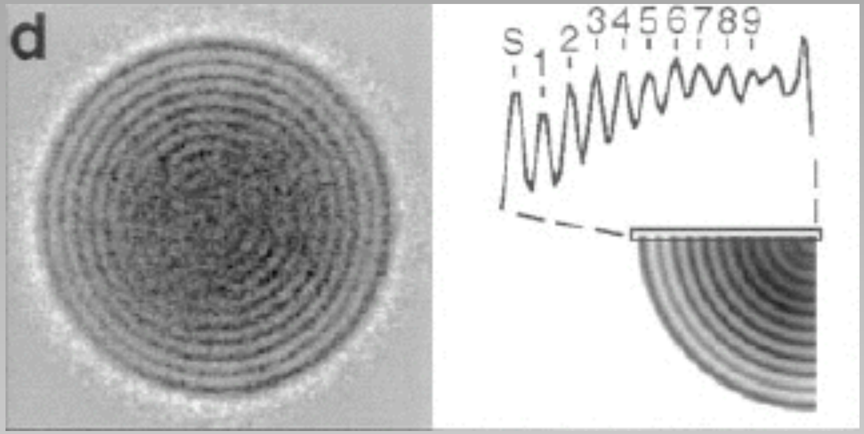


$$m\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2} = F^b \sin\left(\frac{2\pi}{V^{\varphi}}\left|\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}\right|\right)\frac{\mathrm{d}\mathbf{r}/\mathrm{d}t}{|\mathrm{d}\mathbf{r}/\mathrm{d}t|} - f^{\nu}\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} + F'^b \exp\left(-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda_A}\right)\sqrt{\frac{\lambda_F}{|\mathbf{r}-\mathbf{r}'|}}\sin\left(2\pi\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda_F}\right)$$



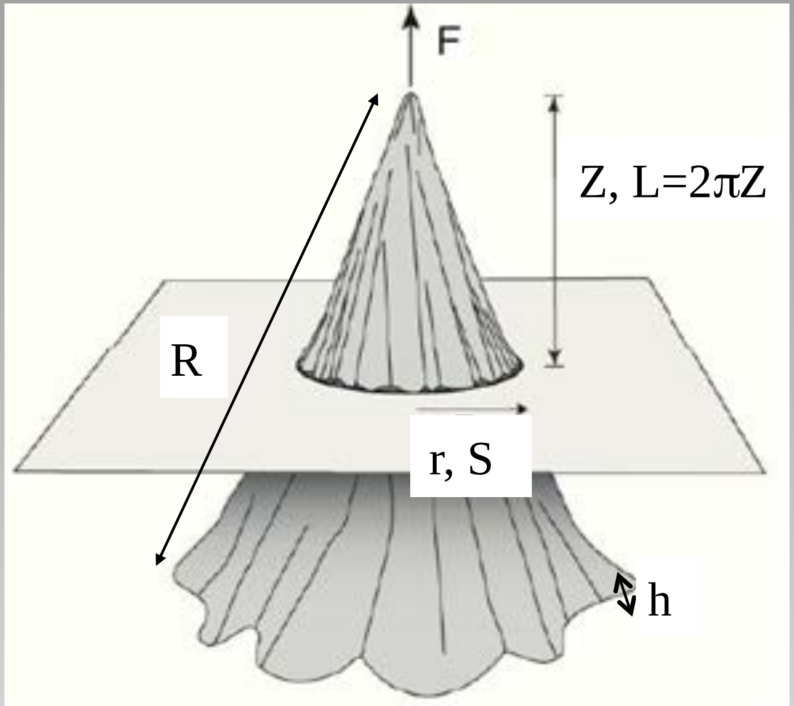
Couder et al. Nature. 2005; Eddi et al. EPL 2011

Packing of thin



César

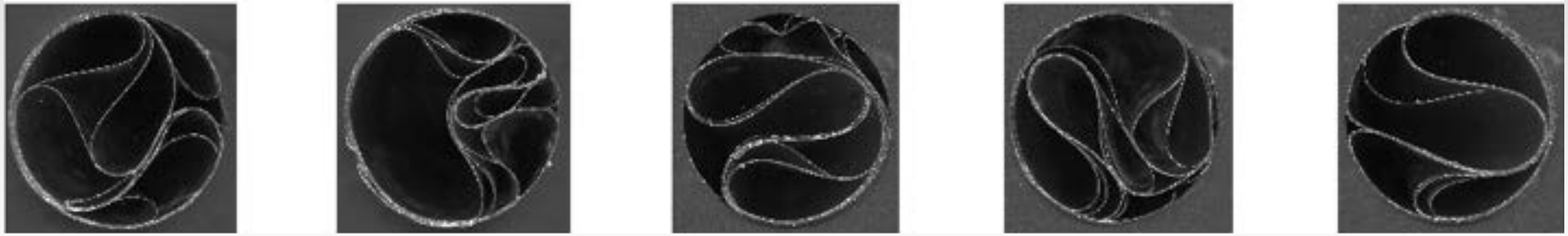
Packing of thin sheets



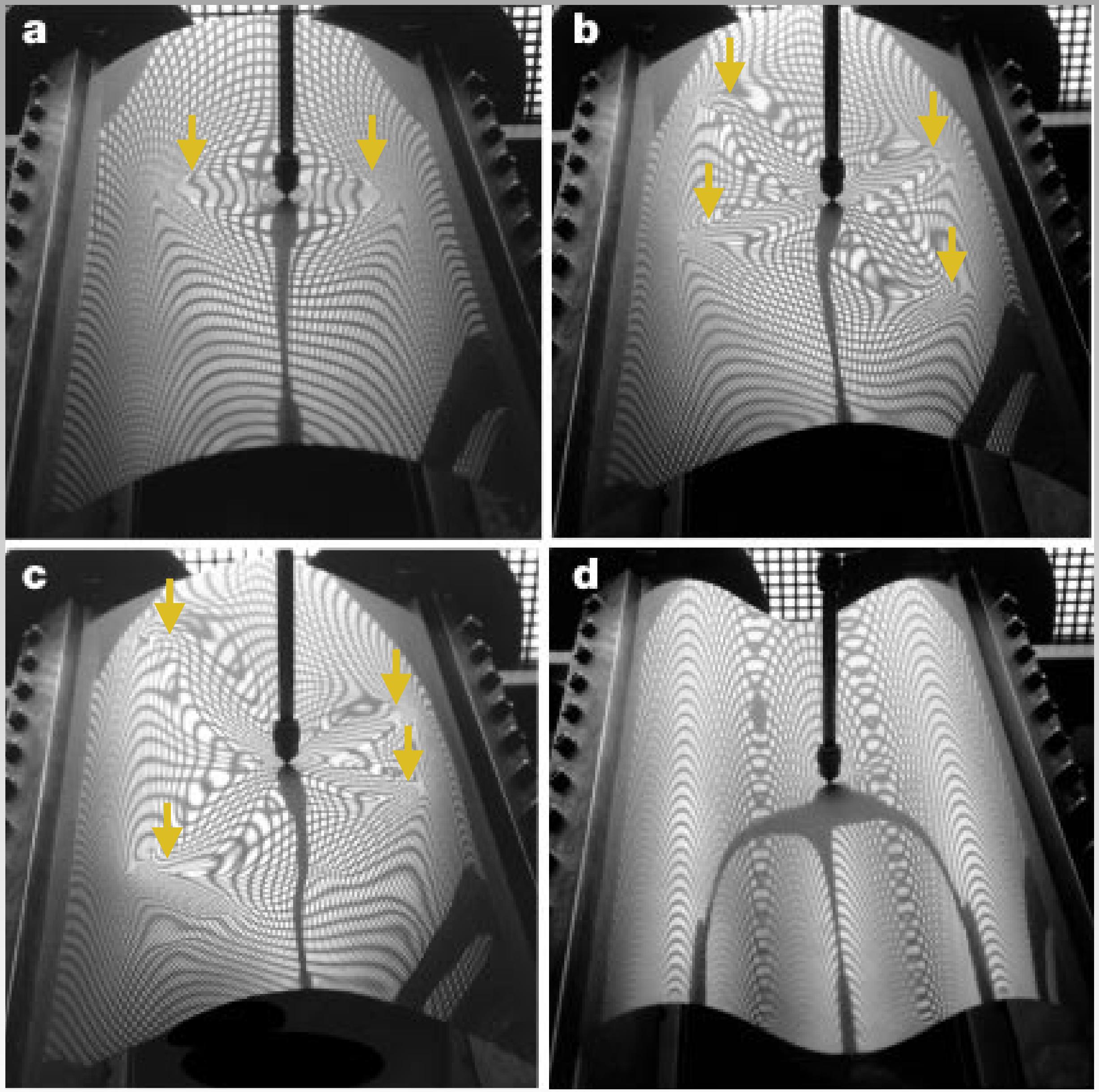
A simplified experimental system: conical packing

- Self-alignment / bundling
- Broad distributions of sizes

Deboeuf et al. EPL 2008



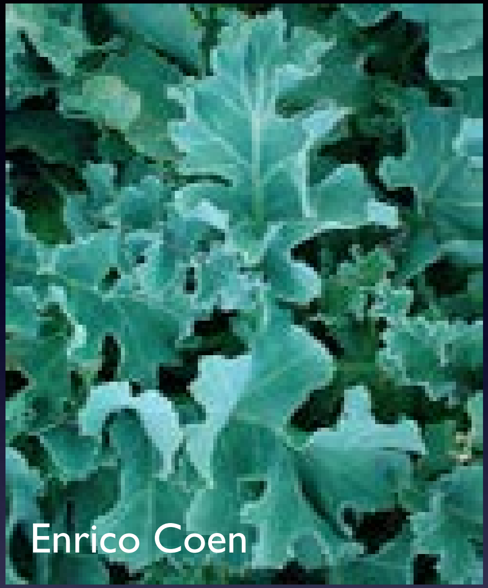
Indentation of a thin sheet

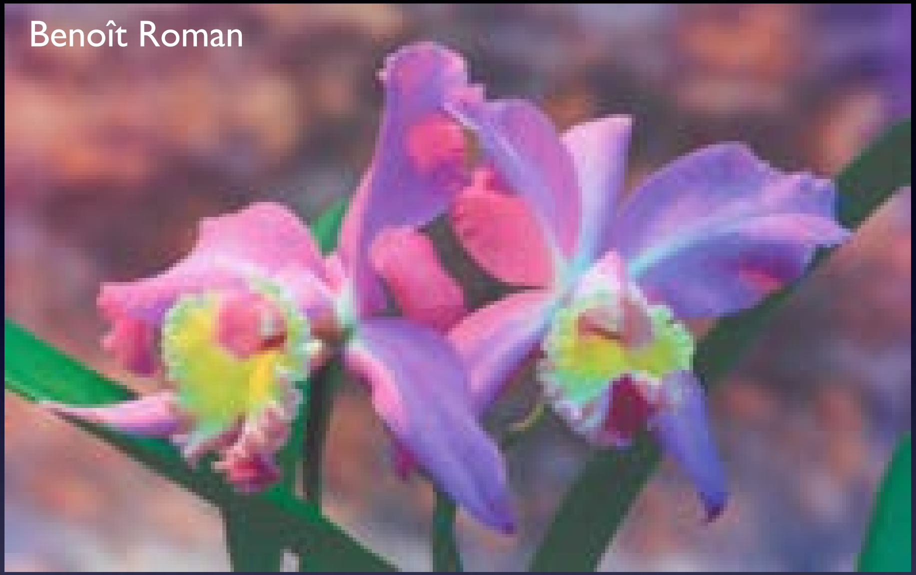


- Dynamics of patterns
- Prediction of patterns

Boudaoud et al. Nature. 2001

Waves at the edge





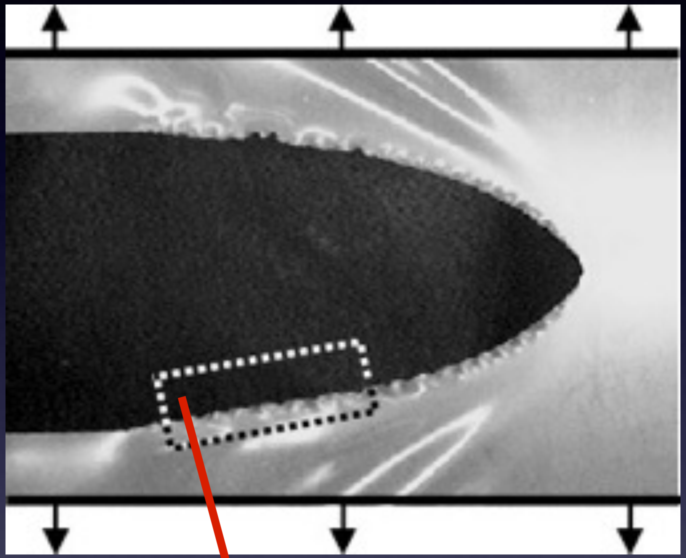
Waves at the edge

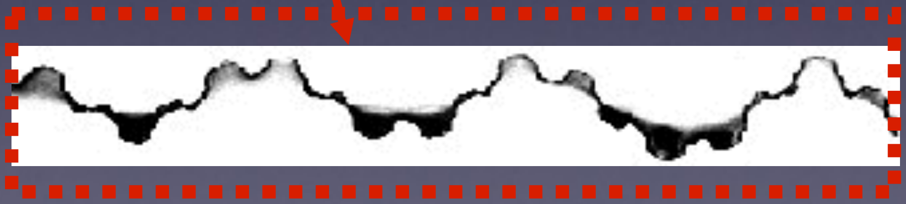
Waves at the edge

Eran Sharon

Auxin application

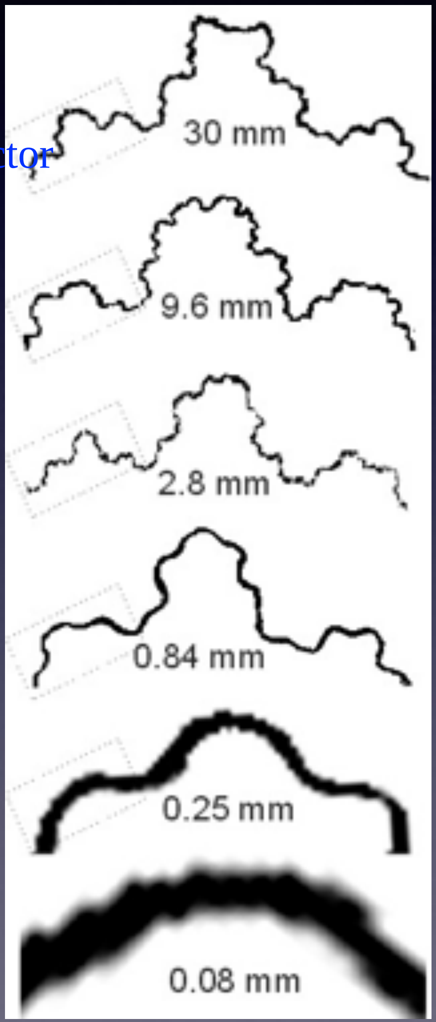
Waves at the edge





Eran Sharon et al 2002

Magnification factor
3.2

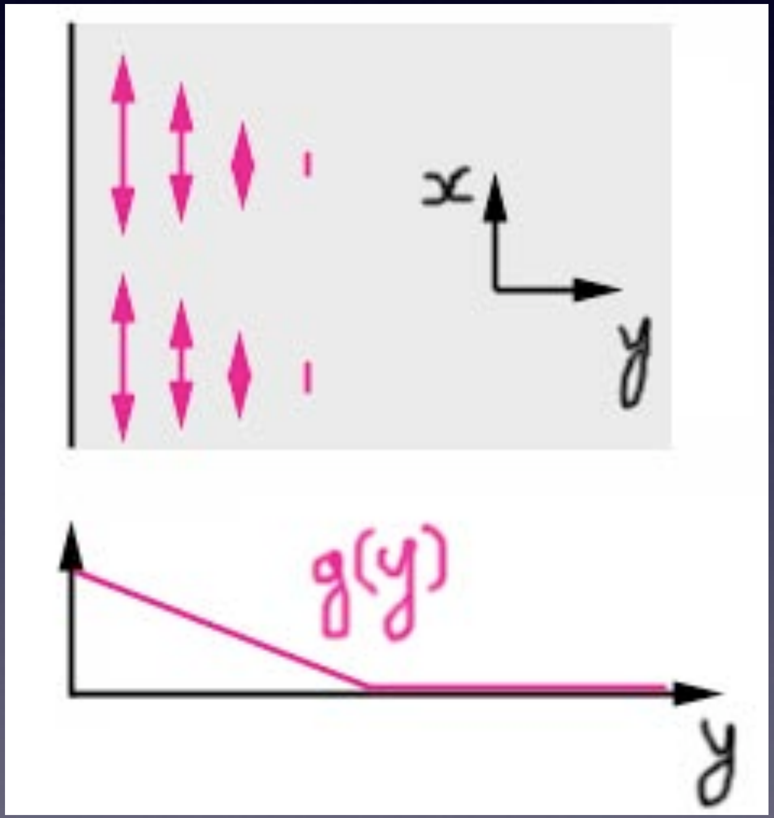


Waves at the edge

Thin elastic sheet with

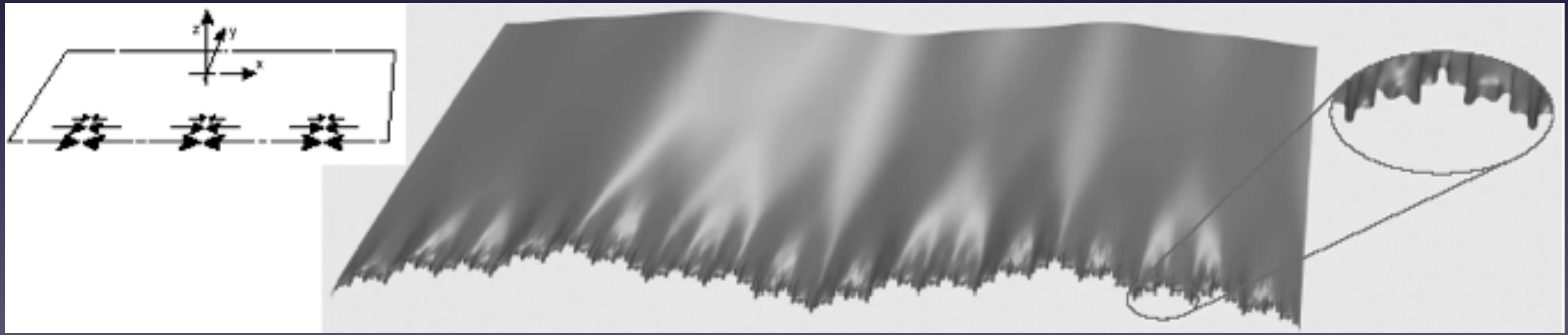
metric $ds^2 = (1+g(y))^2\,dx^2 + dy^2$

$g(y)$: quantifies growth rate



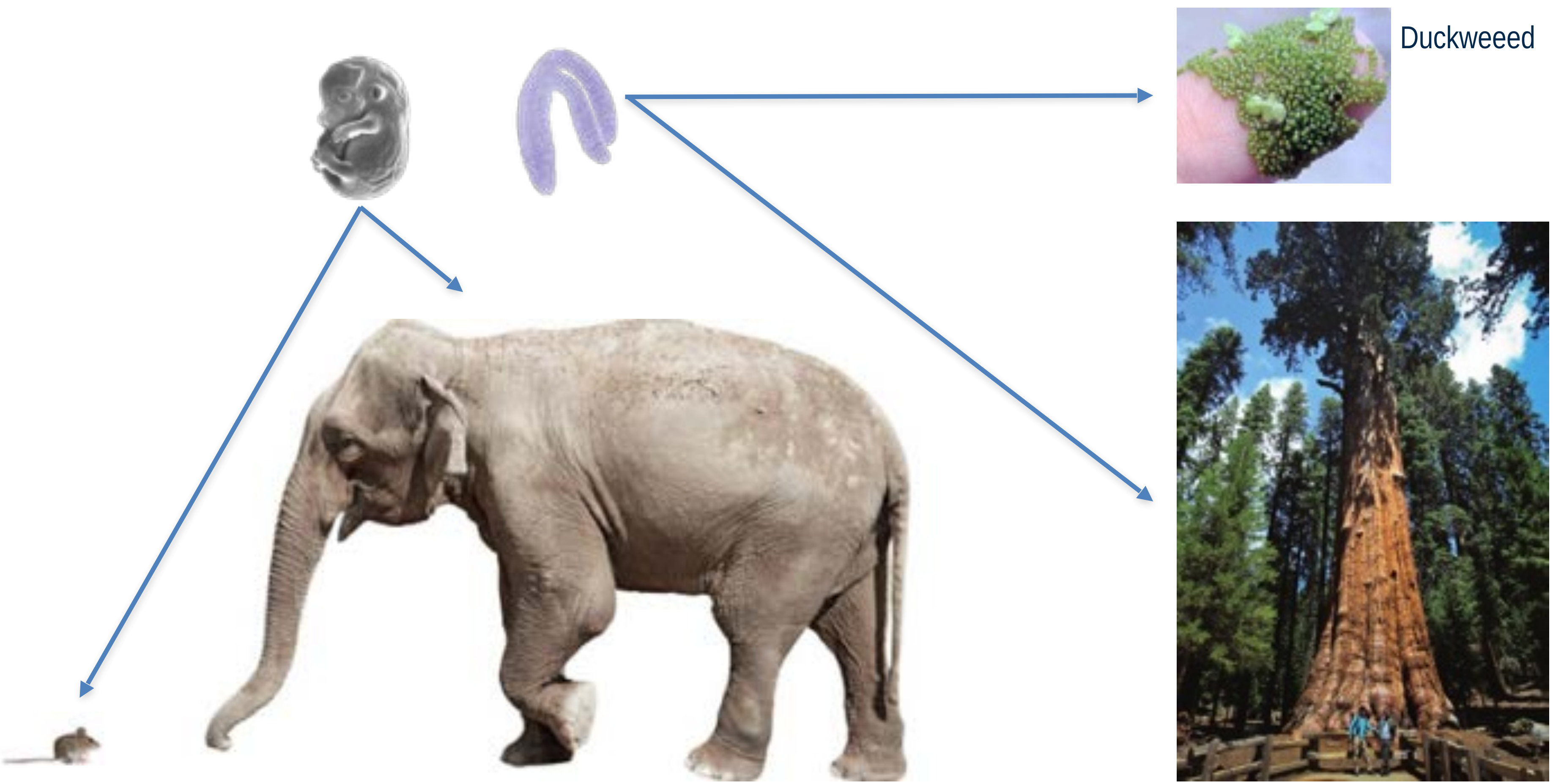
Waves at the edge

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



Audoly & Boudaoud Phys Rev Lett 2003

Form and size of an organism



The genetics of form

Wildtype
thale cress
(*Arabidopsis thaliana*)

T. Blain

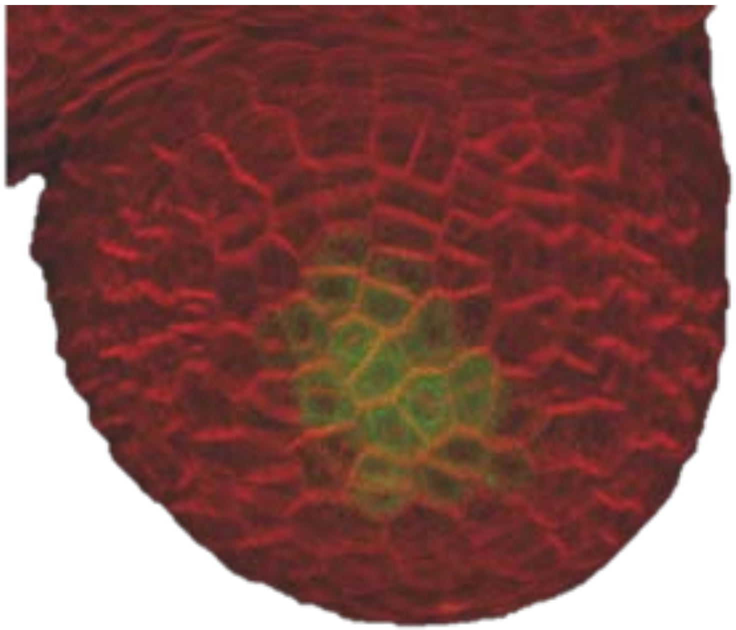
Line with mutation

Finding genes that control teeth morphogenesis
A number of discoveries in genetics and molecular biology

Building an organism

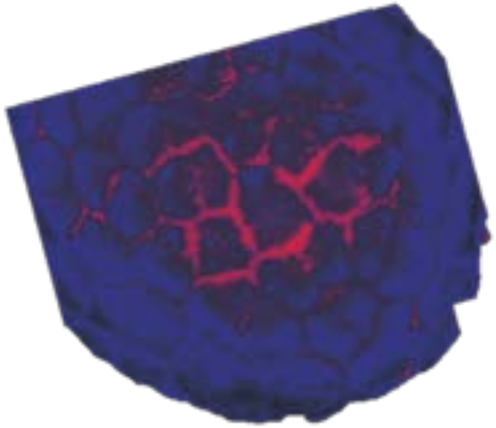
Assembly and stiffness of structural elements determines form

Building an organism

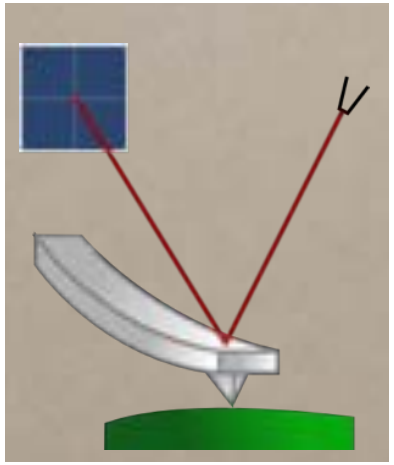


Arabidopsis flower primordium

Optical microscopy
Stem cells



Mechanical microscopy (AFM)
Stiffness

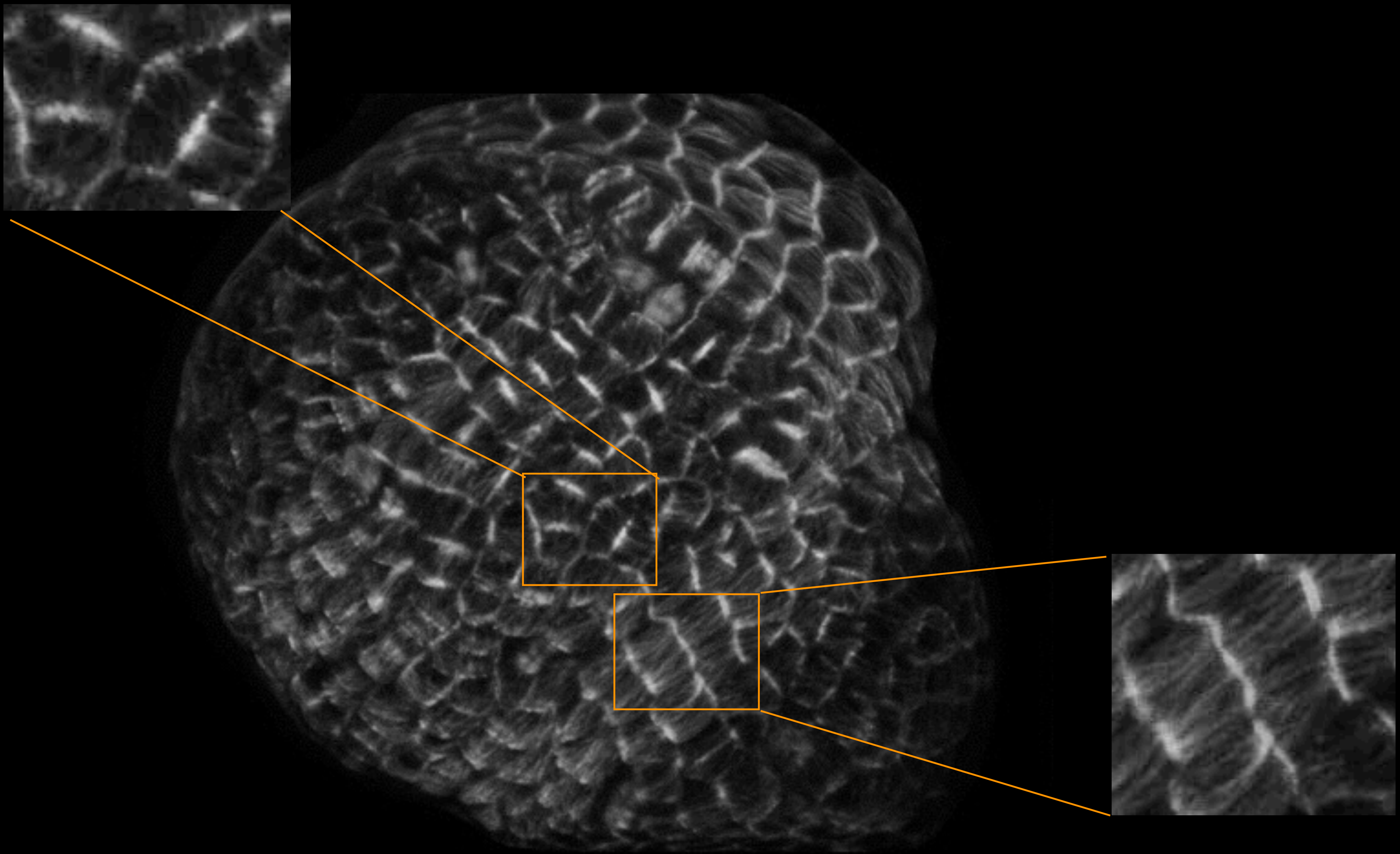


Atomic force microscope

Milani et al. Plant Physiol. 2014

Stem cells are stiffer
The mechanics of structural elements determines form

Building elongated forms



Microtubules in the shoot apex

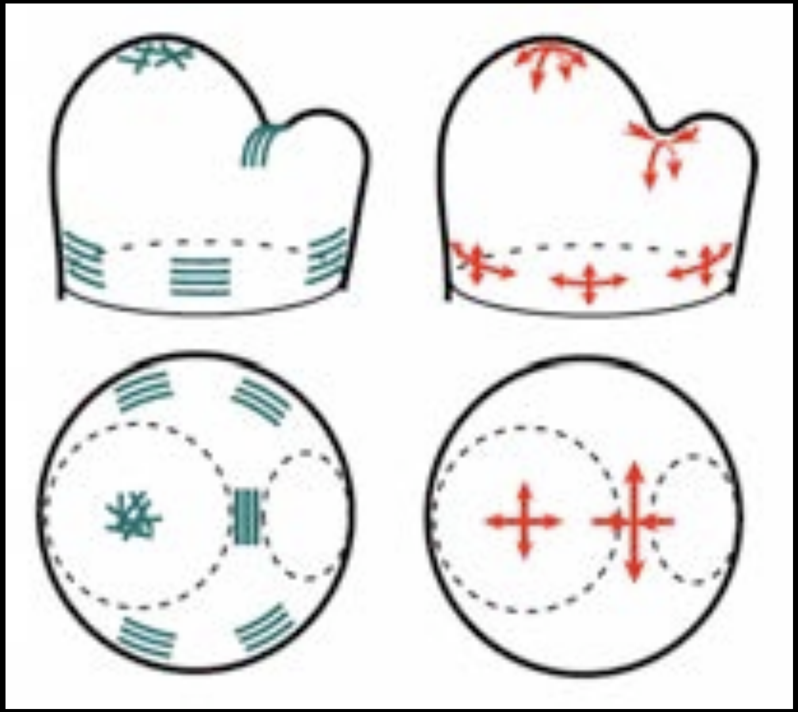
Hamant et al. Science 2008

Building elongated forms

What controls the orientation of microtubules?

- A continuum mechanical model of the shoot apex
  - Much stiffer epidermis
  - Hydrostatic pressure (turgor)

- Prediction of force patterns
  - Microtubules // main tension



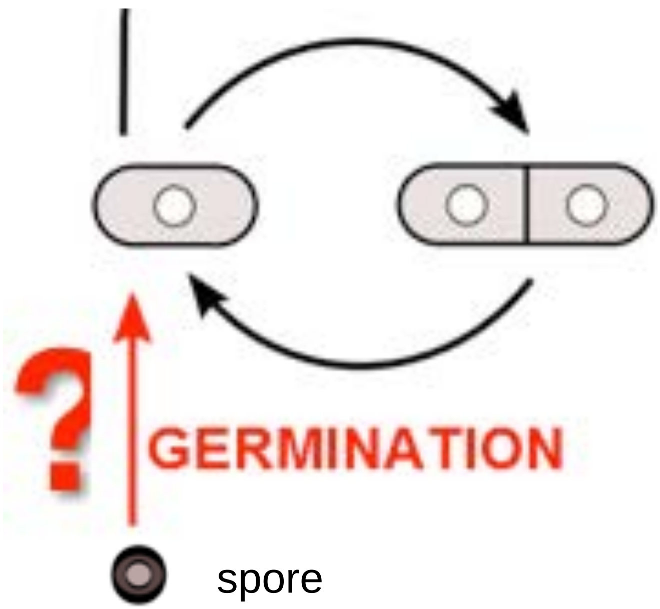
Hamant et al. Science 2008

Building elongated forms

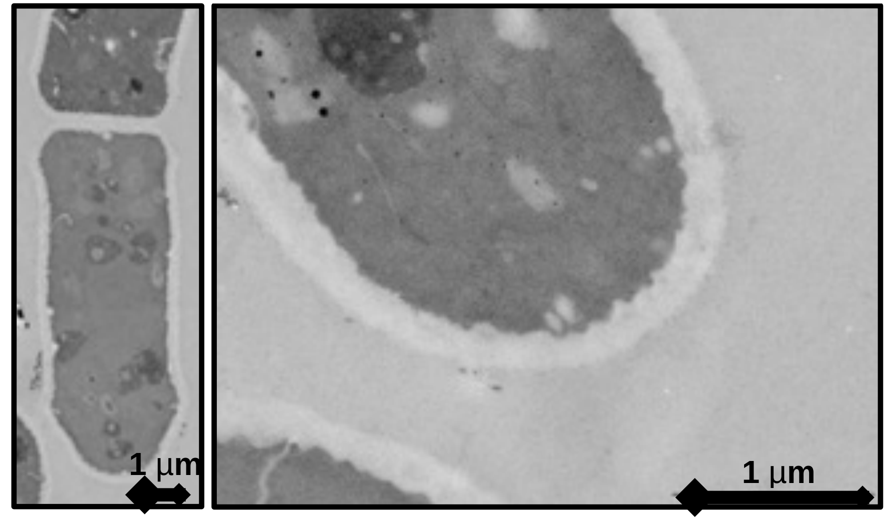
Cell wall reinforcement in the direction of maximal stress

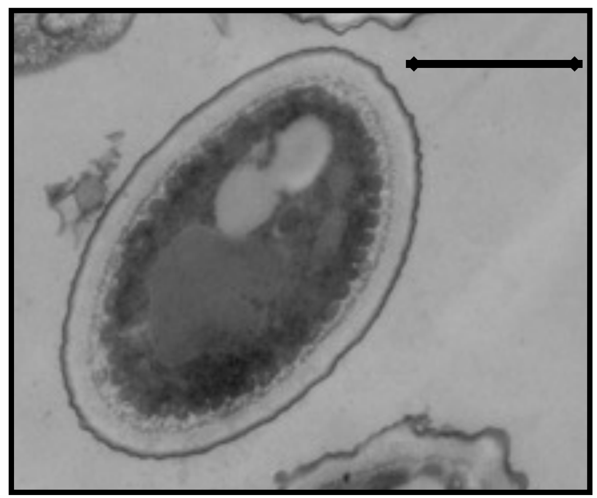
Building elongated forms

Fission yeast

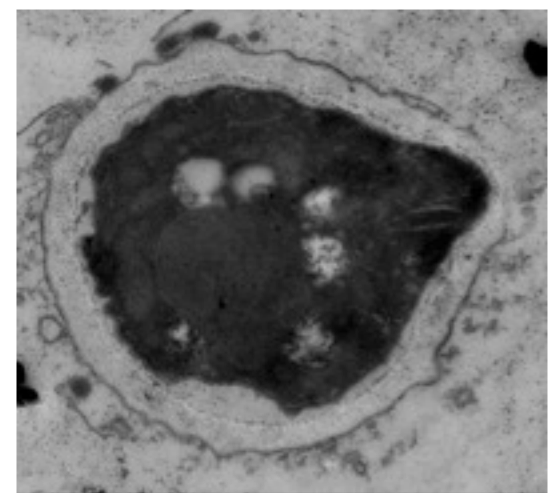


Vegetative cell





Spore (note the dark casing)

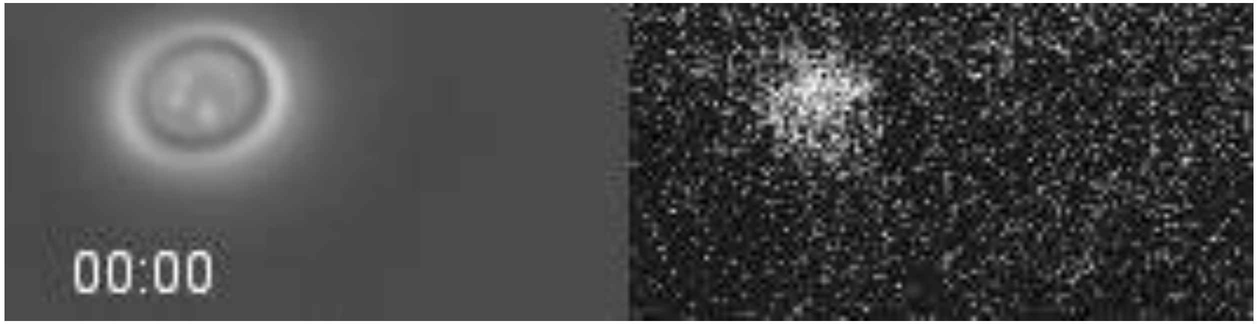


Spore with outgrowth
(note breakage of casing)

Outgrowth occurs when a the outer wall breaks

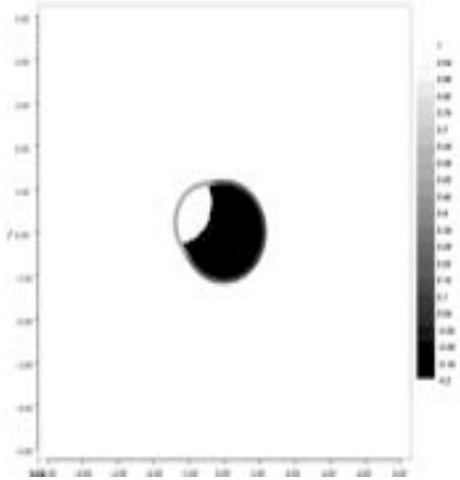
Building elongated forms

Fission yeast cell



Bgs4-GFP = cell wall synthesis

Mathematical model:
coupling between structural elements and cell polarity



Bonazzi et al. Dev. Cell 2014

Coordination between biochemistry and biomechanics
Transition from sphere to elongated shape

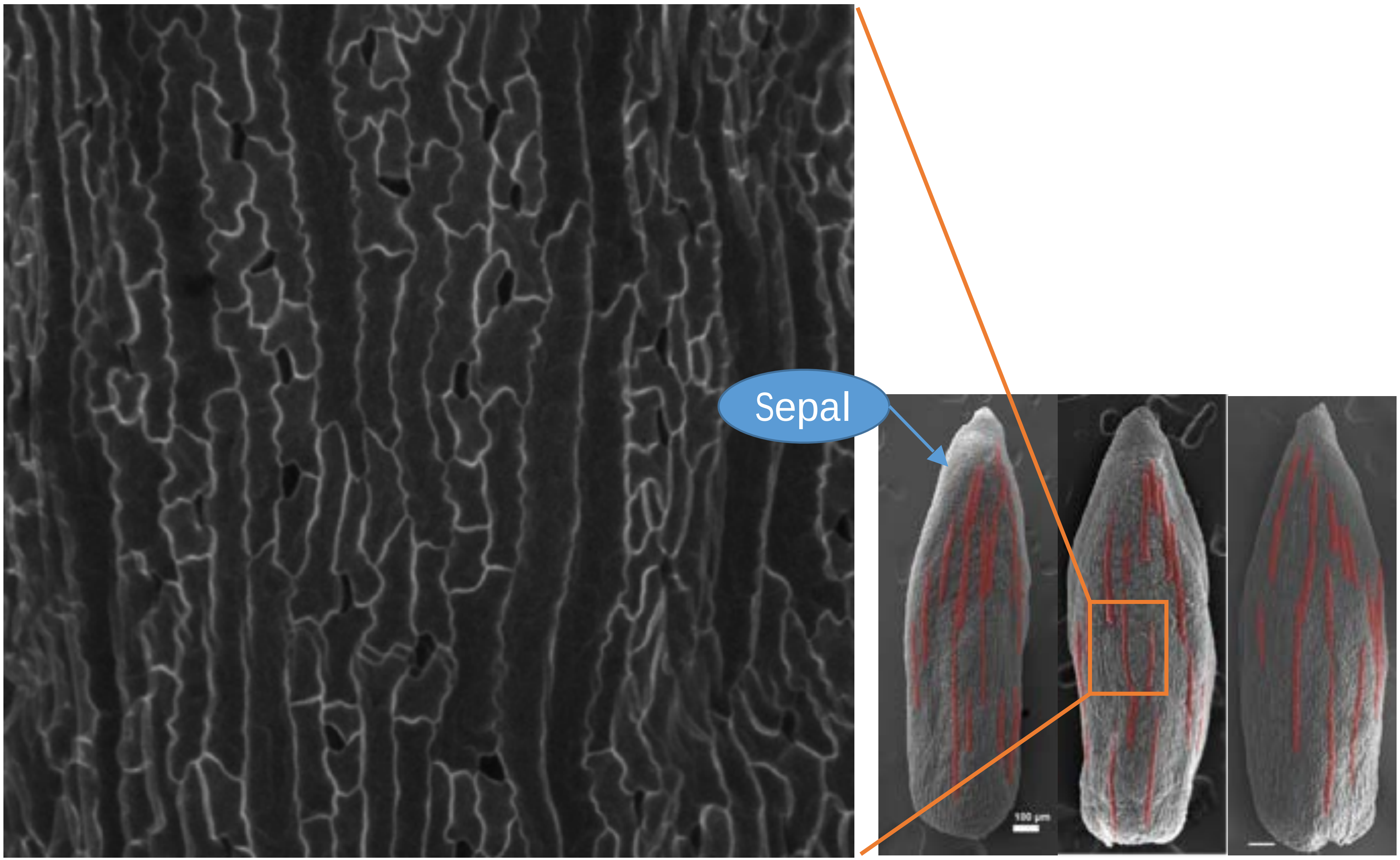
Developmental stability

Morphogenesis: organs with reproducible forms

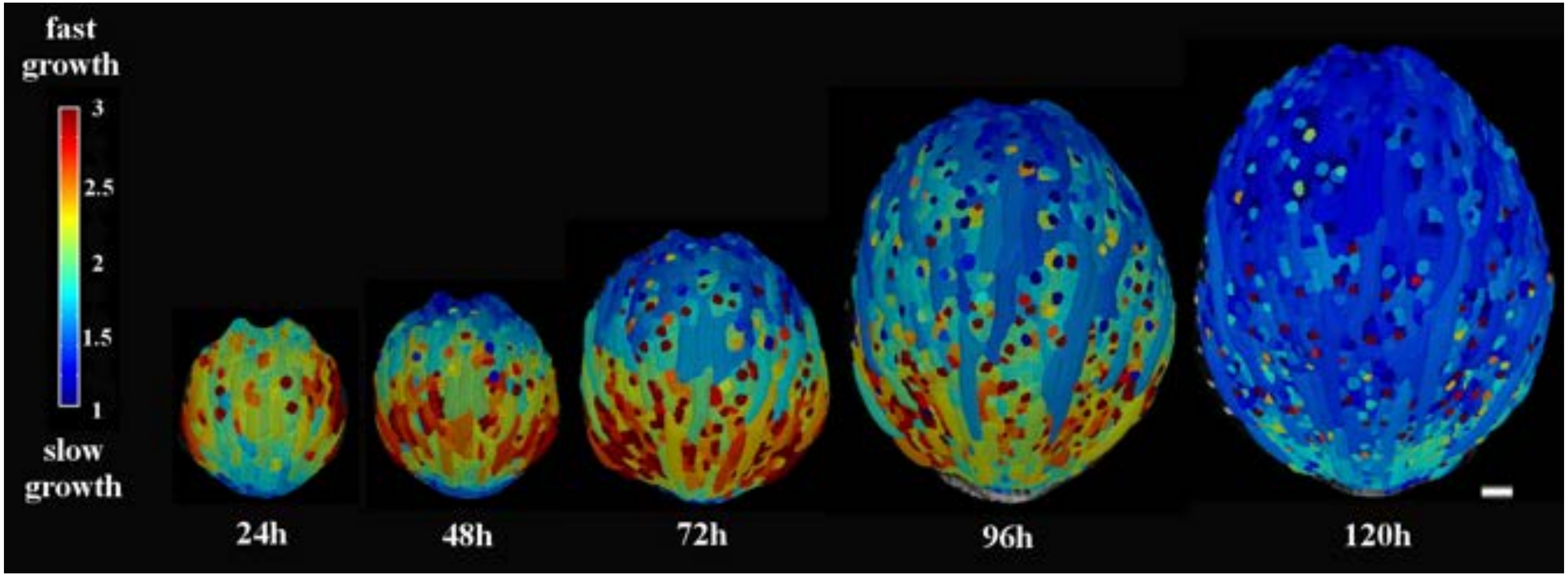
The two hands?

Developmental stability

Flowering plants: ideal systems to study robustness of form



Developmental stability



Hervieux et al. Curr. Biol. 2016

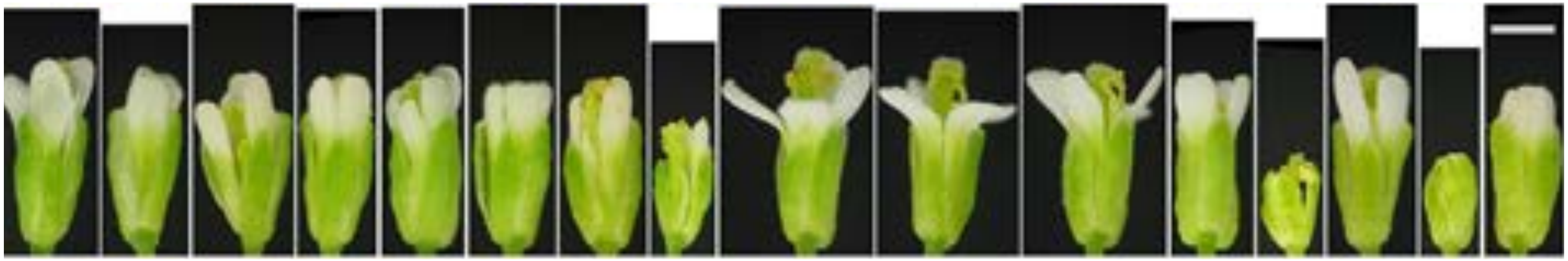
Growth is spatially heterogeneous

Developmental stability

Genetic screen for mutants in variability

Flowers from a single plant (Arabidopsis)

Mutation affecting robustness of flowers



Hong et al. Dev. Cell 2016

Mutant: cell wall stiffness less heterogeneous.

Now: variability in gene expression and robustness of development

Spatiotemporal variability promotes flower robustness!

Conclusions

From simplified systems to living systems

Investigating morphogenesis:
tools from experimental/theoretical physics
in addition to genetics/molecular biology

There is biological information in variability

AND

Acknowledgements

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Alumni: Maryam Aliee, Léna Beauzamy, Véronique Boltz, Sam Collaudin, Sophy Chamot, Aurélie Chauvet, Coralie Cellier, Nelly Dubrulle, Kateryna Fal, Olivier Hamant, Nathan Hervieux, Jean-Daniel Julien, Benoit Landrein, Jonathan Legrand, Mengying Liu, Marion Louveaux, Richard Malgat, Vincent Mirabet, Naomi Nakayama, Rita San Bento, Thomas Stanislas, Stéphane Verger, Magalie Uyttewaal

Institute: Reproduction et Développement des Plantes

Collaborators:
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