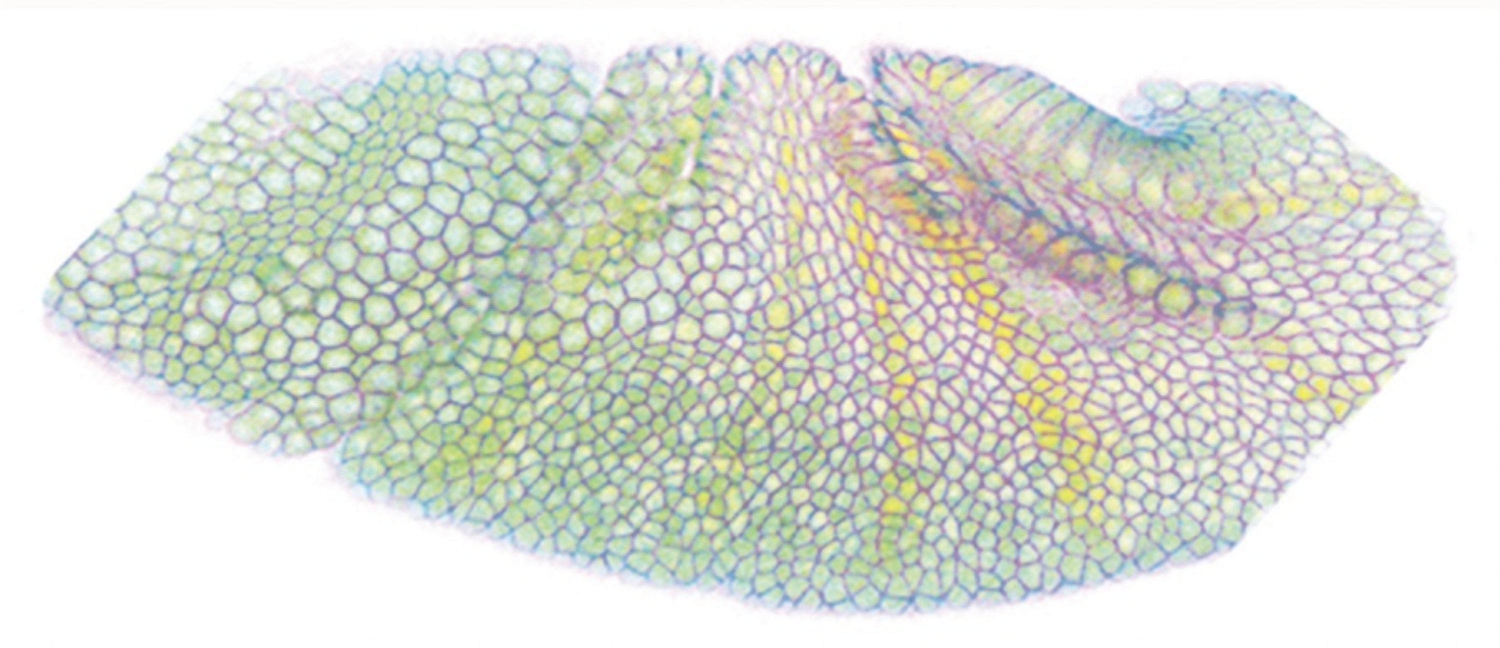
Mécanique de la Morphogenèse



Cours 1: Organisation et plasticité tissulaires

Thomas Lecuit
chaire: Dynamiques du vivant

COLLÈGE DE FRANCE
1530

How to account for the emergence of complex shapes?

Growth
Shape
Control

How to account for the extraordinary diversity of shapes?

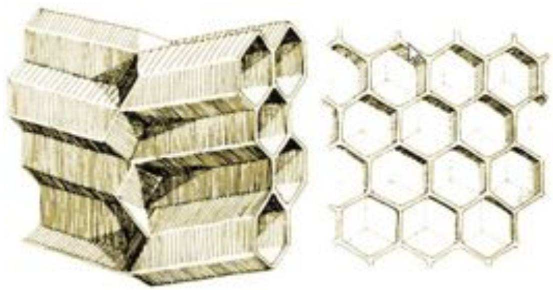
How to account for the extraordinary diversity of shapes?

Diversity of forms:
Are there general principles?

>>mathematical regularities and physical principles underlying forms and transformations

A mathematical understanding of forms

Buffon



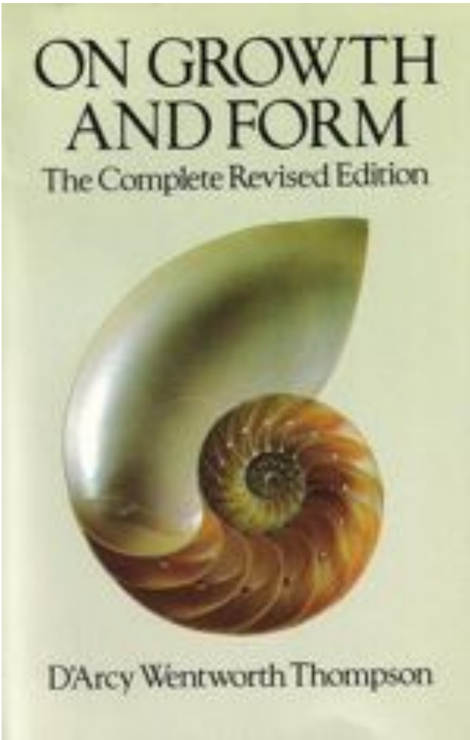
GL Leclerc, comte de Buffon (1707-1788)

« On donne plus d'esprit aux mouches dont les ouvrages sont le plus réguliers; les abeilles sont, dit-on, plus ingénieuses que les guêpes, que les frelons etc., qui savent aussi l'architecture, mais dont les constructions sont plus grossières et plus irrégulières que celles des abeilles:
on ne veut pas voir, ou l'on ne se doute pas, que cette régularité, plus ou moins grande, dépend uniquement du nombre et de la figure, et nullement de l'intelligence de ces petites bêtes; **plus elles sont nombreuses, plus il y a des forces qui agissent également et s'opposent de même, plus il y a par conséquent de contrainte mécanique, de régularité forcée, et de perfection apparente** dans leurs productions ».

Histoire naturelle, IV, 100 (1753).

A mathematical understanding of forms

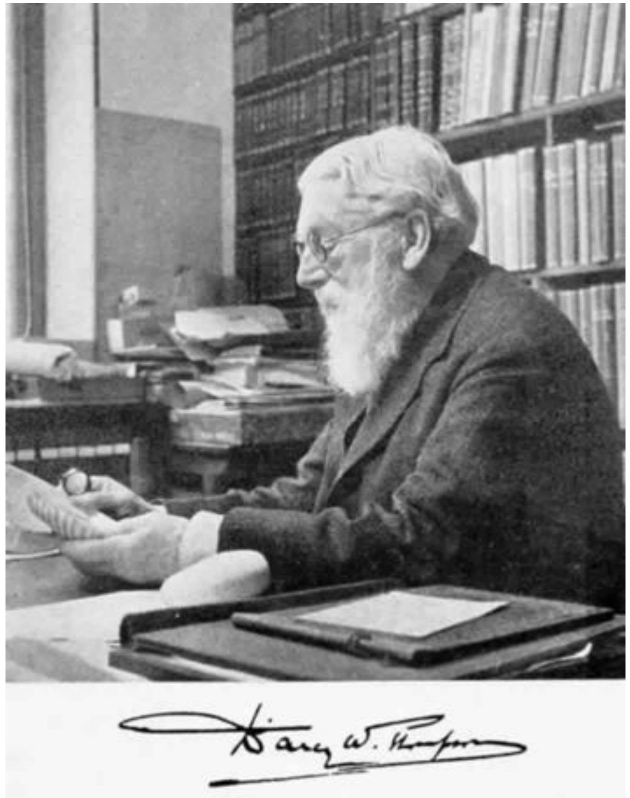
d'Arcy W. Thompson



1917

« A certain mathematical aspect of morphology to which as yet the morphologist gives little heed, is interwoven with his problems, complementary to his descriptive task, and helpful, nay essential to his proper study and comprehension of Growth and Form. »

« For the harmony of the world is made manifest in Form and Number, and the heart and soul of all the poetry of Natural Philosophy are embodied in the concept of mathematical beauty. ».



d'Arcy Wentworth Thompson (1860-1948)

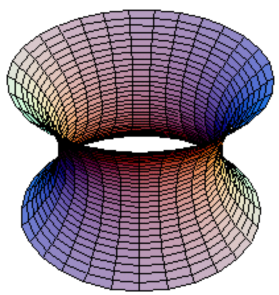
A mathematical understanding of forms

- Form of cells *On Growth and Form. V*

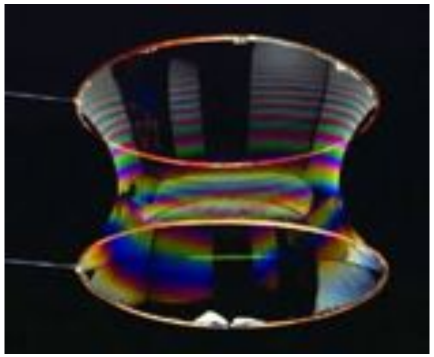
-Thermodynamic description: near equilibrium
-Minimisation of surface energy
-Minimisation of surface

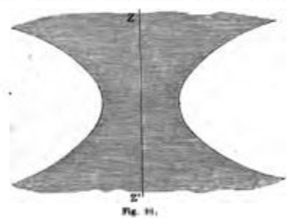
Surfaces of revolution of Plateau:
sphere, cylinder, catenoid

catenoid (Euler)



$$x = c \cosh \frac{v}{c} \cos u$$
$$y = c \cosh \frac{v}{c} \sin u$$
$$z = v \qquad u \in [-\pi, \pi) \quad v \in \mathbb{R}$$





Infusories

d'Arcy W Thompson, *On Growth and Form*, 1917

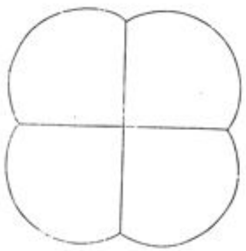
A mathematical understanding of forms

- Form of Cell aggregates *On Growth and Form. VII*

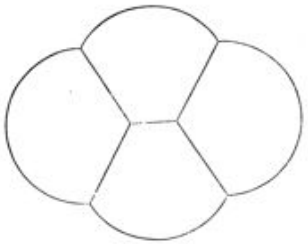
STATIQUE
EXPÉRIMENTALE ET THÉORIQUE
DES LIQUIDES
SOUMIS
AUX SEULES FORCES MOLÉCULAIRES,
PAR
J. PLATEAU,
Professeur à l'Université de Gand,
Membre de l'Académie Royale de Belgique, Correspondant de l'Institut de France,
de la Société Royale de Londres, de l'Académie de Berlin, etc.

1870

CHAPITRE V.
Tension des surfaces et des lames liquides : historique. — Systèmes laminaires. Lois auxquelles ils sont soumis ; comment ils se développent ; principe général qui régit leur constitution. Démonstration théorique de leurs lois.



Unstable equilibrium



Stable equilibrium

Plateau rules:
Experiments with soap films

- Soap films form flat surfaces
- A maximum of 3 surfaces meet at 1 edge:
  > angles between surfaces is 120°
- 4 edges meet at 1 point: angles between edges is 109.47°

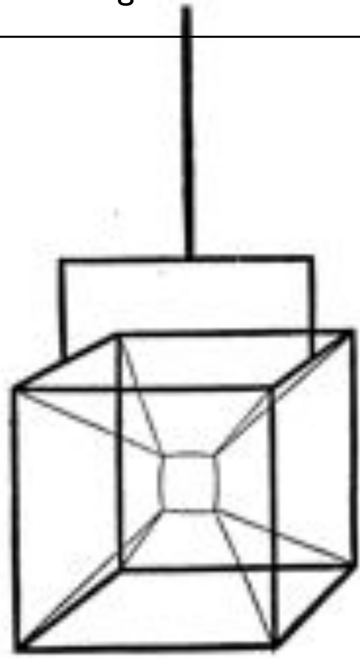


Fig. 71.

A mathematical understanding of forms

- Form of Cell aggregates *On Growth and Form. VII*

Minimisation of surface energy
Cells adopt configuration where angles approach 120°
(all interfacial tensions are equal)
following Plateau rules

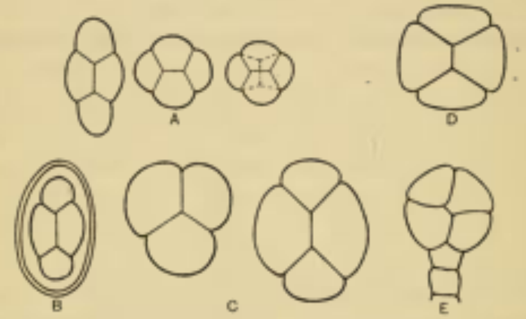


Fig. 173. Examples of the "polar furrow". A, Pollen-grains (tetrads) of *Neottia*. B, Egg of hookworm (*Ankylostoma*). C, First cells of a wasp's nest (*Polistes*). (From Packard, after Saussure.) D, Four-celled stage of Volvox: from Janet. E, Hair of Salvia, after Hanstein.

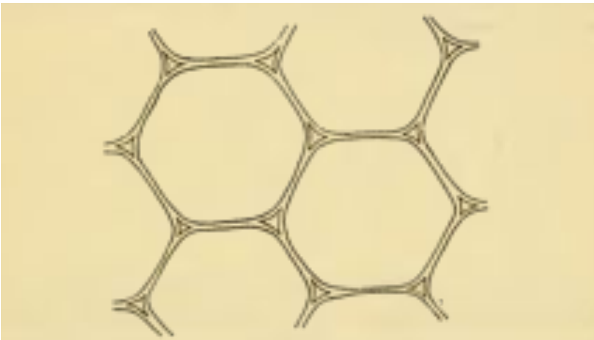
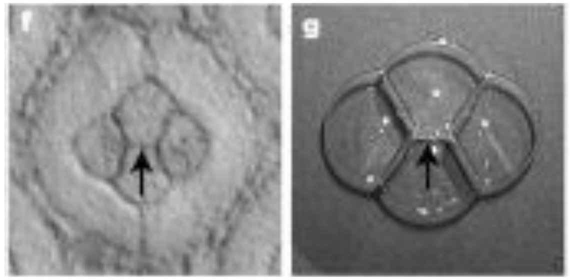
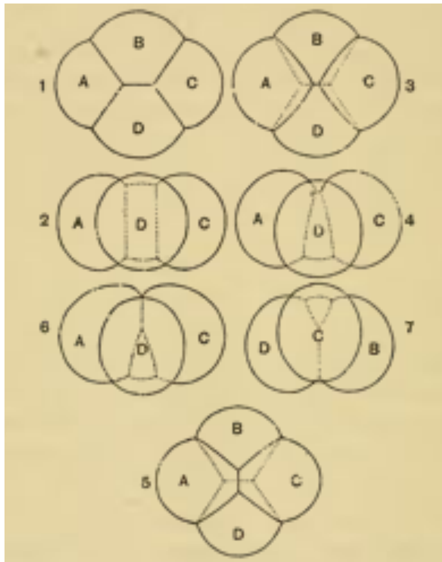


Fig. 156. Parenchyma of maize; shewing intercellular spaces.

Cell aggregates in plants and animals



Hayashi T & Carthew R, *Nature*, 431:647 (2004)



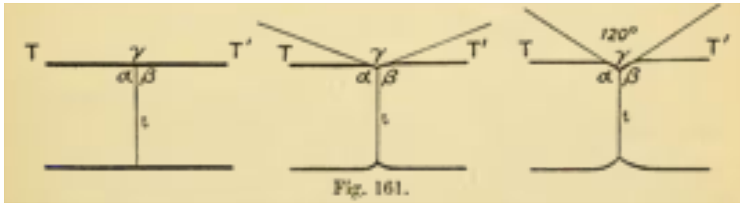
Soap bubbles

d'Arcy W Thompson, *On Growth and Form*, 1917

A mathematical understanding of forms

- Form of Cell aggregates *On Growth and Form. VII*

Non-uniform surface tensions can explain
a variety of cellular/multicellular arrangements



T=T' >> t

T=T' = t

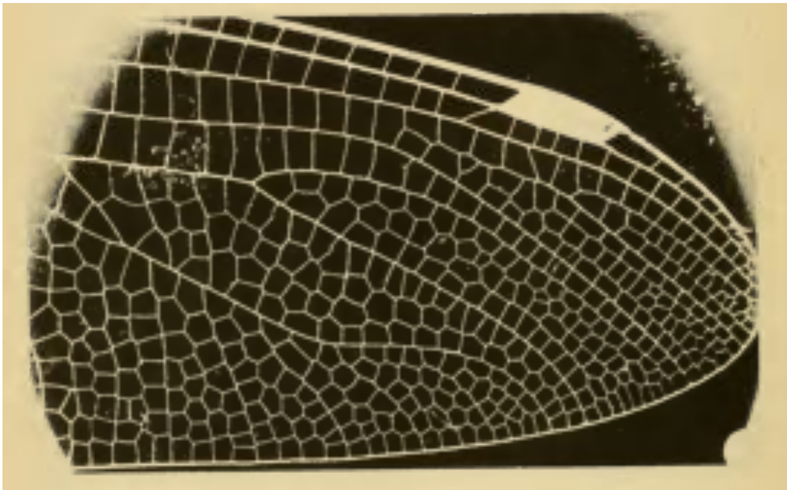
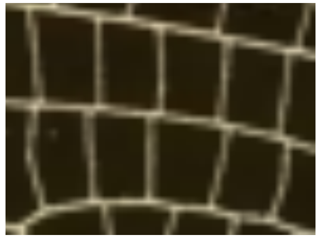
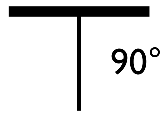
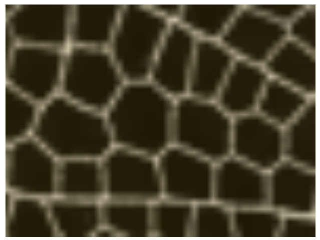
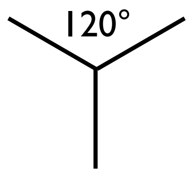


Fig. 162. Part of a dragonfly's wing.









d'Arcy W Thompson, *On Growth and Form*, 1917

A mathematical understanding of forms

- Theory of transformations *On Growth and Form. XVII*

- System of coordinates
- Closely related forms may be transformed into one another via deformation of the coordinate system.
- A system of forces is responsible for such deformation (defines the magnitude and orientation of forces)

« dispense with many more complicated hypotheses of biological causation »

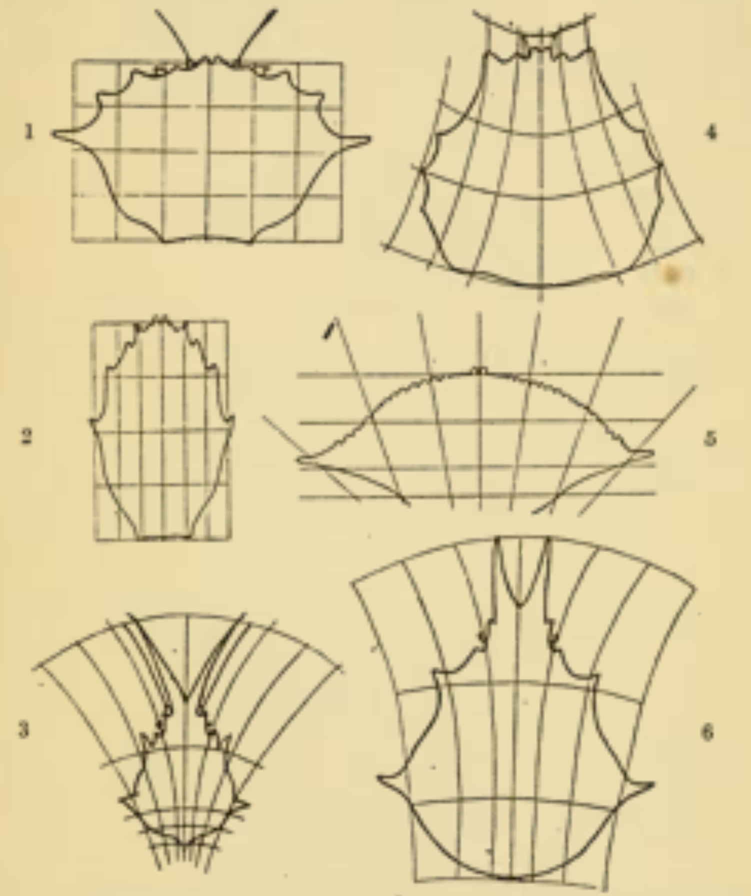
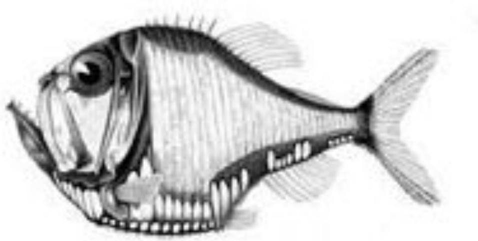
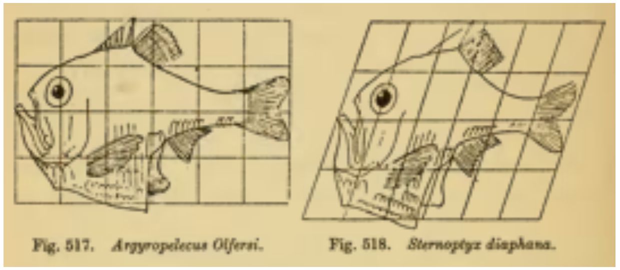


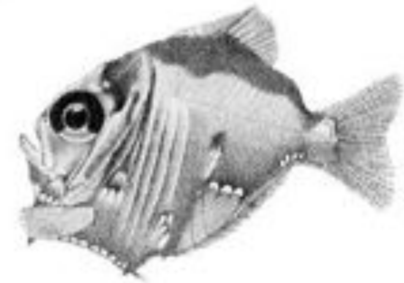
Fig. 513. Carapaces of various crabs. 1, *Geryon*; 2, *Corystes*; 3, *Scyramathia*; 4, *Paralomis*; 5, *Lupa*; 6, *Chorinus*.

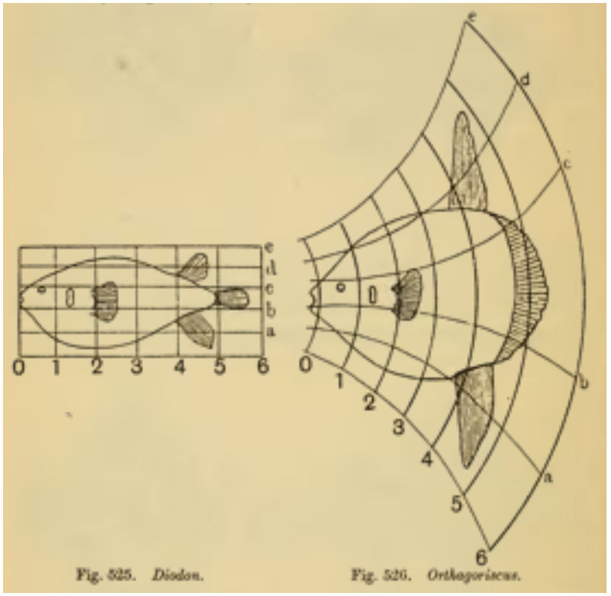
d'Arcy W Thompson, *On Growth and Form*, 1917

A mathematical understanding of forms

- Theory of transformations *On Growth and Form. XVII*





d'Arcy W Thompson, *On Growth and Form*, 1917

How to account for the extraordinary diversity of shapes?

Can one identify *general principles?*

- physical : constraints.
  > Mechanics, Geometry and Dynamics

- biological: evolving chemistry.
  >Modes of Regulation

Hard problem: understand how evolving chemistry guides the formation and transformation of shapes within physical constraints

1) Organisation / Static

2) Plasticity / Dynamics

Organisation

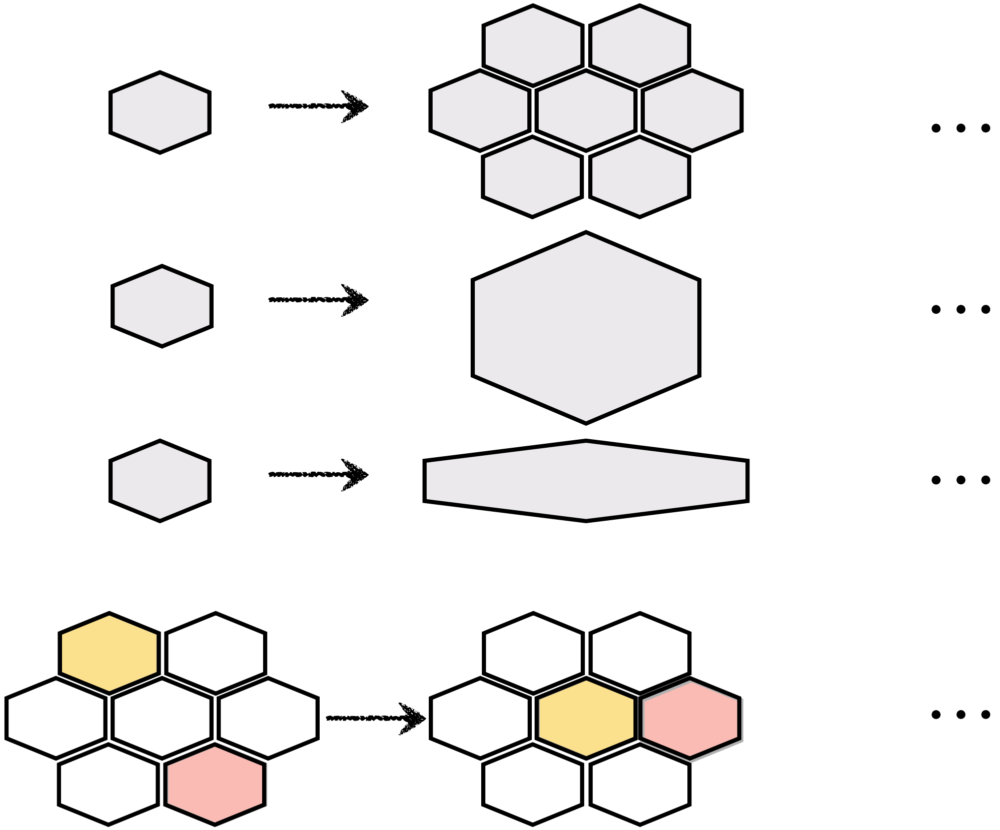
Cell parameters X | 2D | 3D

Number

Size

Shape

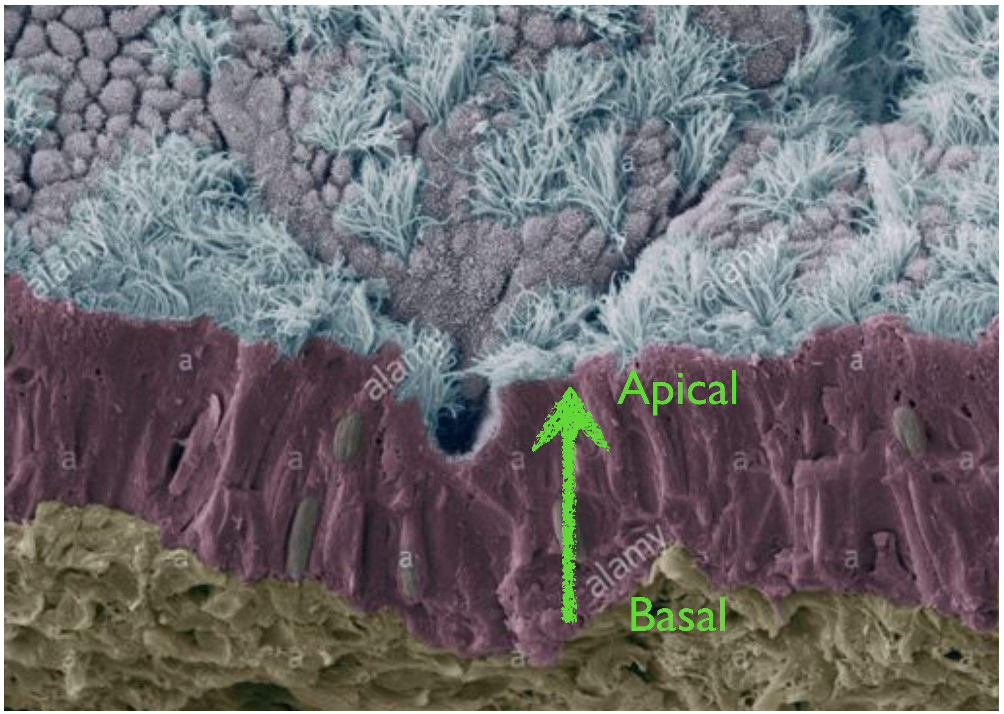
Position



Tissue Organisation: Epithelia

>2D Morphogenesis: sheets of cells

Epithelia:
- Chemical barrier
- Mechanical fence
- Polarised/vectorial organisation: apico-basal and planar.



Tissue Organisation: Epithelia

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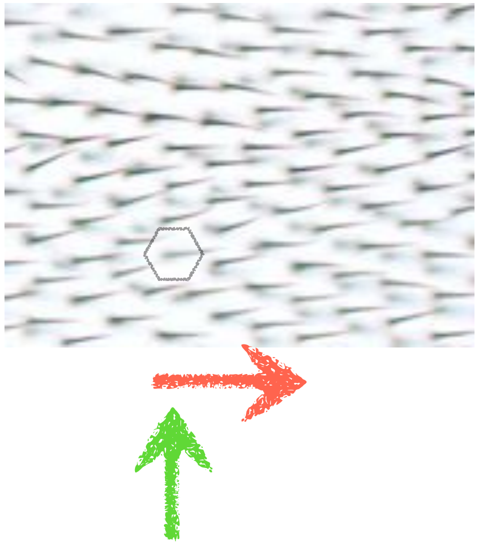
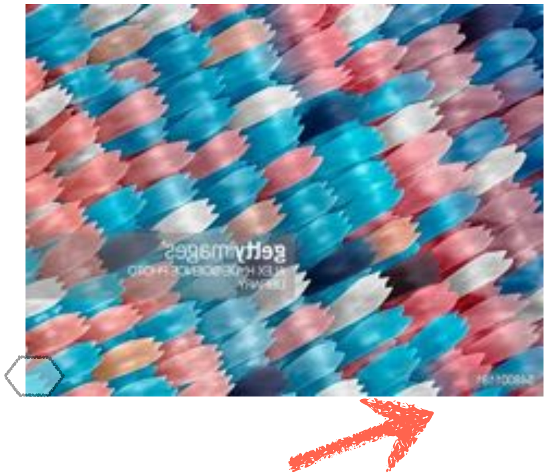
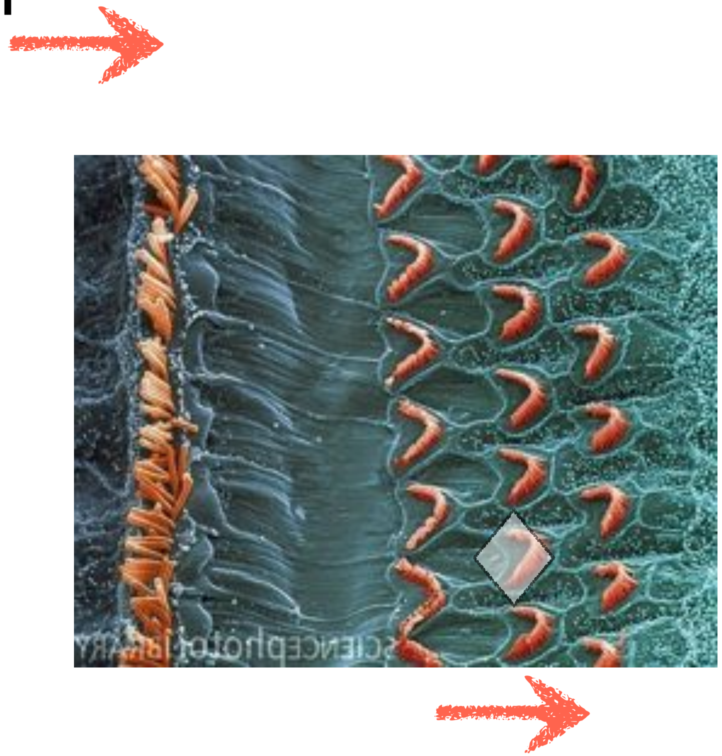
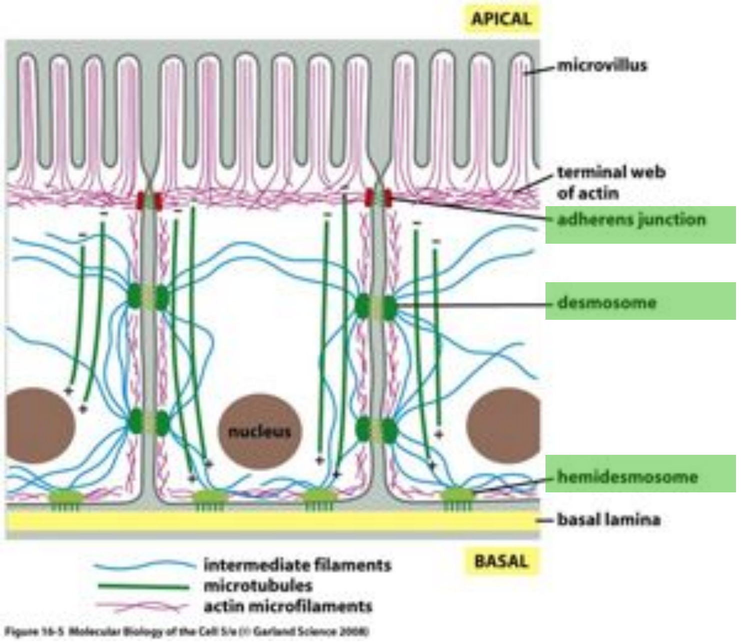


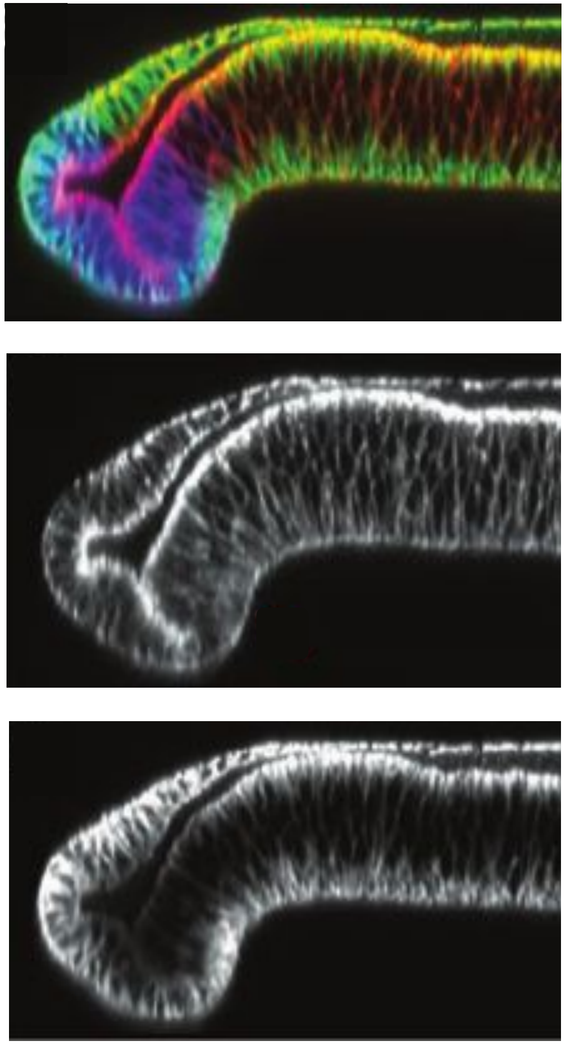




Tissue Organisation: Epithelia

- Apico-basal polarity
- Intercellular adhesion
- F-actin scaffold
- Conserved properties across animals





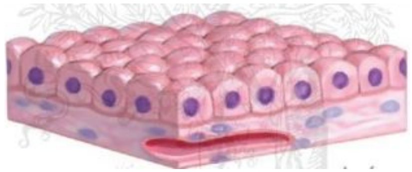
Gibson M. & Perrimon N. *Science*. 307:1785. 2005

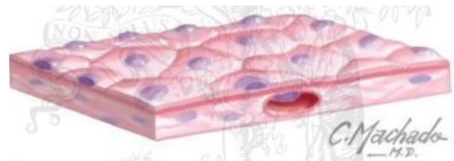
Tissue Organisation: Epithelia

- sheets of cells

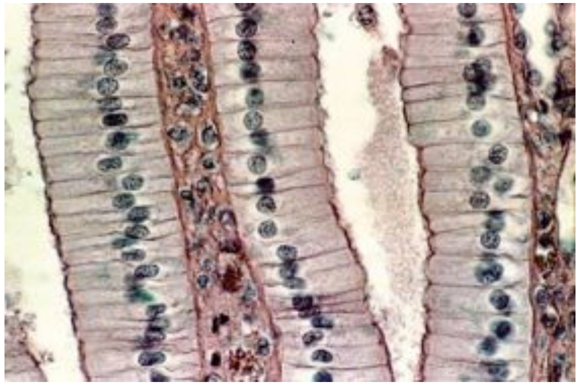
Epithelia: Variation on the theme of cell shape

Columnar | Cuboidal | Squamous





Elsevier



Gut vili

human kidney tubules, collecting duct

human vagina

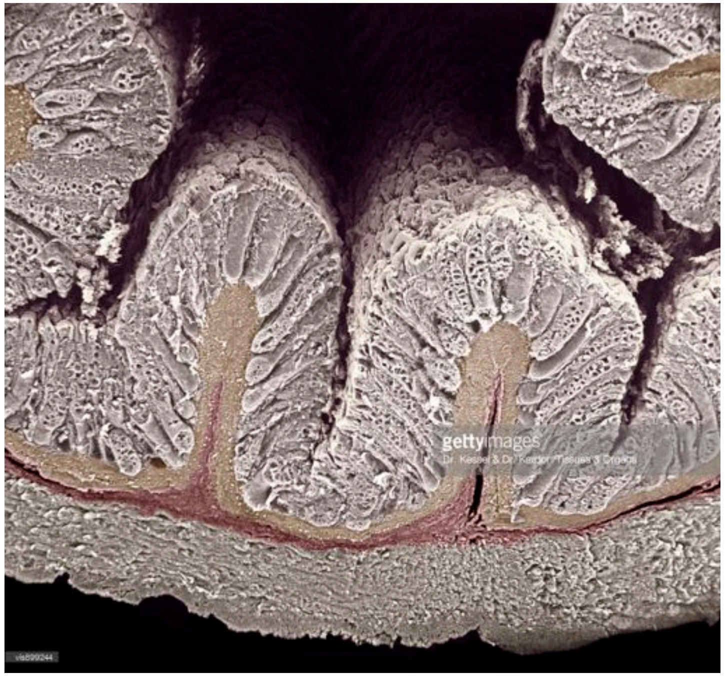
Tissue Organisation: Epithelia

2D sheets of cells

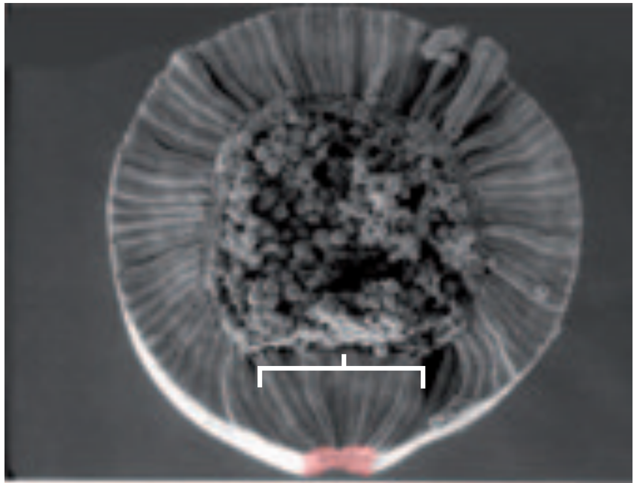
Epithelia: Variation on the theme of tissue shape

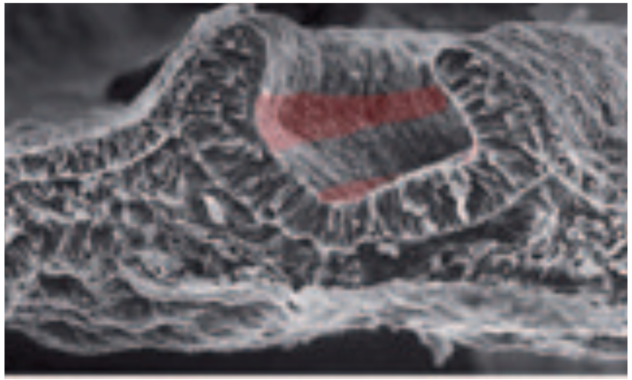
- flat: skin, epidermis/ectoderm
- curved: gut, embryos

Human gallbladder



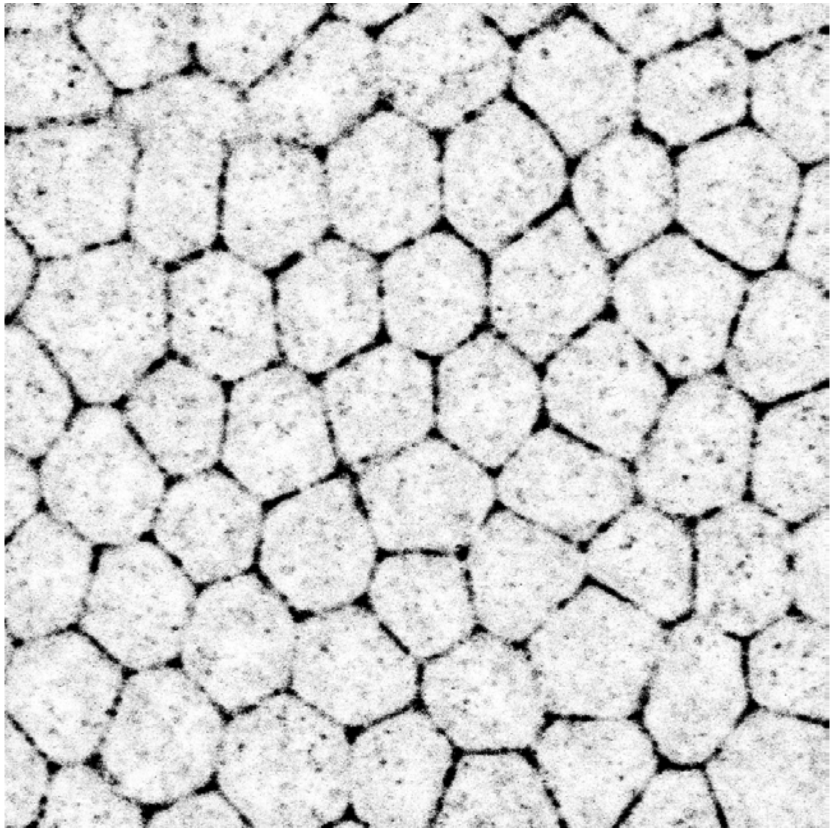
Human colon


Drosophila embryo


Chick neural tube

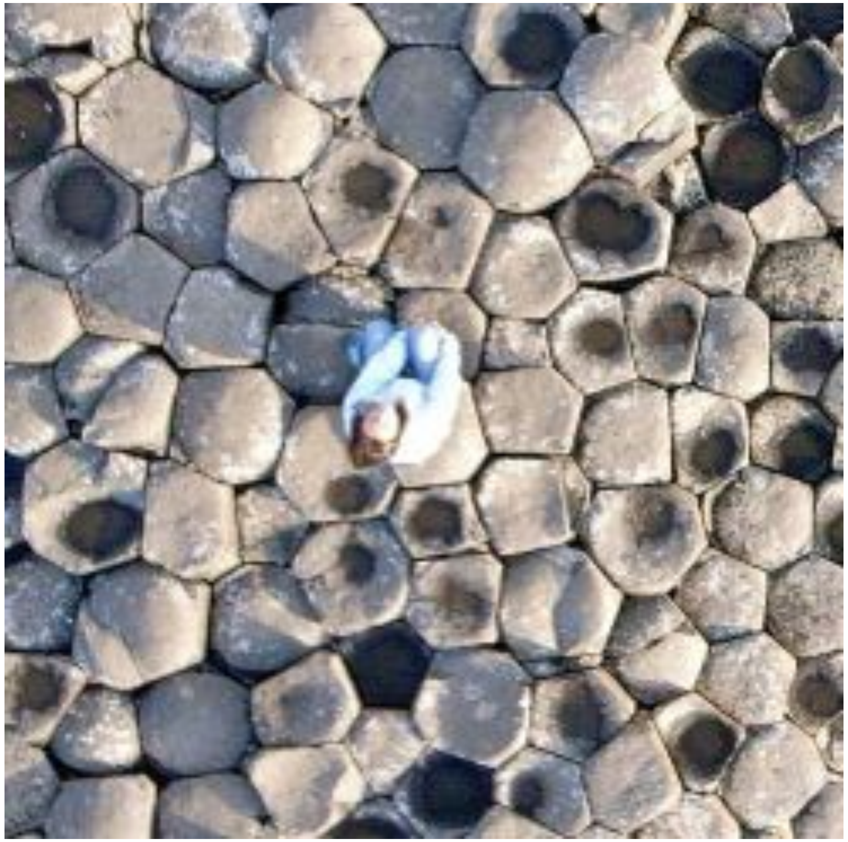
Tissue Organisation: Epithelia

Robust geometric tiling



Epithelial Cells

x100 000

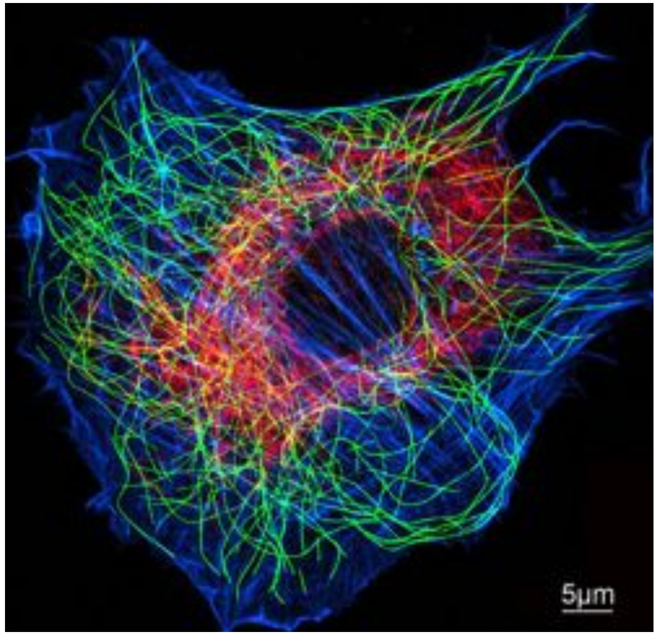


Basaltic tiling (Ireland)

Tissue Organisation: Fibroblasts and mesenchymal cells

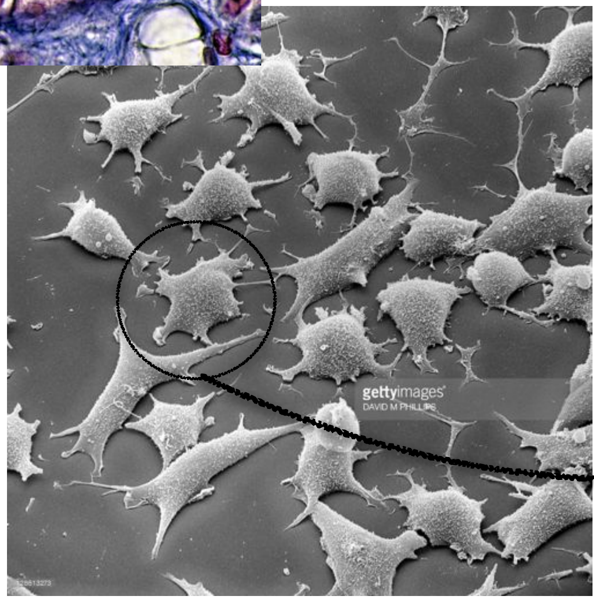
Fibroblasts

- Adhesion to substratum (extracellular matrix)
- Motile cells: protrusive activity (Actin filaments)



Actin filaments
Microtubules
Intermediate filaments
Thomas Pollard. *The Cytoskeleton*

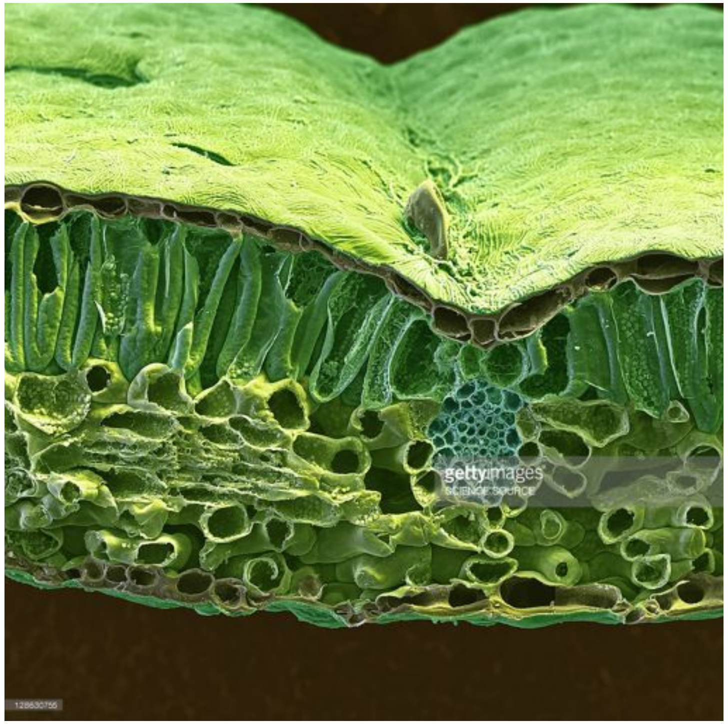
connective tissue



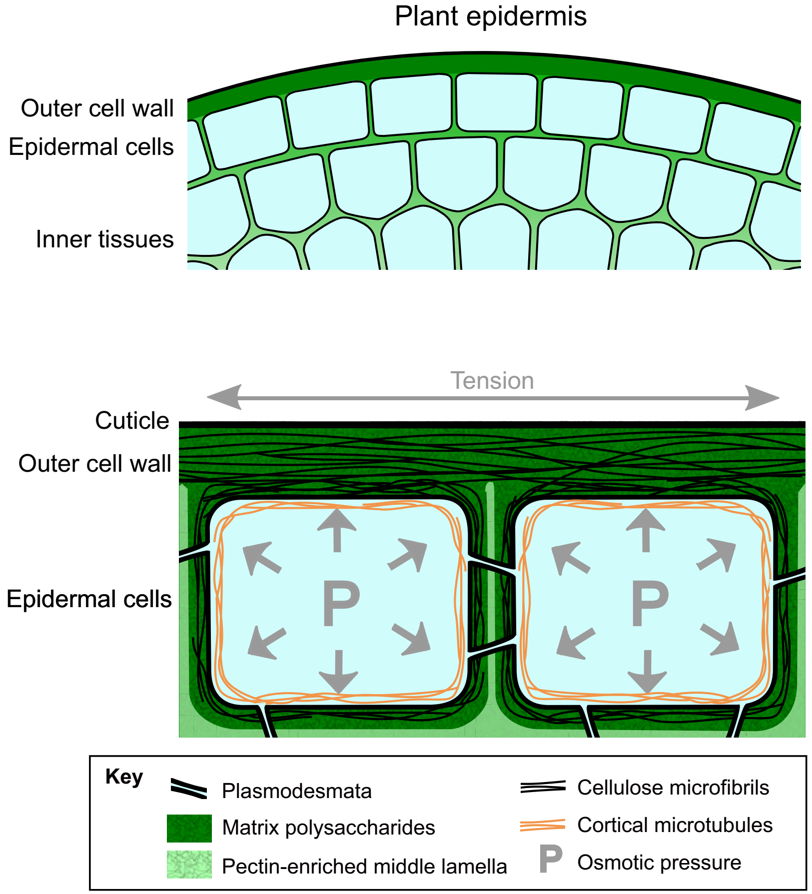
Human Fibroblasts

Tissue organisation: plant epidermal cells

- Cells are immobile
- Cells grow and divide
- Cells are surrounded by a rigid wall
- Cell-Cell adhesion

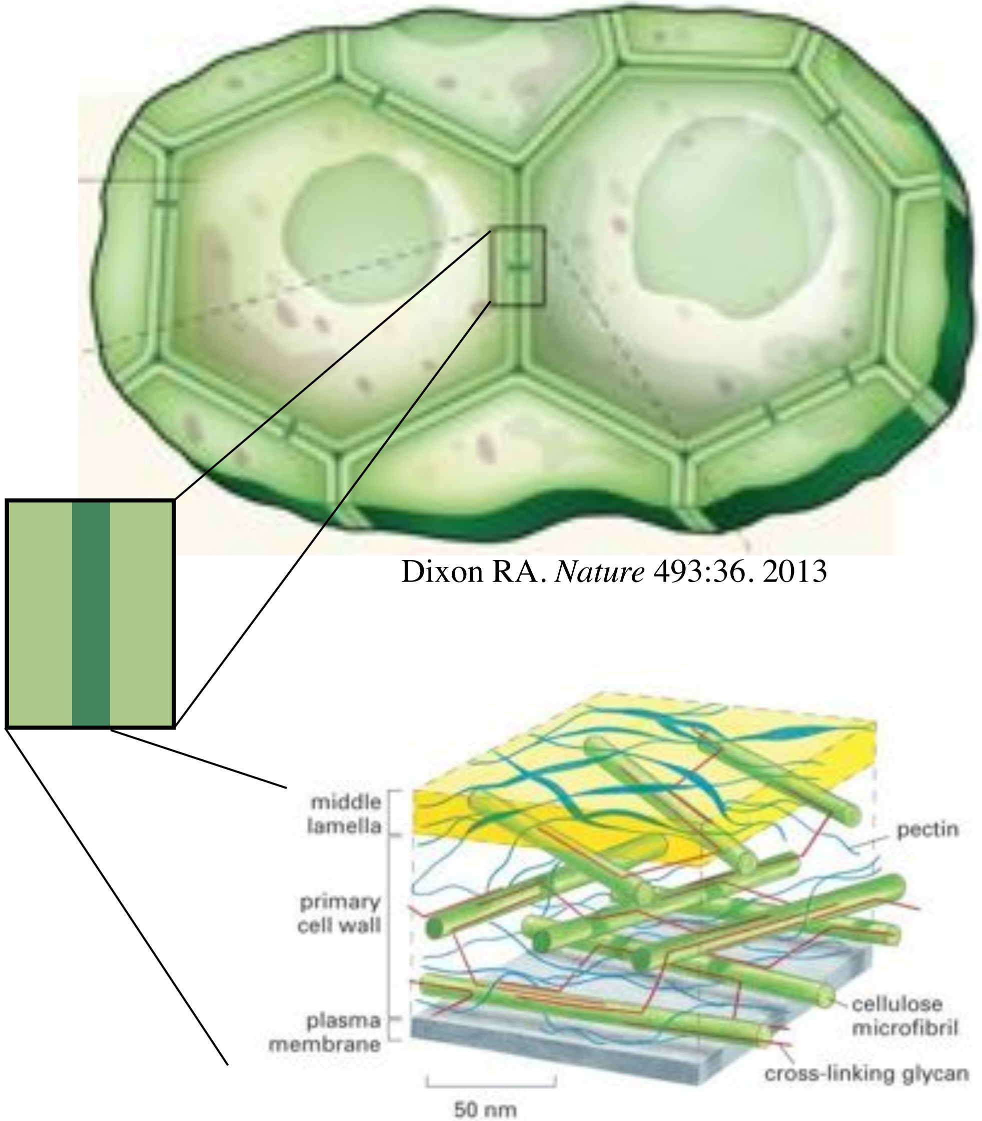


Leaf *Helleborus niger*



Tissue organisation: plant epidermal cells

- Cells are surrounded by a rigid wall
- Cell-Cell adhesion: middle lamella (pectin cross linking)



Dixon RA. *Nature* 493:36. 2013

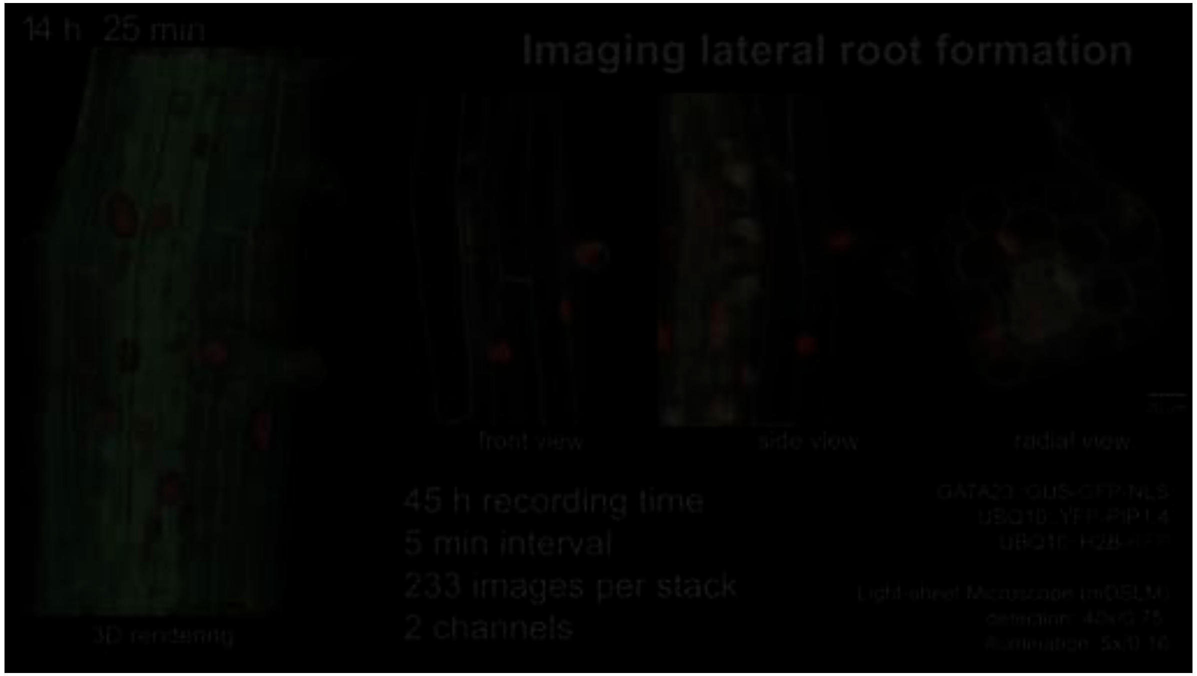
http://web.mnstate.edu/marryand/research_interests.htm

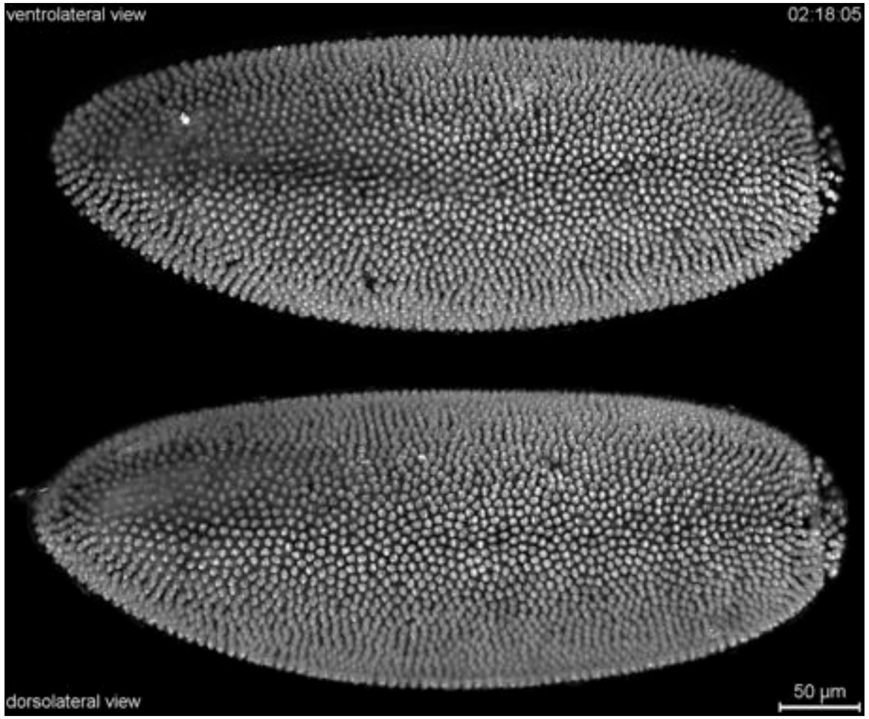
Onion epidermis

1) Organisation / Static

2) Plasticity / Dynamics

Cellular Dynamics in Plant and Animal Morphogenesis





von Wangenheim et al. and Maizel A. *Current Biol.* 26:1-11. 2016

Arabidopsis thaliana

Tomer R.et al. and Keller PJ. *Nature Methods*. 9:755. 2012

Drosophila melanogaster

Dynamics

Cell parameters X	Time	Space	Outcome
Number Size Shape Position	Rates $d(X)/dt$	Orientation $d(X)/dxdydz$	Growth Remodelling Movement

Origin of Dynamics

At cellular level

	Machines	*Function*
• Active Forces:		
- Contractility/tension:	*Motors*	*Shape changes*
- Protrusive forces:	*F-actin polymerisation*	*Motility*
• Turgor pressure:		*Growth*
- « osmotic engine »	*Ion and water transporters*	
- mass increase	*Protein translation*	
• Resistive forces:		
- adhesion: cell-cell and to substratum (animals)		*Motility/ Shape changes*
- wall synthesis (plants)		*Growth/ Shape changes*

Connectedness between cells

- Three Modalities

(along gradients of cell adhesion and stiffness)

« Free » ⟷ Gaz

- Mesenchymal cells in 3D

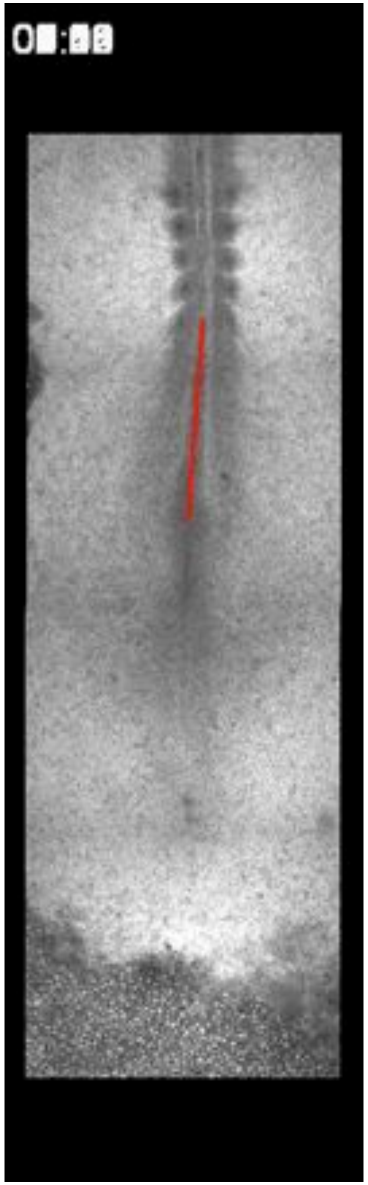
Adhesive ⟷ Fluid (viscoelastic)

- Epithelial cells in 2D

Strongly Coupled ⟷ Solid (elastic/plastic)

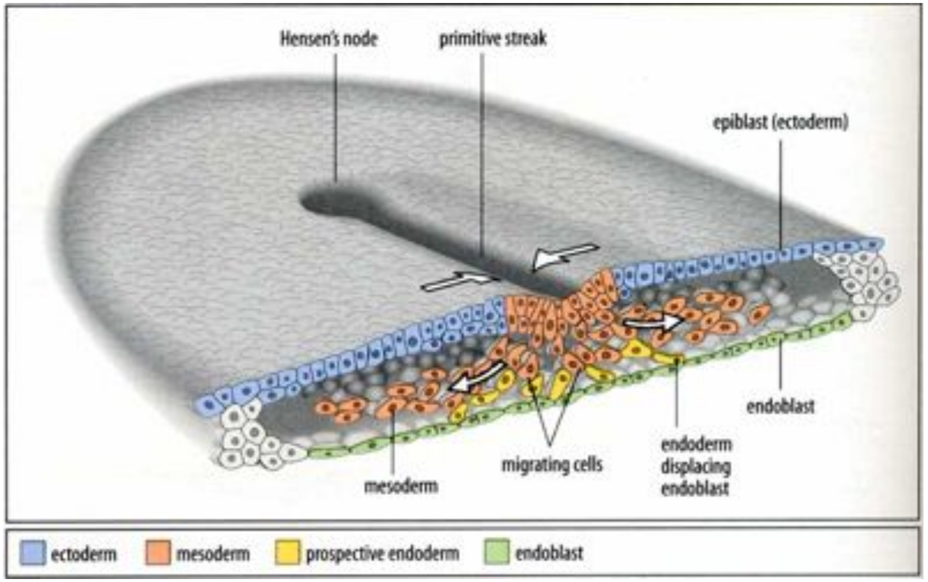
- Plant cells in 3D

Mesenchymal Morphogenesis in 3D

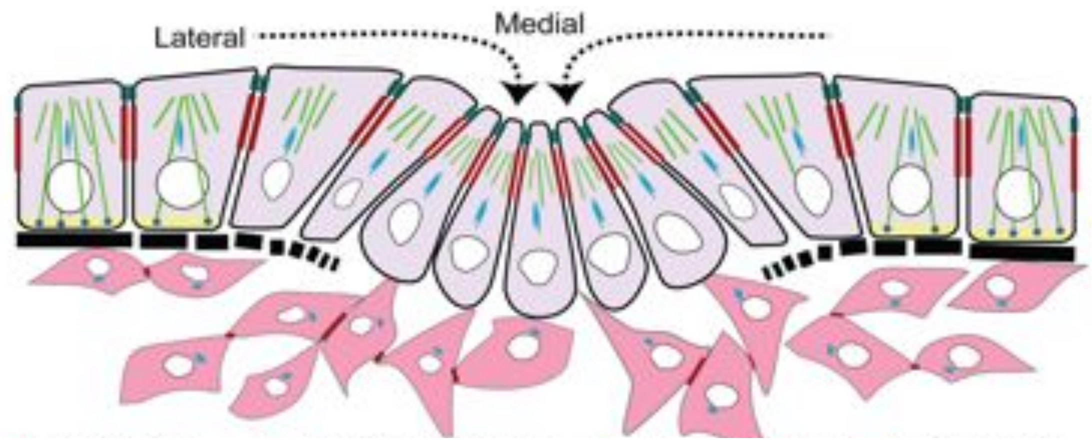


« free » ⟷ Gaz

- Chick Gastrulation and axis elongation



Developmental Biology. S. Gilbert

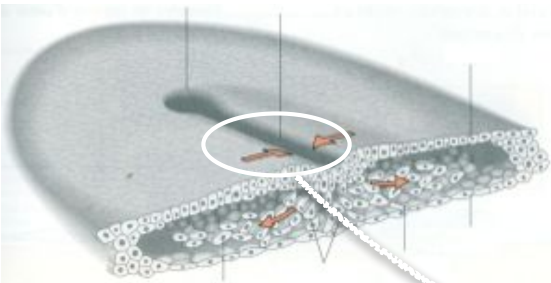


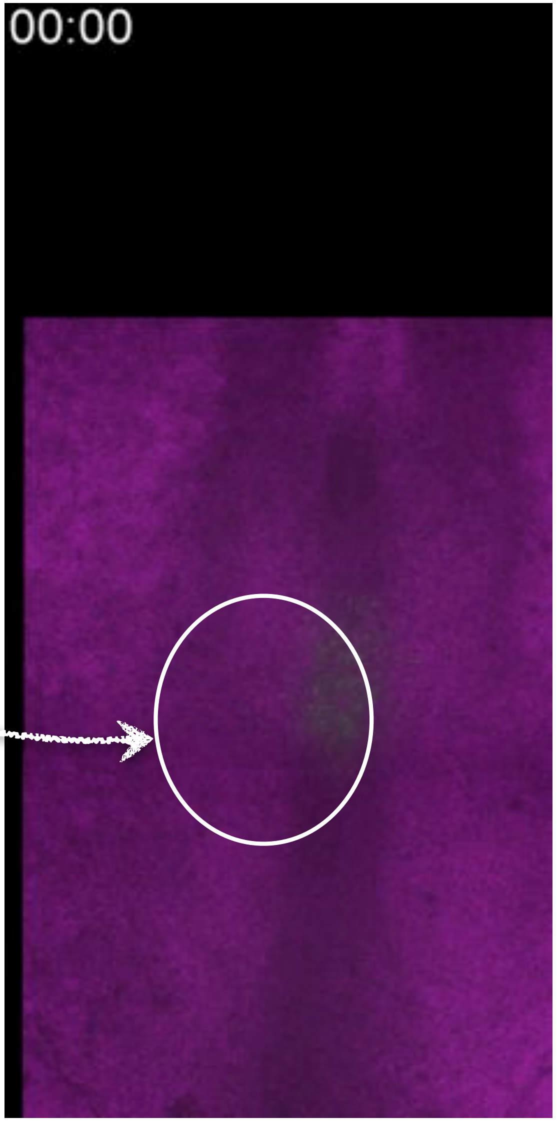
Bénazéraf B. et al, Pourquie O. *Nature*. 466:248. 2010

Nakaya Y. and Sheng G. *Cell Adh Migr* 3:160. 2009

Mesenchymal Morphogenesis in 3D

- Chick Gastrulation and axis elongation



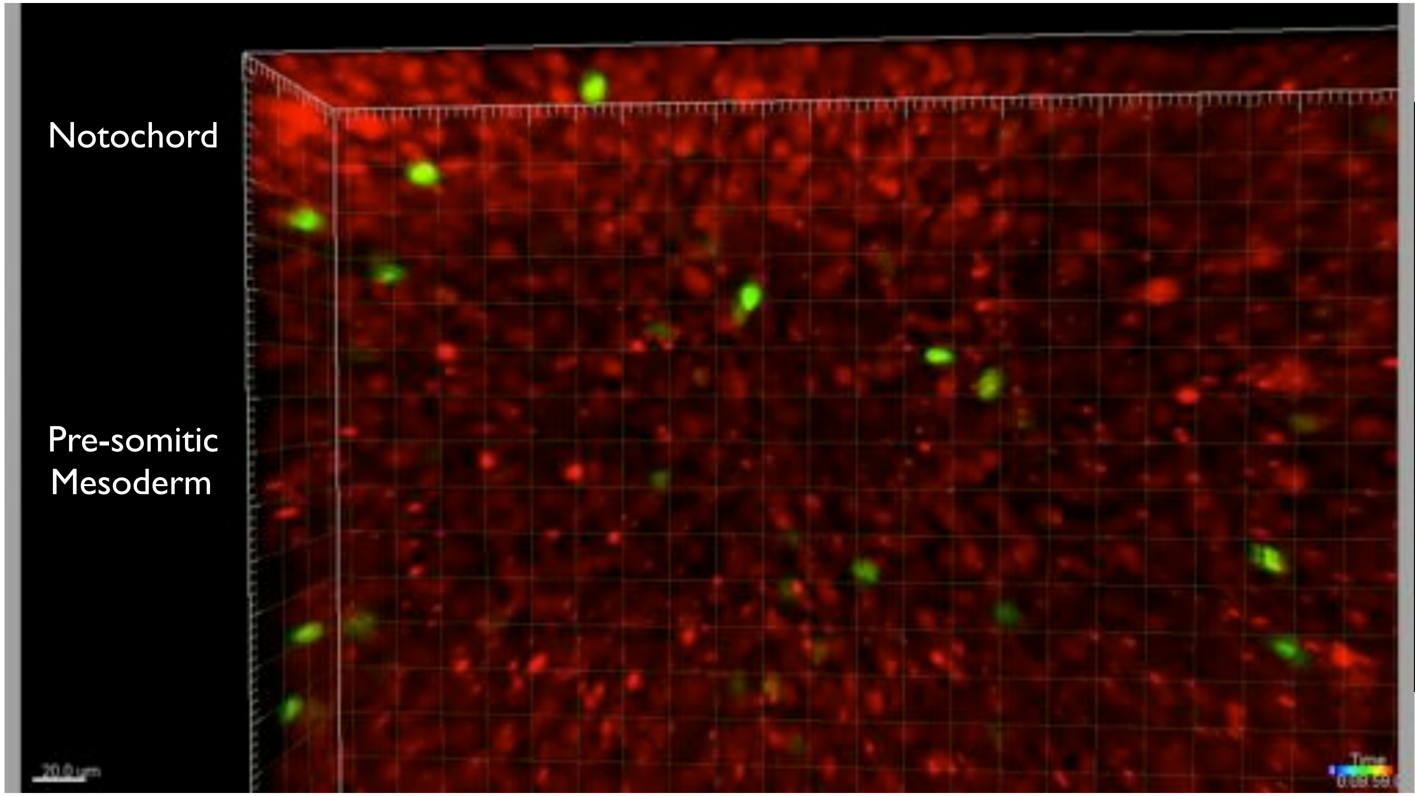


Bénazéraf B. et al, Pourquie O. *Nature*. 466:248. 2010

Mesenchymal Morphogenesis in 3D

« free » ⟷ Gaz

- Chick Gastrulation and axis elongation



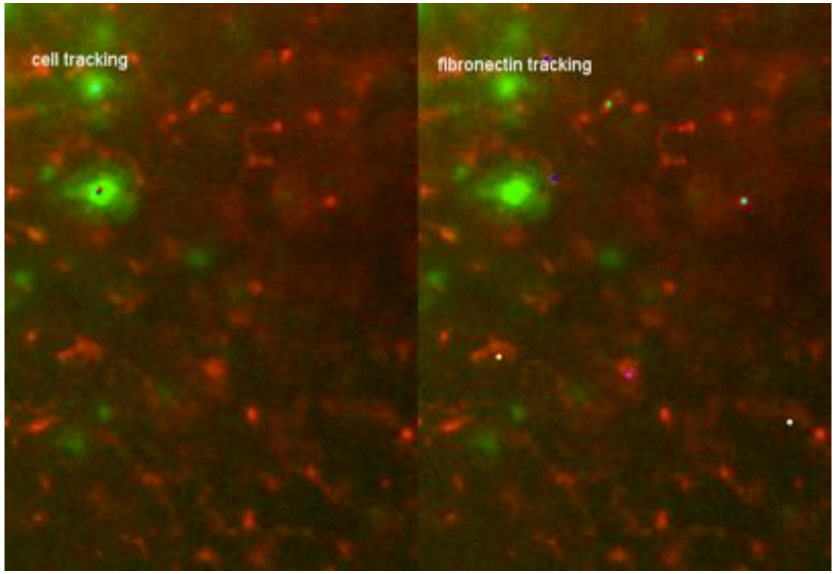
B. Bénazéraf (Pourquié lab)

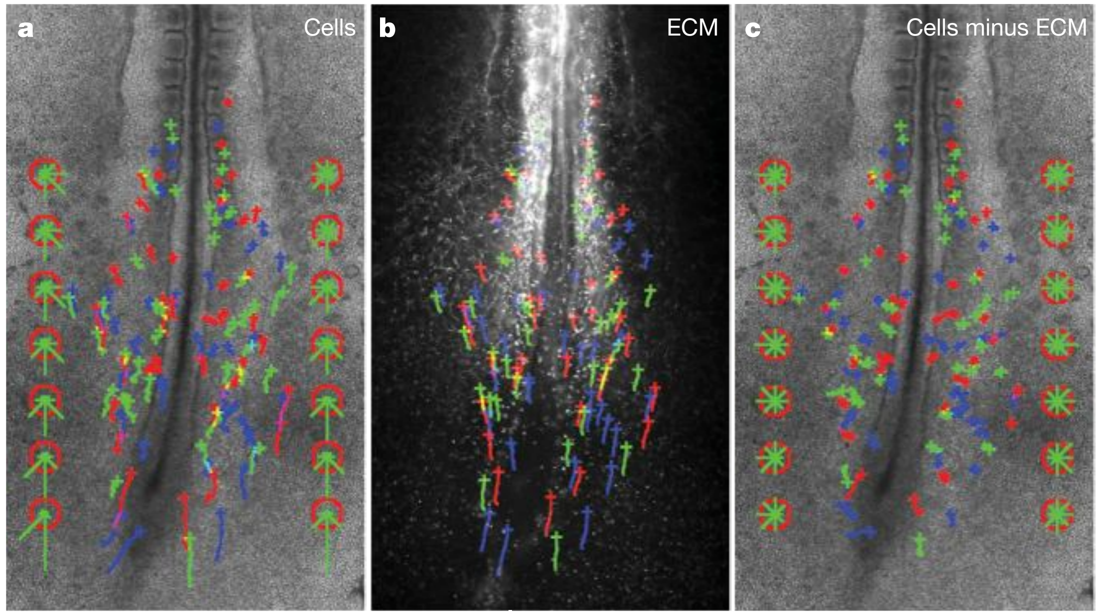
Bénazéraf B. et al, Pourquie O. *Nature*. 466:248. 2010

Mesenchymal Morphogenesis in 3D

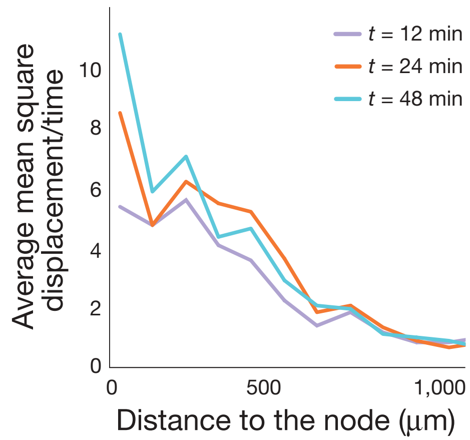
« free » ⟷ Gaz

- Chick Gastrulation and axis elongation





- Cells exhibit directional flow within embryo referential
- Cells have random « diffusive » behaviour with respect to extra cellular matrice
- Gradient of cell « diffusion »/motility from the node



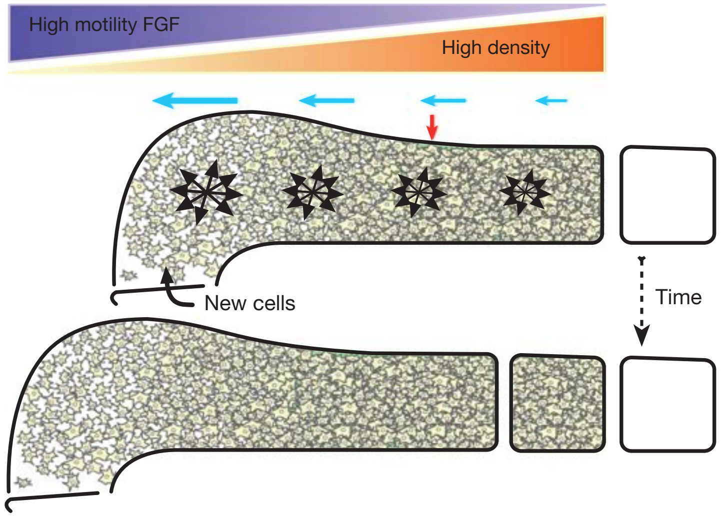
Bénazéraf B. et al, Pourquie O. *Nature*. 466:248. 2010

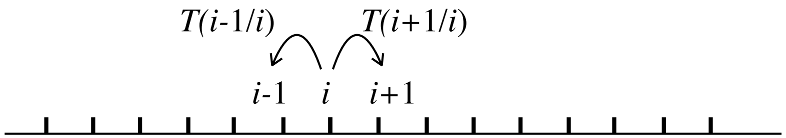
Mesenchymal Morphogenesis in 3D

« free » ⟷ Gaz

- Chick Gastrulation and axis elongation

motility factor



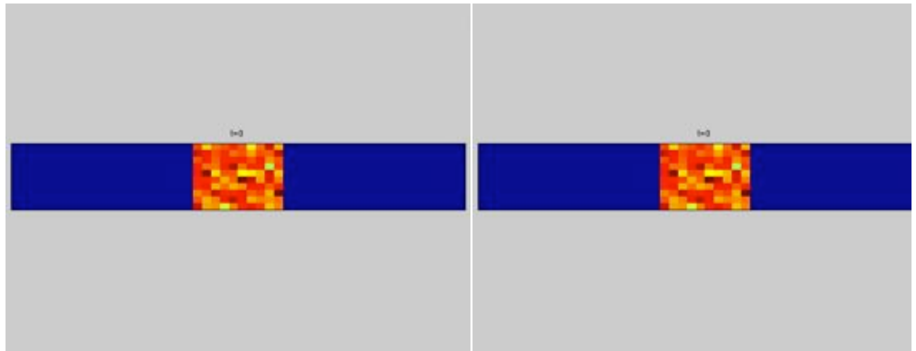


$$T(i \pm 1|i) = \frac{\Delta t}{(\Delta x)^2}\left(\frac{D(u,s)_i + D(u,s)_{i\pm 1}}{2}\right)$$

$T(i \pm 1|i)$ = Transition probability for the cell in position i to move in position i+1 or i-1

$D(u,s)$: cell diffusivity depends on local signaling molecule, s concentration (FGF) and local cell density, u

Cai et al. *Bull Math Biol*. 68:25. 2006



Box 1 Figure | Simulation results at *t* = 0,50,100,250. Without a gradient of cell motility (left panel), and with a gradient of cell motility (right panel).

Bénazéraf B. et al, Pourquie O. *Nature*. 466:248. 2010

Connectedness between cells

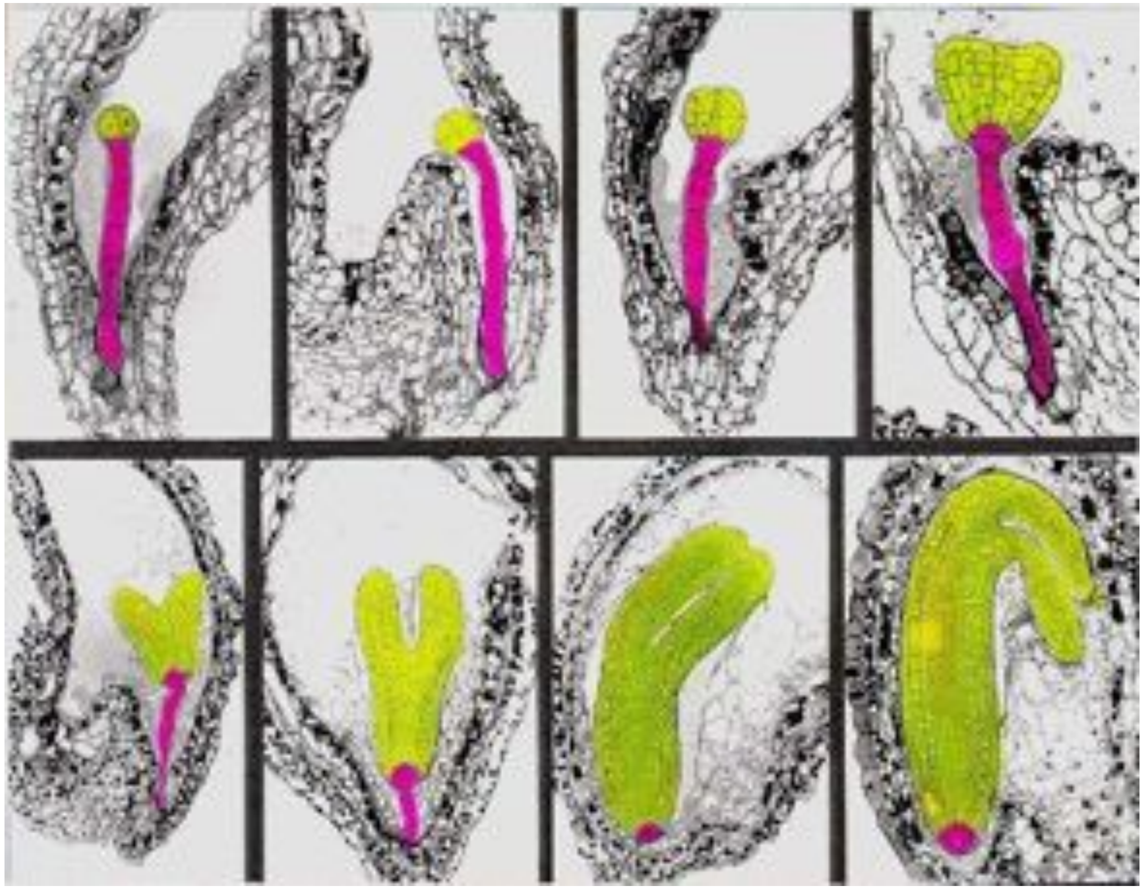
« free » ⟷ Gaz

adhesive ⟷ Fluid (viscoelastic)

strongly coupled ⟷ Solid (elastic/plastic)

3D Morphogenesis in plants

Dictated by growth and cell division patterns

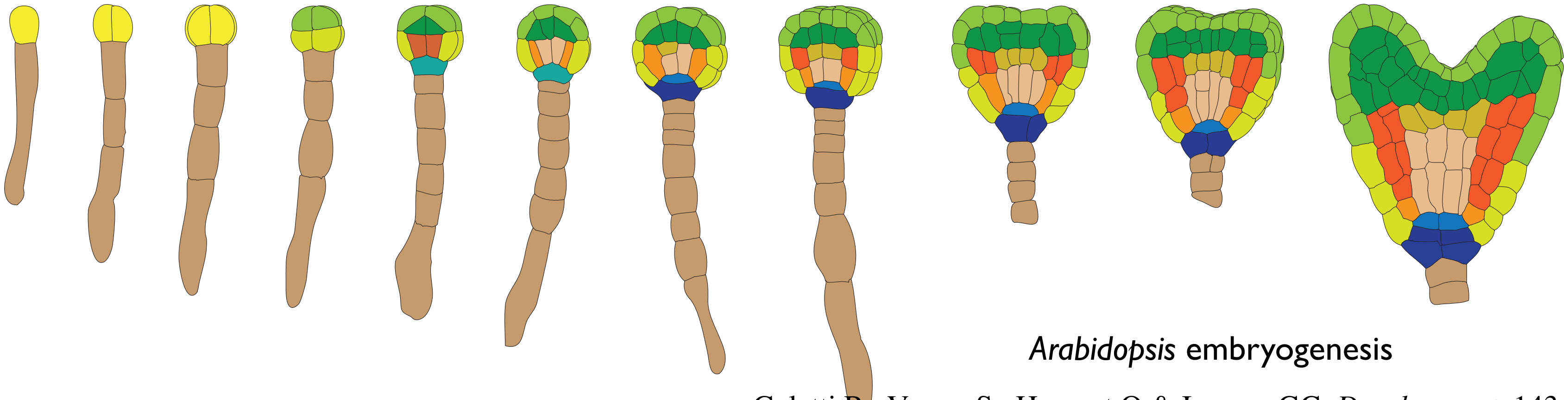


from Chun Ming-Liu (C.A.S. Beijing), via http://biology.kenyon.edu/

Embryogenesis in *Arabidopsis thaliana*

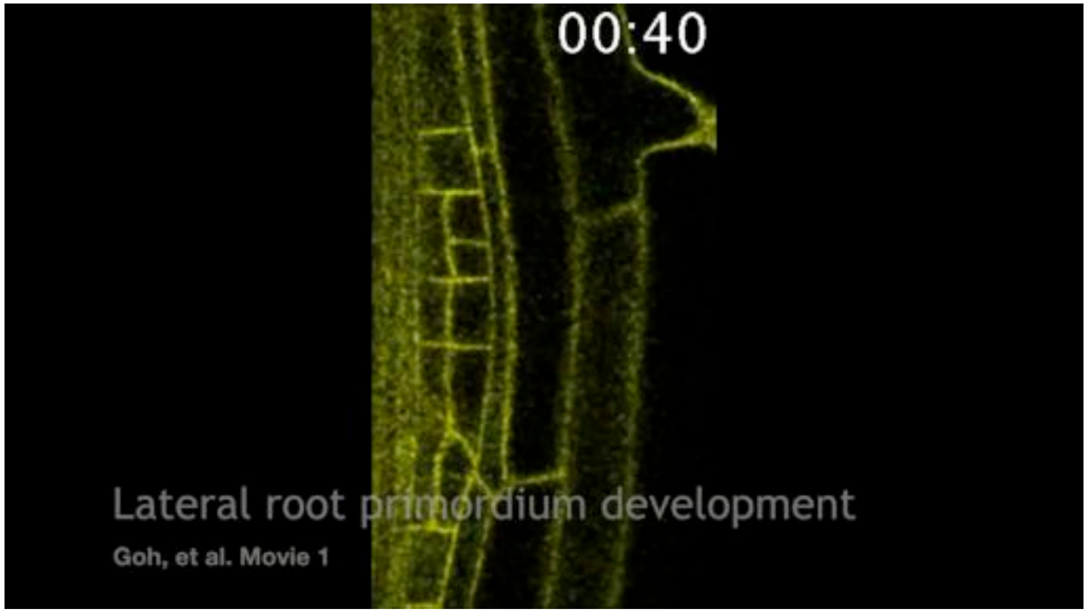
3D Morphogenesis in plants

Dictated by specific growth and cell division patterns



Arabidopsis embryogenesis

Galetti R., Verger S., Hamant O.& Ingram GC. *Development*. 143:3249. 2016

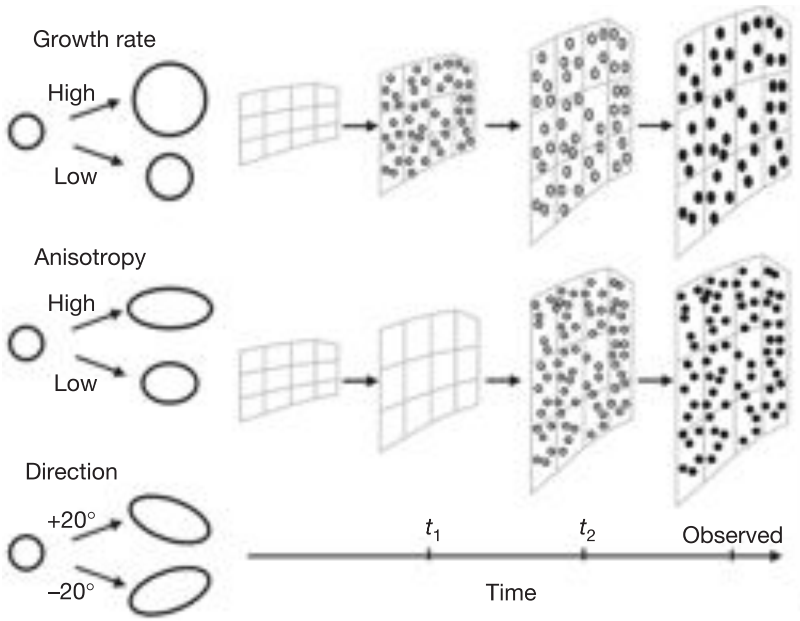


Goh T. et al, and Guyomarc'h S. *Development*. 143:3363. 2016

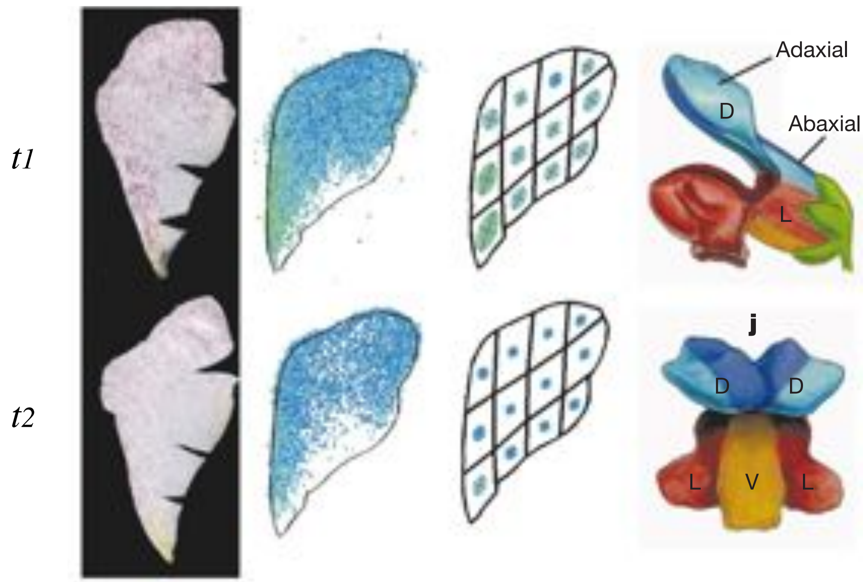
3D Morphogenesis in plants

Growth dynamics underlying petal shape and asymmetry

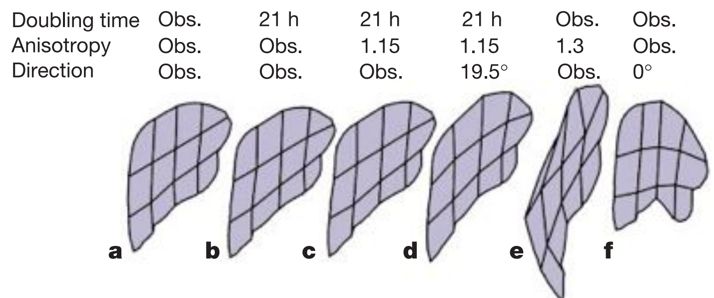
see Conformal transformations (e.g. d'Arcy Thompson)



Growth parameters



Observations: clonal analysis

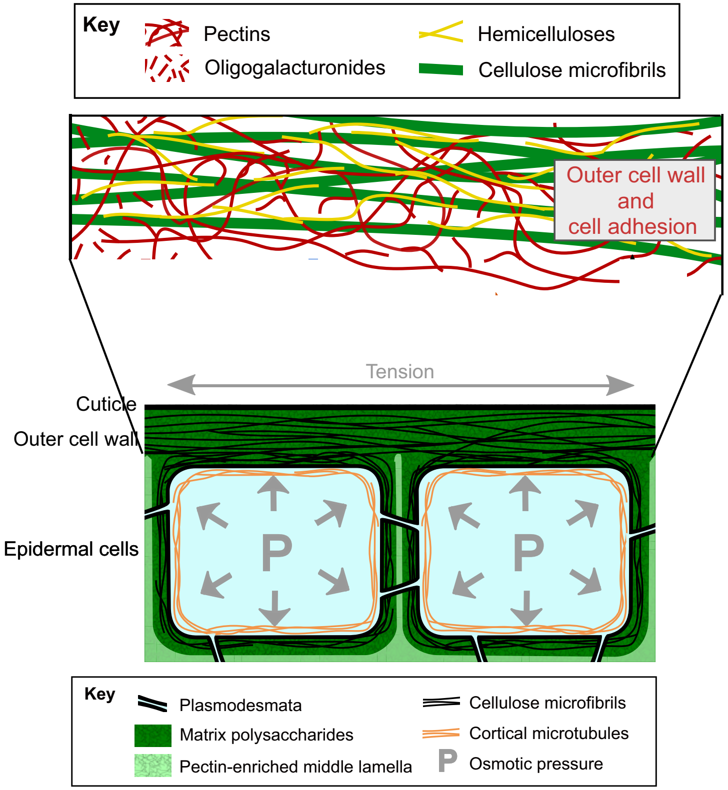


Simulations of growth

Rolland-Lagan AG. et al. and Coen E. *Nature*. 422:161. 2003

3D Morphogenesis in plants

Mechanics of walled cells growth: Elasticity



- Turgor Pressure: 0.4-0.8 MPa

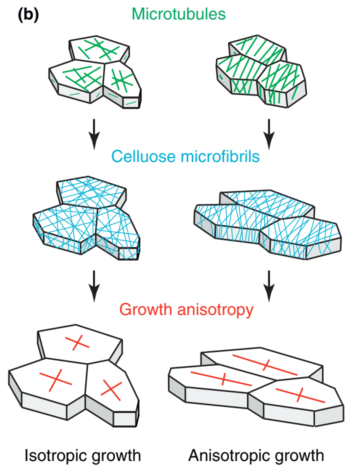
(in animal cells, hydrostatic pressure 50-150 Pa)

Beauzamy L. et al. and Hamant O, Boudaoud A. *Front. Plant Sc.* 6:1038. 2015
Stewart MP et al. and Müller D, Hyman A. *Nature.* 469:226. 2011

- Wall stiffness opposes and balances turgor pressure.

  (in animal cells, actomyosin cortex has a similar, albeit intracellular function: see blebs)

- Regulation of wall stiffness *E*.
  - Polarisation: E_{xx}, E_{yy}
    MT/Cellulose anisotropy
  - Magnitude: cellulose, pectin density, crosslinking



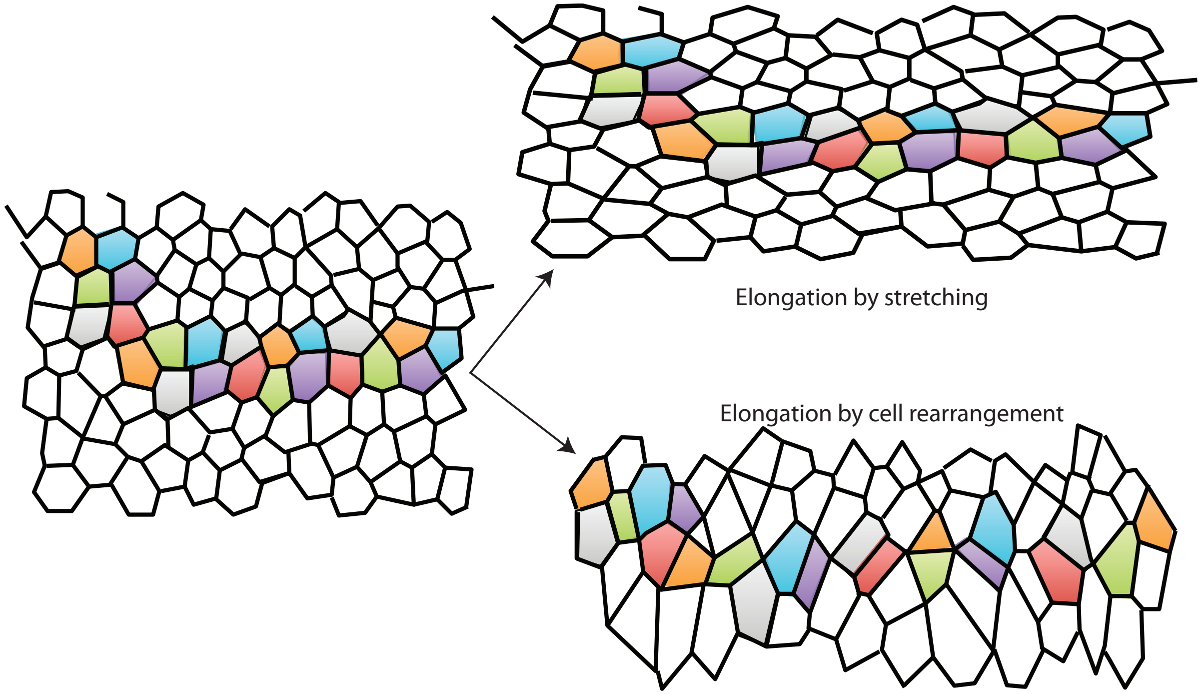
Bringmann M et al. *Trends Plant Science.* 17:666. 2012

Connectedness between cells

« free »	⟷	Gaz
adhesive	⟷	Fluid (viscoelastic)
strongly coupled	⟷	Solid (elastic/plastic)

Epithelial tissues are visco-elastic

- Time-dependency of responses to stress



Elastic deformation (few s - 1min)

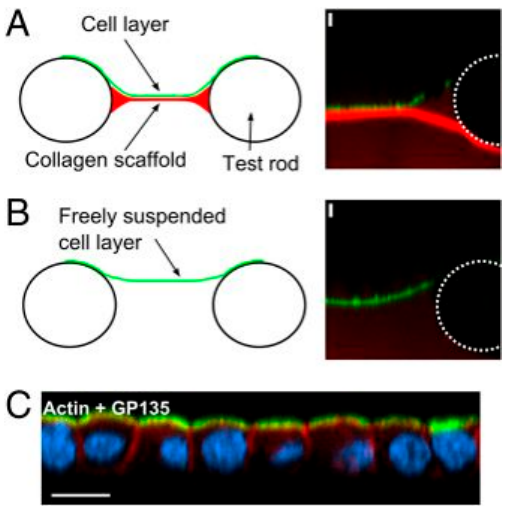
Viscous flow (10s of min to hrs)

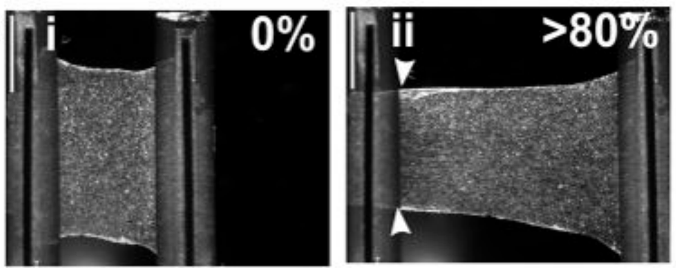
Guillot C. and Lecuit T. *Science*. 340:1185. 2013

Elastic properties of epithelia

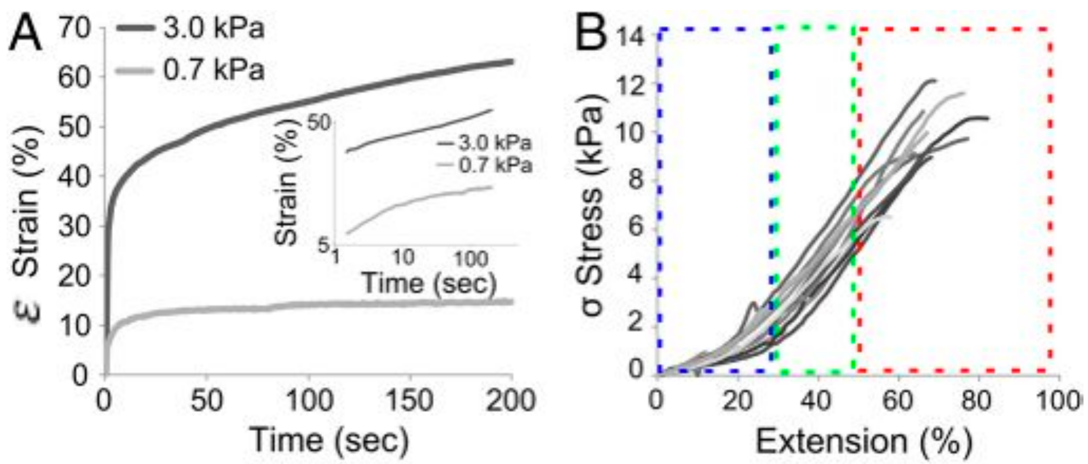
- Elasticity on short time scales (<10-20s)

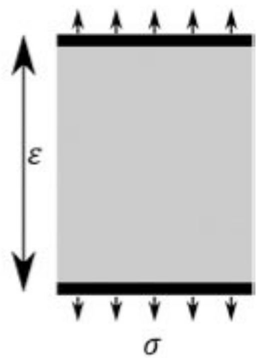
Creep response experiments:





Strain rates of 0.5-5%. s^{-1}





$$\sigma = E\,\varepsilon$$

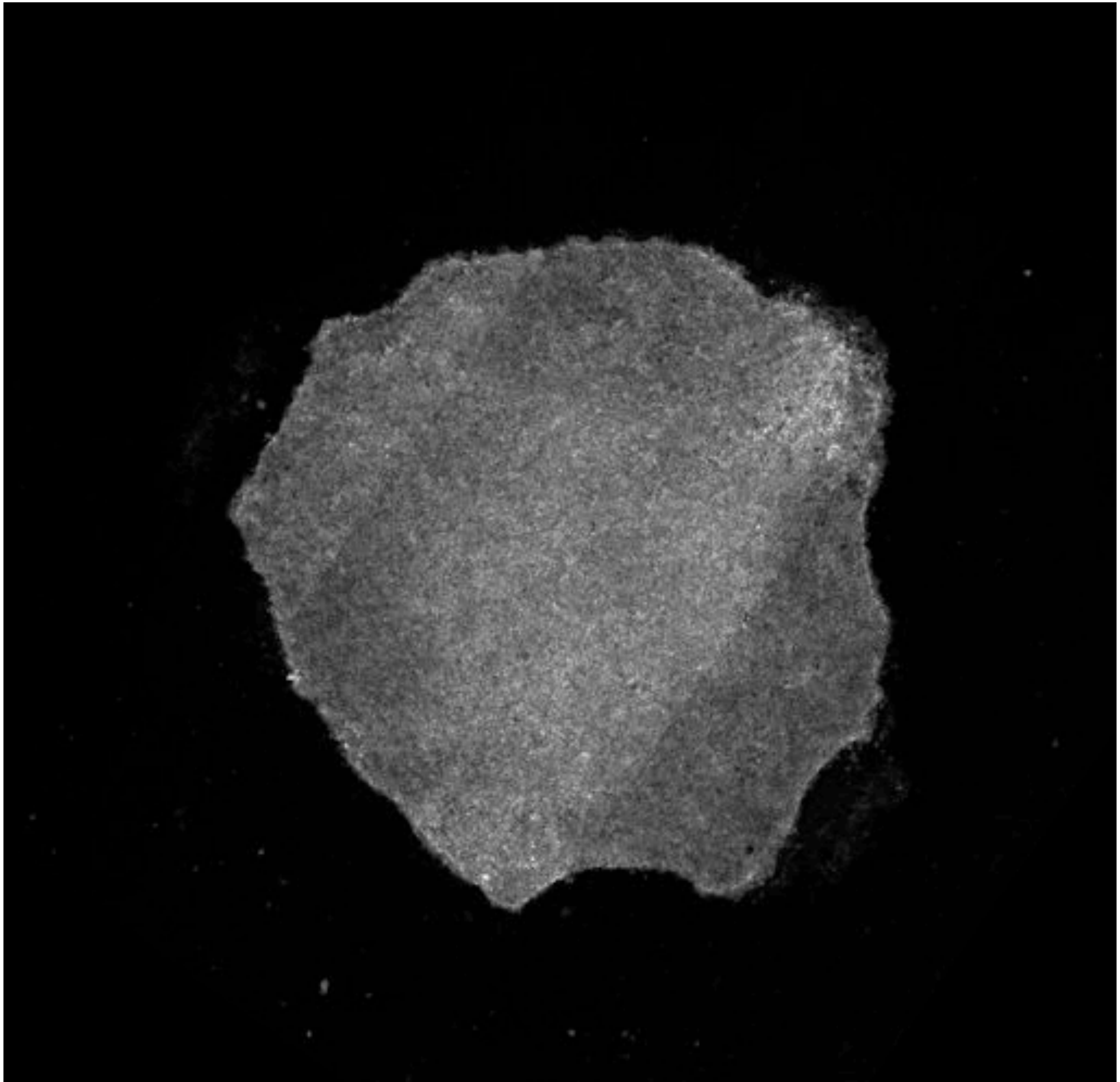
E= 20 +/-2 kPa

E : stiffness of epithelial monolayer

Harris M. et al. and Baum B, Kabla A, Charras G. *PNAS*. 109:16449. 2012

Epithelial tissues are viscous fluids

- Tissue fluid flow on long time scales (24h)



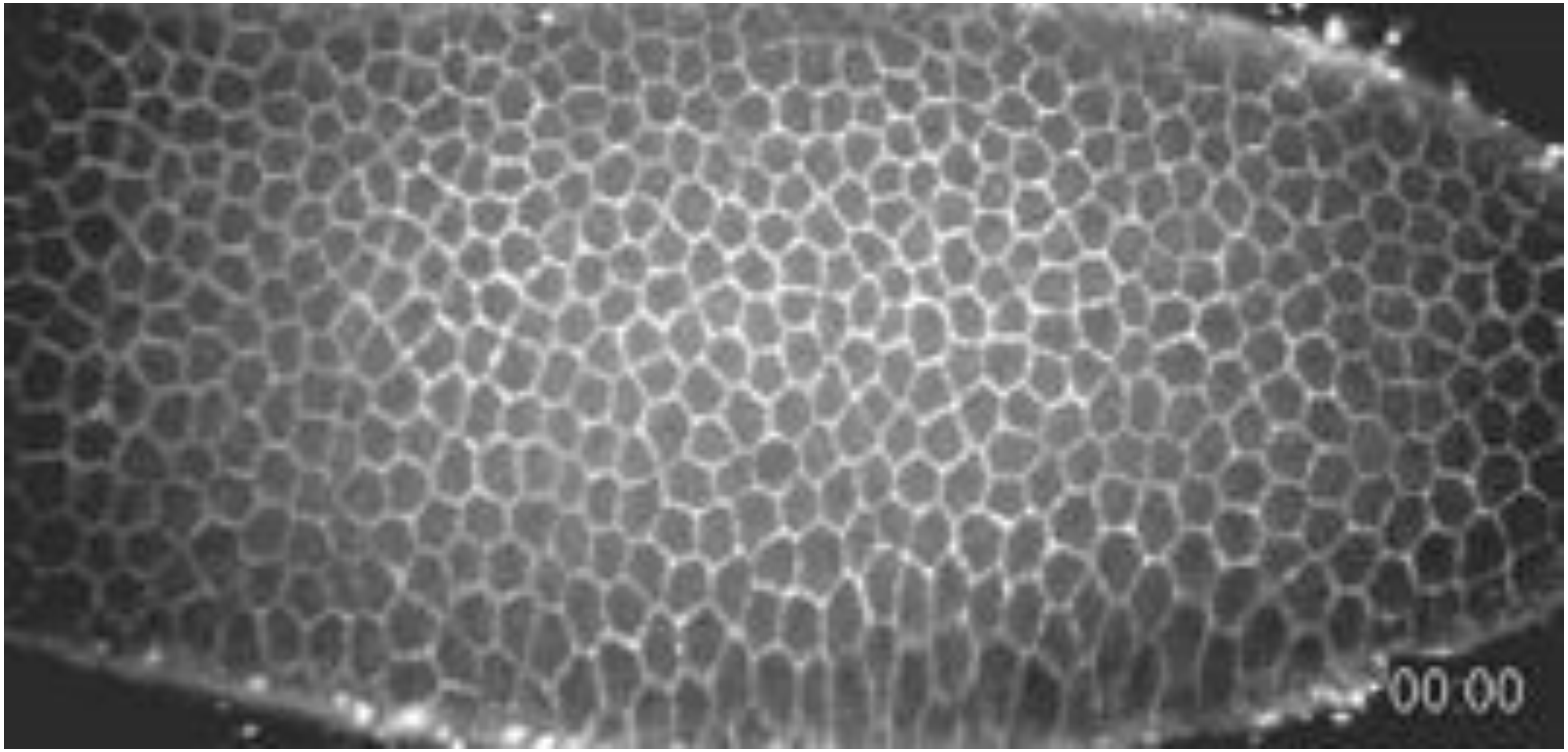
Epiblast of quail embryo
J. Gros Institut Pasteur

membrane-GFP

COLLÈGE DE FRANCE 1530

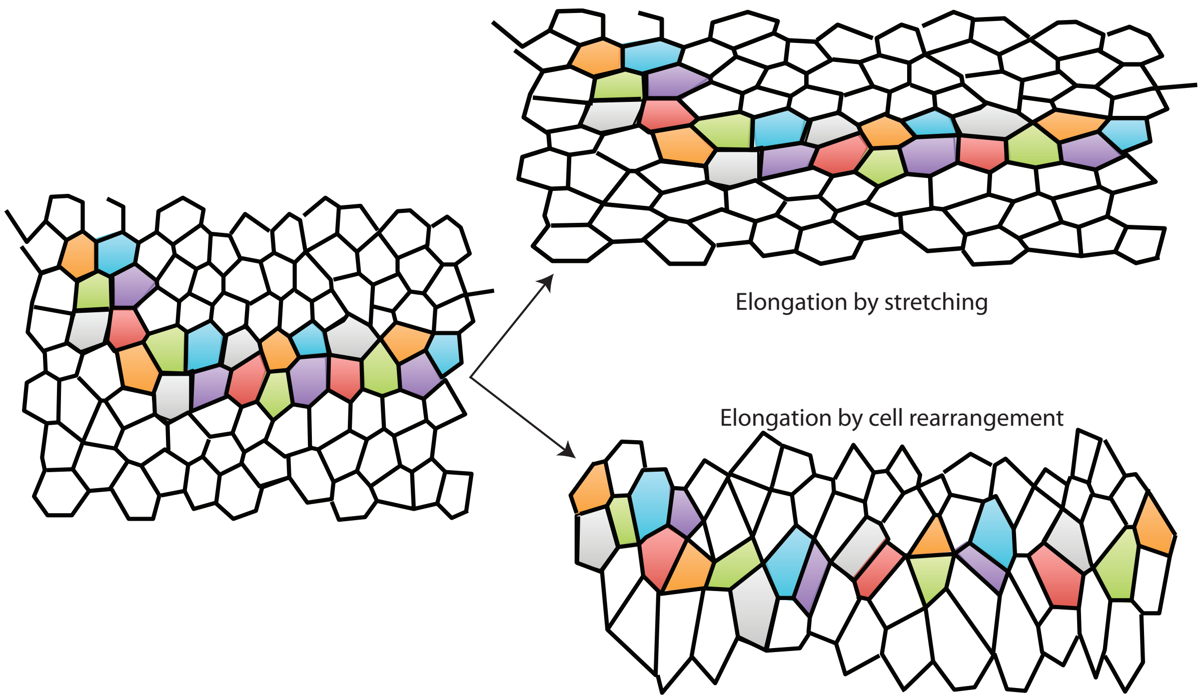
Epithelial tissues are viscous fluids

- Tissue fluid flow on long time scale(45 min)



E-cadherin::GFP *Drosophila* embryo

Epithelia are viscoelastic



Elastic deformation (few min)

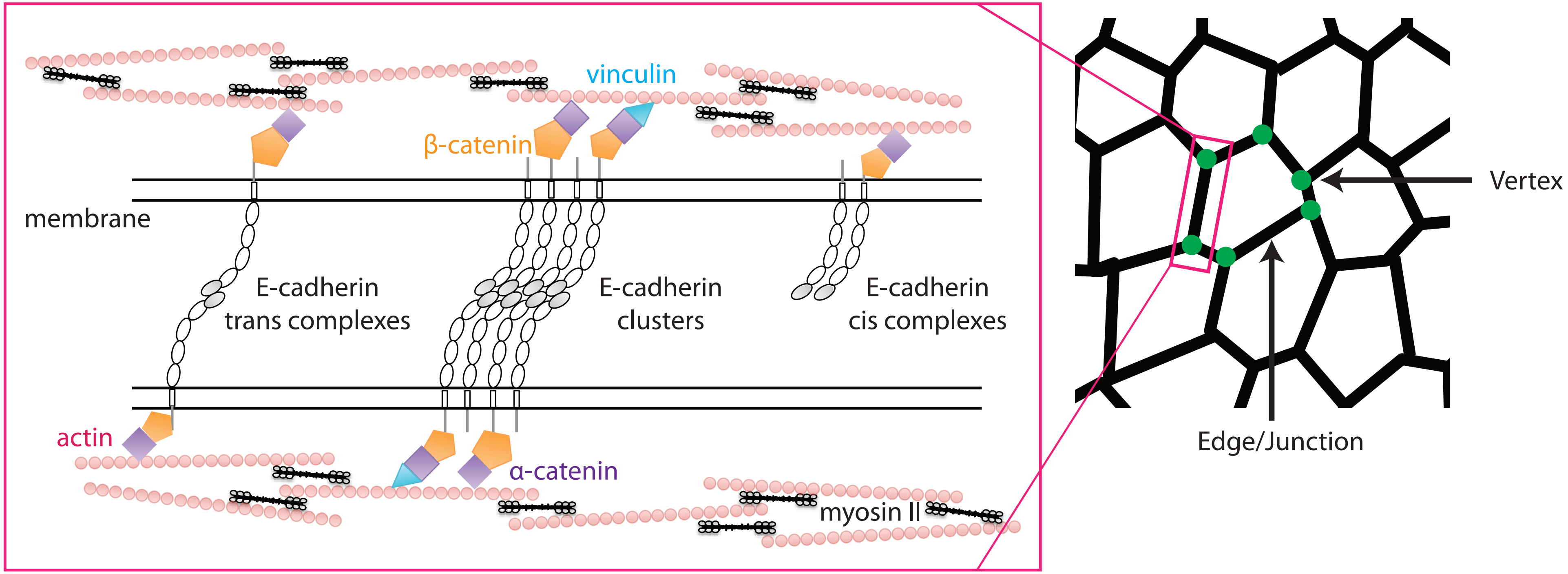
Viscous flow (10s of min to hrs)

>>junction dynamics

Guillot C. and Lecuit T. *Science*. 340:1185. 2013

Epithelia are viscoelastic

Junctions are sites of adhesion and cortical tension

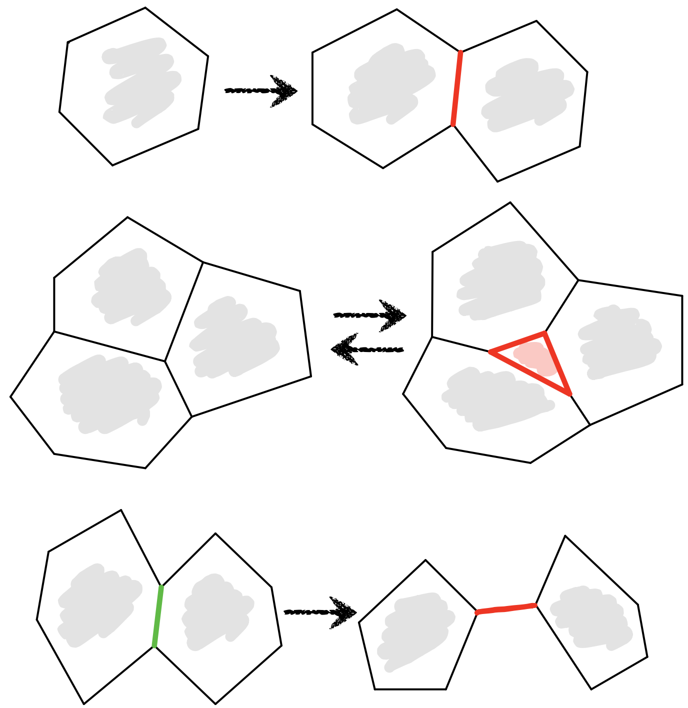


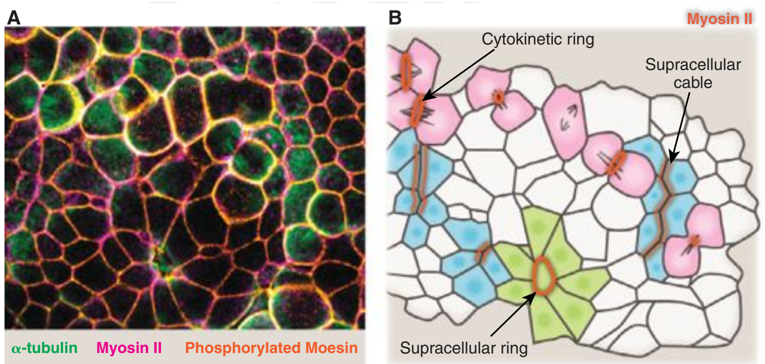
Guillot C. and Lecuit T. *Science*. 340:1185. 2013

Epithelial visco-elasticity - Impact of Topological transitions

4 types of cell contact remodelling underly epithelial fluid behaviour

- Junction formation: cell division
- Junction formation: cell apical emergence
- Junction removal: cell extrusion
- Junction exchange: cell intercalation

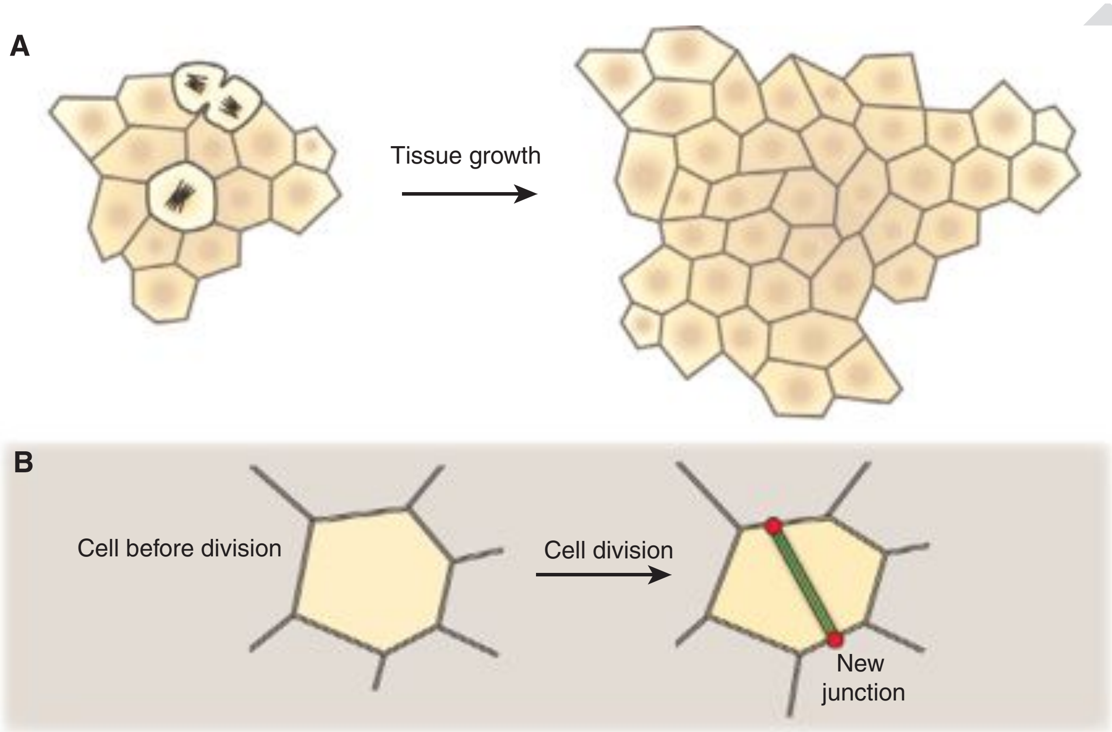


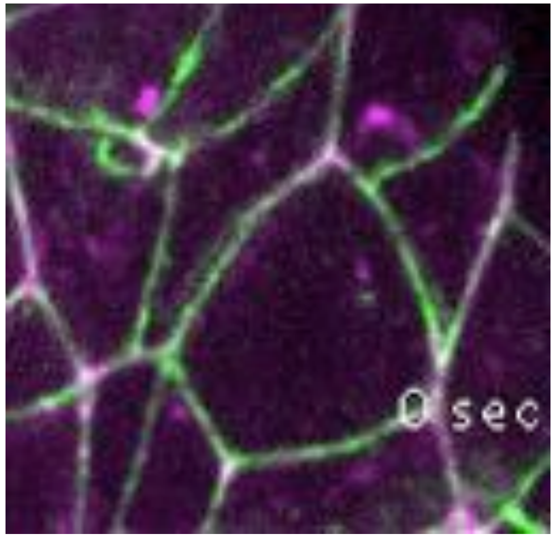


Guillot C. and Lecuit T. *Science*. 340:1185. 2013

Epithelial visco-elasticity - Impact of Topological transitions

Formation of new junctions during cell division

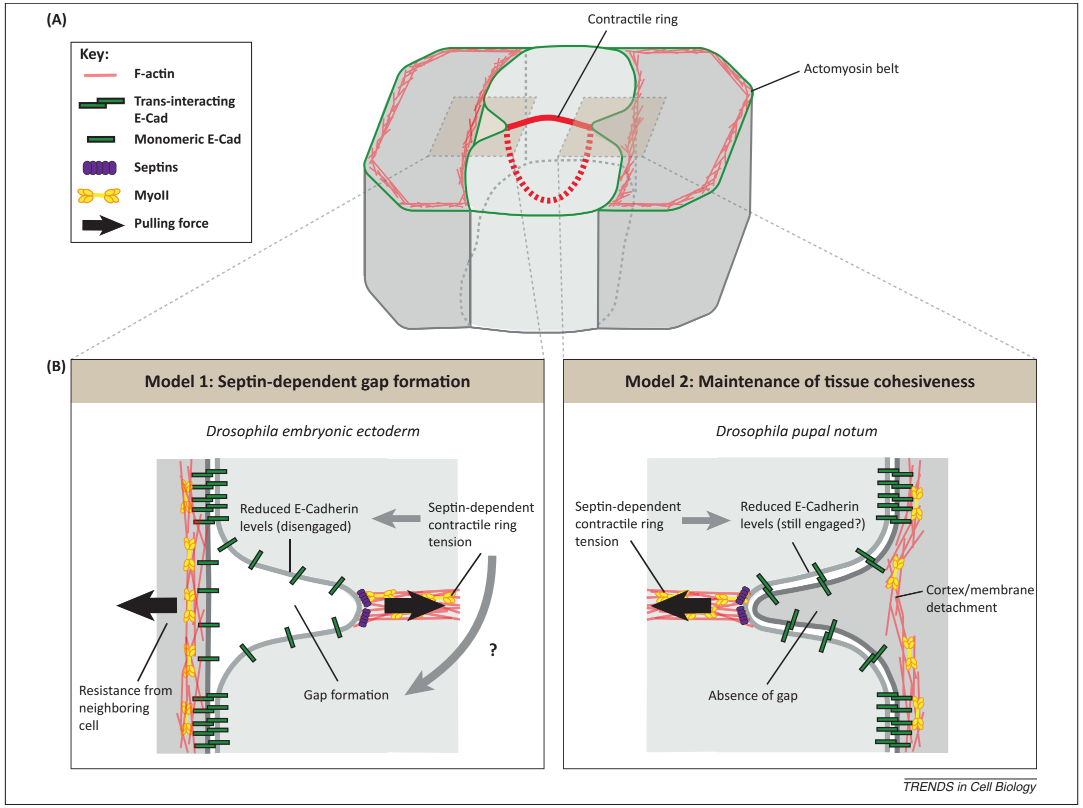


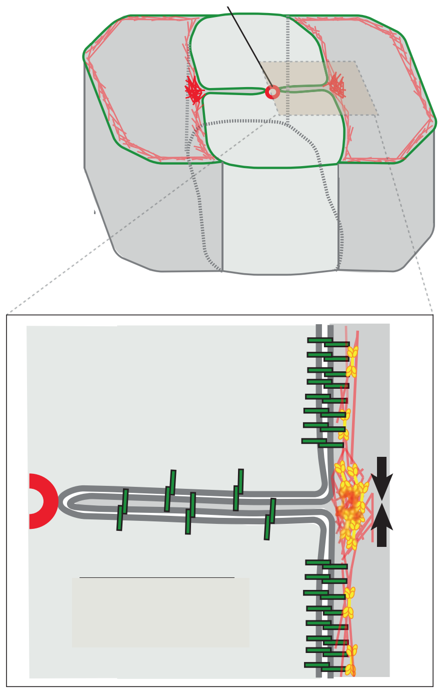


Guillot C. and Lecuit T. *Science*. 340:1185. 2013

Epithelial visco-elasticity - Impact of Topological transitions

Formation of a new junction is an active multicellular process



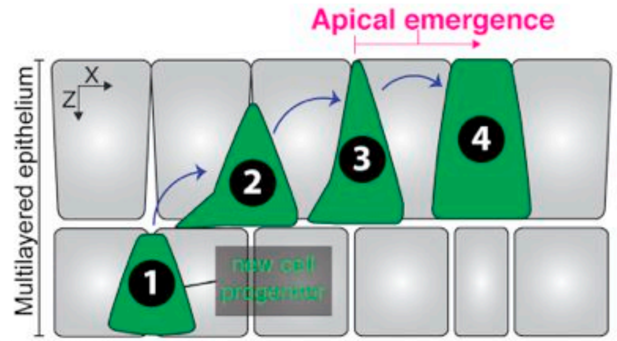


Herszteg & Bellaïche *Trends in Cell Biol*. 24:285. 2014

Founounou N, Loyer N, Le Borgne R. *Dev Cell*. 24:242-55. 2013
Guillot C, Lecuit T. *Dev Cell*. 24:227-41. 2013
Herszterg S, Leibfried A, Bosveld F, Martin C, Bellaiche Y. *Dev Cell*. 24:256. 2013
Morais-de-Sá E, Sunkel C. *EMBO Rep*. 14(8):696-703. 2013

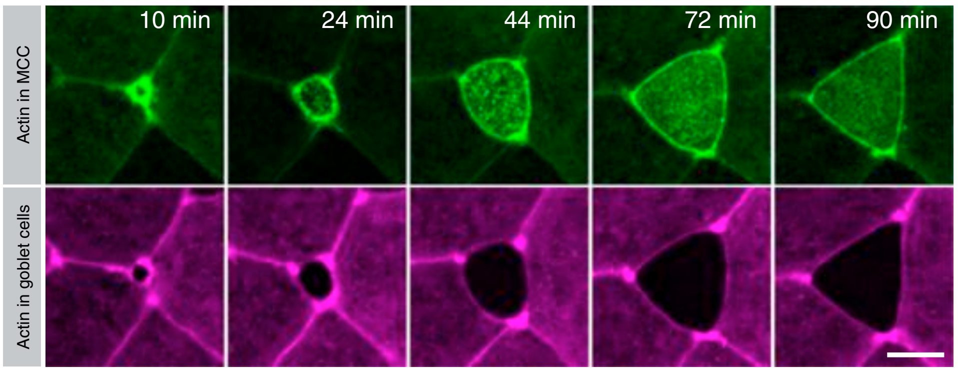
Epithelial visco-elasticity - Impact of Topological transitions

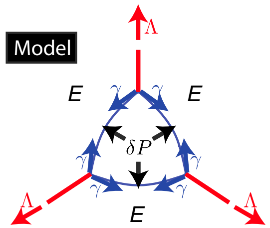
- Cell emergence

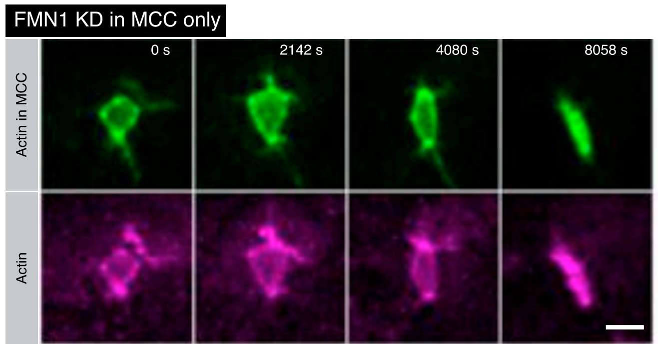


Radial intercalation: (1) Progenitor cell specification (2-3) Apical movement and docking (3-4) **Apical emergence**

- Radial cell intercalation associated with apical emergence
- This is associated with compressive stresses exerted by emerging cell on neighbours
- Requires F-actin network assembly





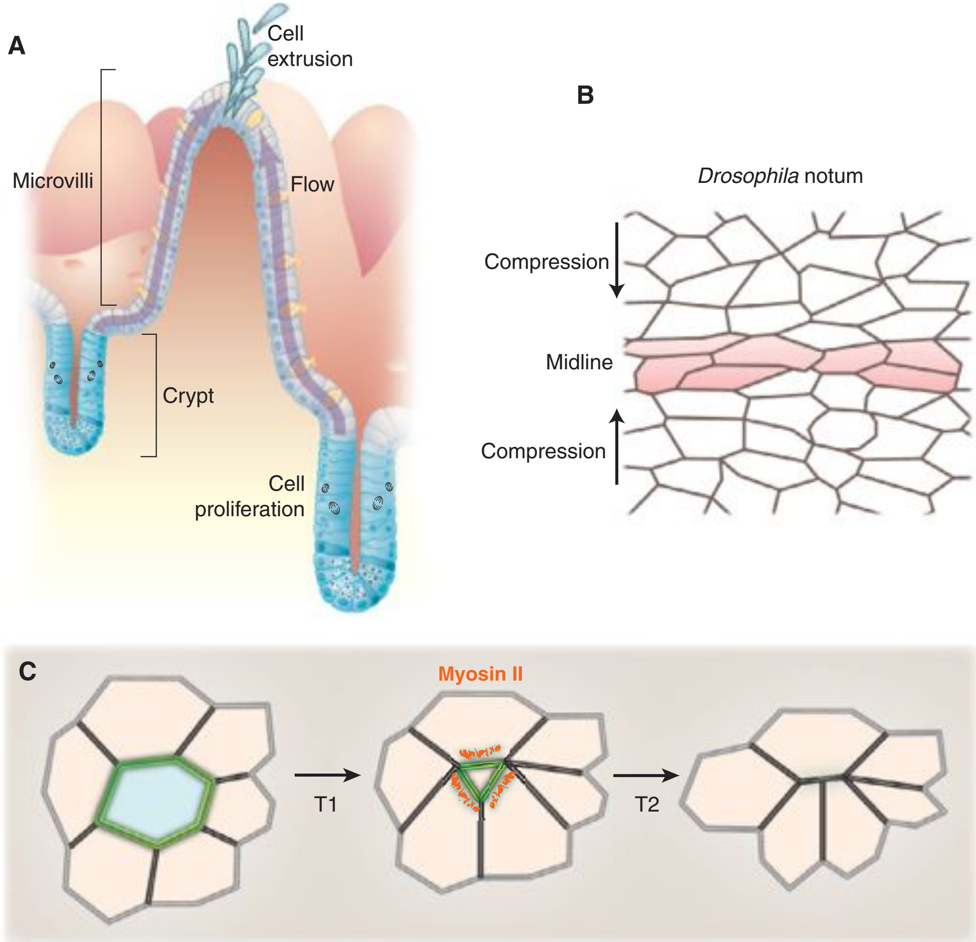


Formin knock down

Sedzinski et al, Wallingford JB. *Dev Cell* 36:24. 2016

Epithelial visco-elasticity - Impact of Topological transitions

- Active removal of junctions during cell extrusion and delimitation

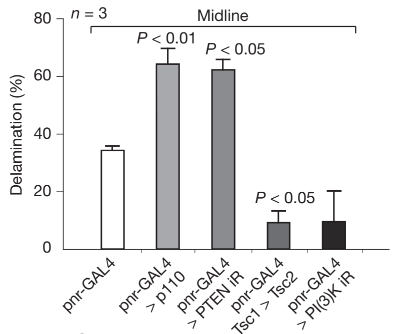


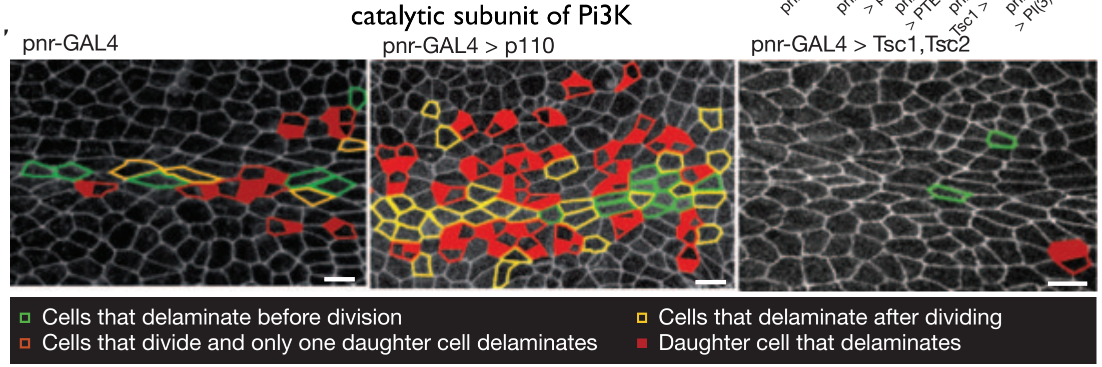
Guillot C. and Lecuit T. *Science*. 340:1185. 2013

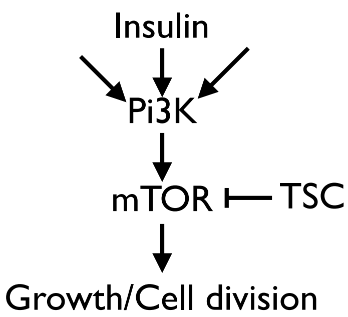
Epithelial visco-elasticity - Impact of Topological transitions

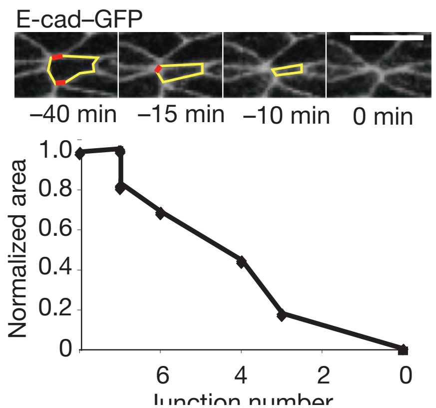
- Cell delamination balances cell division

- Increased cell division/growth induces delamination
- Removal of cell junctions and reduction of apical cell surface







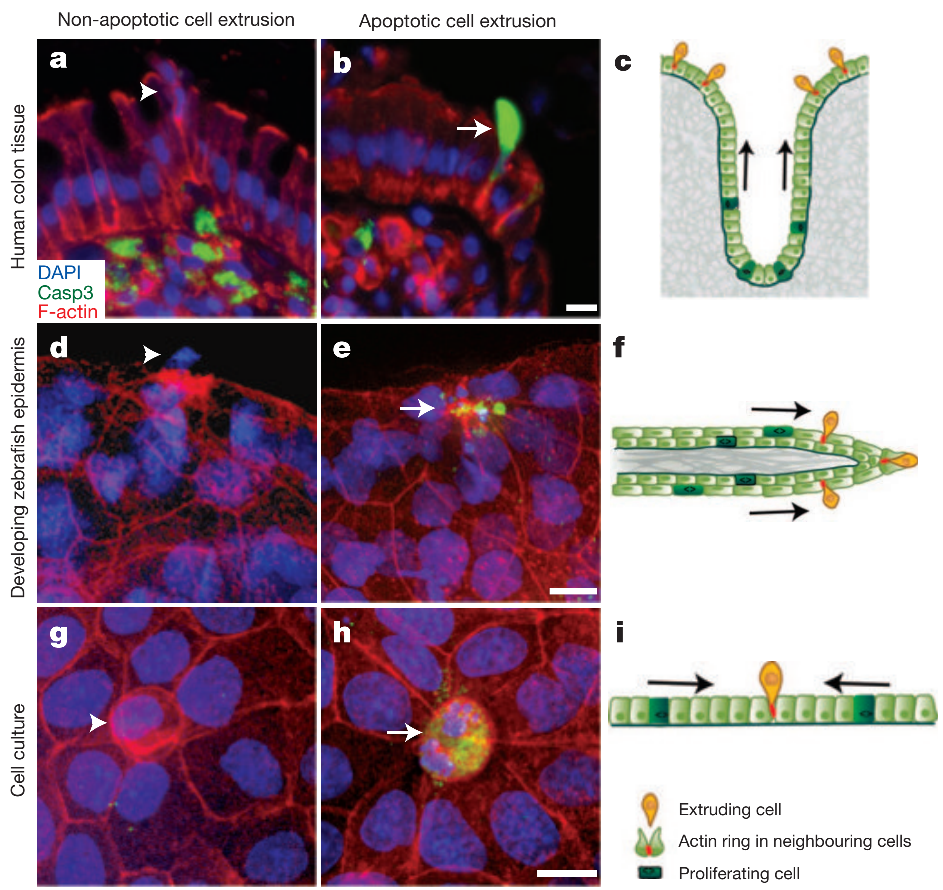


Marinari E. et al, Baum B. *Nature* 484:542. 2016

Epithelial visco-elasticity - Impact of Topological transitions

- Cell extrusion

- Cells extrude in region of high cellular crowding

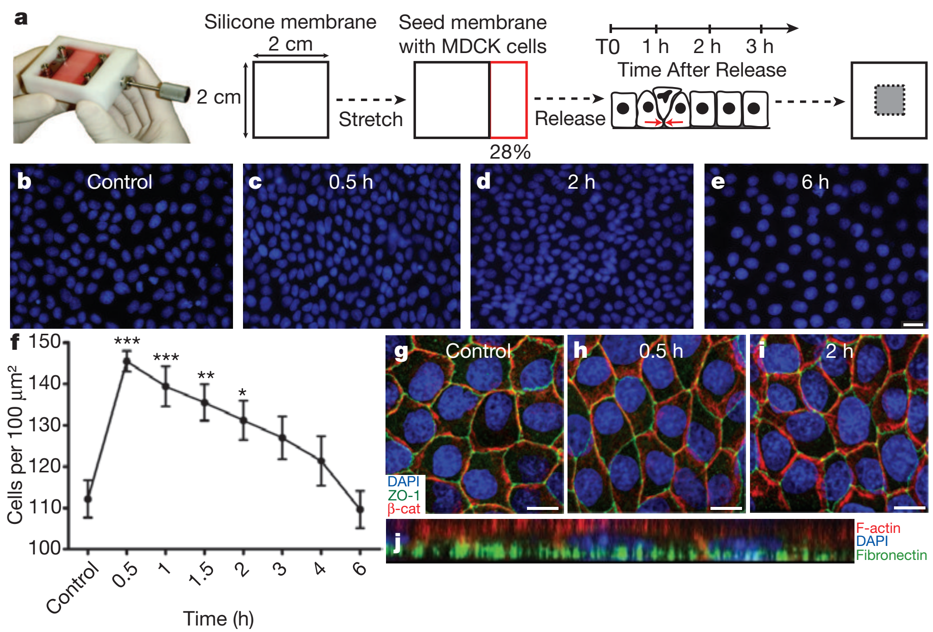


Eisenhoffer GT. et al, Rosenblatt J. *Nature* 484:546. 2012

Epithelial visco-elasticity - Impact of Topological transitions

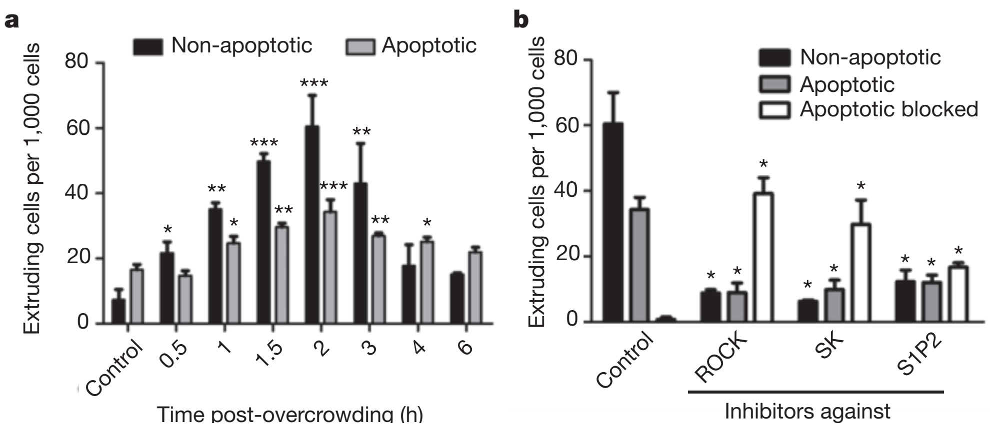
Homeostatic cell extrusion

- Induced crowding with tissue stretcher promotes extrusion
- Extrusion requires contractility and and stretch activated signals



Homeostatic cell death

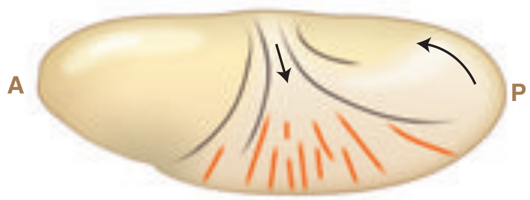
Stretch-activated signals
Piezo1 ⊣ Gd^{3+}
↓
Sphingosine-1-phosphate
↓
Rho
↓
Extrusion



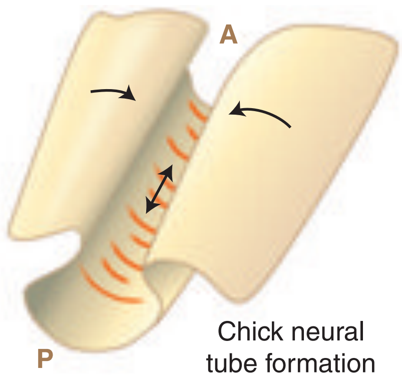
Eisenhoffer GT. et al, Rosenblatt J. *Nature* 484:546. 2012

Epithelial visco-elasticity - Impact of Topological transitions

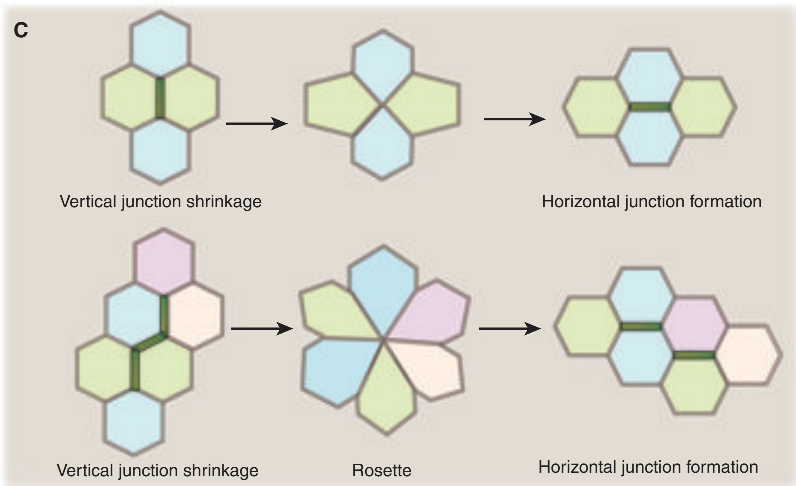
Cell intercalation and tissue elongation



Germ band elongation
in *Drosophila* embryo

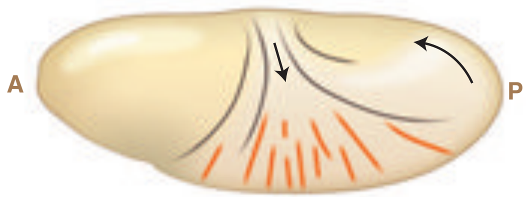


Chick neural
tube formation

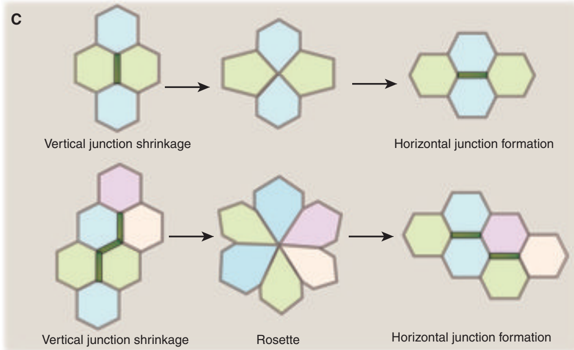


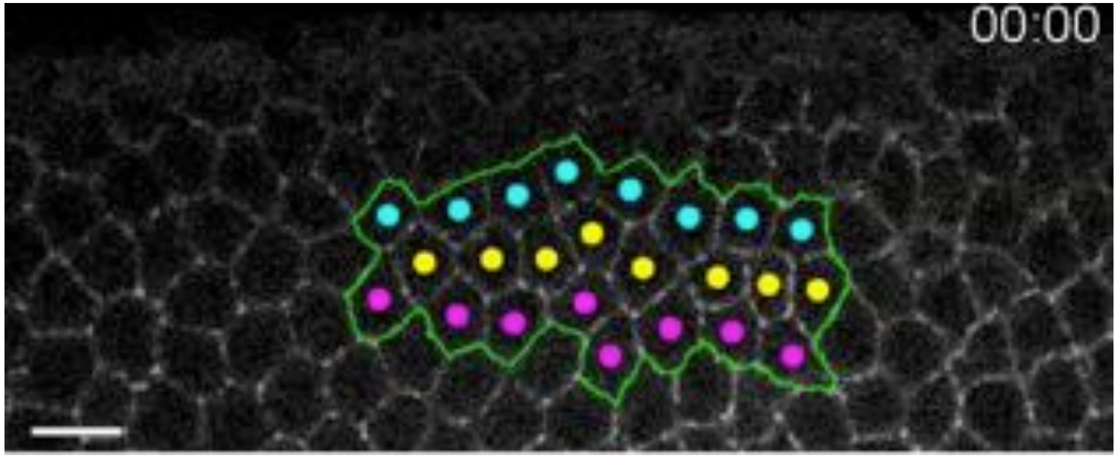
Epithelial visco-elasticity - Impact of Topological transitions

Cell intercalation and tissue elongation



Germ band elongation
in *Drosophila* embryo





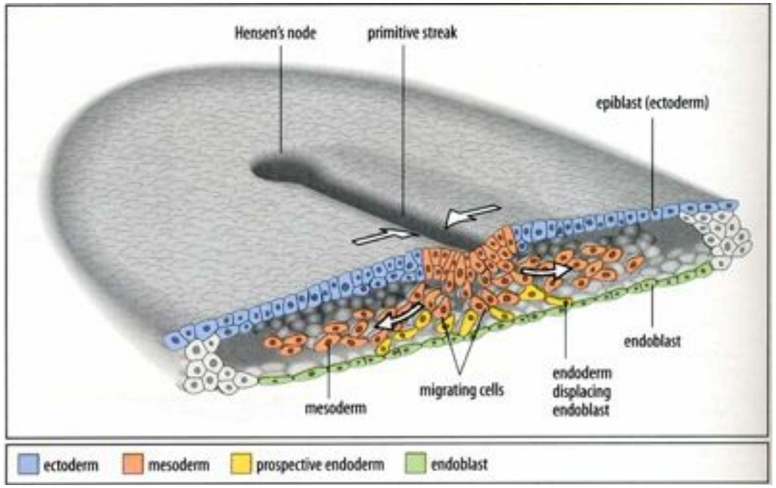
Bertet et al. *Nature* 429:667. 2004

Blankenship et al. *Dev Cell* 11:459. 2006

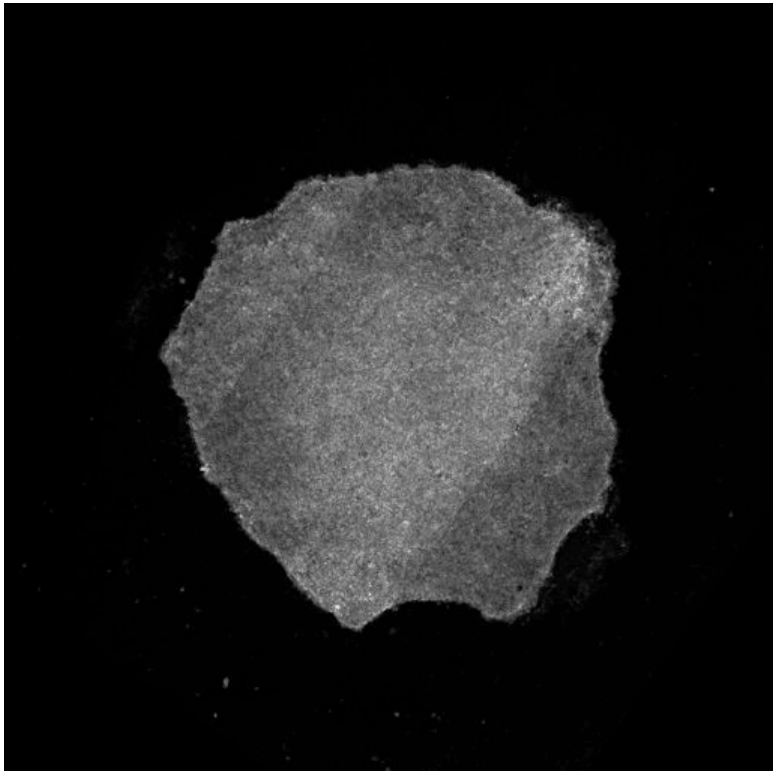
Epithelial visco-elasticity - Impact of Topological transitions

- Cell intercalation and tissue elongation

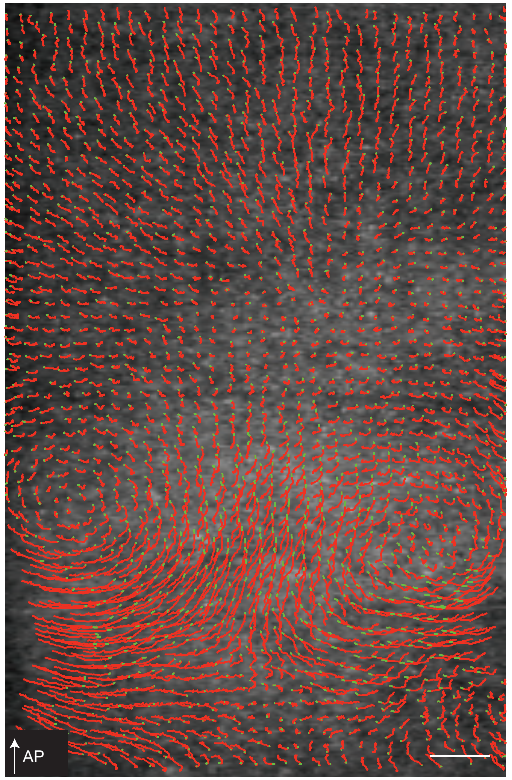
Planar movement of Epiblast Cells



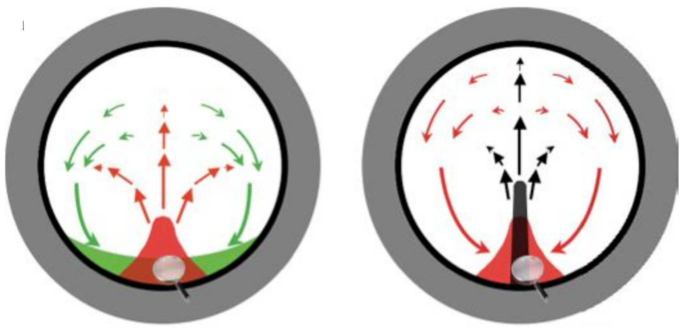
Developmental Biology. S. Gilbert



Firmino J. et al, and Gros J.
Dev. Cell. 36:249. 2016



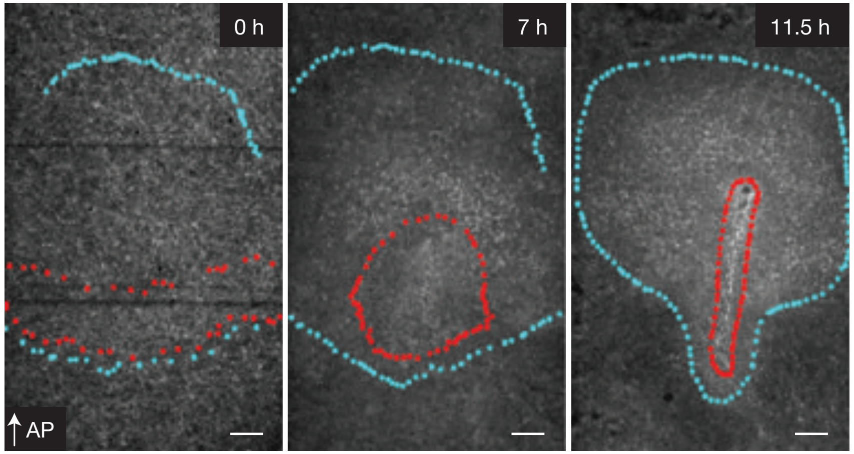
Rozbicki E. et al, and Weijer CI.
Nature Cell Biol. 17:397. 2015

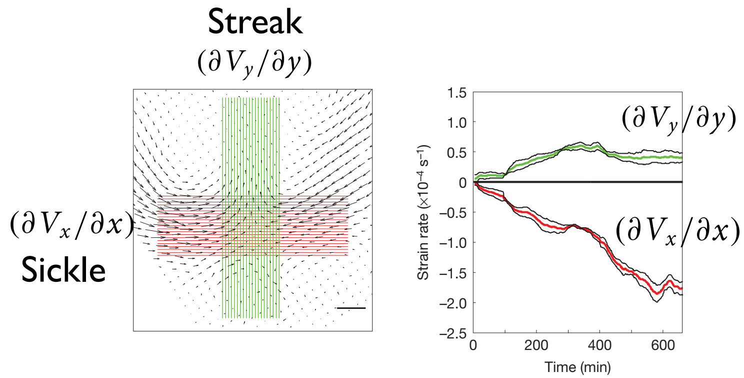


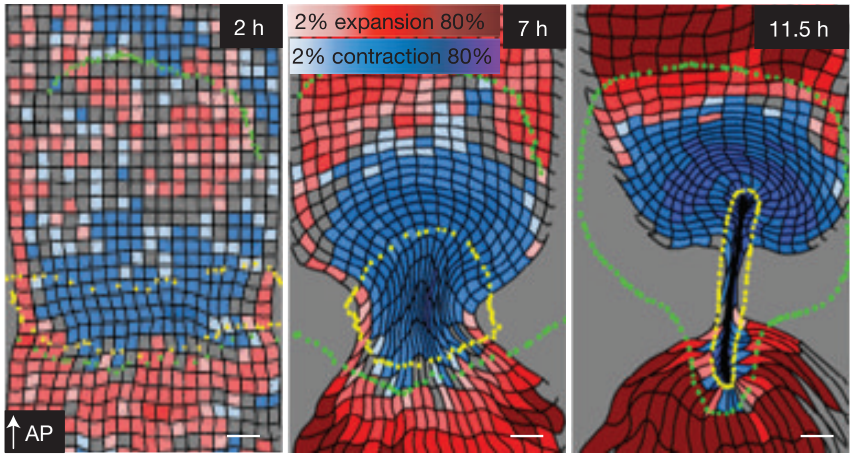
Voiculescu et al, and Stern C. *Nature* 449:1049. 2007

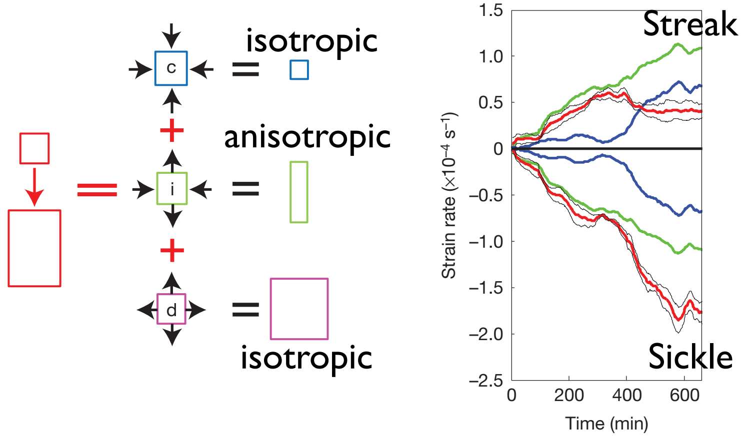
Epithelial visco-elasticity - Impact of Topological transitions

Distribution of strain rates





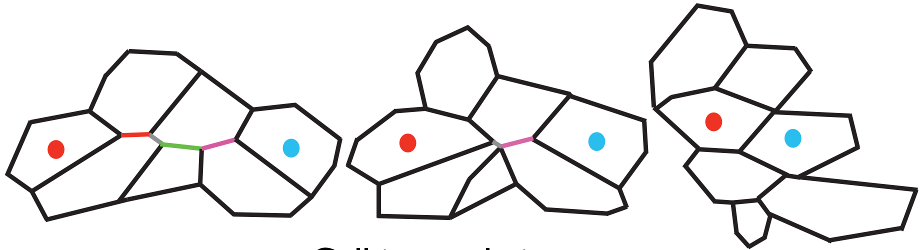




Rozbicki E. et al, and Weijer CI. *Nature Cell Biol*. 17:397. 2015

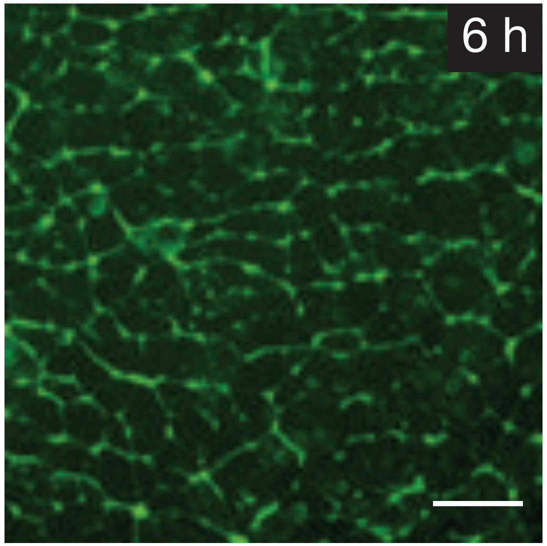
Epithelial visco-elasticity - Impact of Topological transitions

Cellular origin of anisotropic deformations
Cell intercalation



Cell intercalation

Polarized cell intercalation is driven by
contraction of junction
by actomyosin networks
(see 28 November 2017)

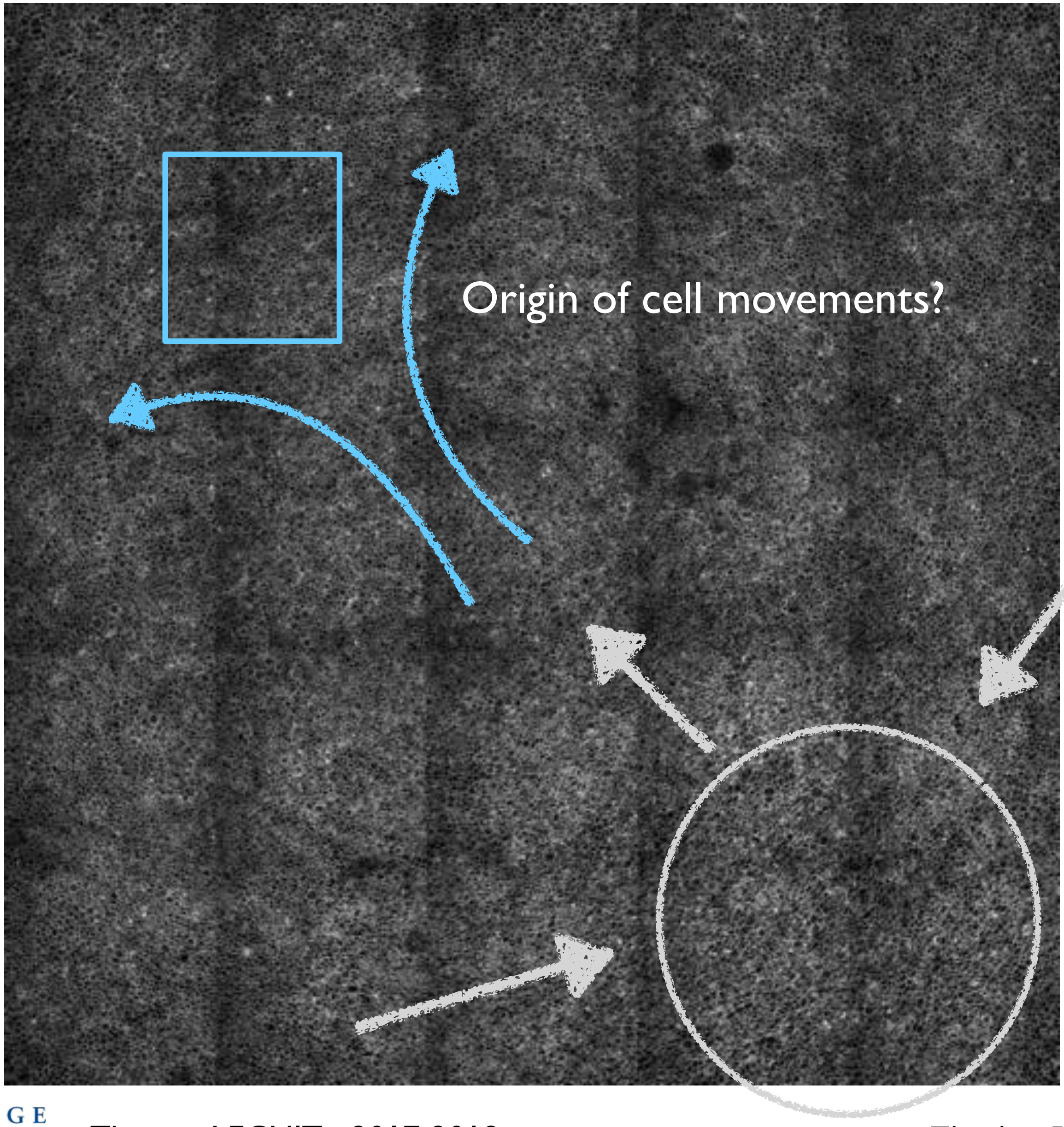


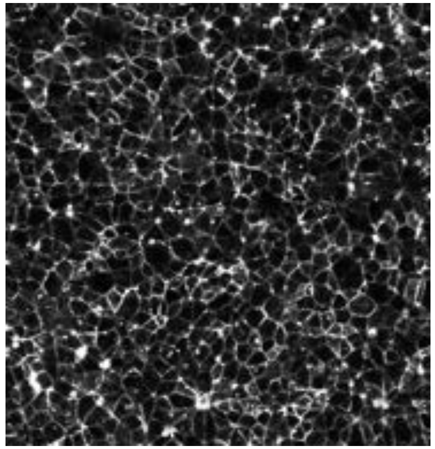
Planar Myosin-II distribution

Rozbicki E. et al, and Weijer CI. *Nature Cell Biol*. 17:397. 2015

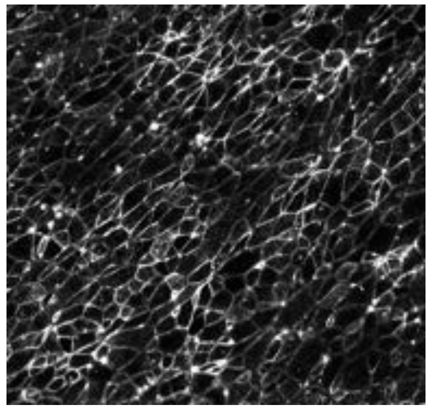
Epithelial visco-elasticity - Impact of Topological transitions

Contribution of cell divisions to cell movements





Myosin-II

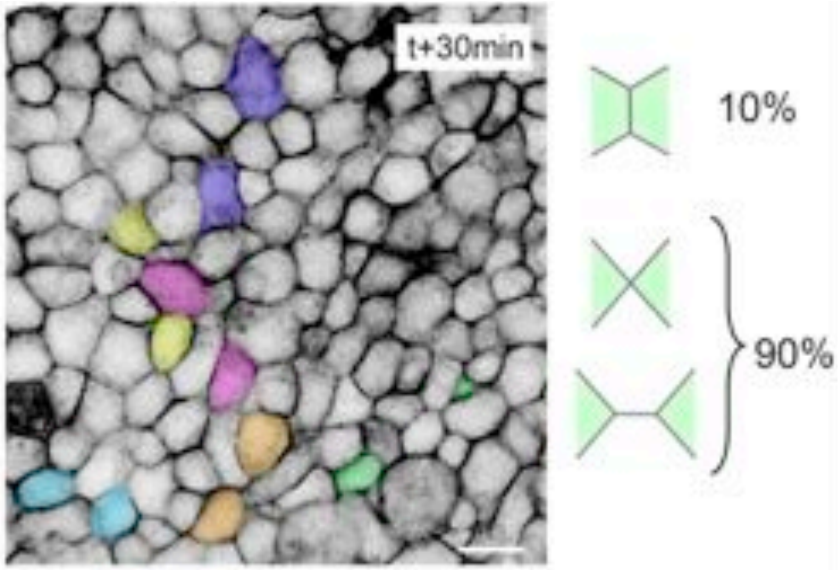


Convergence/Extension
driven by Myosin-II
dependent cell intercalation

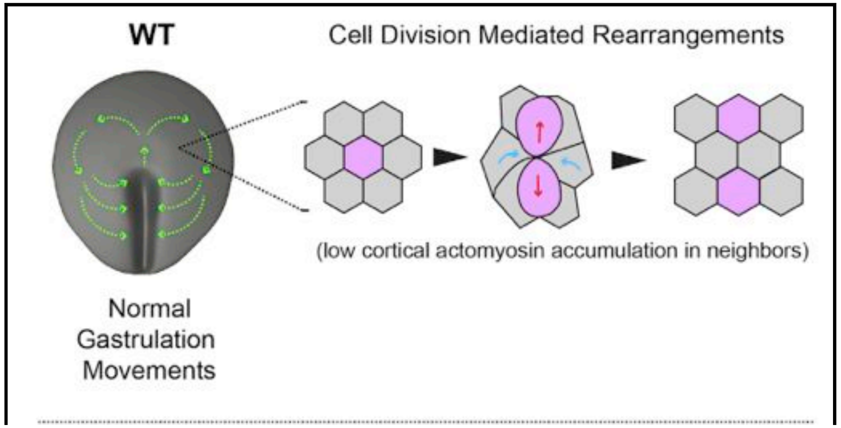
Firmino J. et al, and Gros J. *Dev. Cell*. 36:249. 2016

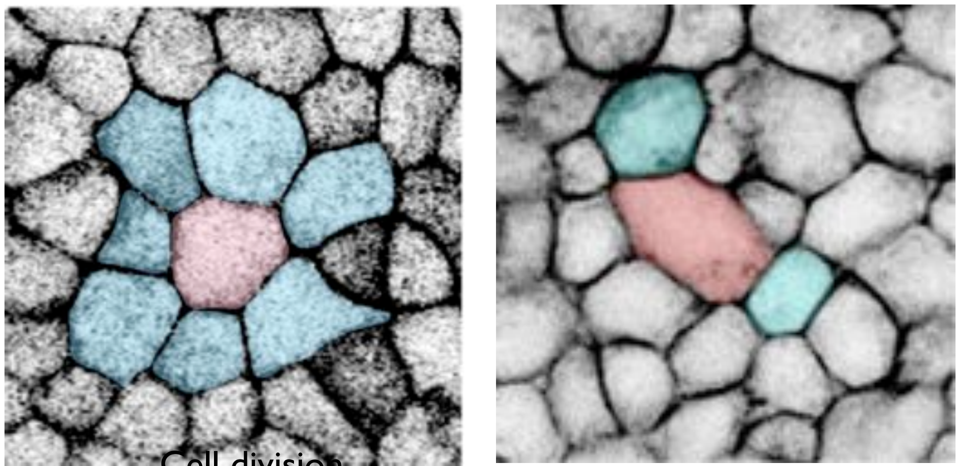
Epithelial visco-elasticity - Impact of Topological transitions

Contribution of cell divisions to cell movements



Associated with cell intercalation



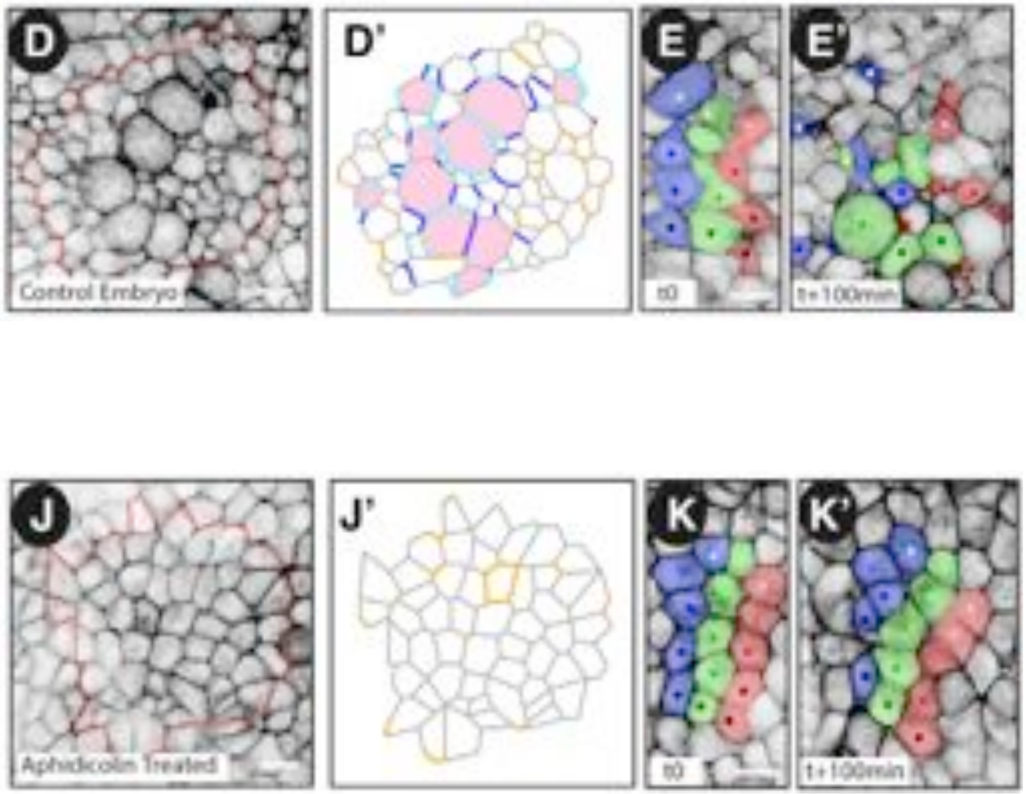


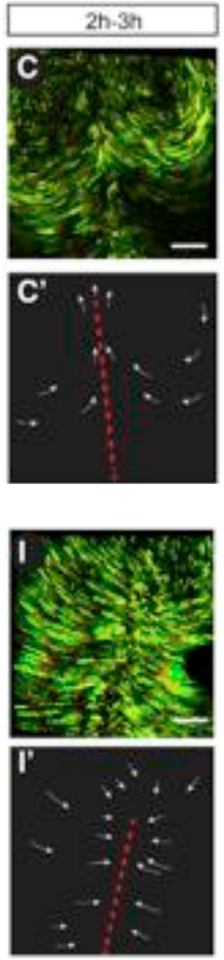
Cell division
without cell intercalation

Intercalary cell division

Firmino J. et al, and Gros J. *Dev. Cell*. 36:249. 2016

Contribution of intercalary cell divisions to cell movements





Inhibitor of DNA replication/cell cycle (arrest in S phase)

Firmino J. et al, and Gros J. *Dev. Cell*. 36:249. 2016

Contribution of intercalary cell divisions to cell movements

- Energy dissipation via fluidisation of tissue?

Cell intercalation causes cell movement within an epithelial layer

- Randomly oriented intercalation: « cell diffusion »
- Polarised intercalation: convergent/extension of tissue

- Origin of junction dynamics? Cell adhesion and cortical tension

> Notion of active fluid

Epithelial visco-elasticity - Fluidisation by cell division

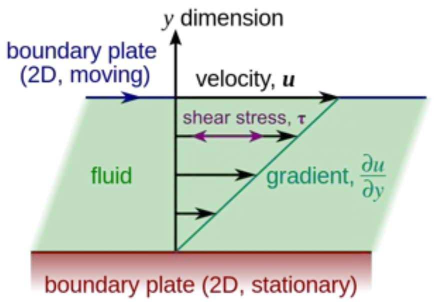
Contribution of oriented cell divisions to energy dissipation of a tissue under stress

>Tissue fluidisation.

- Cell divisions lower shear viscosity

Theory and computer simulations

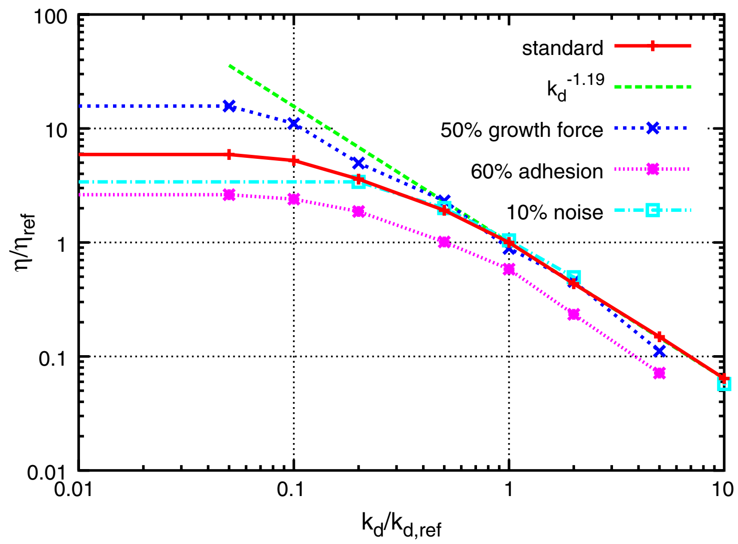
η : Shear viscosity (dynamic viscosity)
Fluidity = $1/\eta$



applied force

$$\tau = \frac{F}{A} = \eta \frac{\partial u}{\partial y}$$

shear stress — area — velocity gradient

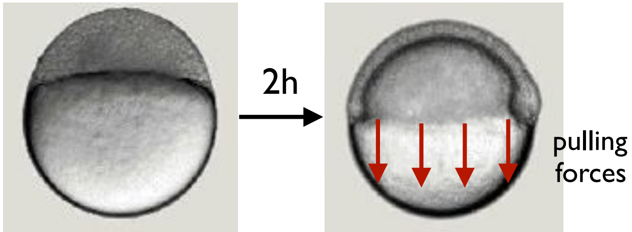


kd: cell division rate

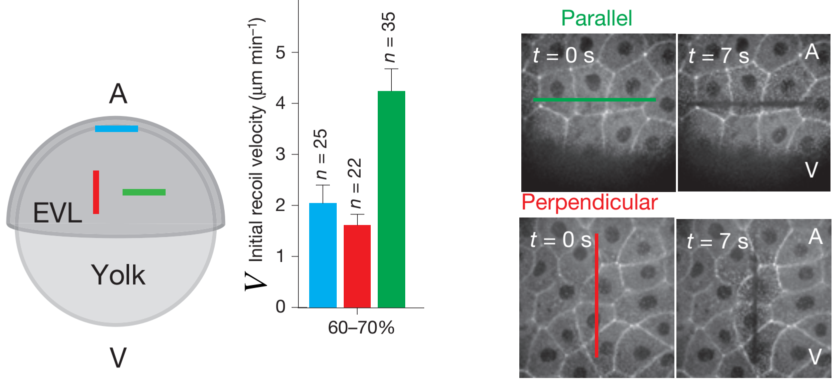
Ranft J. Basan M., Elgeti J. Joanny J-F., Prost J. and Jülicher F. *PNAS* 49:20863. 2010

Epithelial visco-elasticity - Fluidisation by cell division

Contribution of oriented cell divisions to energy dissipation of a tissue under stress

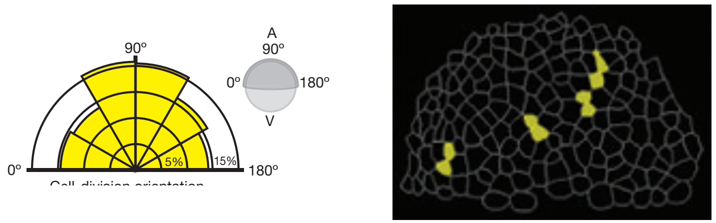


Zebrafish epiboly



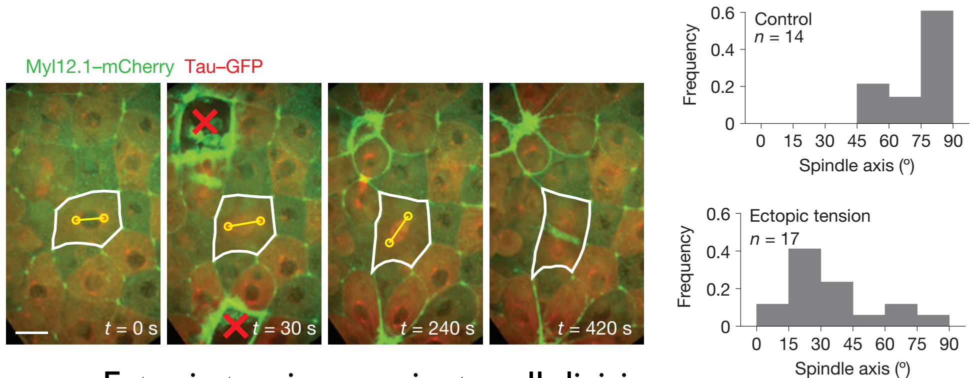
Anisotropic tension (T) probed using laser ablation $V= T/\eta$

- Polarized cell division correlate with anisotropic tension *in vivo*



Division orientation along stretch axis

- Ectopic tension reorients cell division axis



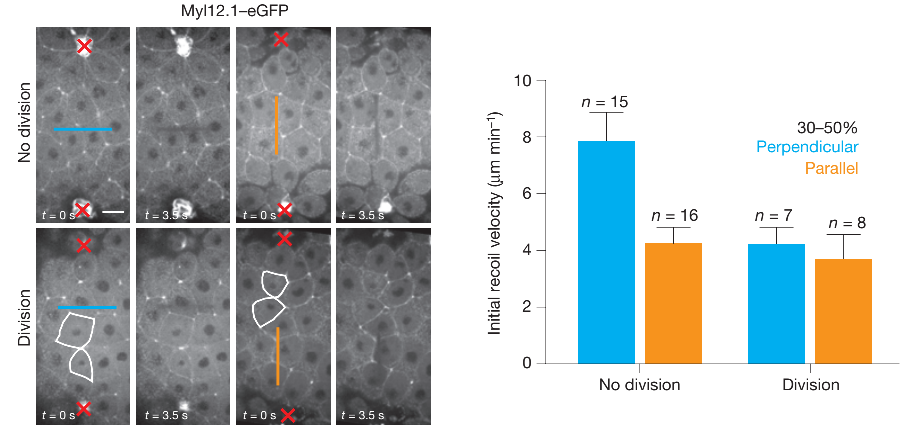
Ectopic tension reorients cell divisions

Campinho P. et al, Risler T., Minc N. and Heisenberg CP. *Nature Cell Biol*. 15:1405. 2013

Epithelial visco-elasticity - Fluidisation by cell division

Contribution of oriented cell divisions to energy dissipation of a tissue under stress

- Experiments: Cell division lowers tissue tension

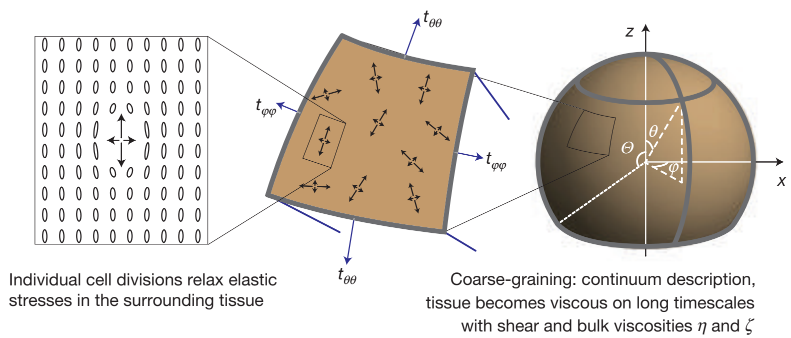


- Theoretical model:

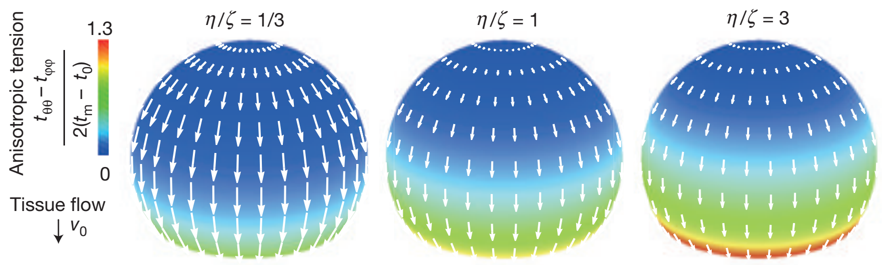
Cell division lowers shear (ie. dynamic) viscosity.

η : shear viscosity

ζ : bulk viscosity



Blocking cell division increases shear viscosity, increases tension anisotropy, and reduces tissue flow

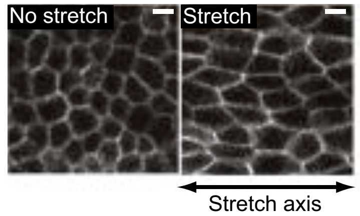


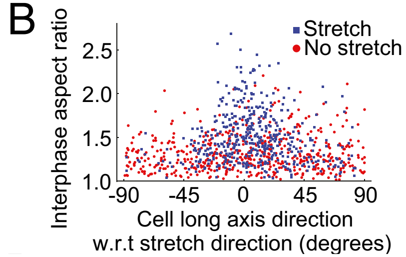
Campinho P. et al, Risler T., Minc N. and Heisenberg CP. *Nature Cell Biol*. 15:1405. 2013

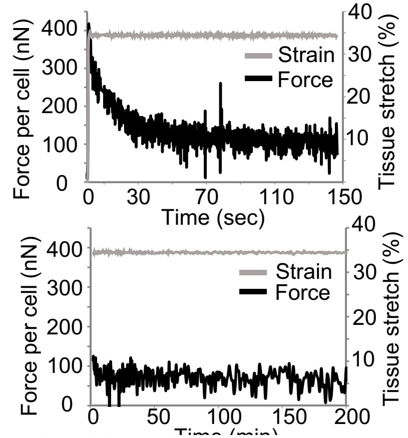
Epithelial visco-elasticity - Fluidisation by cell division

Contribution of oriented cell divisions to energy dissipation of a tissue under stress

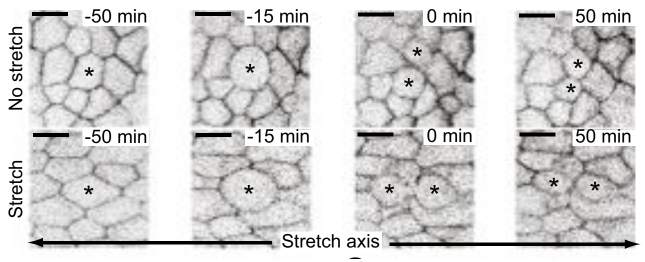
- Tissue stretching induces cell strain.
- Stress relaxes in 2 phases (rapid: cytoskeleton; slow: cell division?)

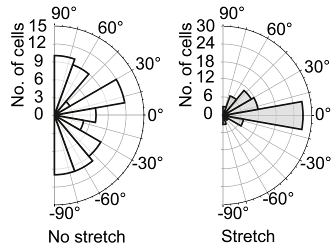




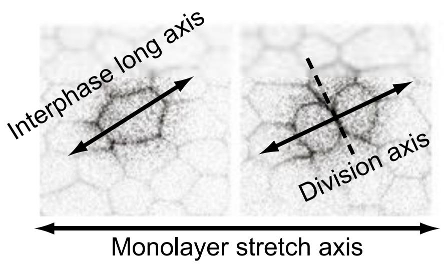


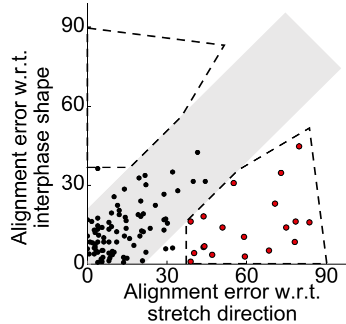
- Cells divide along stretch axis.





- The axis of division is determined by geometry, not stretch *per se*.





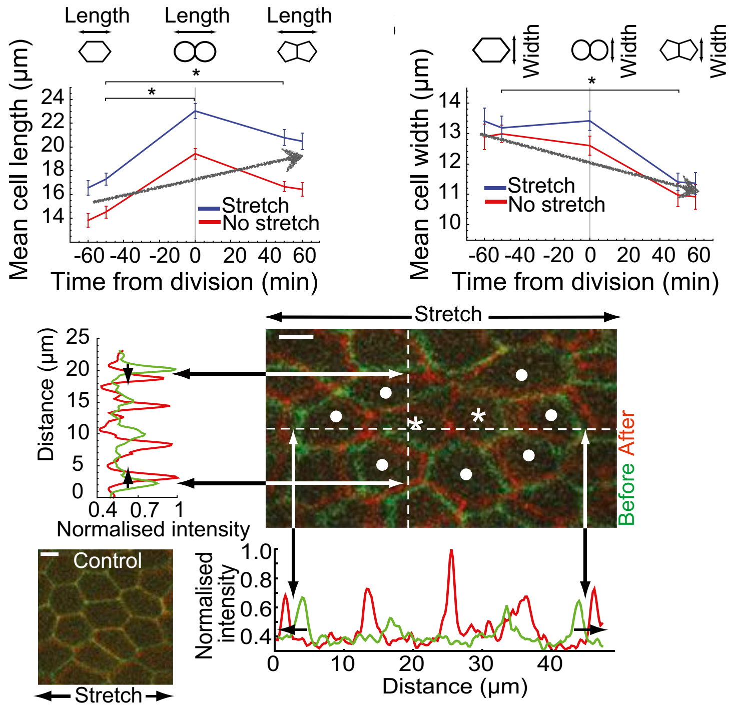
Contribution of Geometry

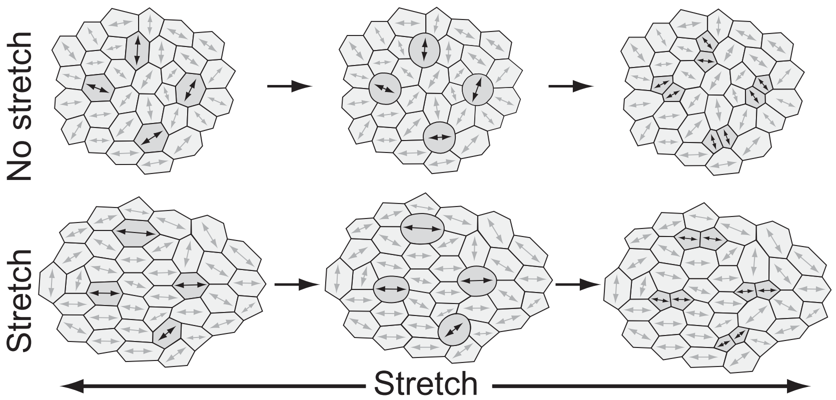
Wyatt T et al. and Kabla A, Charras G., Baum B. *PNAS*. 112:5726. 2015

Epithelial visco-elasticity - Fluidisation by cell division

Contribution of oriented cell divisions to energy dissipation of a tissue under stress

- Cell division redistributes cellular mass with respect to the axis of division





Wyatt T et al. and Kabla A, Charras G., Baum B. *PNAS*. 112:5726. 2015

Conclusions

- *Organisation:*
  - Cells adopt morphologies and configurations that tend to approach minimal surface energy
  - Reflects balance between:
    - -hydrostatic/turgor pressure
    - -cortex contractility
    - -cell walls/cortex and adhesion system
- *Dynamics:*
  - Cell connectedness varies so tissues can be modelled as gaz, viscoelastic fluids or elastic solids.
  - Reflects differences in adhesion and stiffness
  - Cell shape changes and cell movements are driven by active contractile systems in animals and regulated wall remodelling in plants
  - Cell-cell adhesion resists active remodelling and maintains tissue cohesion under stress.

Next

1) Adhesion

2) Cortical tension

Conclusions

Prochain cours: 31 October 2017
Plasticité: suite et fin

Adhesion 1: du concept d'affinité aux modèles thermodynamiques