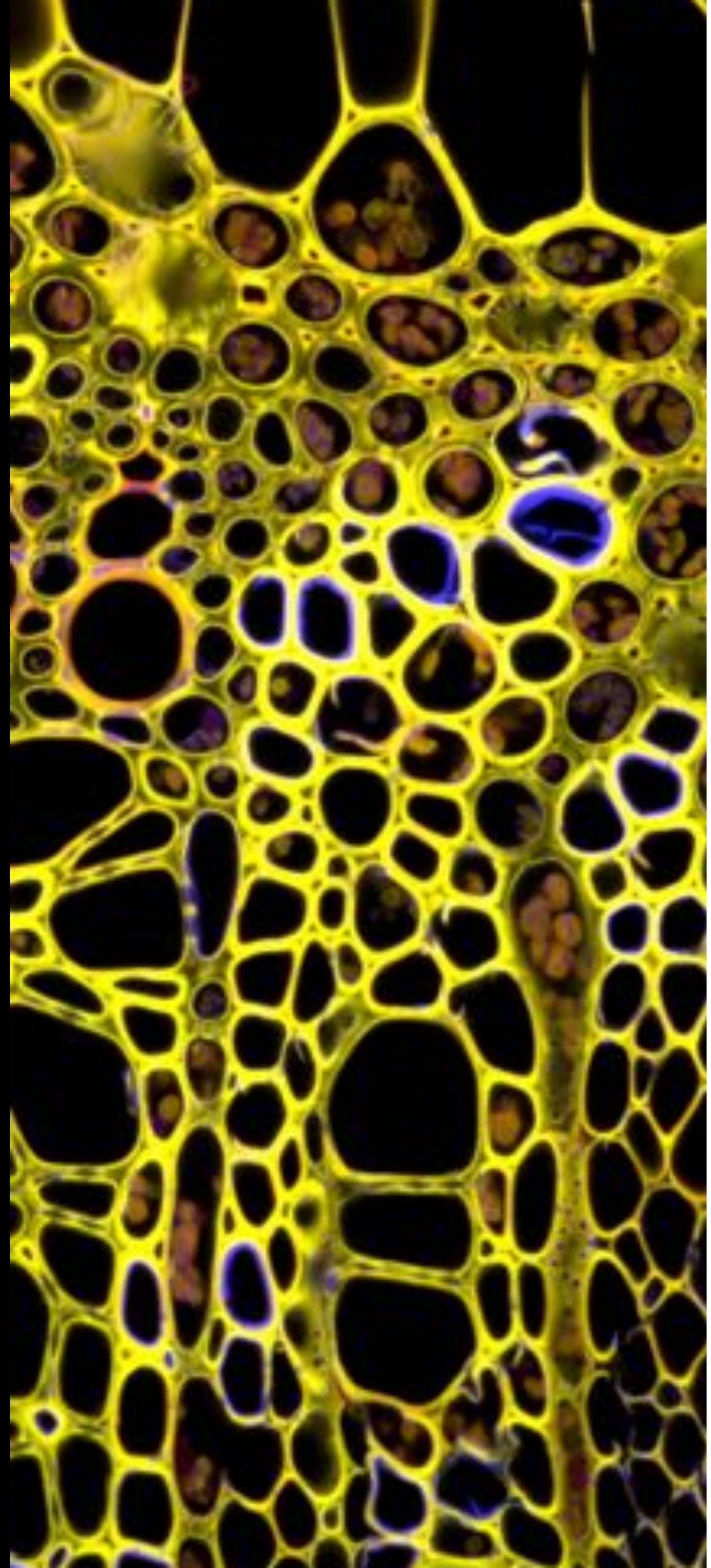
2018 CDB Part IB
Plant Development

Lecture 6.
Morphogenesis



Jim Haseloff
Department of Plant Sciences

Plant Development

Lecture 1: Plant architecture and embryogenesis.

Lecture 2: Polarity and auxin flow.

Lecture 3: Regulation of gene expression by auxin.

Lecture 4: Patterning of indeterminate growth.

Lecture 5: Formation and specification of lateral organs.

Lecture 6: Morphogenesis.

- Growth is an emergent multiscale process
- Nanoscale organisation of cell division
- Tissue physics and morphogenesis
- Feedback and branching
- Turing and self-organising patterns
- Meristem organisation and plant form

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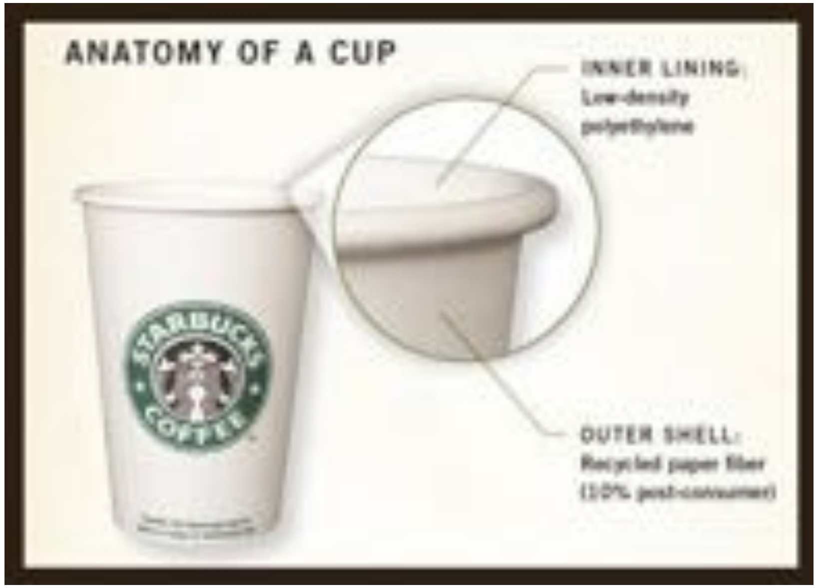
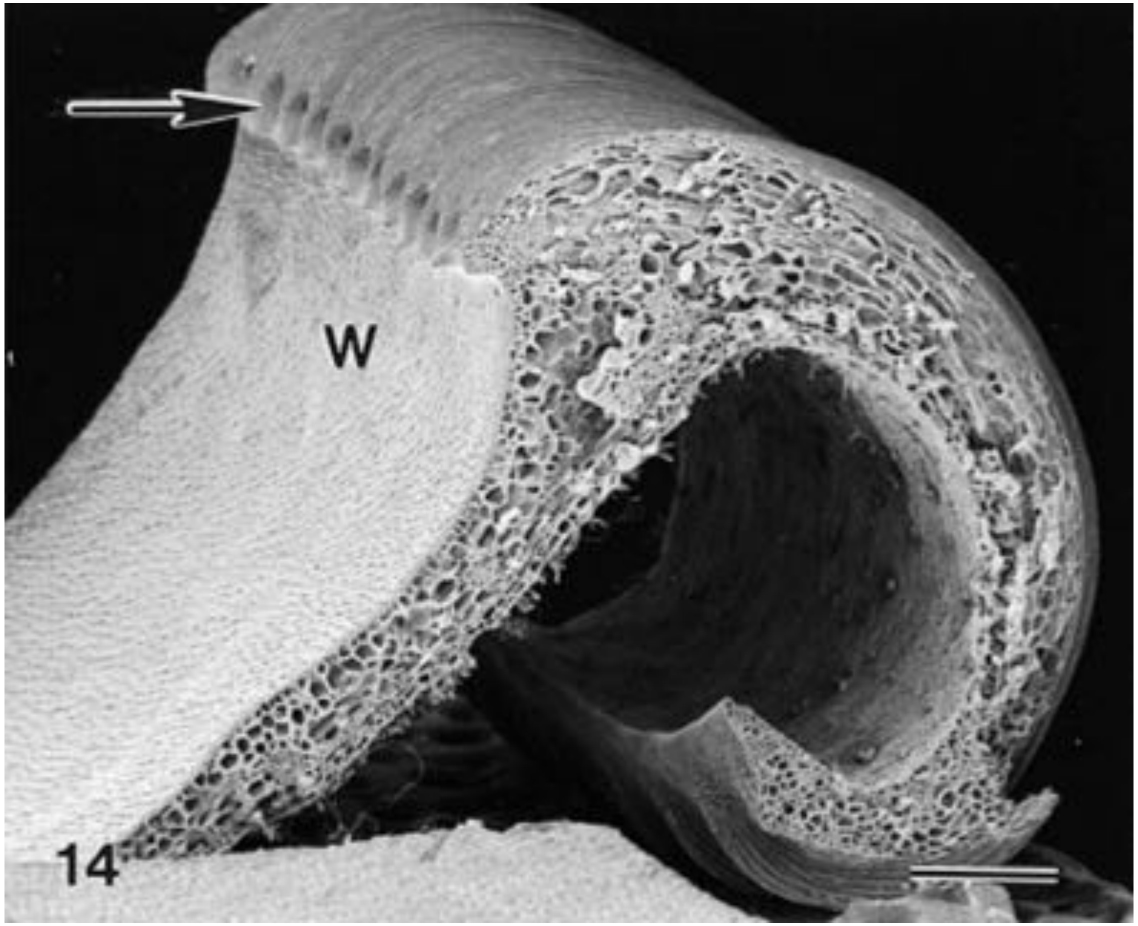
Morphogenesis


Careful, the beverage

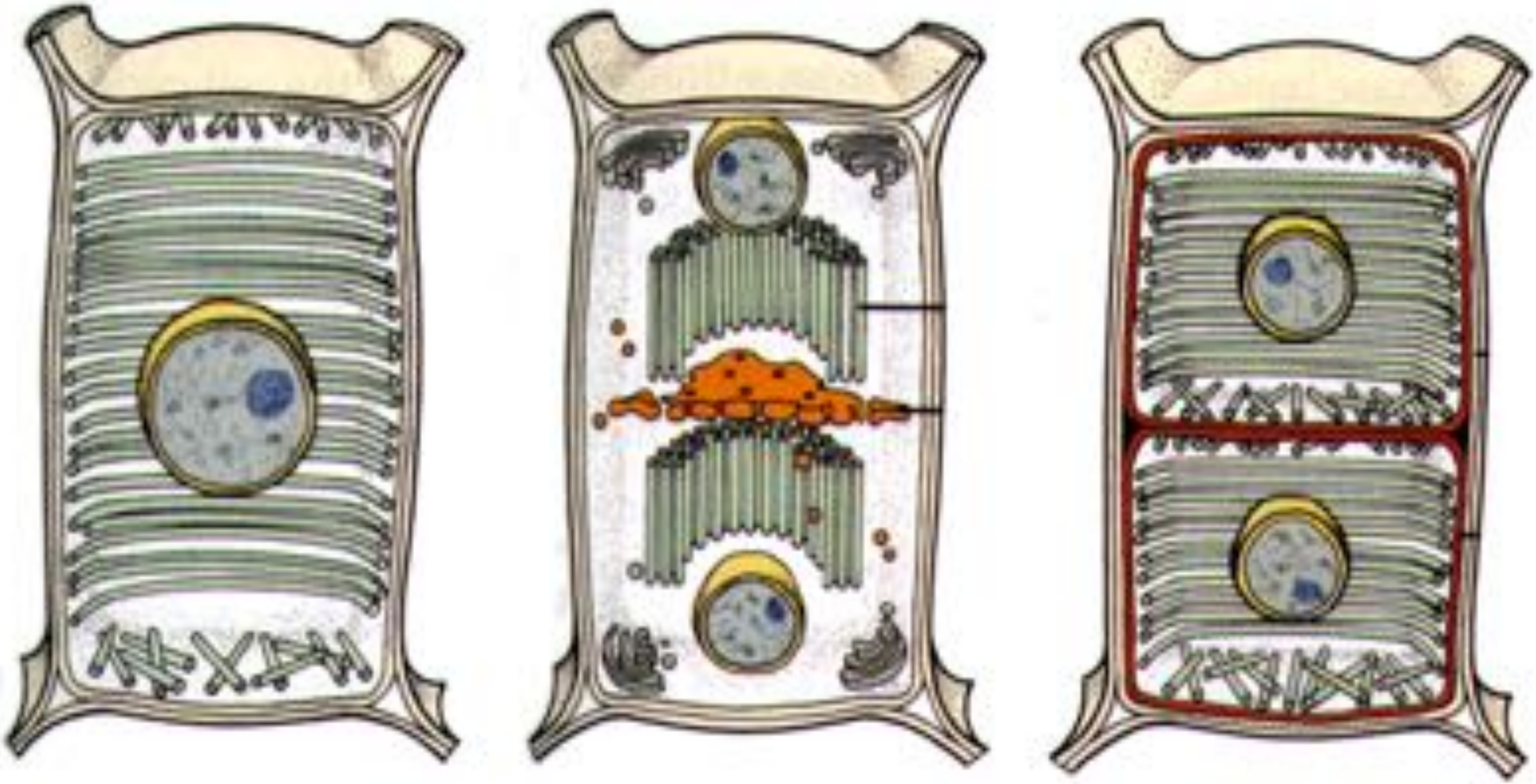


paper cup



pitcher plant

Plant cells are immobilised.
Morphogenesis is driven by cell division and elongation.






sarracenia.com

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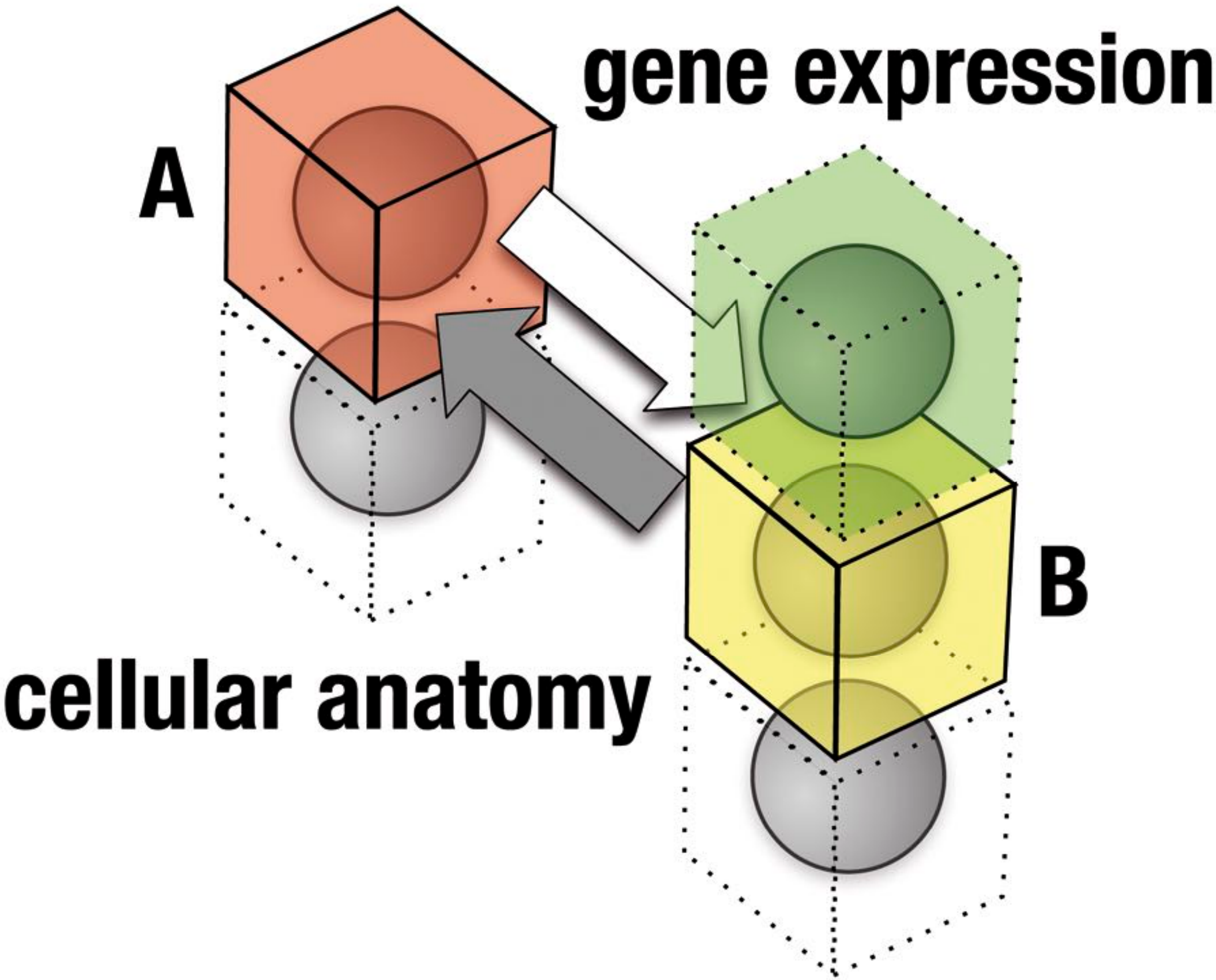
Feedback regulation of morphogenesis

(i) Cell interactions regulate gene expression

(ii) Gene expression regulates cell proliferation

(iii) Feedback results in self organisation and morphogenesis



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Empirical rules describe cell division

1. Hofmeister's rule (1863)
Cell plate formation normal to the growth axis.

2. Sachs' rule (1878)
Cell plate formation at right angles to existing walls.

3. Errera's rule (1888)
Cell plate of minimal area for cutting the volume of the cell in half.

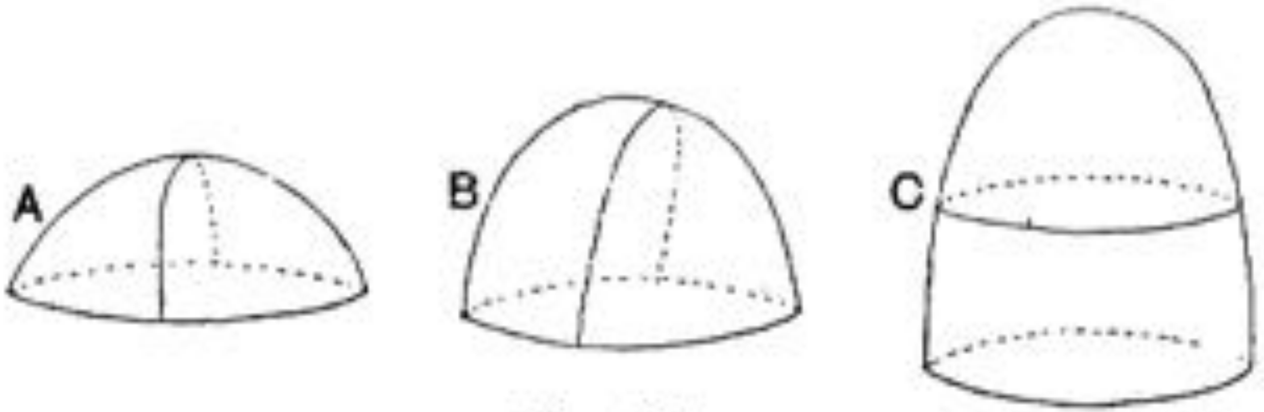
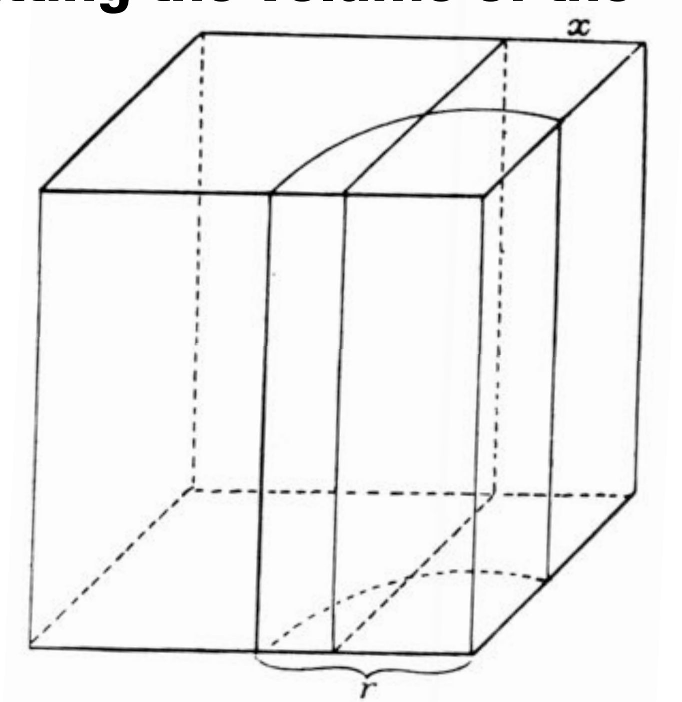
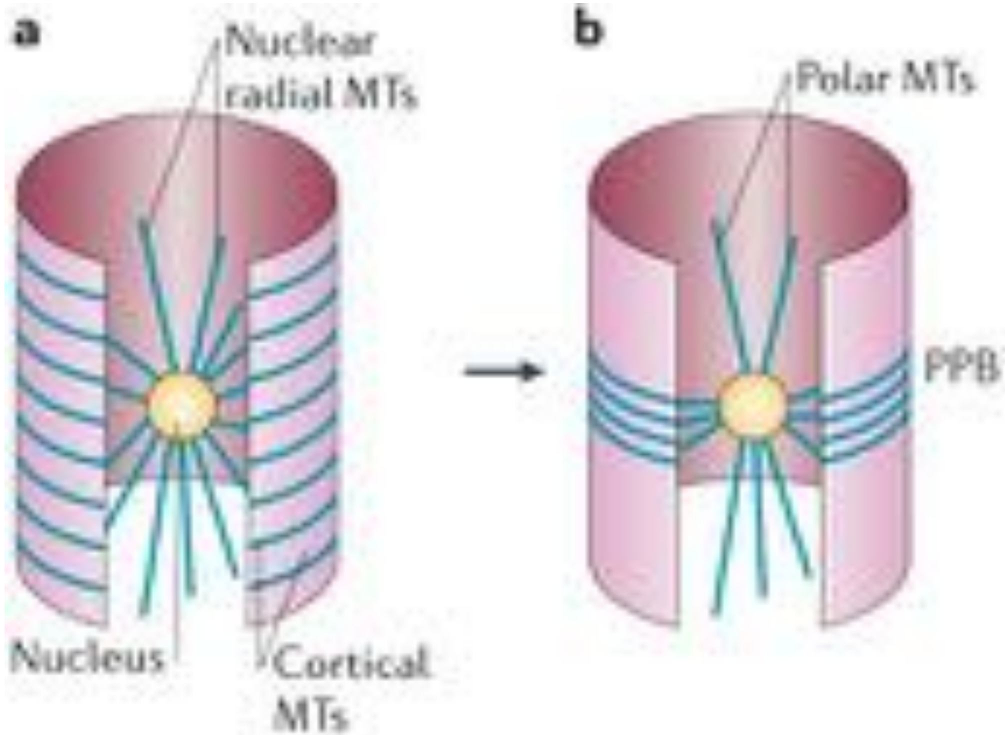
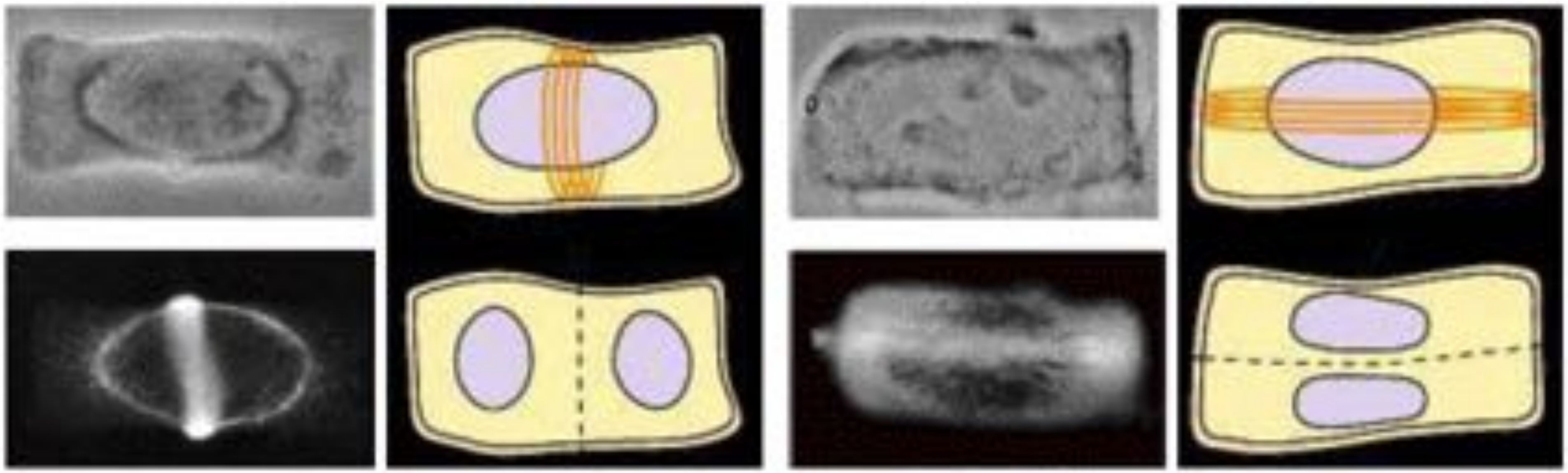


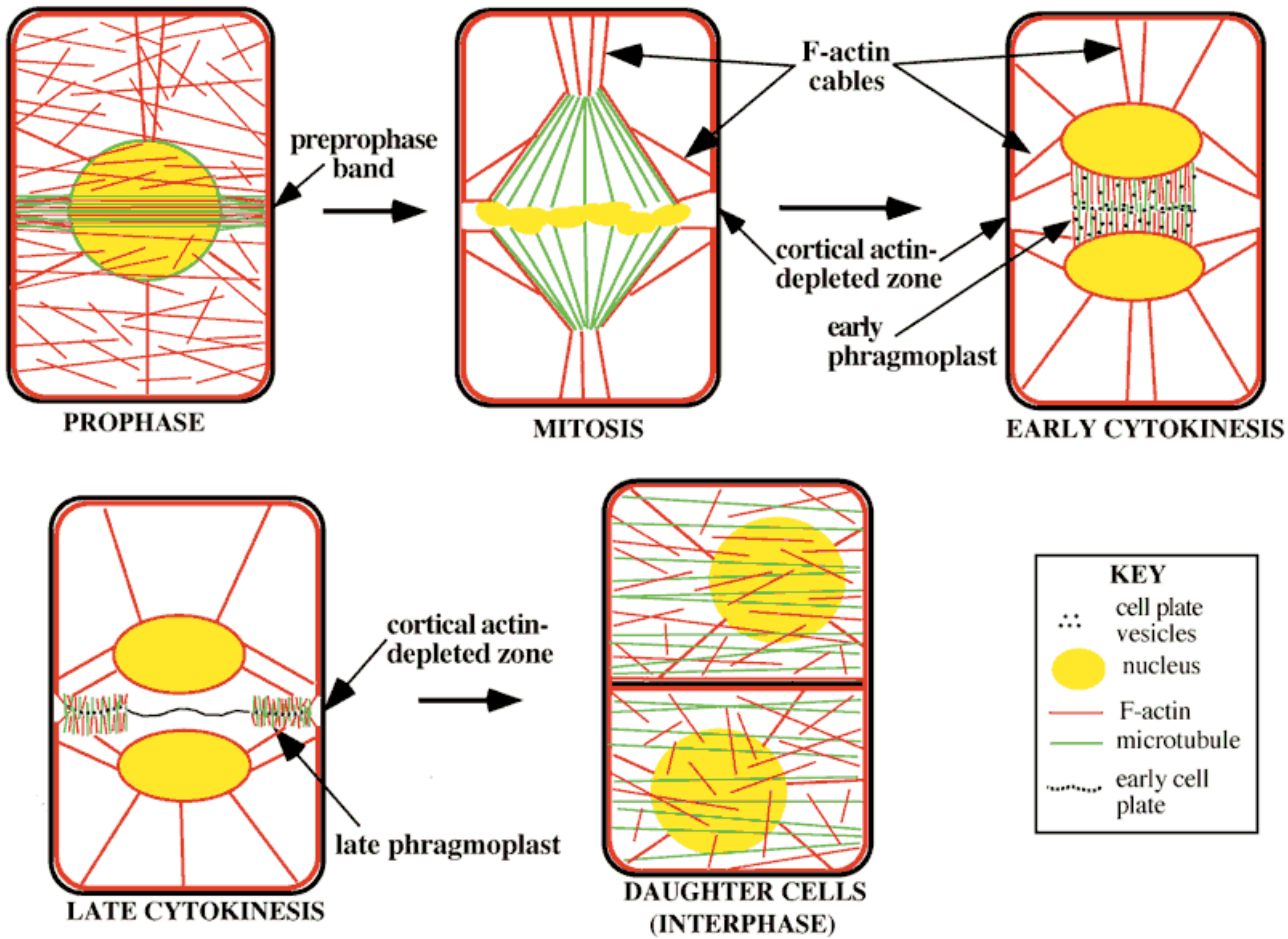
Fig. 225.



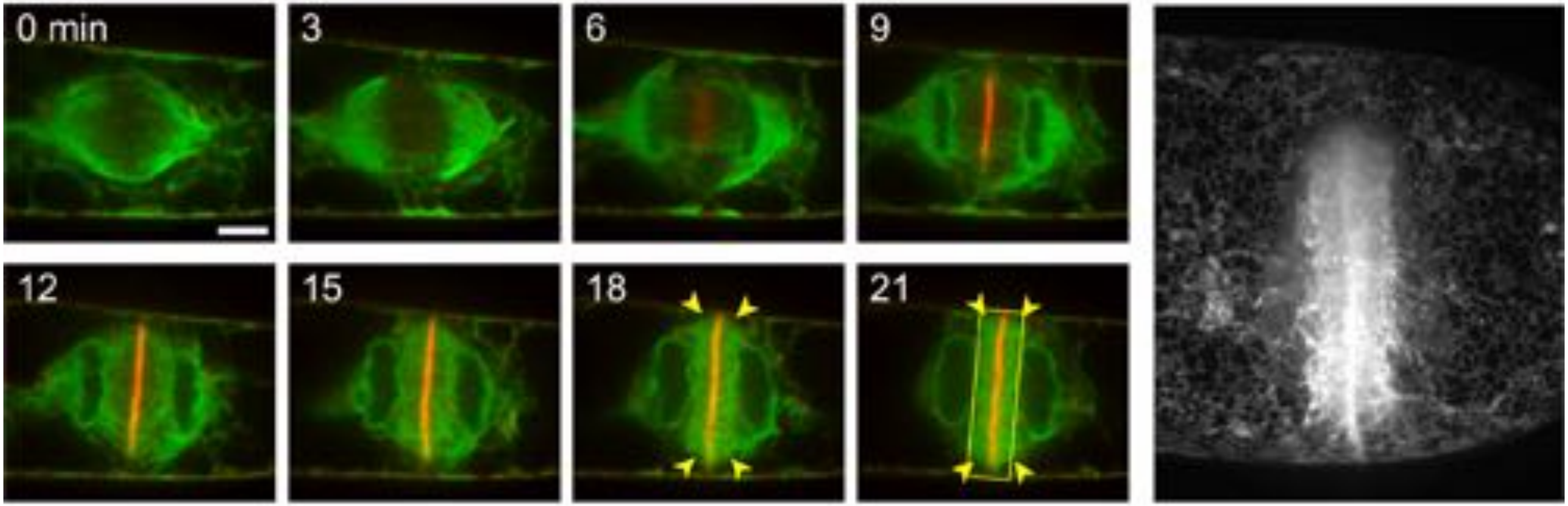


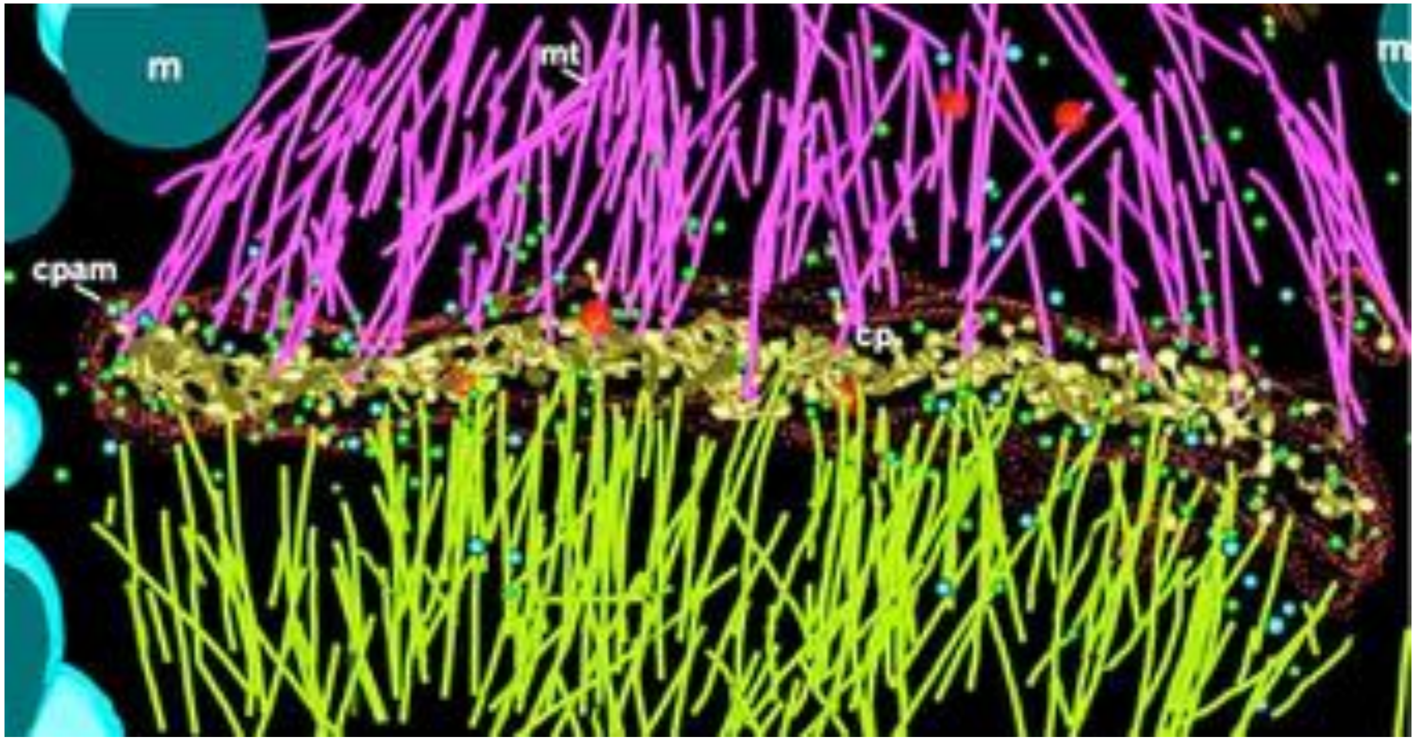
Preprophase bands of microtubules mark planes of cell division

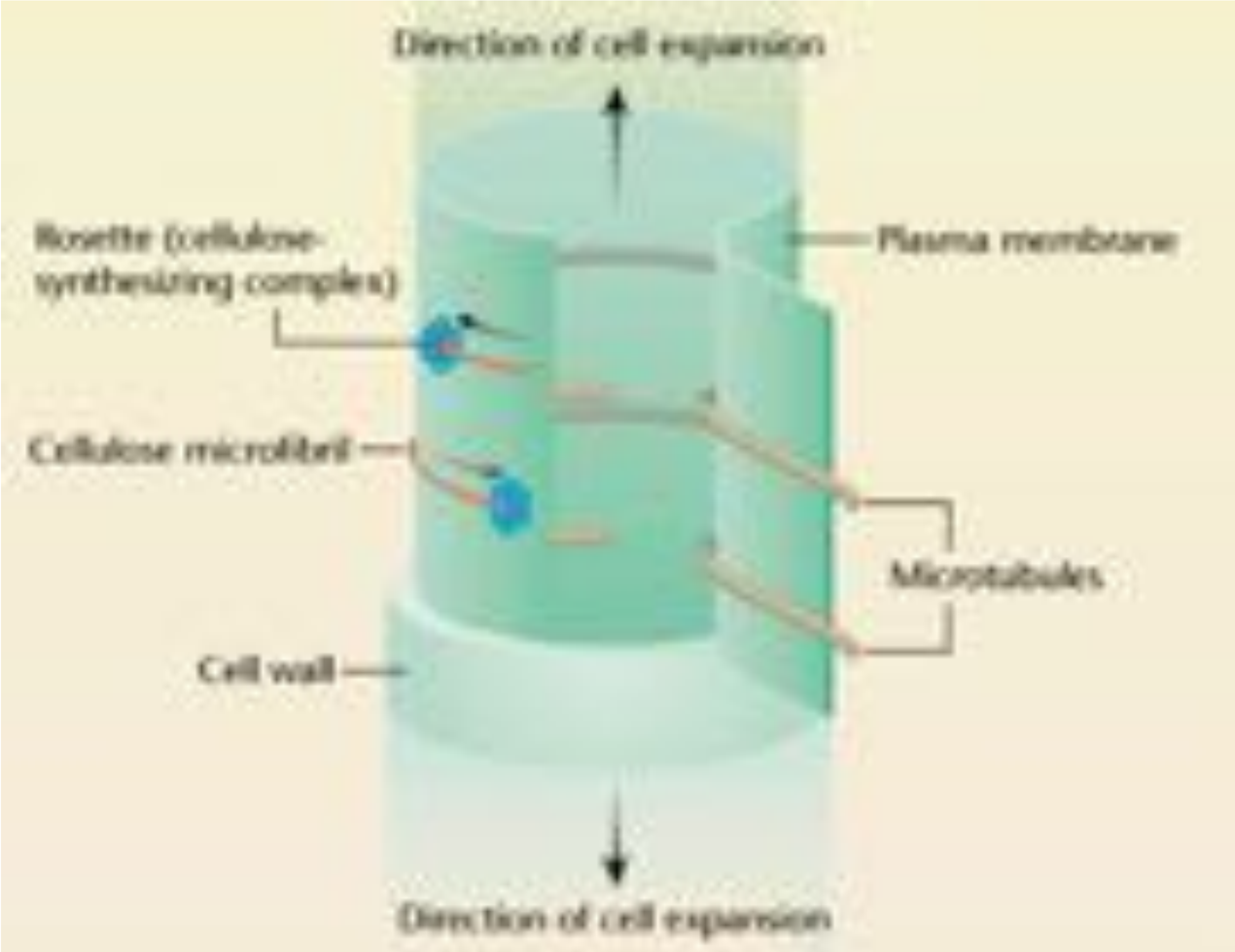




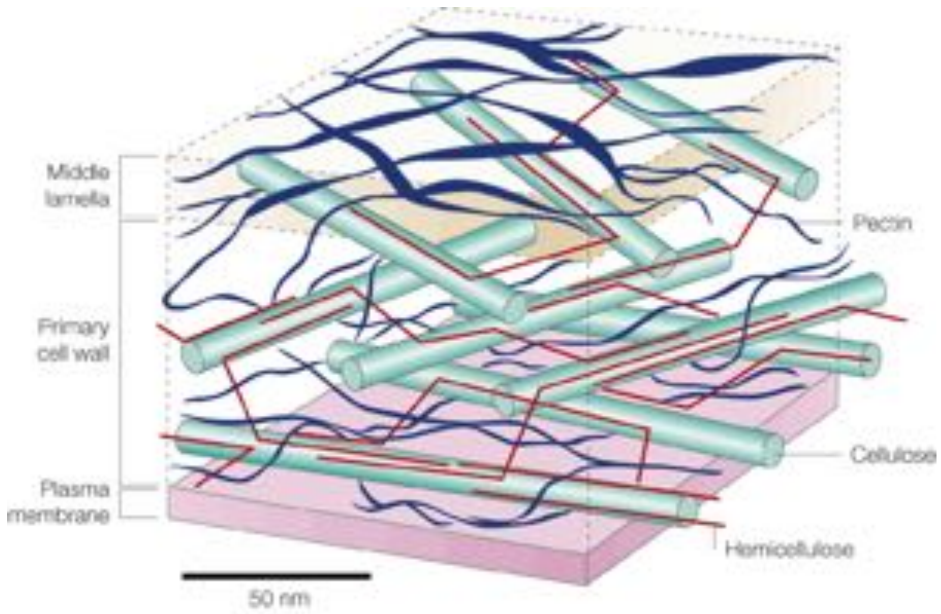
preprophase
band
F-actin
cables
cortical actin-
depleted zone
early
phragmoplast
PROPHASE
MITOSIS
EARLY CYTOKINESIS
cortical actin-
depleted zone
late phragmoplast
LATE CYTOKINESIS
DAUGHTER CELLS
(INTERPHASE)
KEY
cell plate
vesicles
nucleus
F-actin
microtubule
early cell
plate


0 min
3
6
9
12
15
18
21

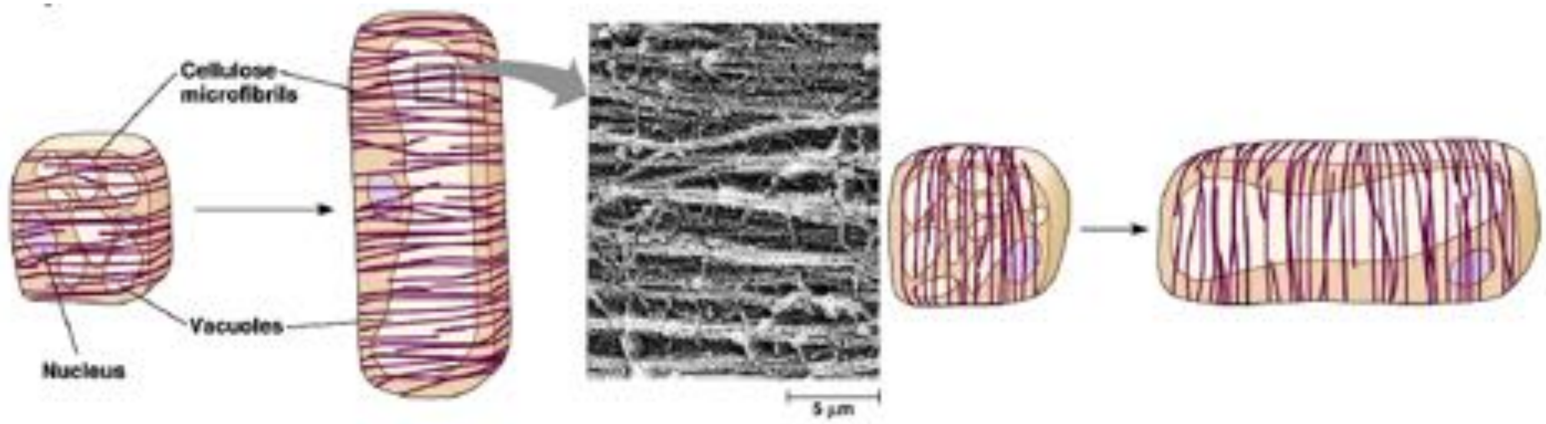

m
mt
cpam
cp


Direction of cell expansion
Rosette (cellulose-synthesizing complex)
Plasma membrane
Cellulose microfibril
Microtubules
Cell wall
Direction of cell expansion

Plant cell walls are a composite structure



Nature Reviews | Molecular Cell Biology



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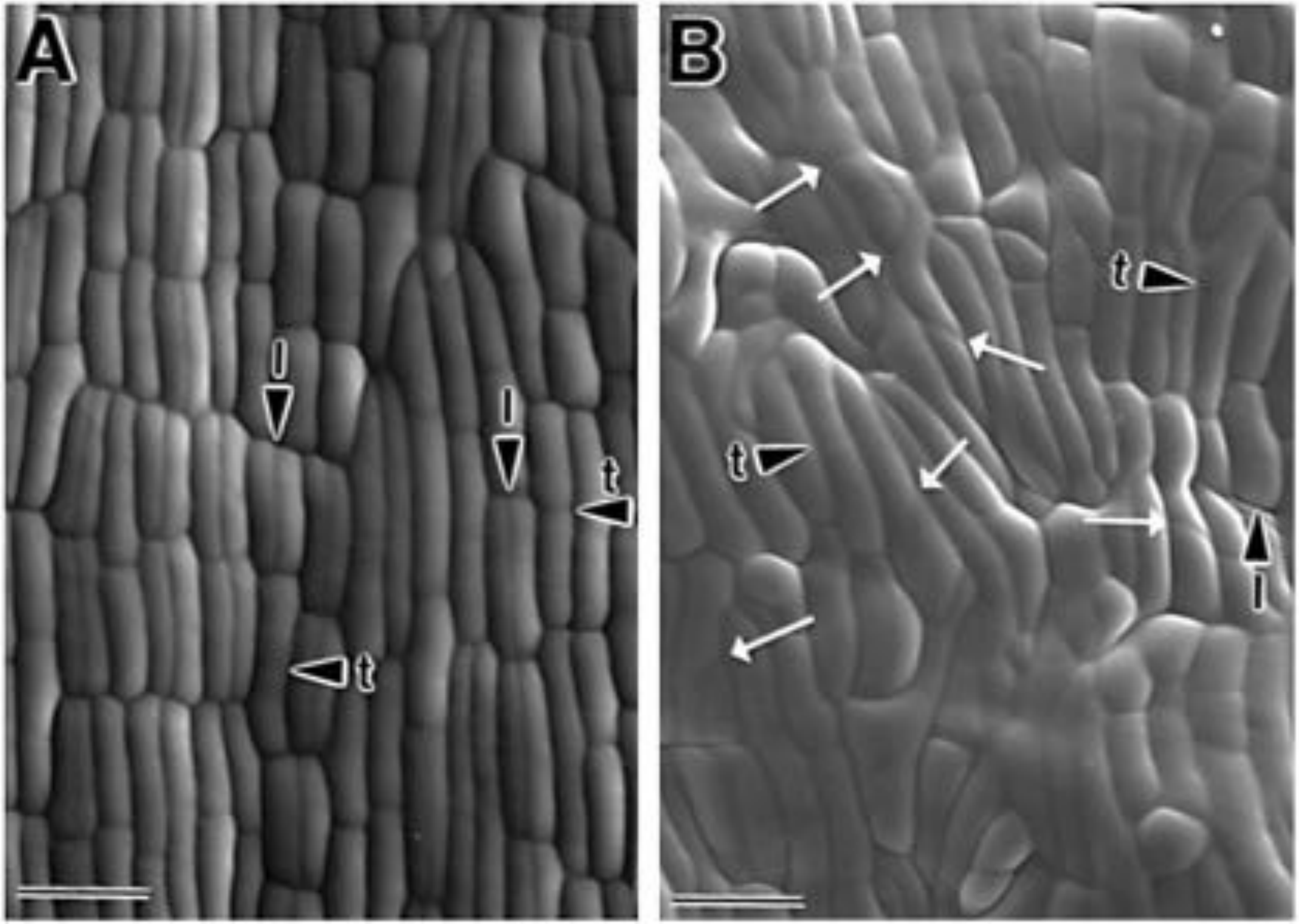
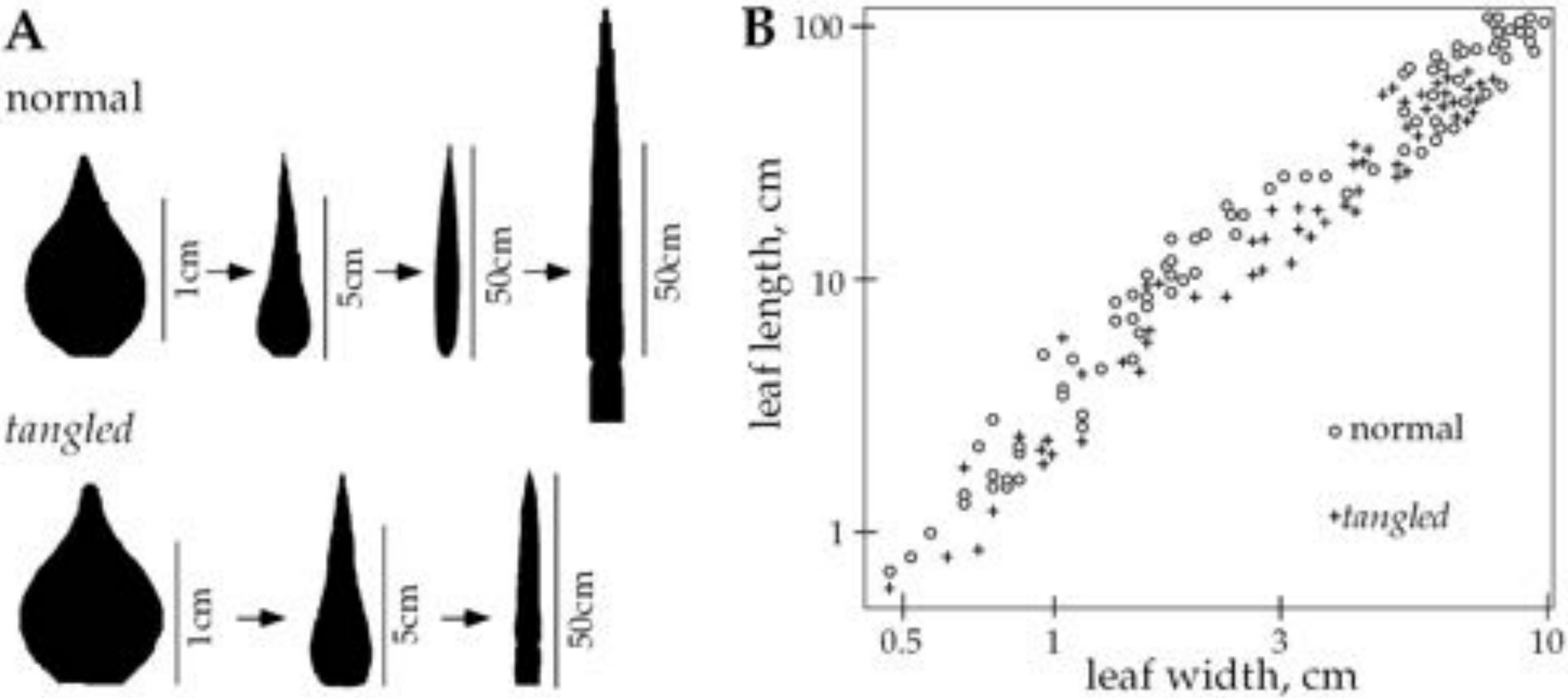
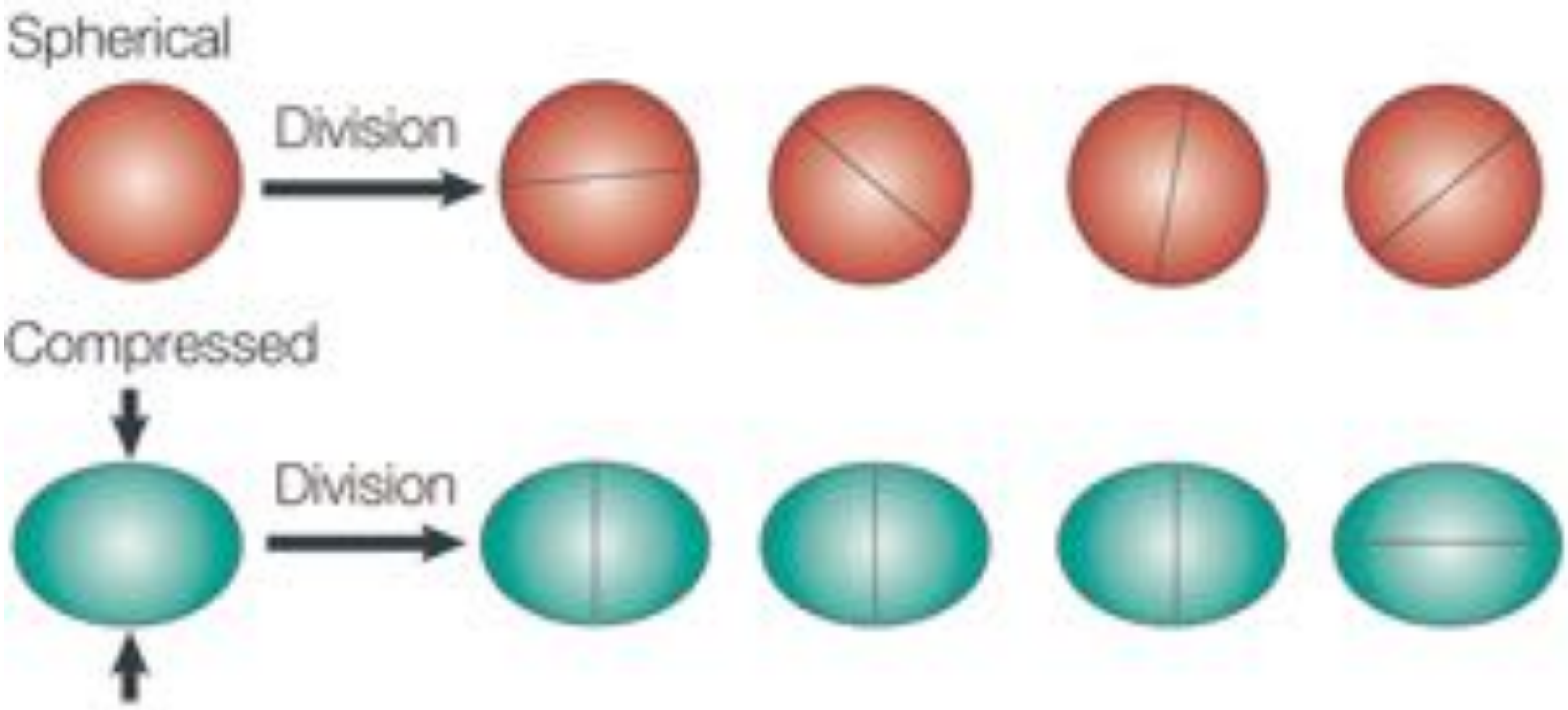
The tangled-1 mutation alters cell division orientations throughout maize leaf development without altering leaf shape

LG Smith, S Hake and AW Sylvester
USDA/UC Berkeley Plant Gene Expression Center, Albany, CA 94710, USA.



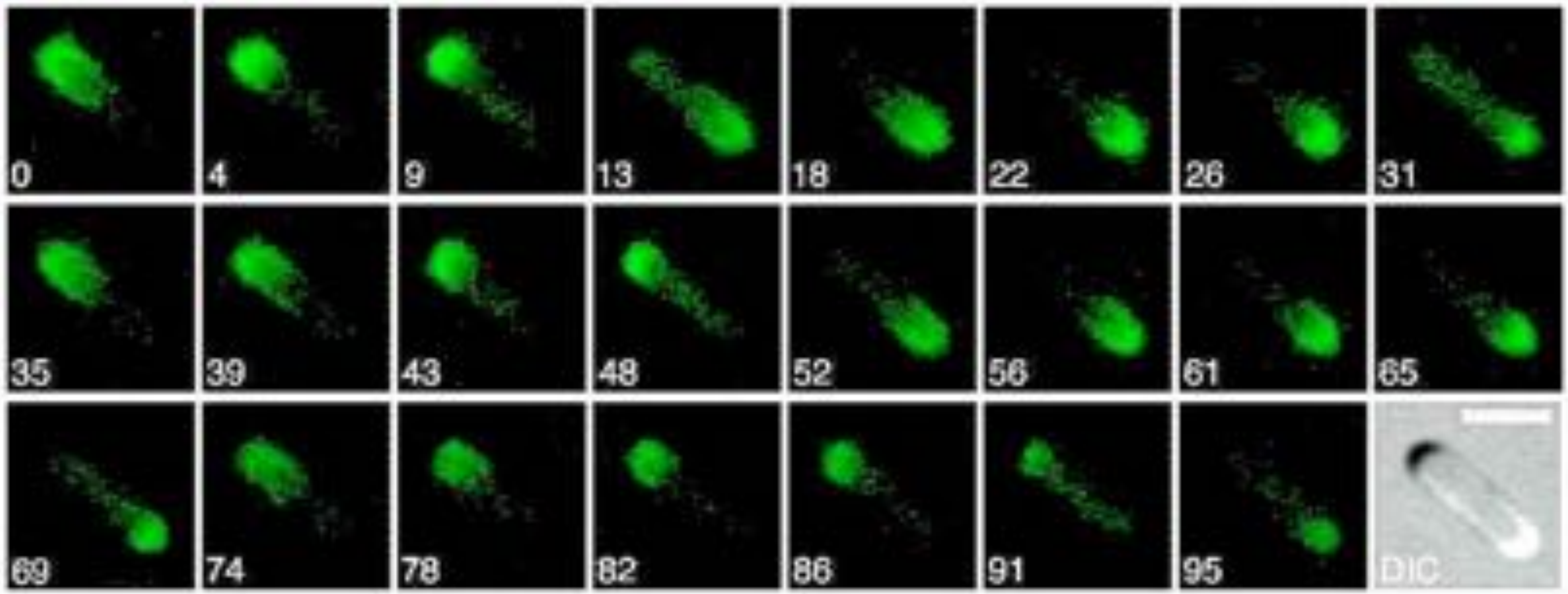

A
normal
1cm
5cm
50cm
50cm
tangled
1cm
5cm
50cm
B
100
10
1
0.5
1
3
10
leaf length, cm
leaf width, cm
normal
tangled

Physical forces affect the orientation of cell division

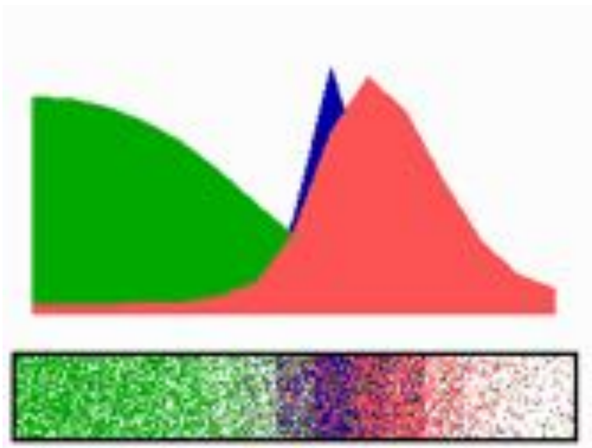


Nature Reviews | Molecular Cell Biology

Mapping cell geometry
oscillation of MinD:GFP within the bacterial cell

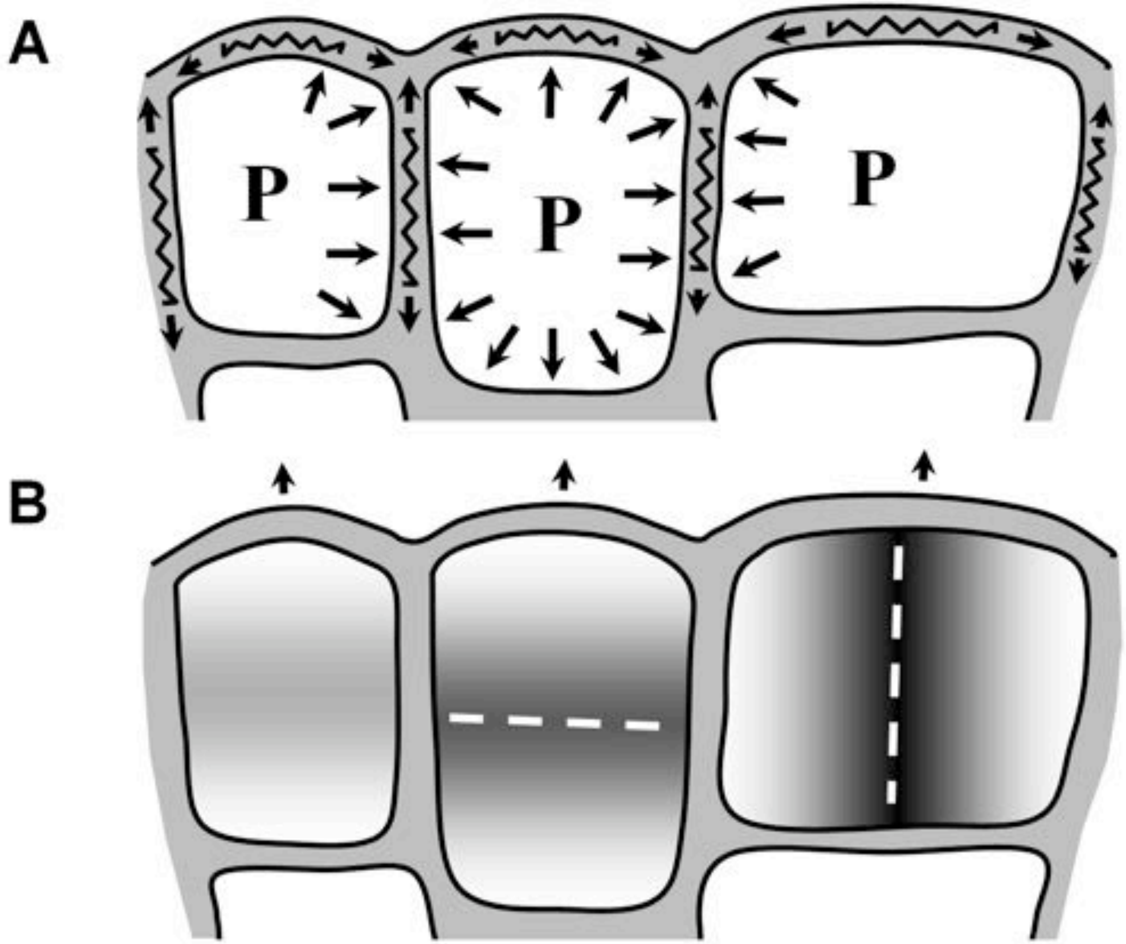


Raskin, D. M., and de Boer, P. A. J. (1999b). Rapid pole-to-pole oscillation of a protein required for directing division to the middle of Escherichia coli., PNAS 96, 4971-4976



Hans Meinhardt
http://www.eb.tuebingen.mpg.de/departments/former-departments/h-meinhardt/web_ecoli/mincd.htm

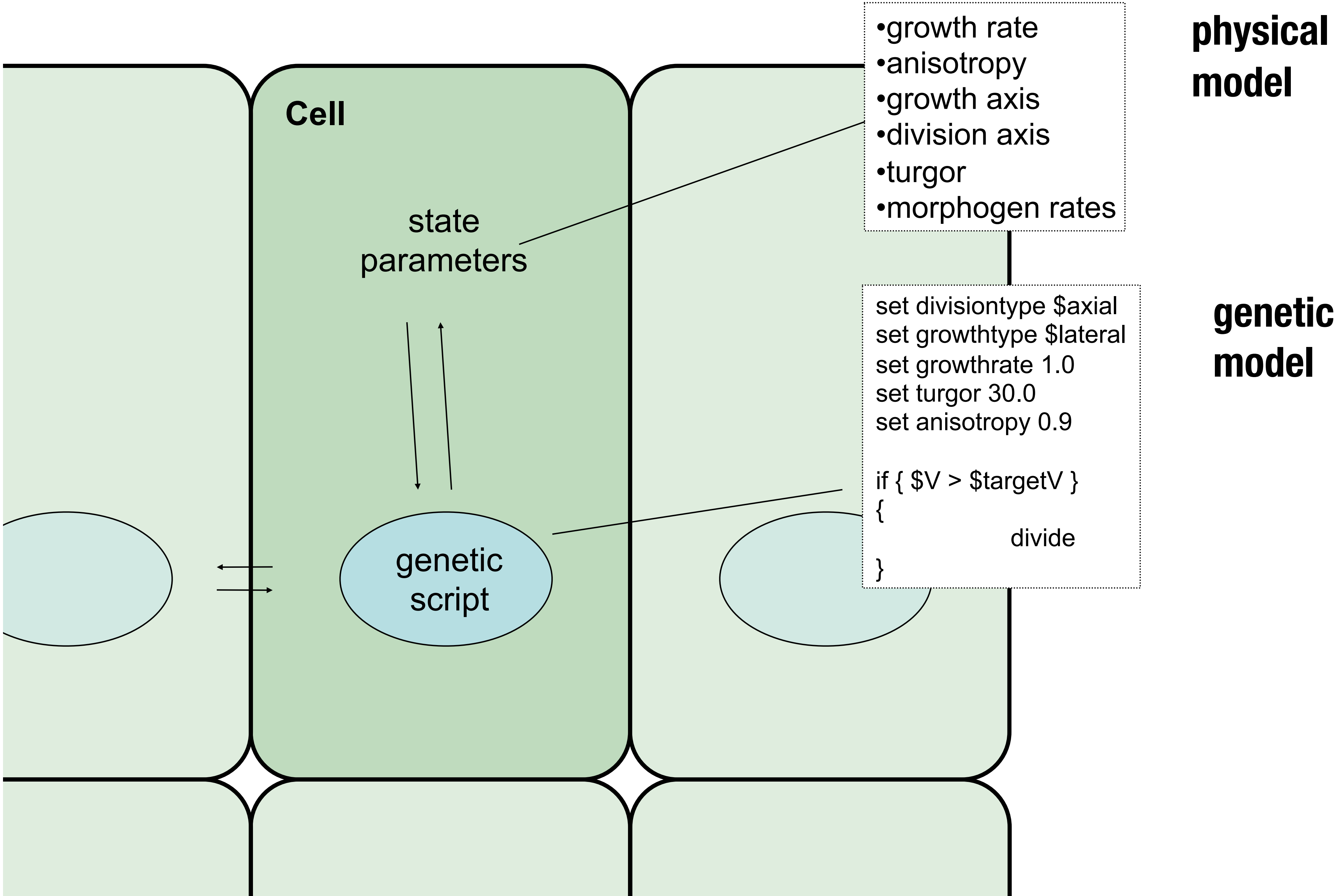
Autonomous regulation of cell division



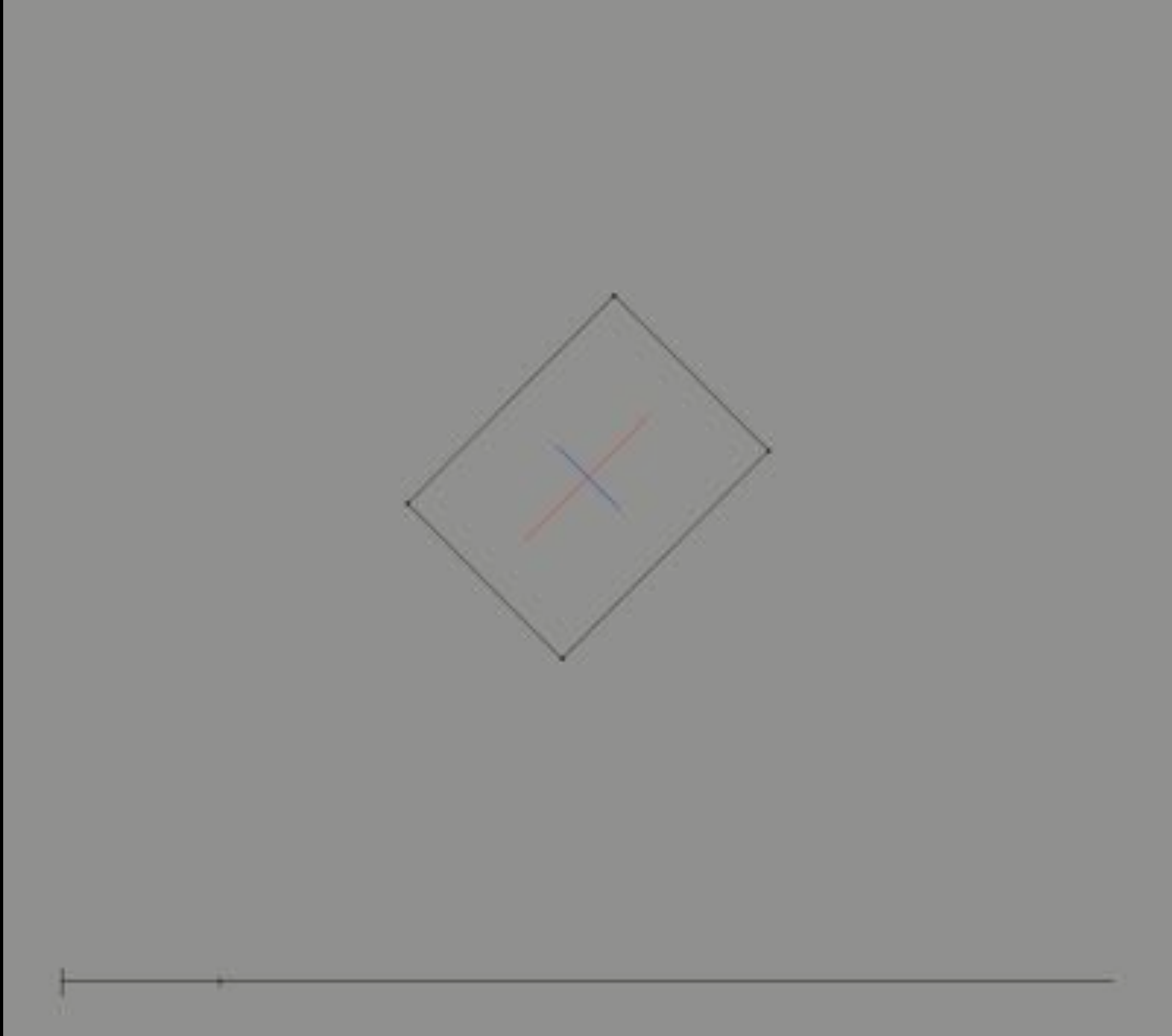
Model for the regulation of cell division:

(A) Cell activity influences cell and walls physical properties.
(B) Tissue growth constrains cell expansion and shape during development.
Cells then simply need a mechanism for sensing their own size and shape to allow the correct partitioning during division.

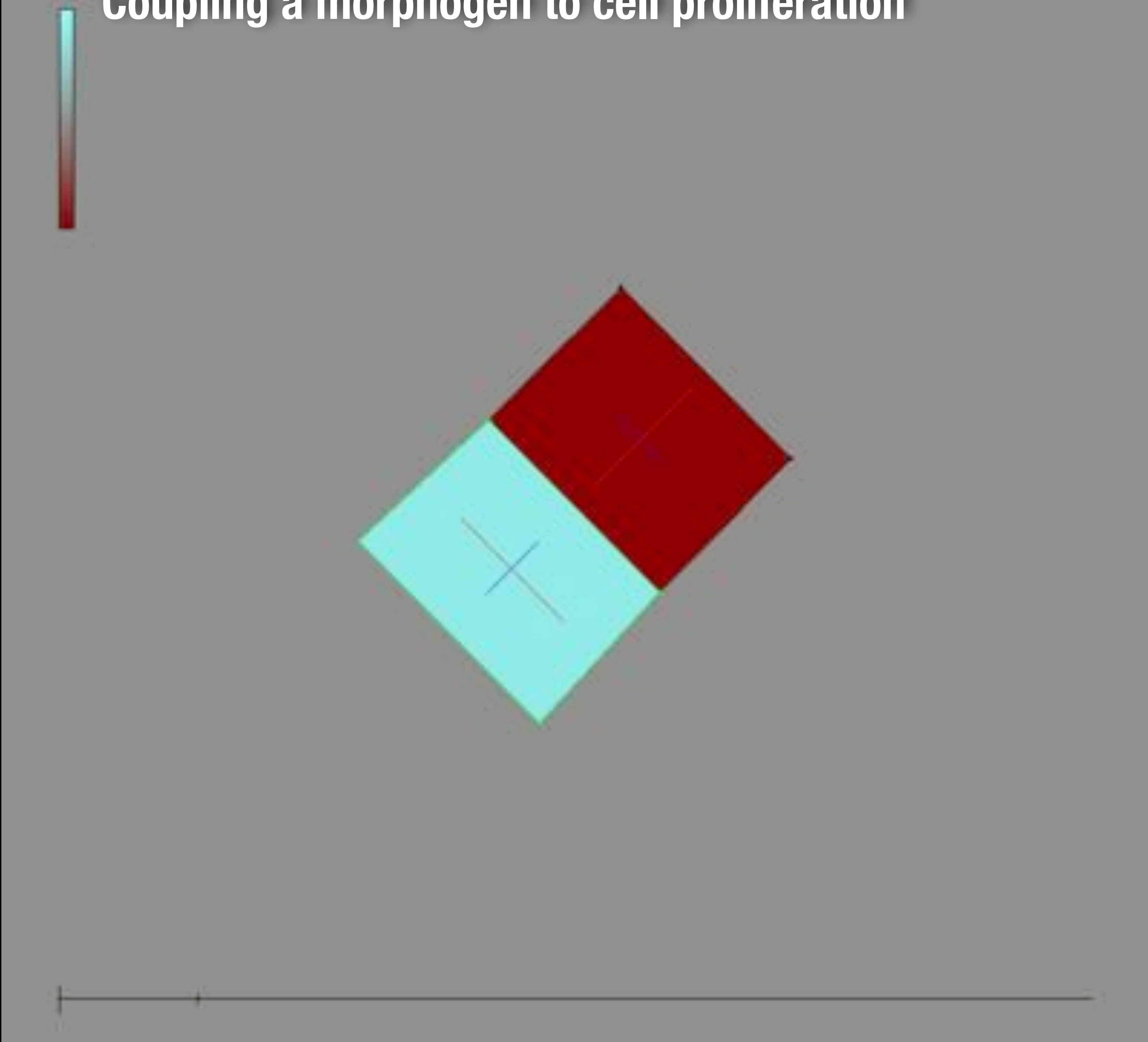
Cellular automata models for plant morphogenesis



Computer model for cellular growth



Coupling a morphogen to cell proliferation



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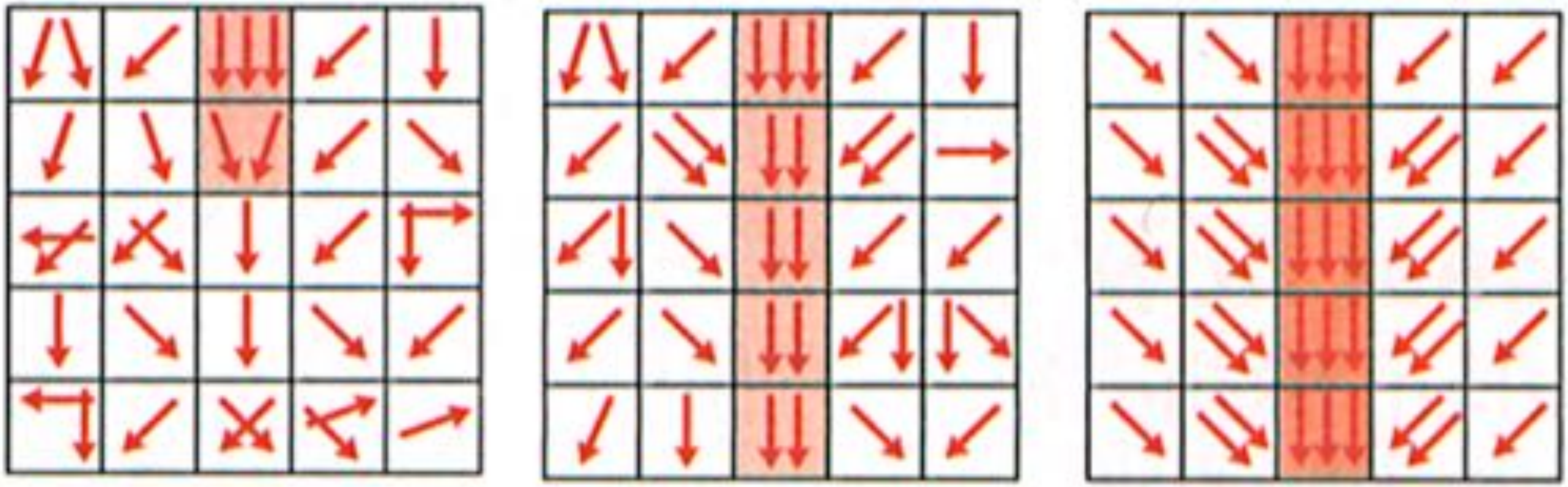
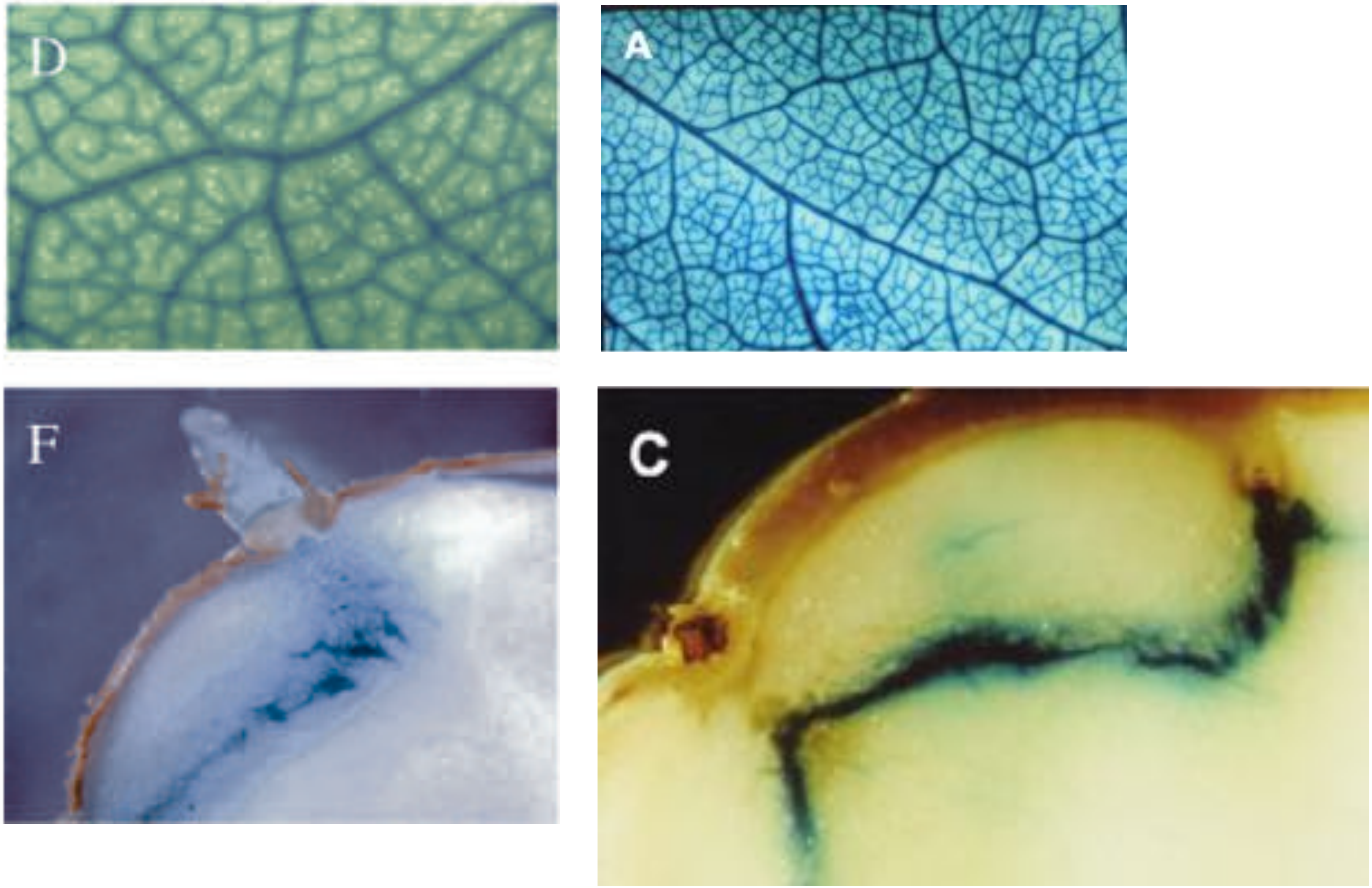
“Canalisation”



Patterning processes emerge from local cellular interactions

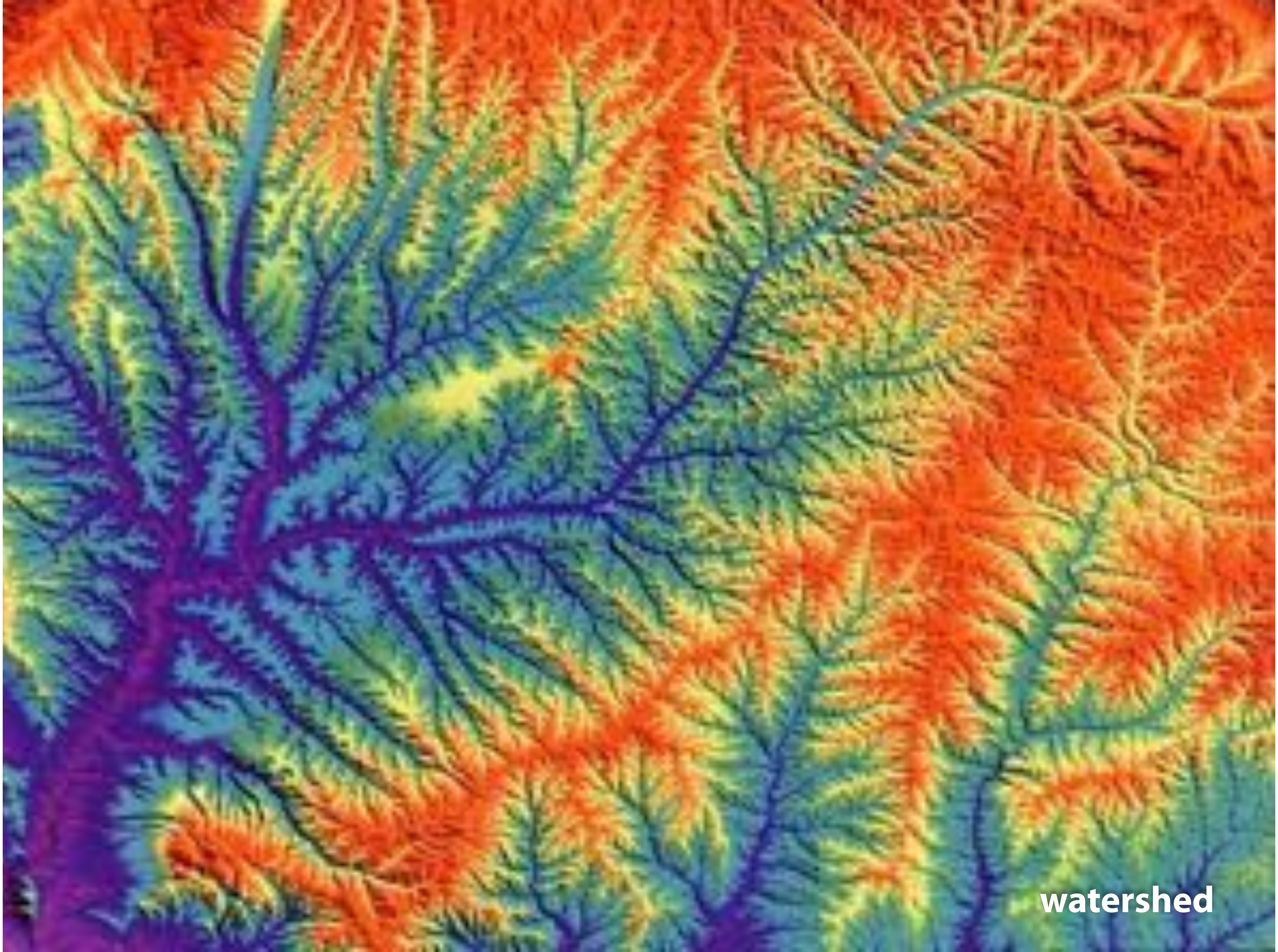
Jerusalem artichoke (*Helianthus tuberosus*)

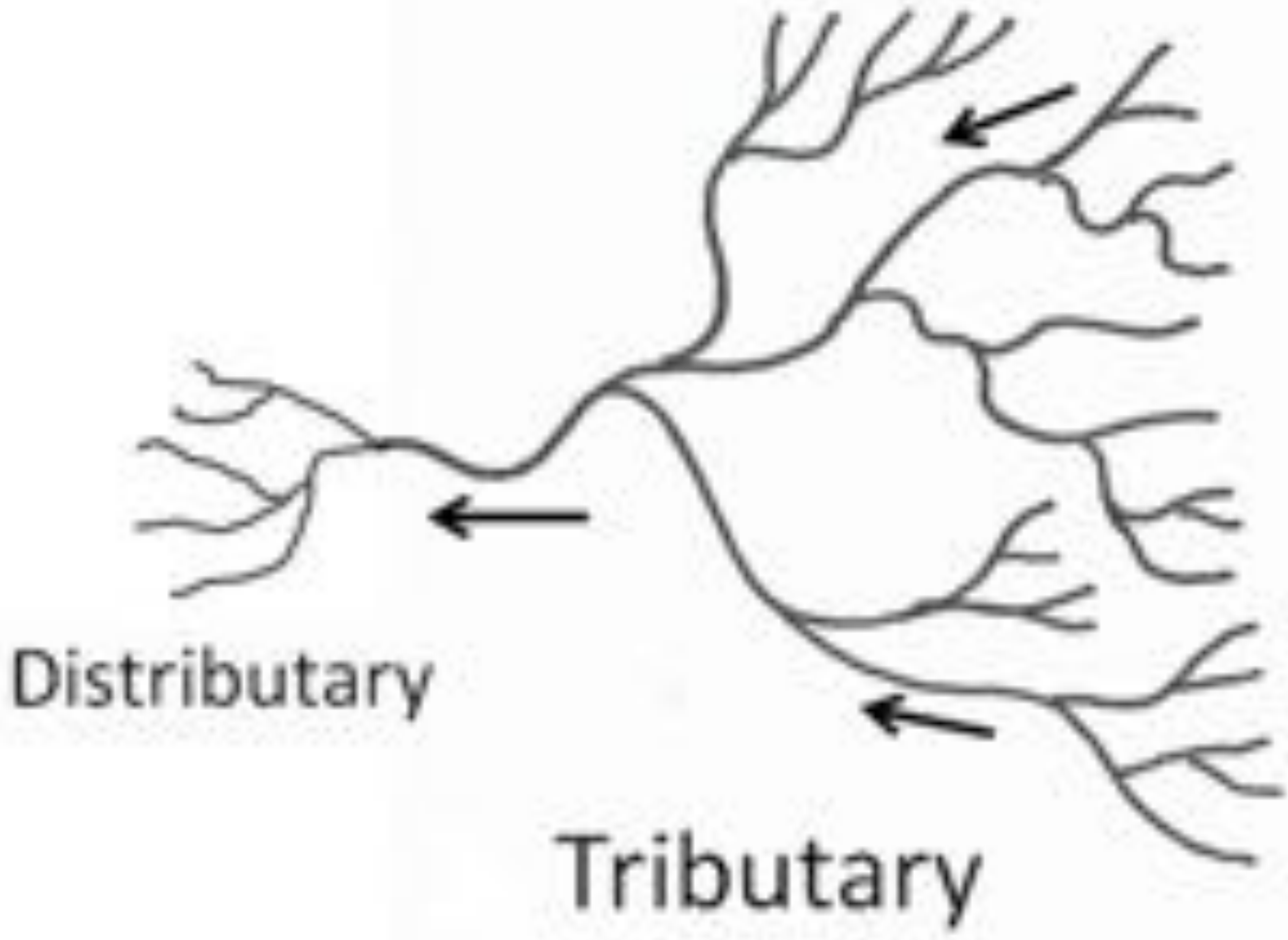
Sut1 sucrose transporter gene expression in leaves and germinating potato tubers



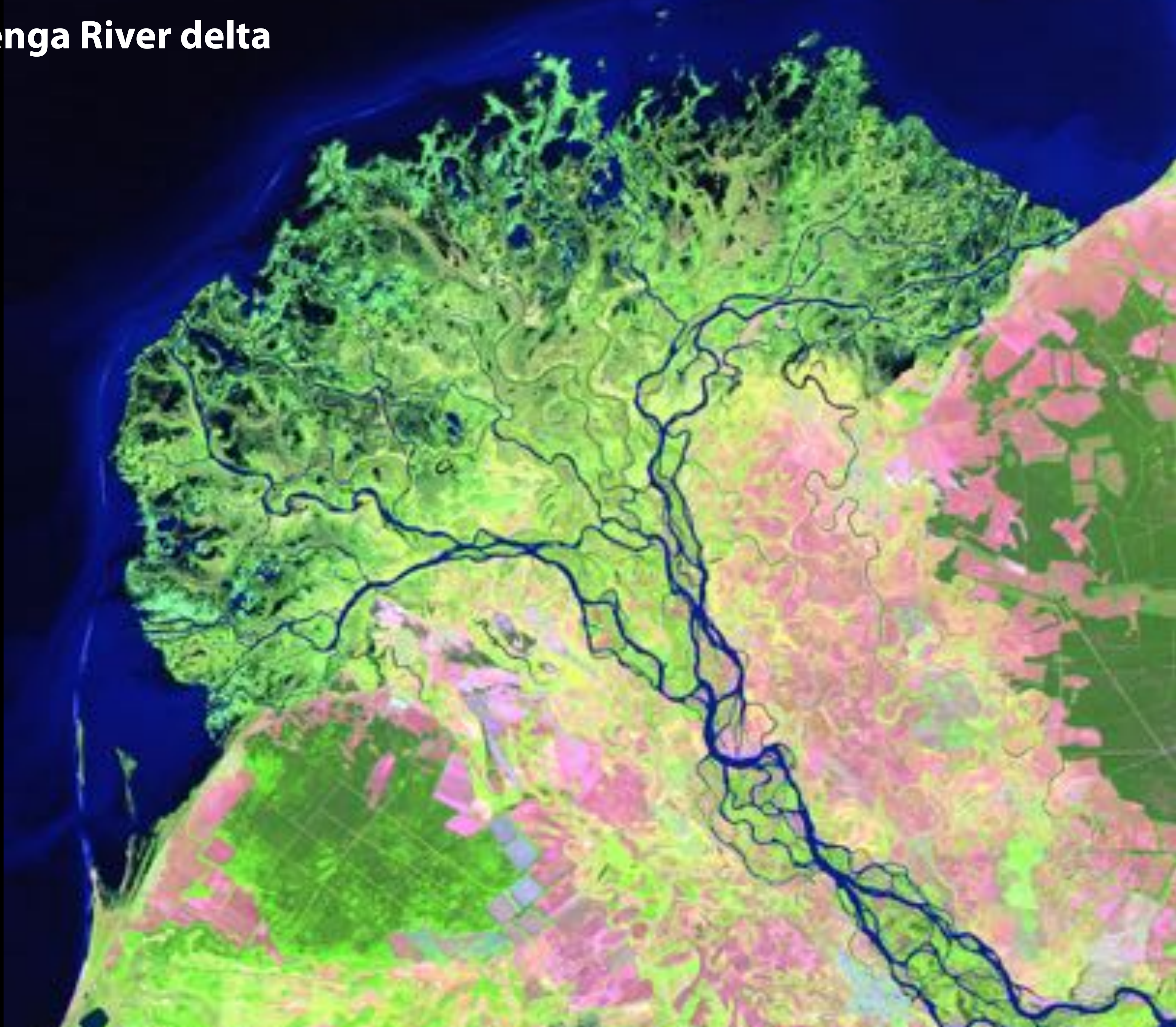
Jerusalem artichoke
(*Helianthus tuberosus*)


leaf veins

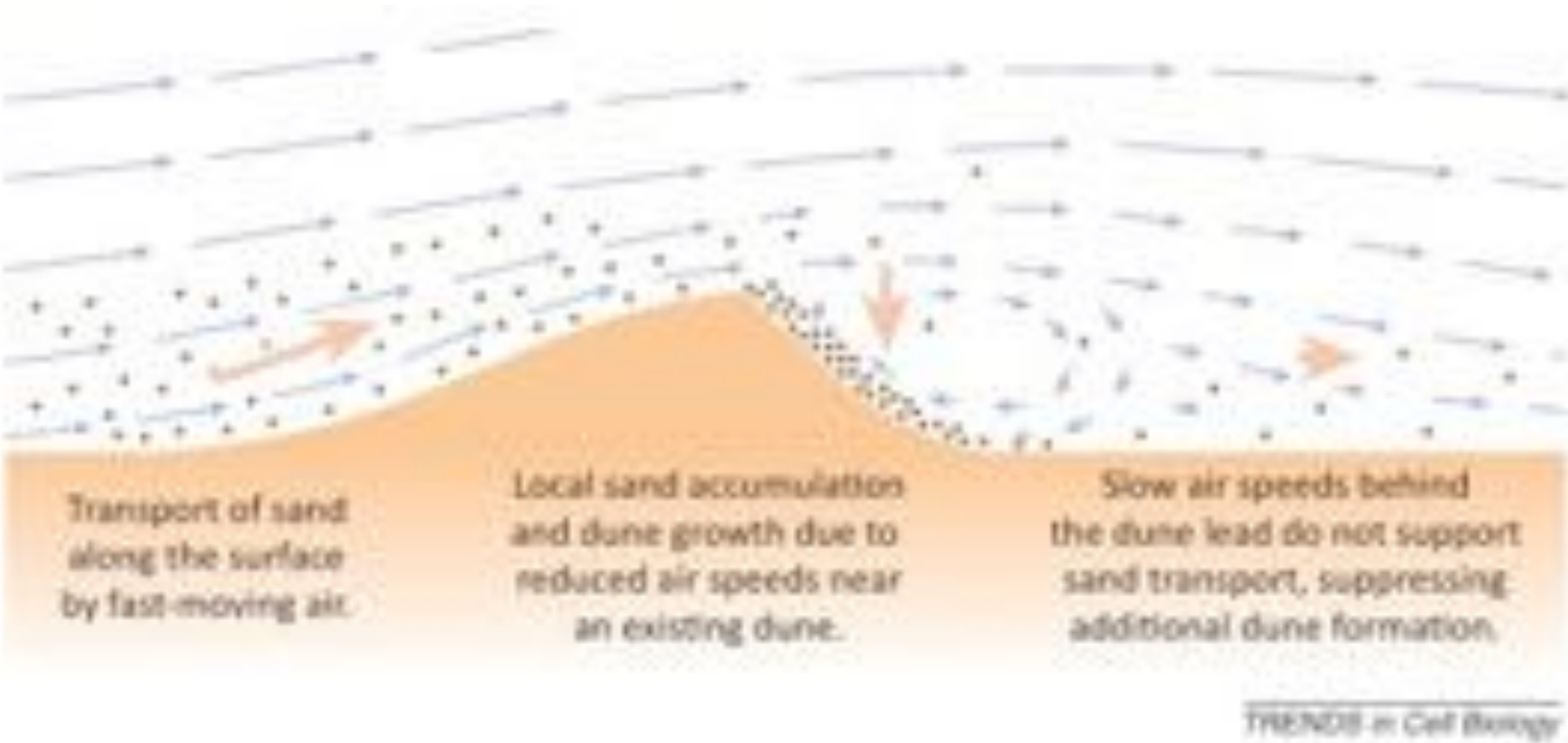

watershed


Distributary
Tributary

Selenga River delta




Ian Parker


Transport of sand along the surface by fast-moving air.
Local sand accumulation and dune growth due to reduced air speeds near an existing dune.
Slow air speeds behind the dune lead do not support sand transport, suppressing additional dune formation.
TRENDS in Cell Biology

Secret Life of Chaos

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Turing, 1952

The Chemical Basis of Morphogenesis

(*Phil. Trans. Roy. Soc. London*)

Diffusion-driven instability

Under appropriate conditions, a spatially homogeneous equilibrium of a chemical reaction can be stable in the absence of diffusion and unstable in the presence of diffusion.

Such a reaction is capable of exhibiting spatially *inhomogeneous* equilibria, *i.e.*, patterns.

Diffusion-driven instability might explain some of the complex dynamics of nature.

Alan Mathison Turing on election to Fellowship of the Royal Society, 1951.

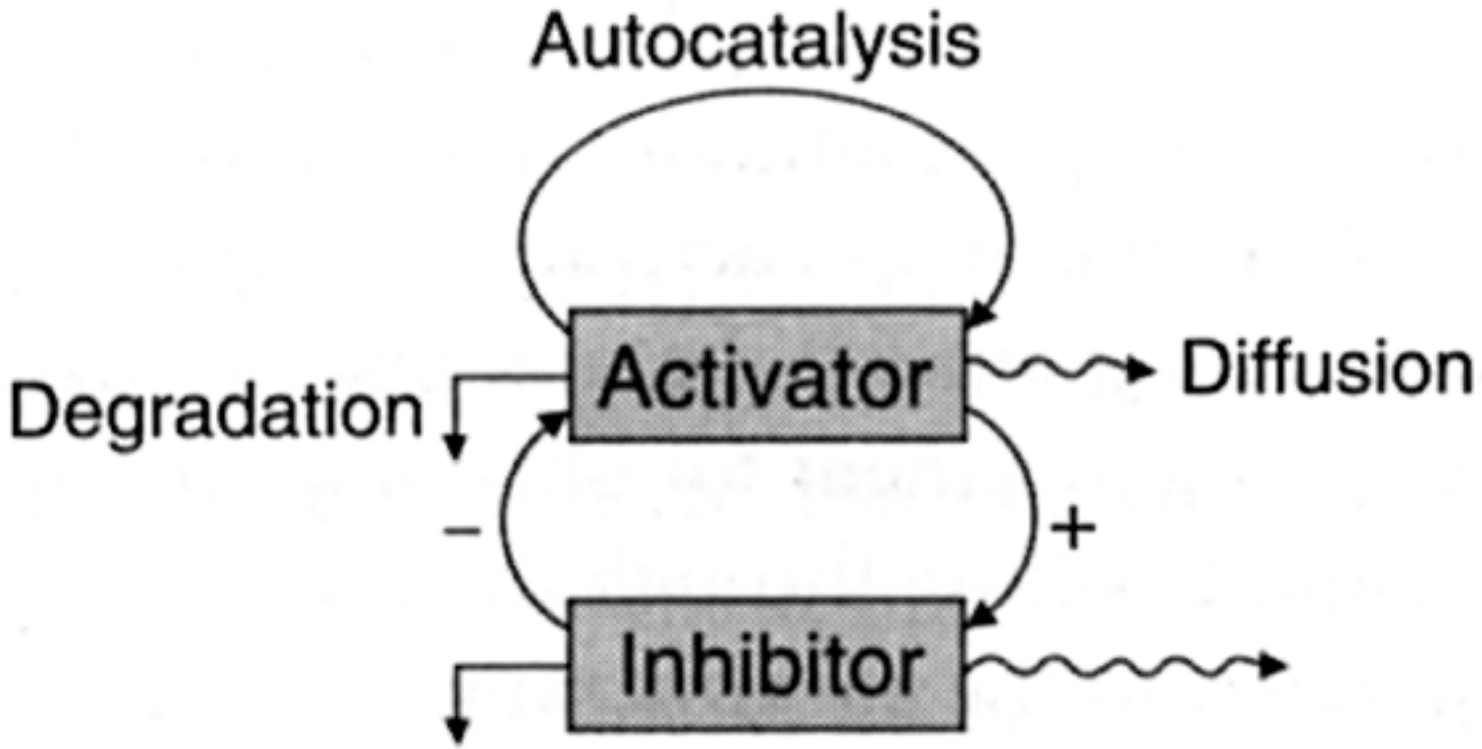
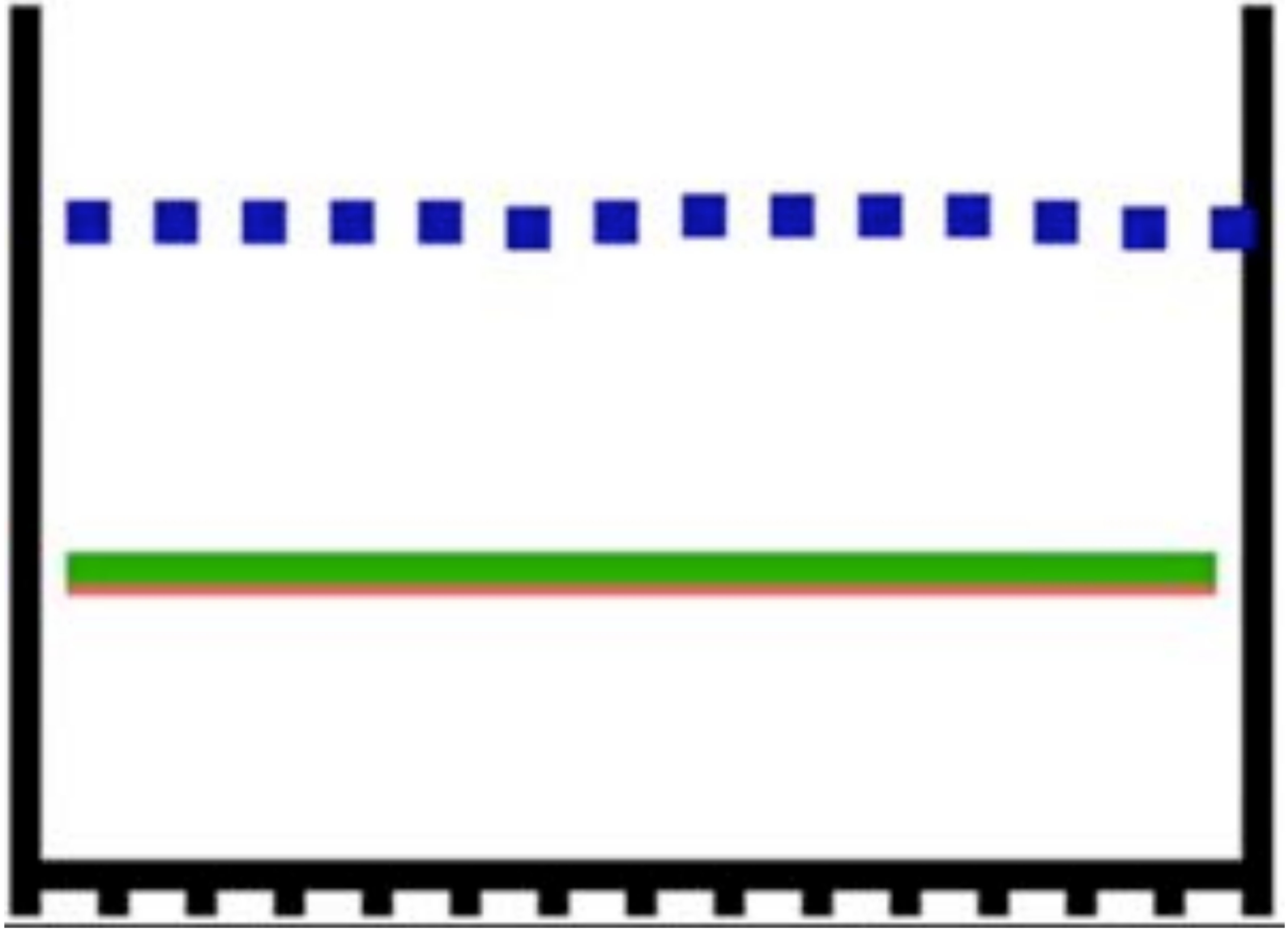
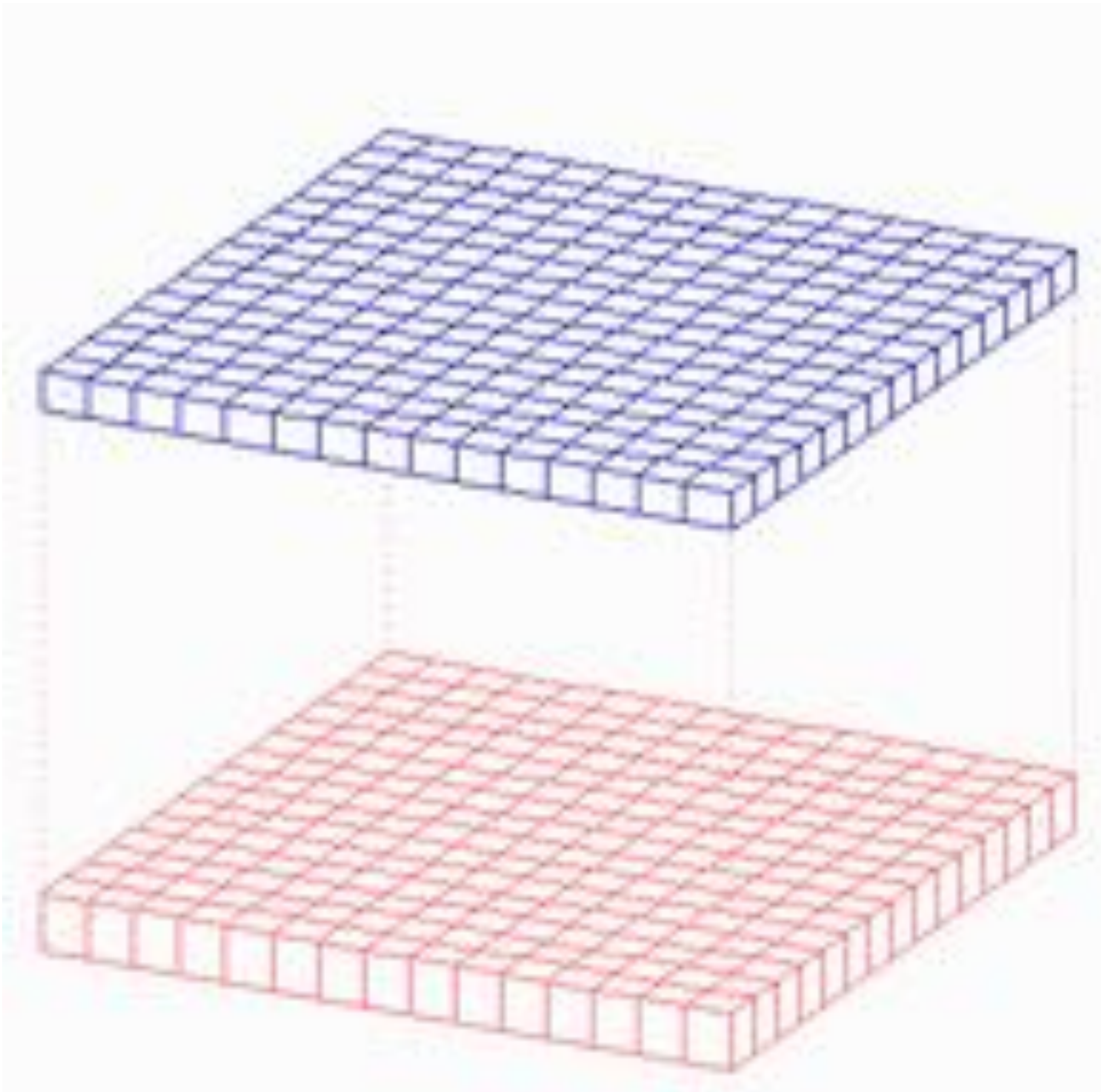


Fig. 4.2 How an activator–inhibitor scheme works. The activator generates more of itself by autocatalysis, and also activates the inhibitor. The inhibitor disrupts the autocatalytic formation of the activator. Meanwhile, the two substances diffuse through the system at different rates, with the inhibitor migrating faster.

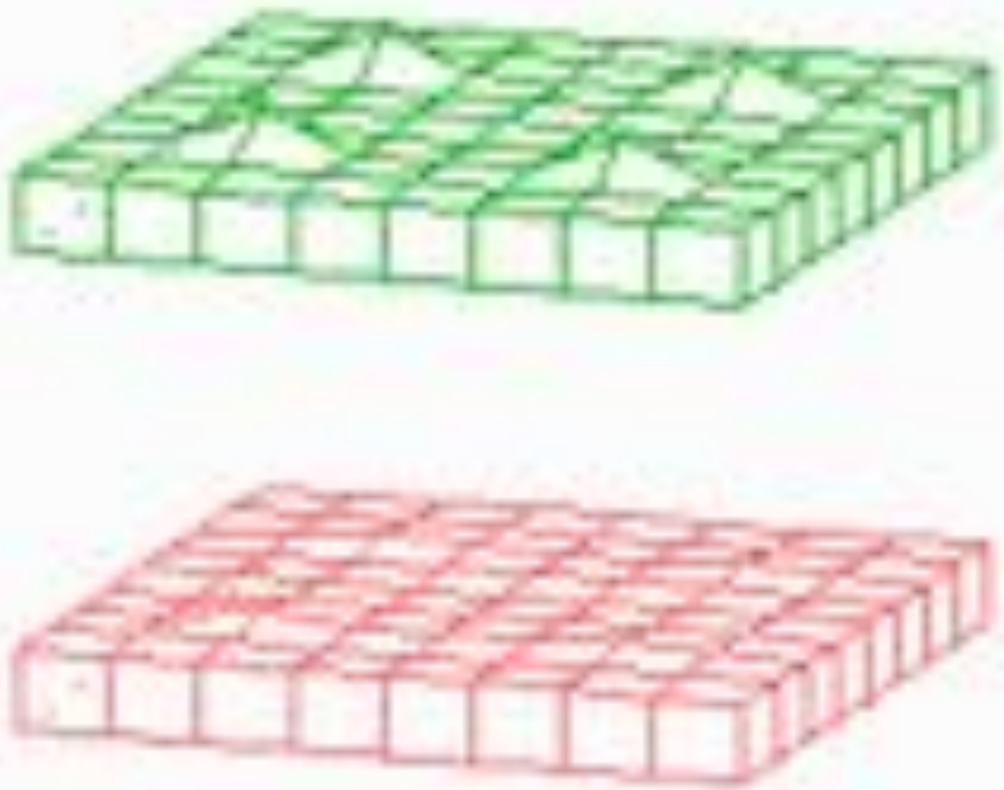
after Gierer & Meinhardt, 1972

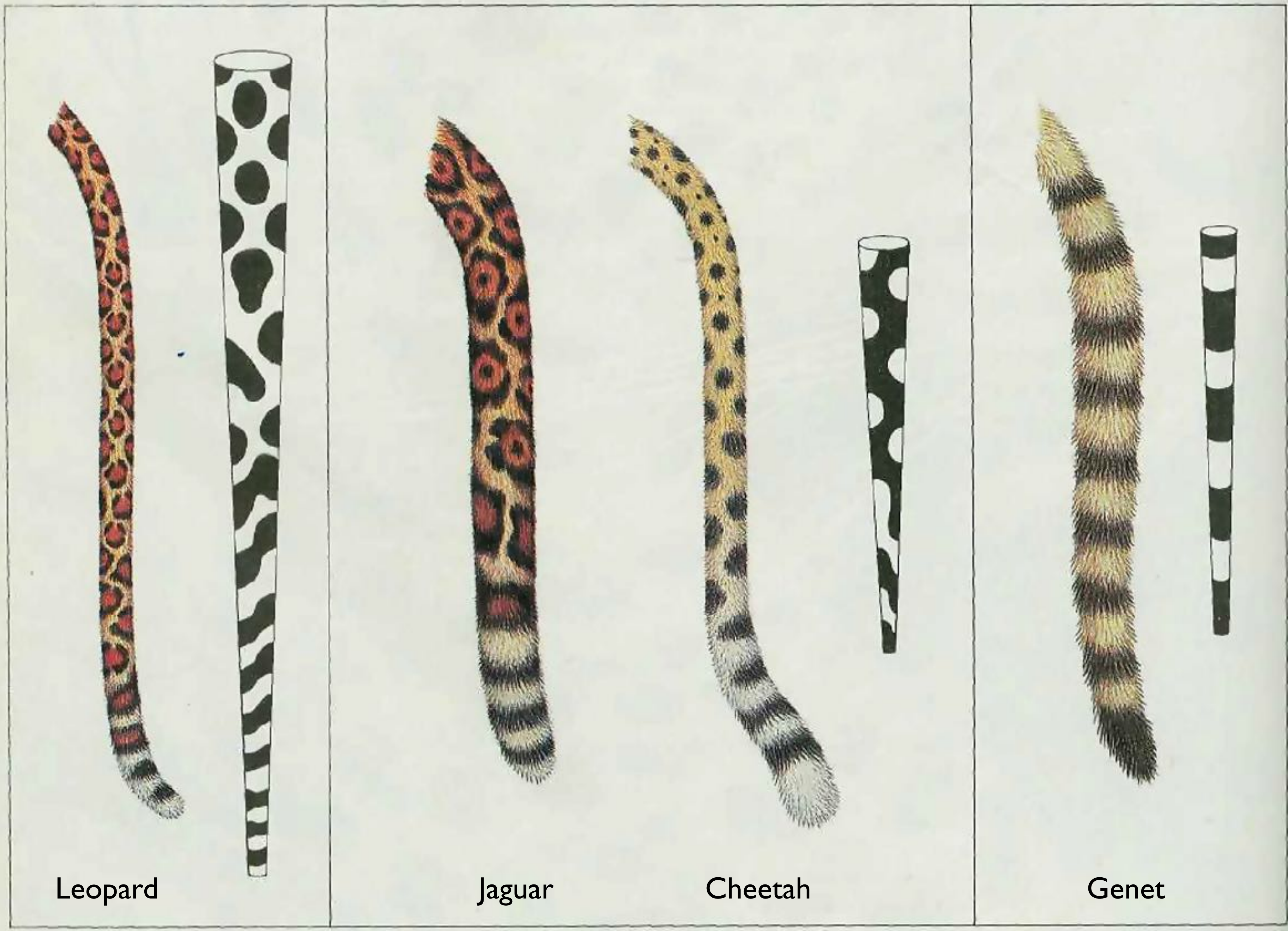


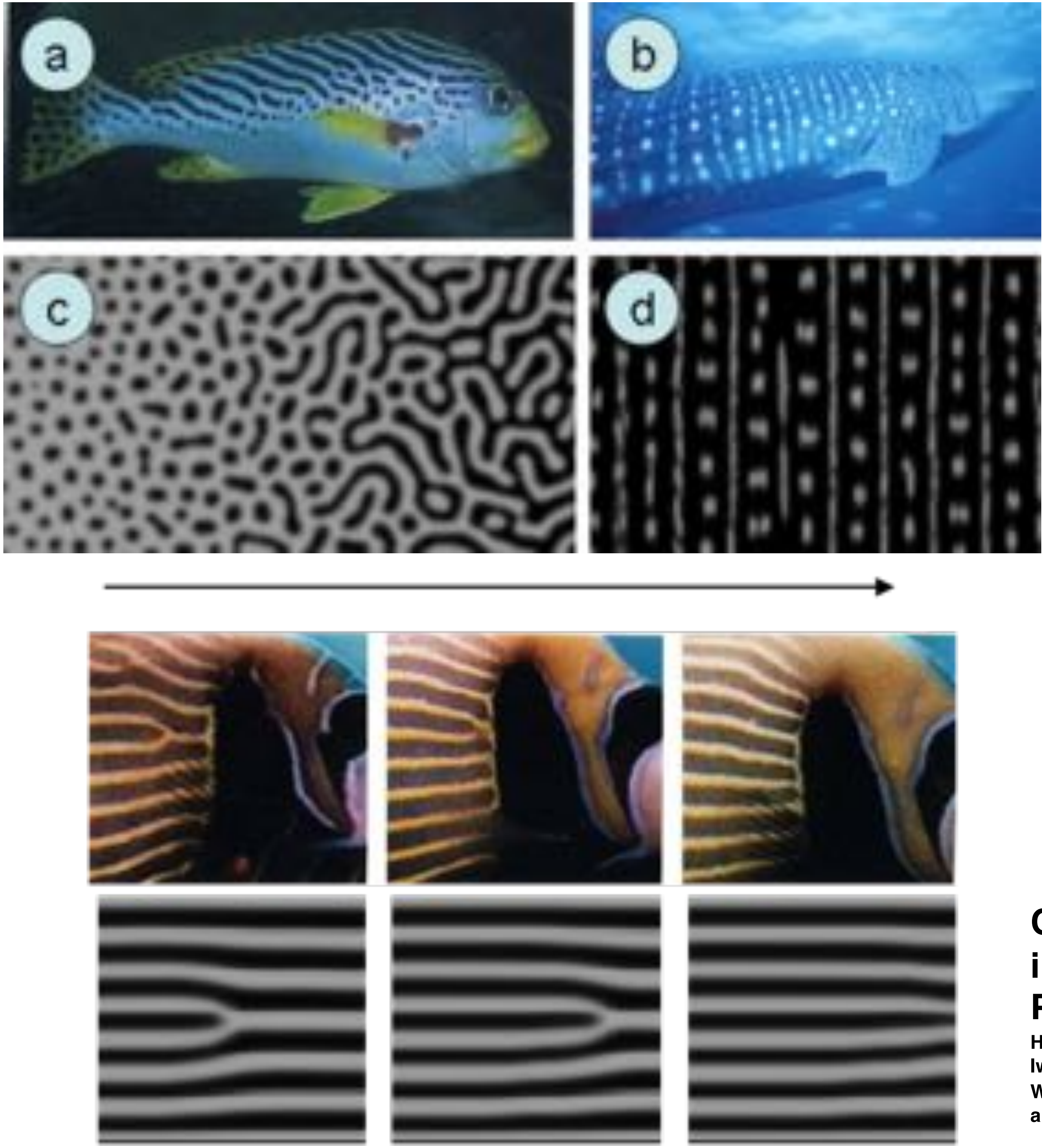
Self-organisation in a Turing pattern



Modification of Turing patterns during growth

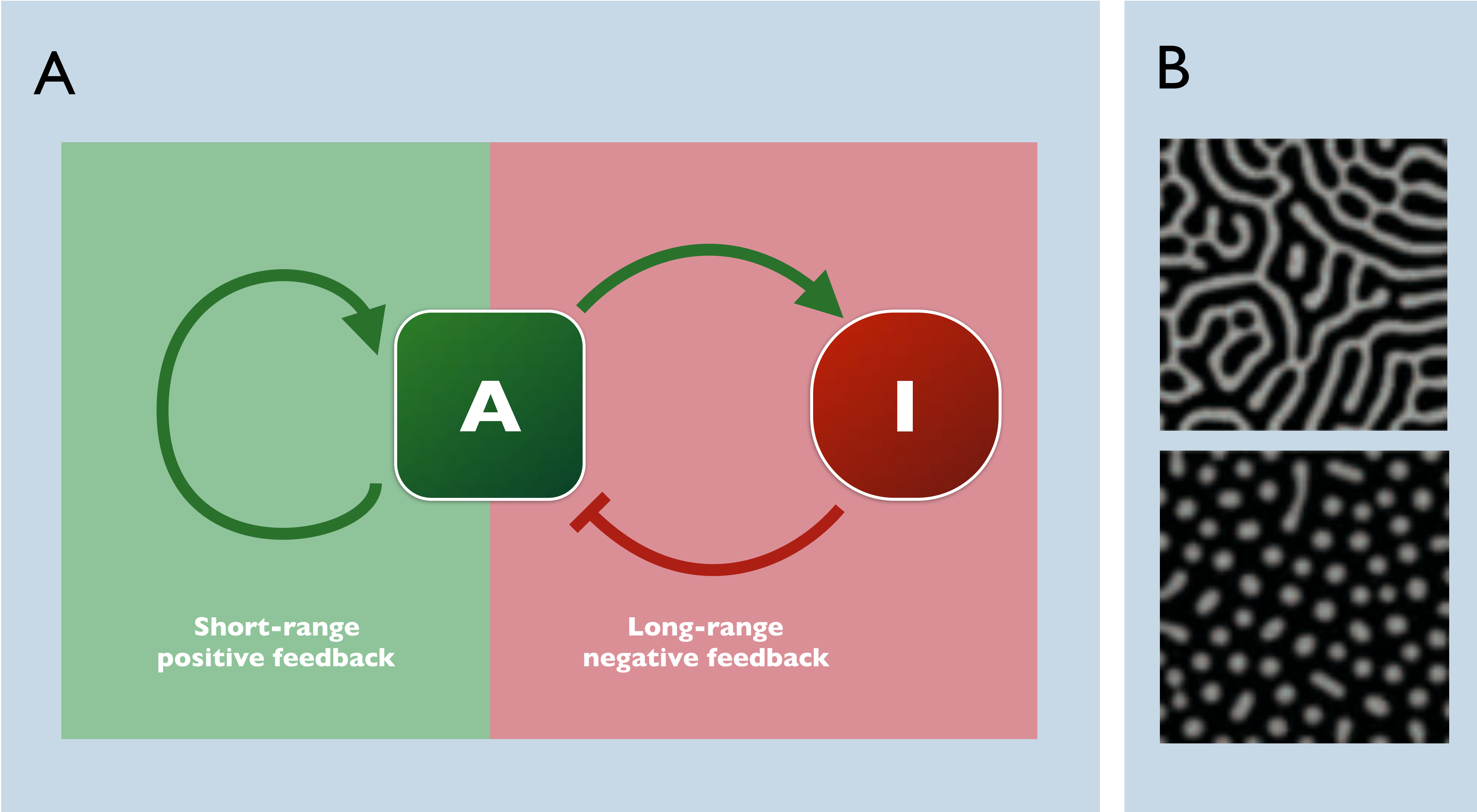



Leopard
Jaguar
Cheetah
Genet



Origin of Directionality in the Fish Stripe Pattern

Hiroto Shoji,[1] Atsushi Mochizuki,[1] Yoh Iwasa,[1] Masashi Hirata,[2,3] Tsuyoshi Watanabe,[2,4] Syozo Hioki,[5] and Shigeru Kondo[2,3]*



Turing-inspired systems for self-organisation

The activator generates more of itself through positive feedback, which also activates the inhibitor. The inhibitor disrupts autocatalytic formation of the activator. The substances move through the medium at different rates.
Noise and diffusion produce spontaneous local patterns of activation and lateral inhibition.

Compound Turing systems

Jonathon McCabe "Bone Music"   http://vimeo.com/jonathanmccabe

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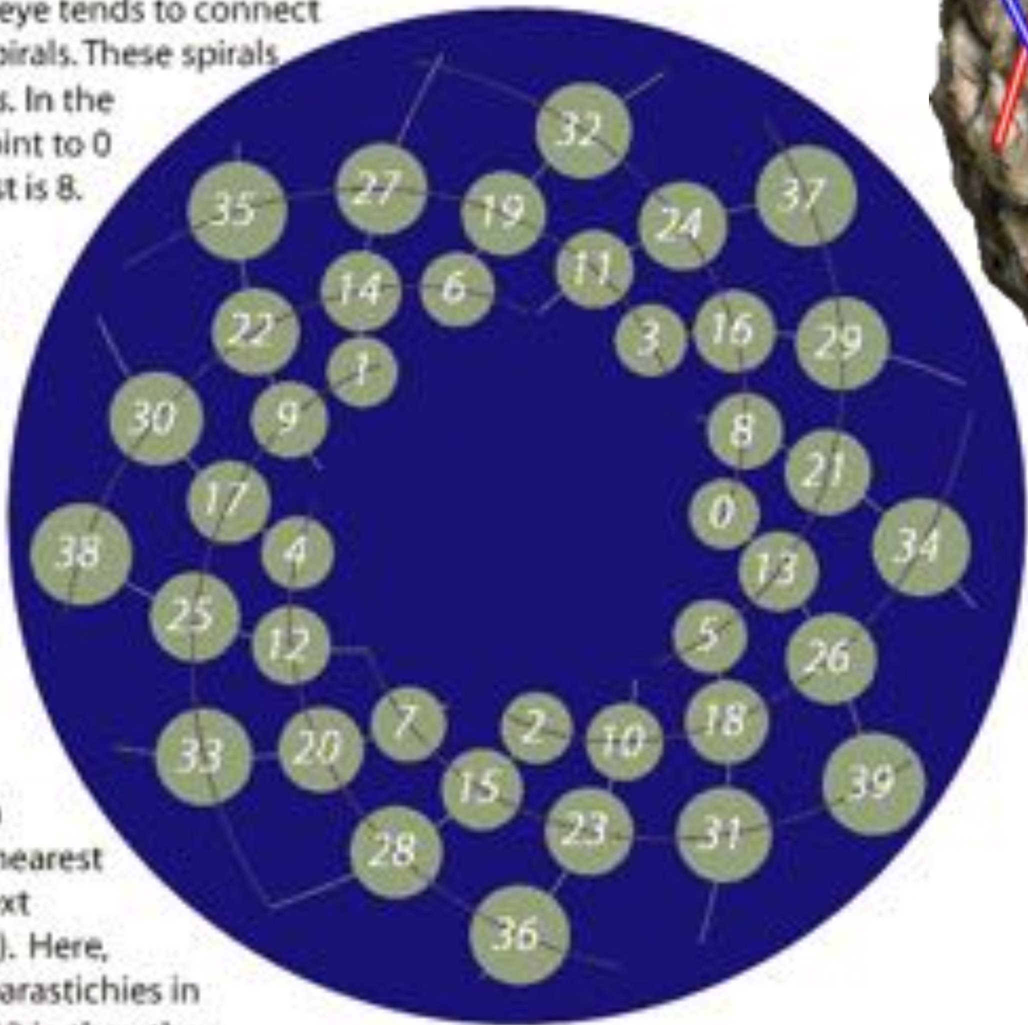
Jerusalem artichoke (*Helianthus tuberosus*)

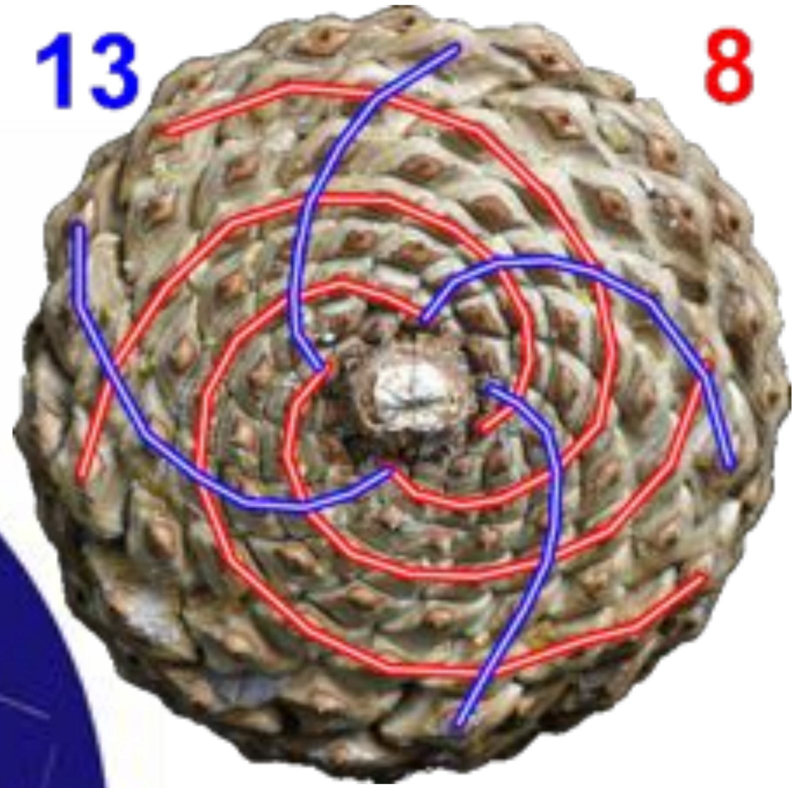
Visible Spirals: Parastichies

In a spiral lattice, the eye tends to connect nearest points into spirals. These spirals are called *parastichies*. In the figure, the nearest point to 0 is 13; the next nearest is 8.

There are two sets of parastichies winding in different directions. In the figure, 0, 8, 16 … winds in one direction and 0, 13, 26 … in the other.

The number of parastichies in each direction is the difference between a point, e.g., 7, and its nearest neighbor (20) and next nearest neighbor (15). Here, there are 15 - 7 = 8 parastichies in one set and 20 - 7 = 13 in the other.

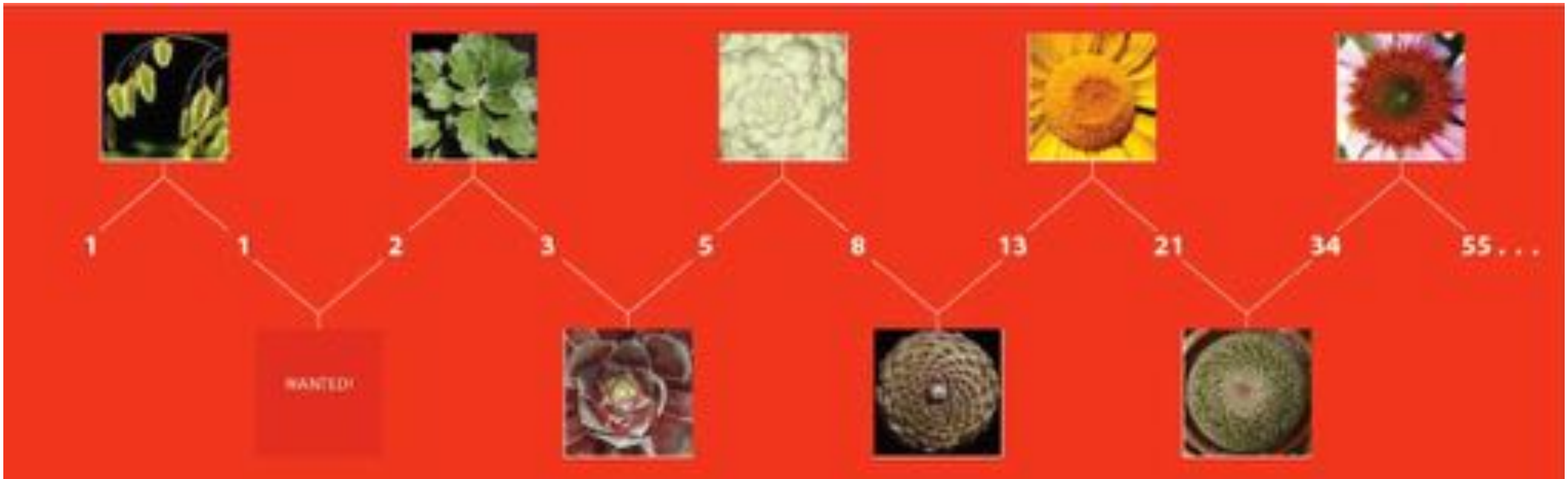


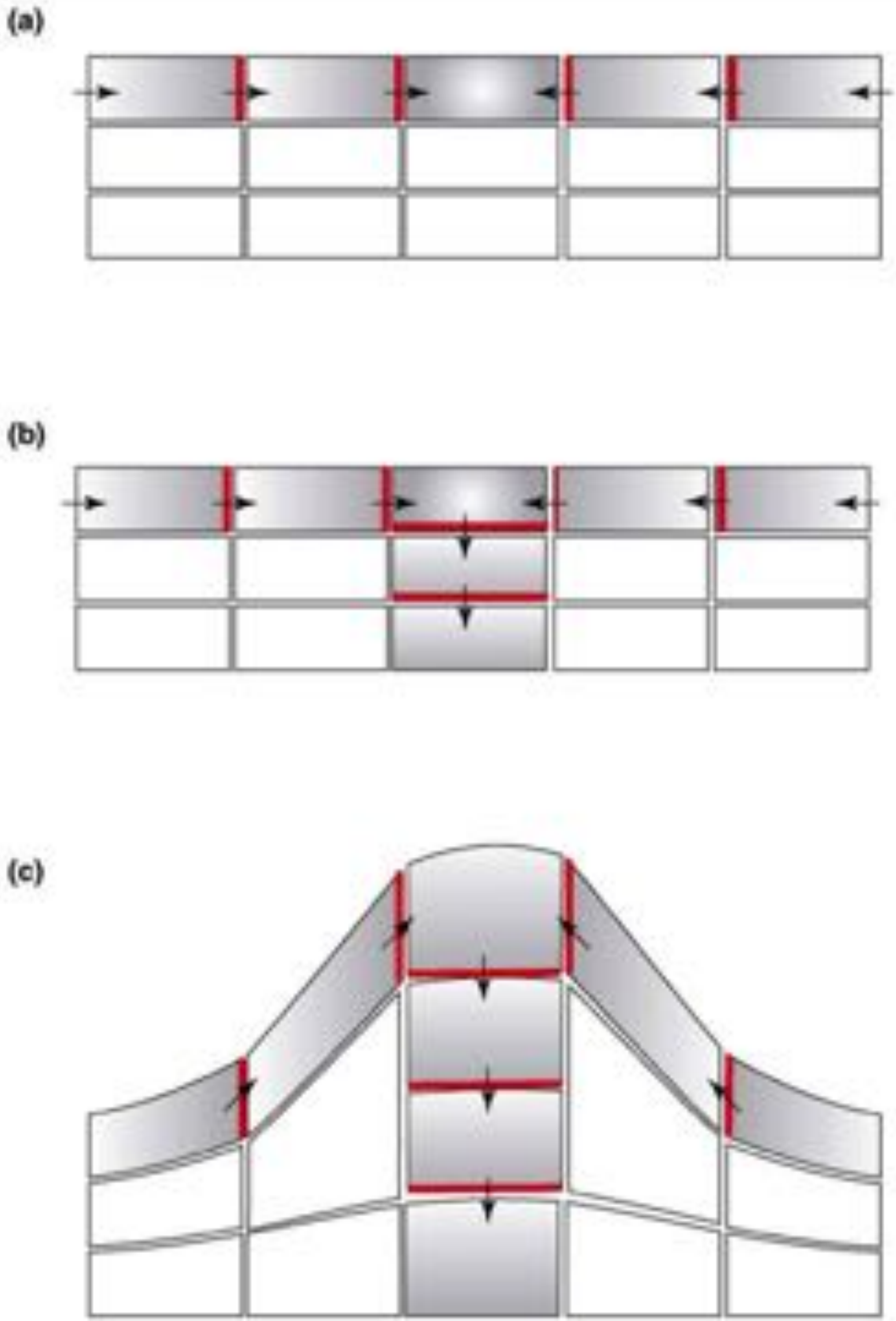


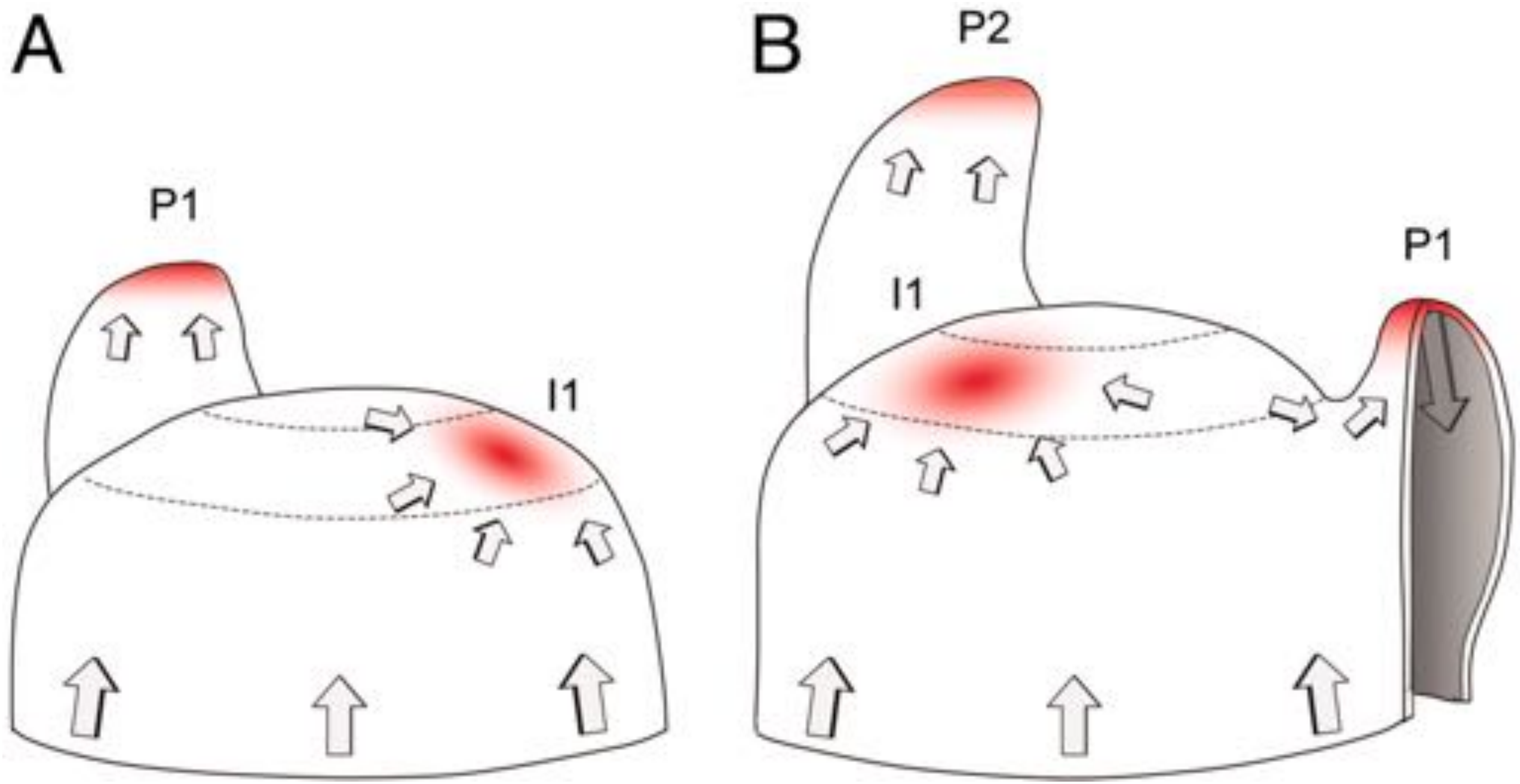
Spiral lattices are classified according to the number of parastichies in each set. This lattice is (8, 13).

Plant organs and the Fibonacci series

3 petals: lily, iris
4 petals: Arabidopsis, fuchsia - decussate arrangement, not spiral.
5 petals: buttercup, wild rose, larkspur, columbine (aquilegia), pinks
8 petals: delphiniums
13 petals: ragwort, corn marigold, cineraria, some daisies
21 petals: aster, black-eyed susan, chicory
34 petals: plantain, pyrethrum
55, 89 petals: michaelmas daisies, the asteraceae family

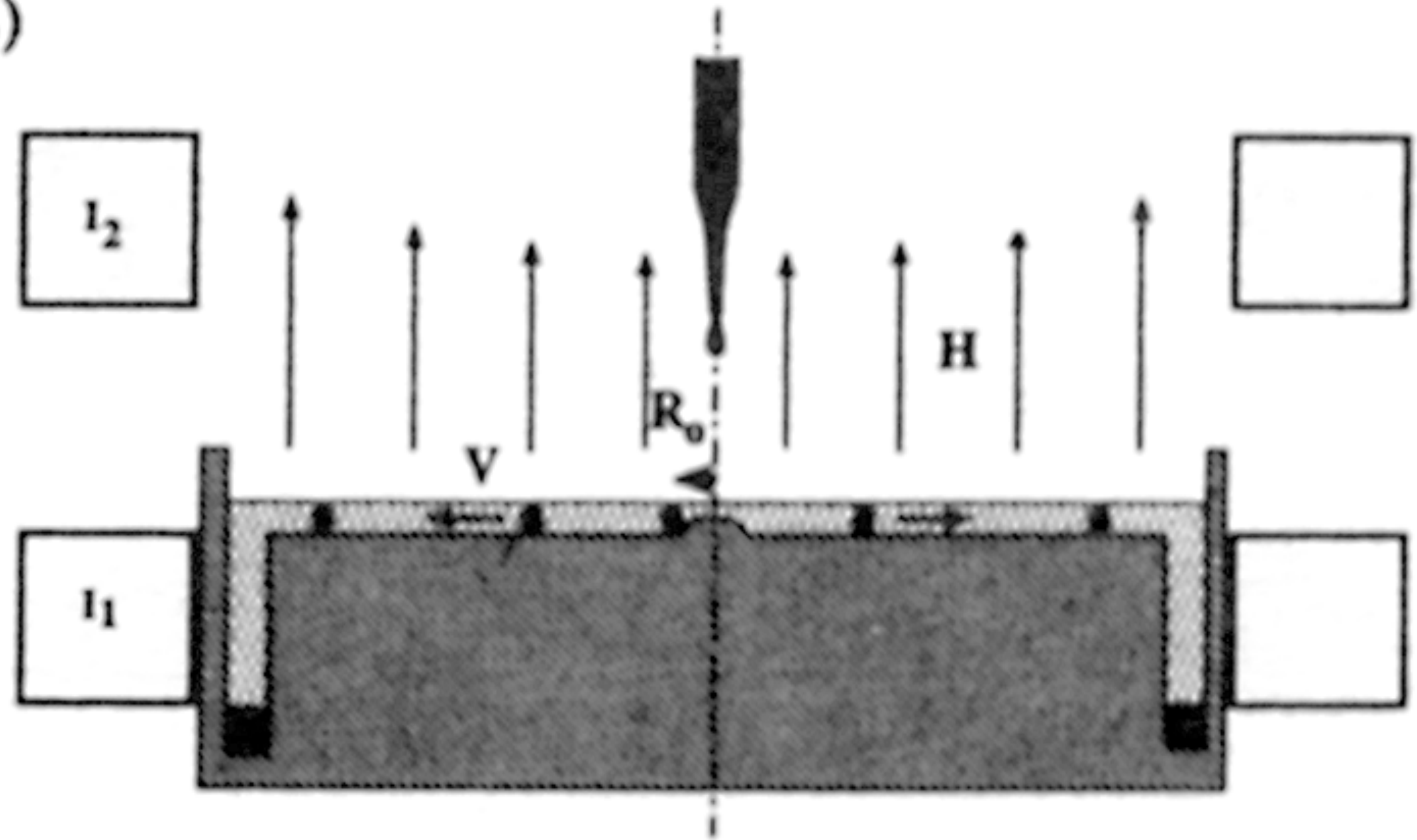



(a)
(b)
(c)



Auxin triggered outgrowth of shoot primordia

(b)



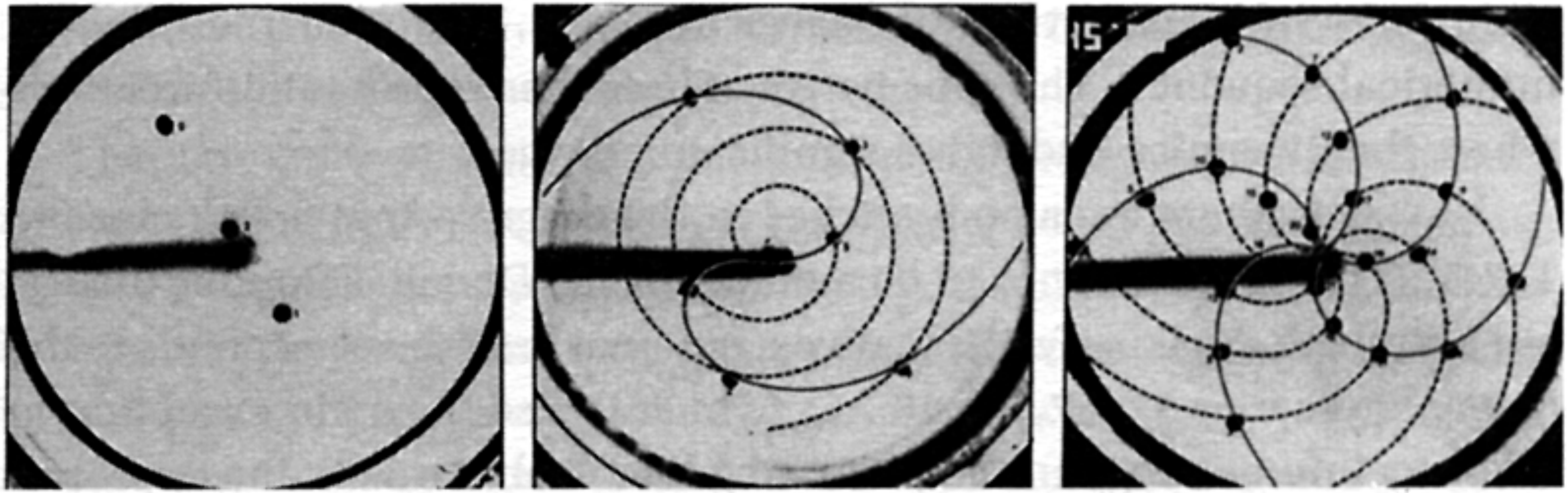
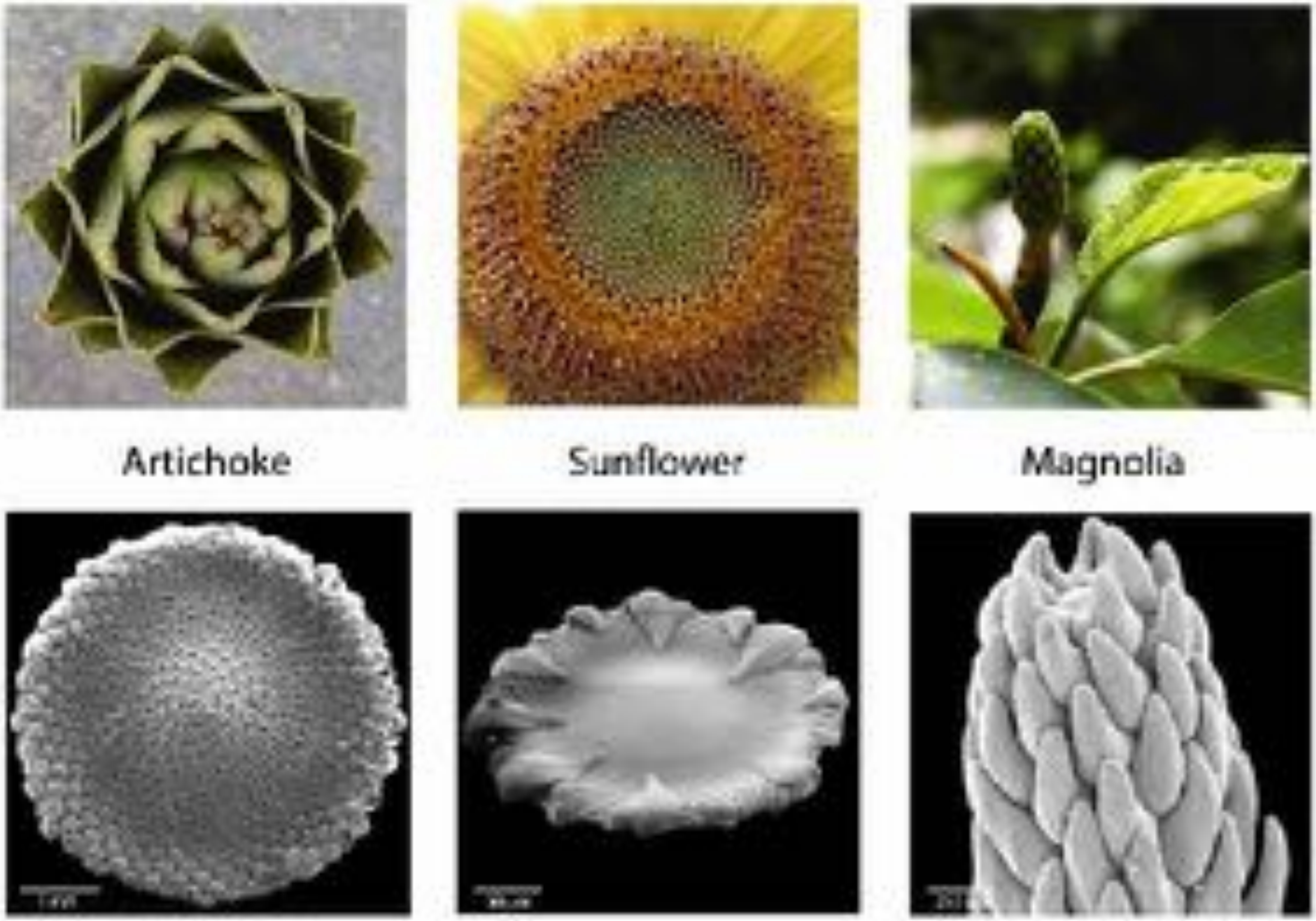


Figure 50
Fibonacci spirals observed in an experiment with electrically charged oil drops.

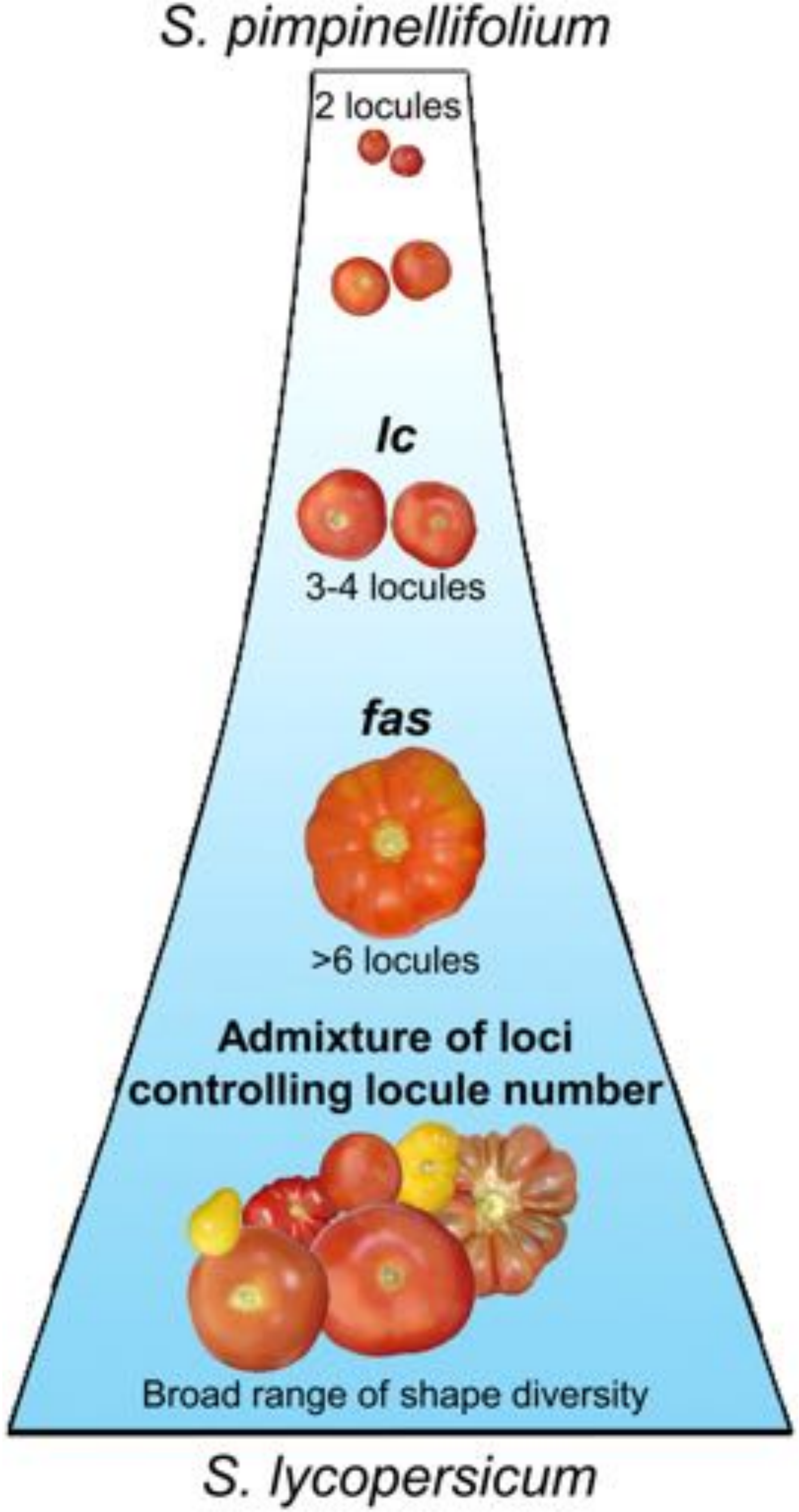
Emergence of patterns at microscopic scales



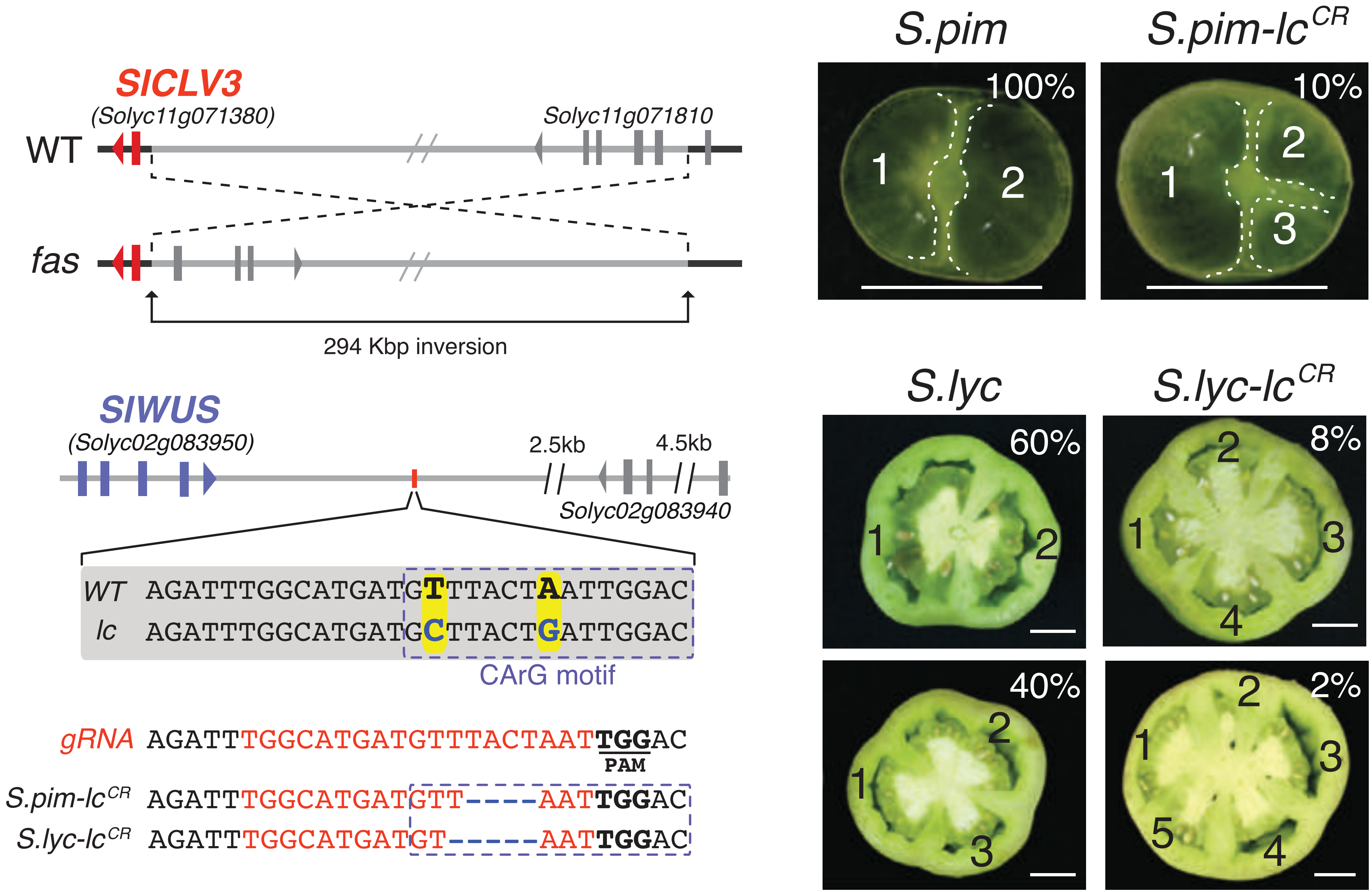
Modern crop plants are derived from their natural ancestors by thousands of generations of selection and breeding.

What if we could reprogram the distribution of existing cell types in living systems?

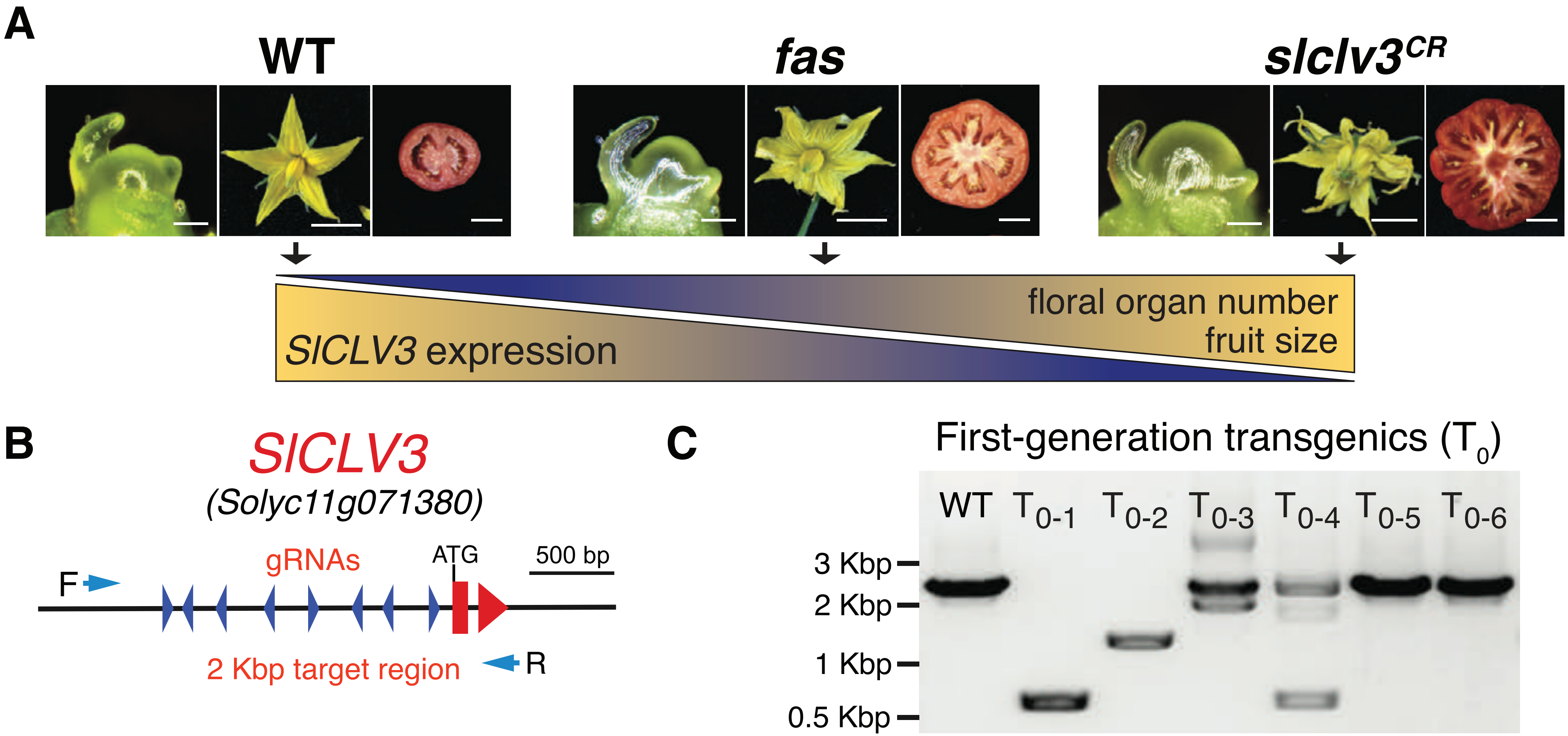
Synthetic Botany. Boehm & Pollak *et al*.
Cold Spring Harbor Perspectives in Biology, (2017)
doi: 10.1101/cshperspect.a023887


S. pimpinellifolium
2 locules
lc
3-4 locules
fas
>6 locules
Admixture of loci
controlling locule number
Broad range of shape diversity
S. lycopersicum

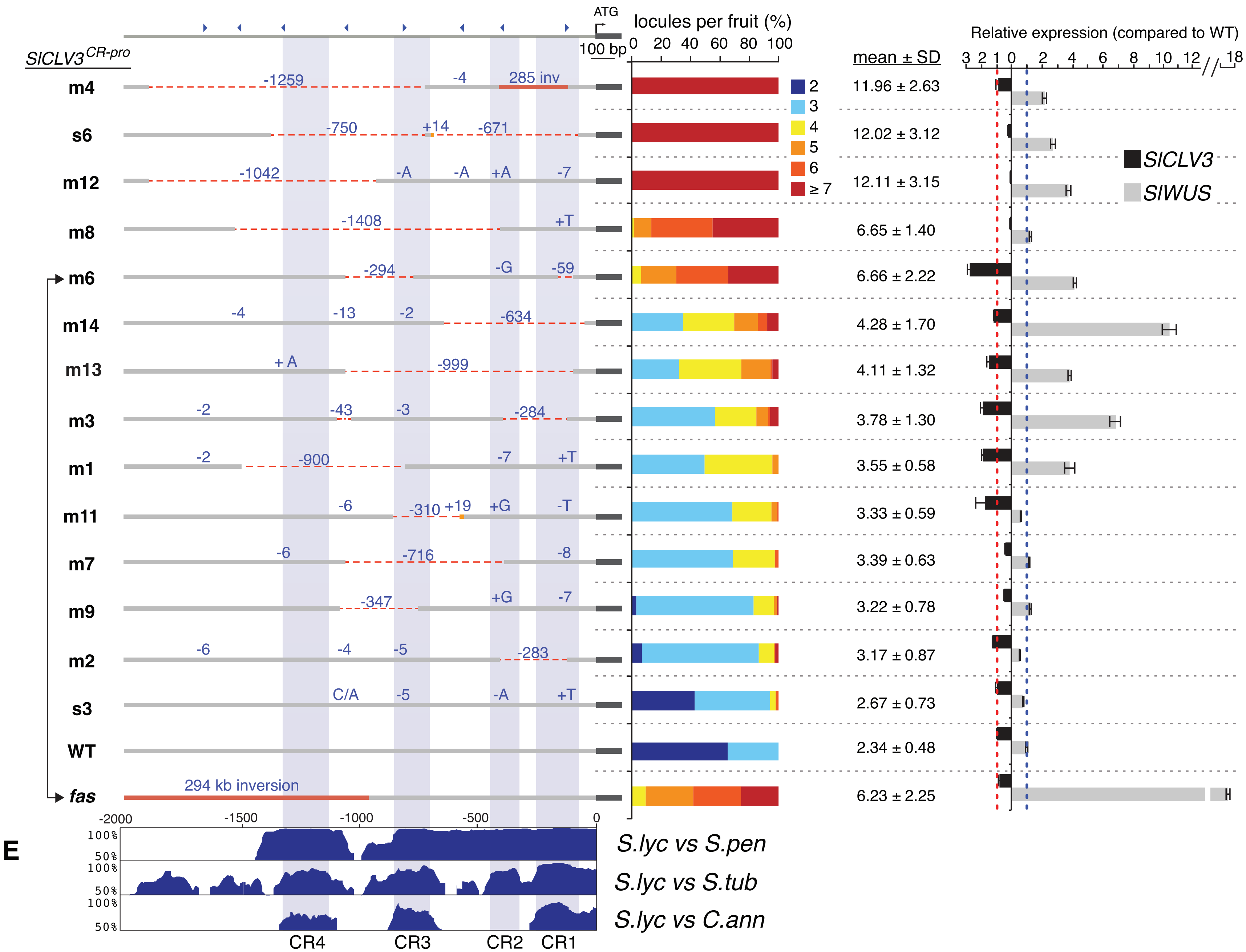
Recreating known fruit size QTLs in tomato with CRISPR-Cas9

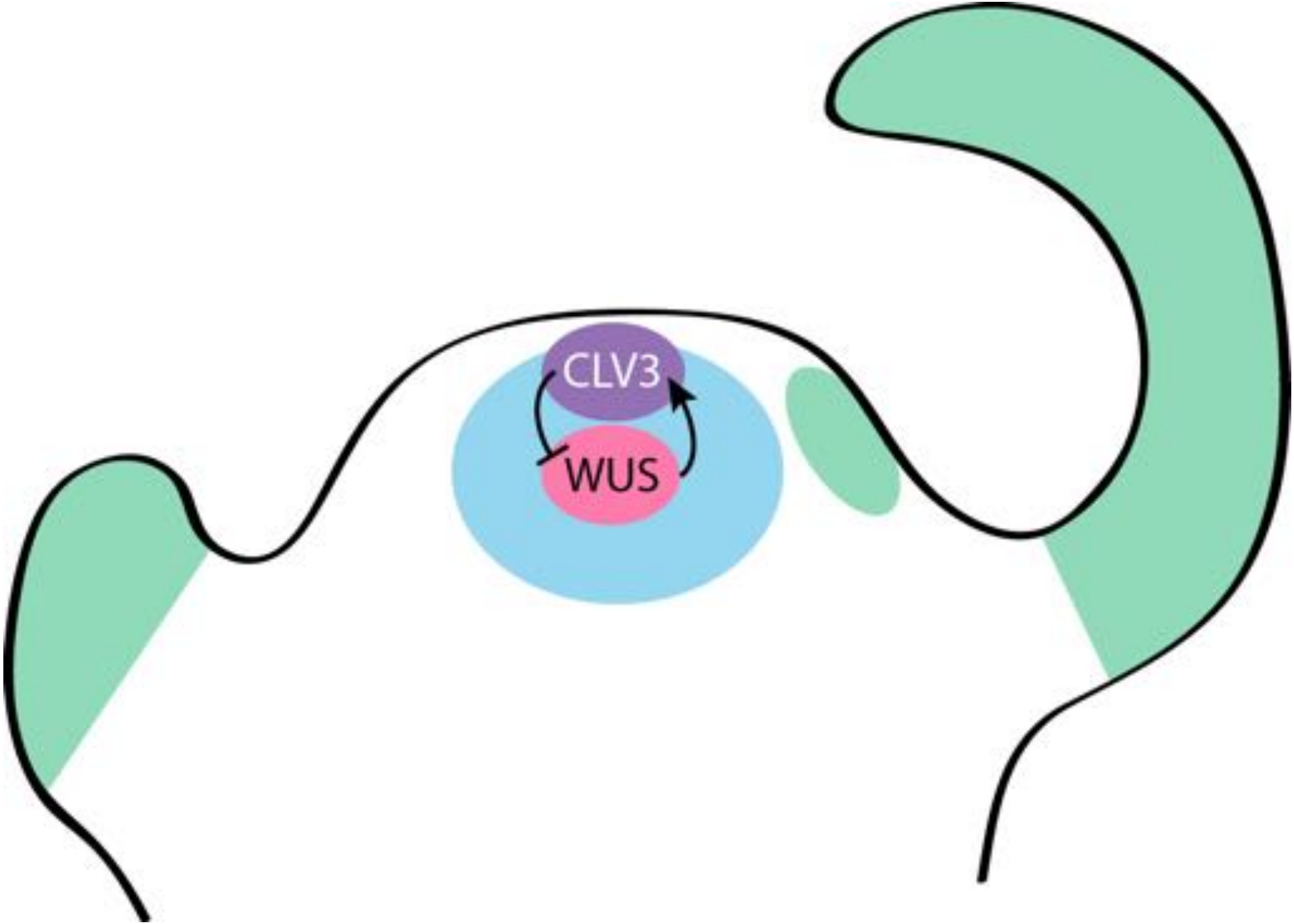


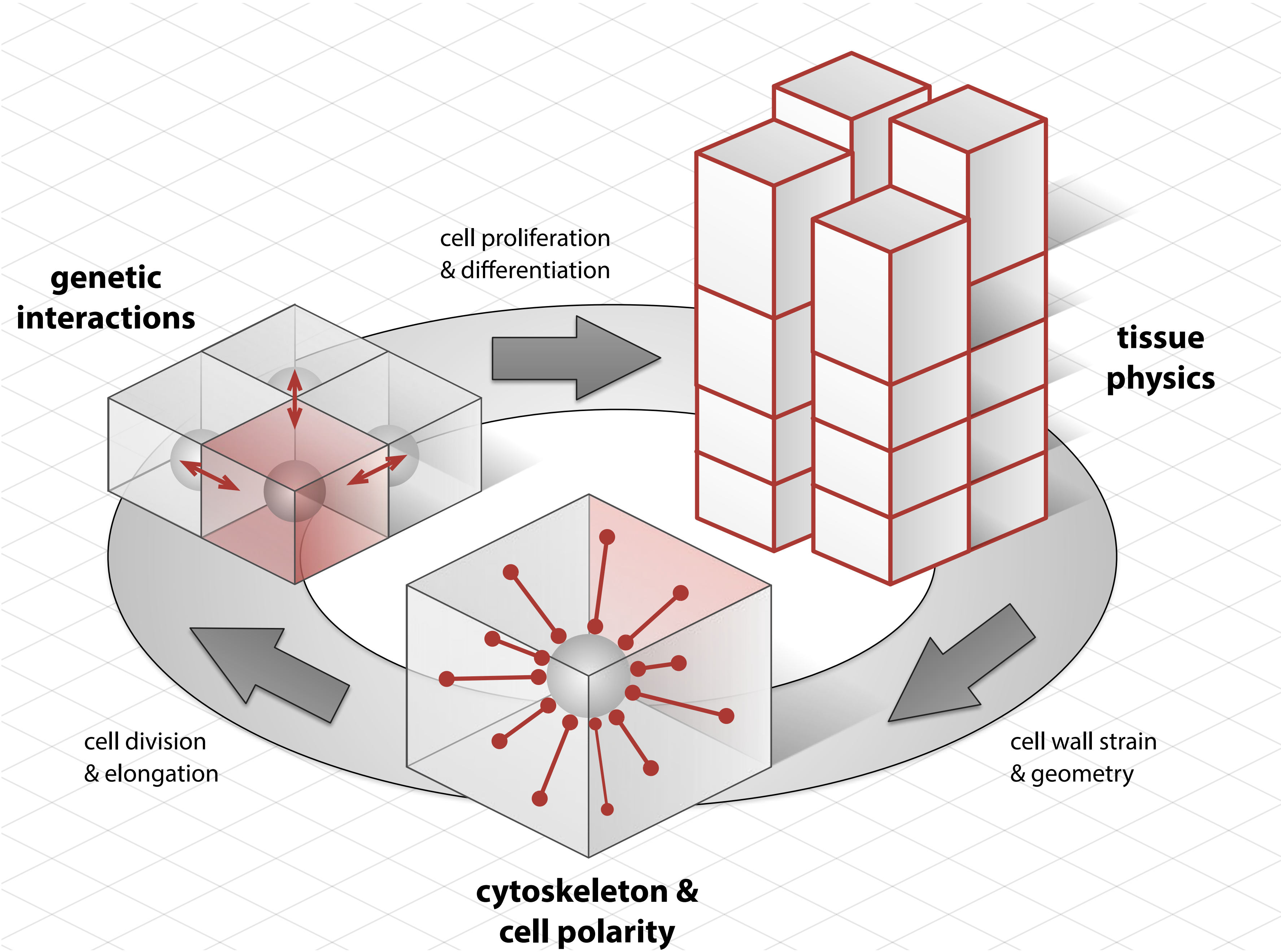
Hashing the SlCLV3 promoter using CRISPR-Cas9



A collection of engineered SlCLV3 promoter alleles provides a continuum of locule number variation




CLV3
WUS



Multi-scale view of plant growth. (i) Interaction between cytoskeletal elements and local cell wall determinants, strain or geometry regulates the polarity of cell division and elongation. (ii) Genetic interactions between neighbouring cells trigger gene expression, cell proliferation and differentiation. (iii) Cellular growth results in physical strains that are transmitted across tissues and constrain cell growth. (iv) Physical constraints on cell size and shape regulate timing and orientation of individual cell divisions and guide morphogenesis.