Evolution of social complexity in the context of multicellularity

Marcus Heisler

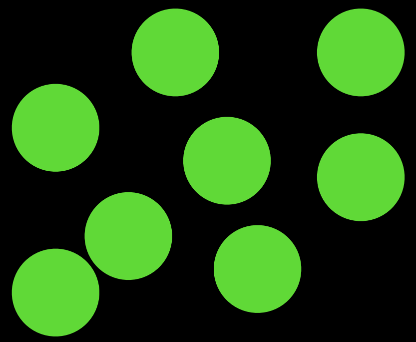
Some perspective...

- Our brain, with approximately 100 billion neurons, each connected to around 10,000 other neurons, making some 100 trillion connections, is thought to be the most complex “thing” we know of in the Universe.

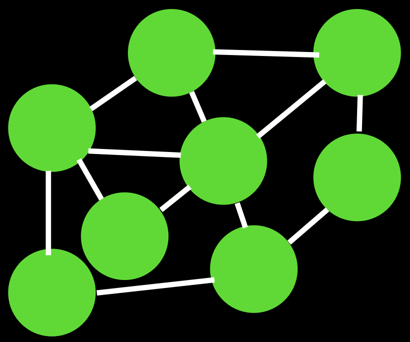
- It is a product of *development* - the process by which all multicellular organisms are constructed.

Development and complex "social" systems

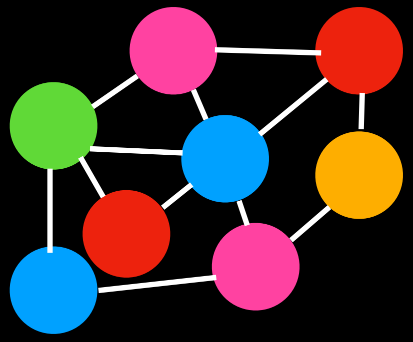
What are complex systems?



- Consist of a large number of entities



- Have a high degree of interaction
  - Can promote specialisation amongst entities (or not)



What favours the formation of complex “social” systems?

In the context of economics, trade networks are incentivised by comparative advantage, leading to specialisation.

In biology, such systems provide interactions that increase individual *inclusive fitness*.

What is *inclusive fitness* and why is it important?

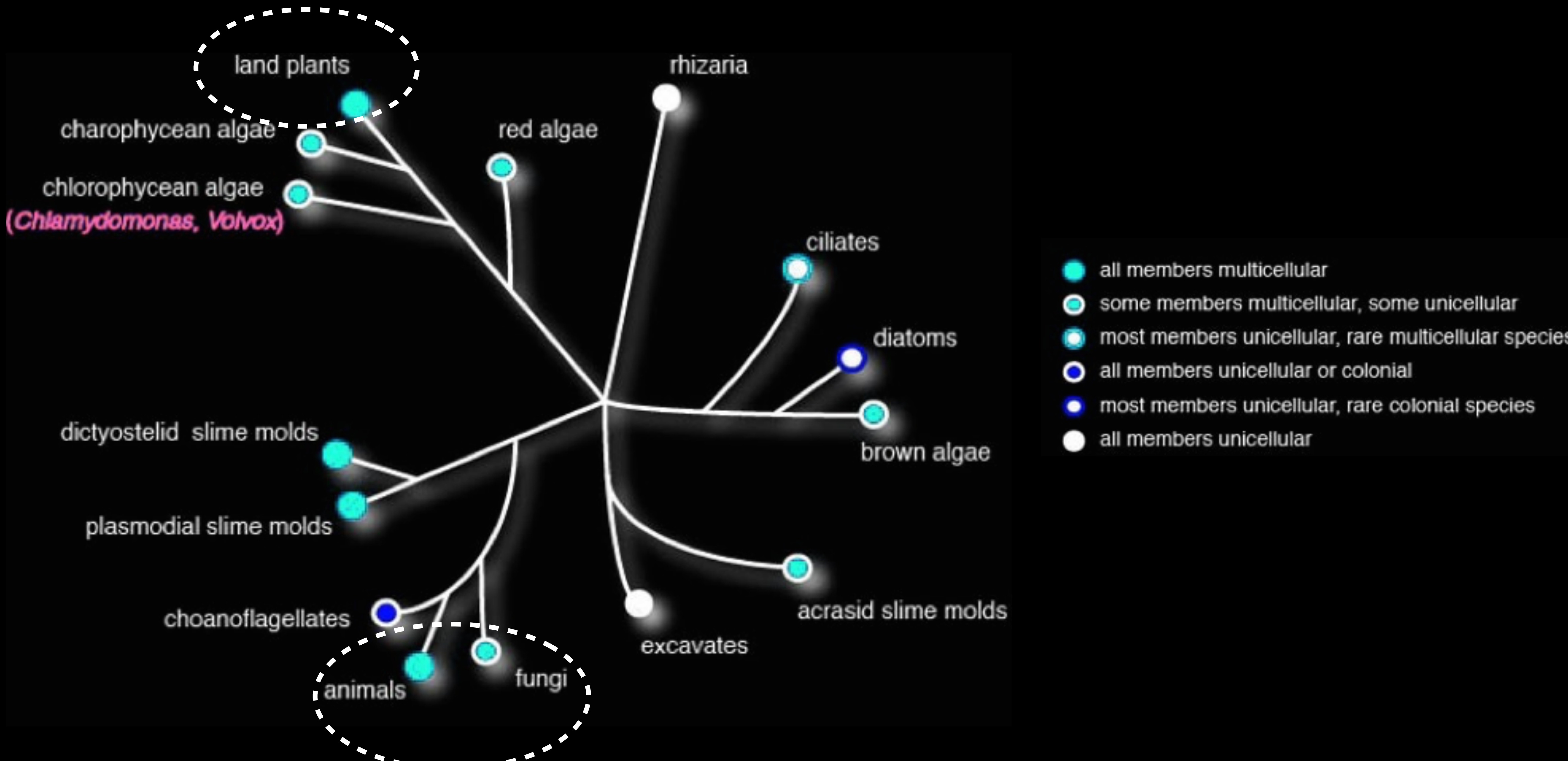
- In biology, what survives, or persists over time are specific DNA sequences - not the individual DNA molecules or cells or organisms.
- They persist over time due to their ability to promote their own replication.

- *Inclusive fitness* is the ability of an individual to transmit genes to the next generation, including genes shared with relatives.
- Thus, an individual's inclusive fitness can depend on altruistic behaviour and cooperation.

Clonal individuals cooperate to the extreme

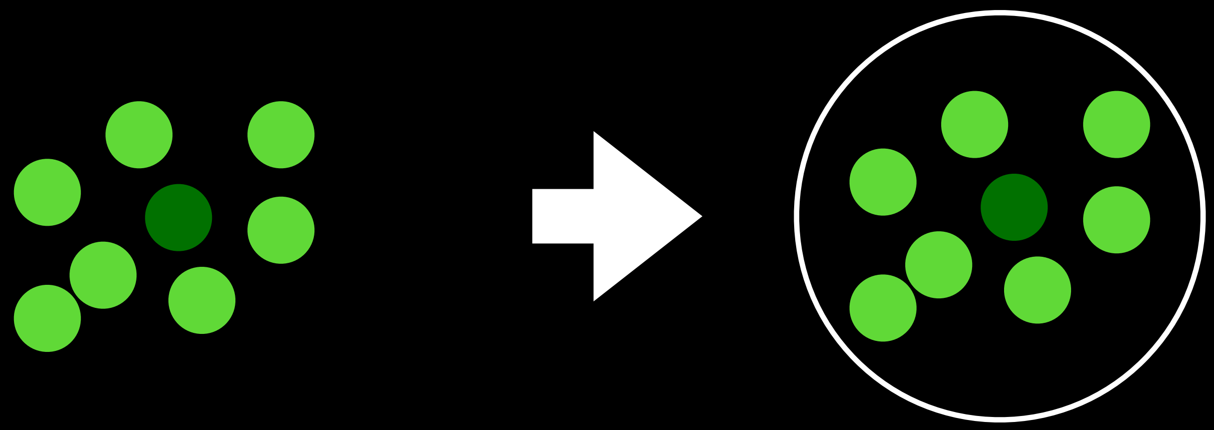
- Altruism common in clonal organisms, e.g. bacteria, slime moulds
- Multicellularity - cells cooperate physically to create organism that includes division of labor in reproduction.
- Clonal insects (e.g. aphids, wasp species) exhibit eusocial behaviour i.e. advanced cooperative social organisation, including division of labor in reproduction - “Super-organisms”.

The evolution of multicellularity has occurred many times

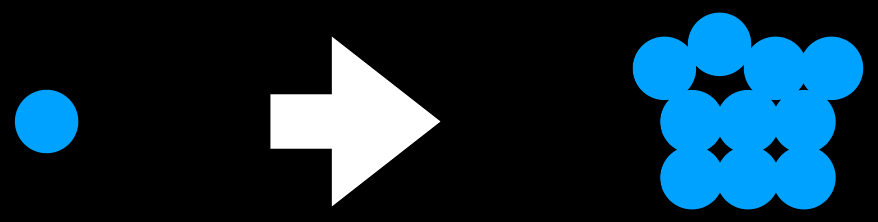


Two fundamental ways to construct multicellular organisms

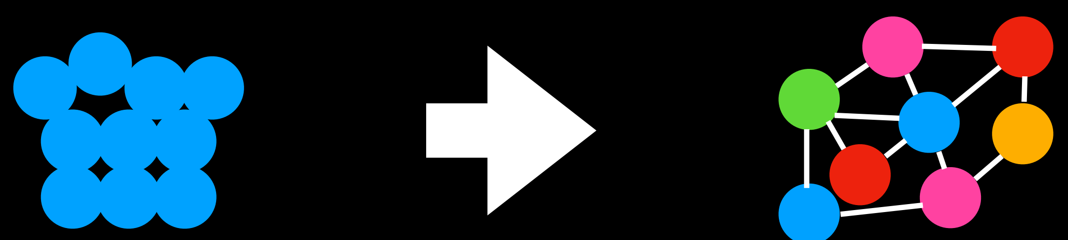
- Cell aggregation



- Cell division without separation (clonal development)



- Differential gene activity and communication



Aggregation

In response to environmental hardship
(Dictyostelium or slime mould)

Jitka Cejkova U. Chem and Tech, Prague

Aggregation

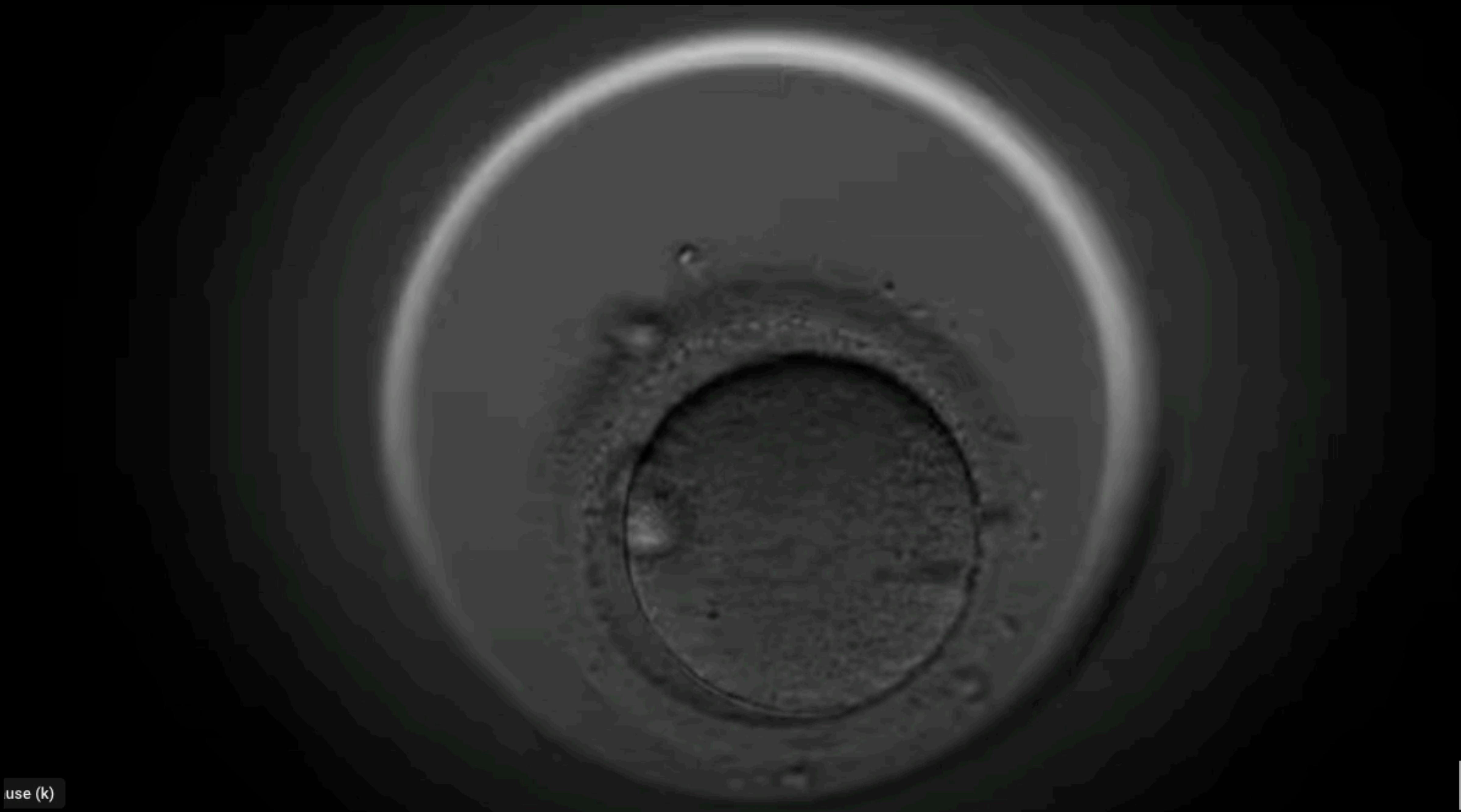
https://youtu.be/7w-wCP7-WEw?si=-U9XKo1sy4yN9Sw2

John Bonner, Princeton

Only cells at the top of the fruiting body pass on their genes

https://youtu.be/bkVhLJLG7ug?si=koxL-NKyC7T4URP6

Clonal development



https://youtu.be/hALGv5lL8Po?si=P1j71y8s2qzDOAlt Human embryogenesis Boston IVF

Selective pressures promoting multicellularity

- Size
    - Spore dispersal (height)
    - predation (most predators can only eat certain sized prey..) - recently demonstrated experimentally

Multicellular Chlamydomonas evolved in the lab in response to the aciliate predator Paramecium tetraurelia (750 generations)

Selective pressures maintaining and enhancing multicellularity

- Division of labor - cell differentiation
- Size

For example…

- A digestive system to more efficiently absorb nutrients
- A vascular system to disperse nutrients

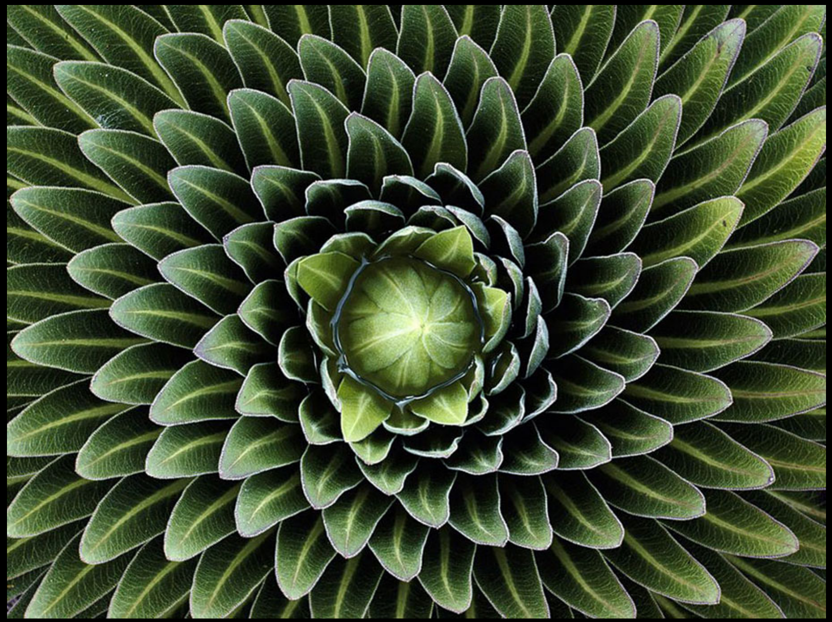
Major transitions in biological complexity - transitions in individuality

- Independent replicating molecules (genes) → chromosomes
- Prokaryotes → Eukaryotes
- Single cell → Multicellular
- Clonal multicellular organisms → Eusocial “super organisms”

By tying each gene’s replication to the survival of higher order structures, selection favours genes the promote survival of the higher order structure. Higher order structures enable greater division of labor/specialisation. What are the trade-offs??…

(See “The Major Transitions in Evolution” by Maynard Smith and Szathmary)

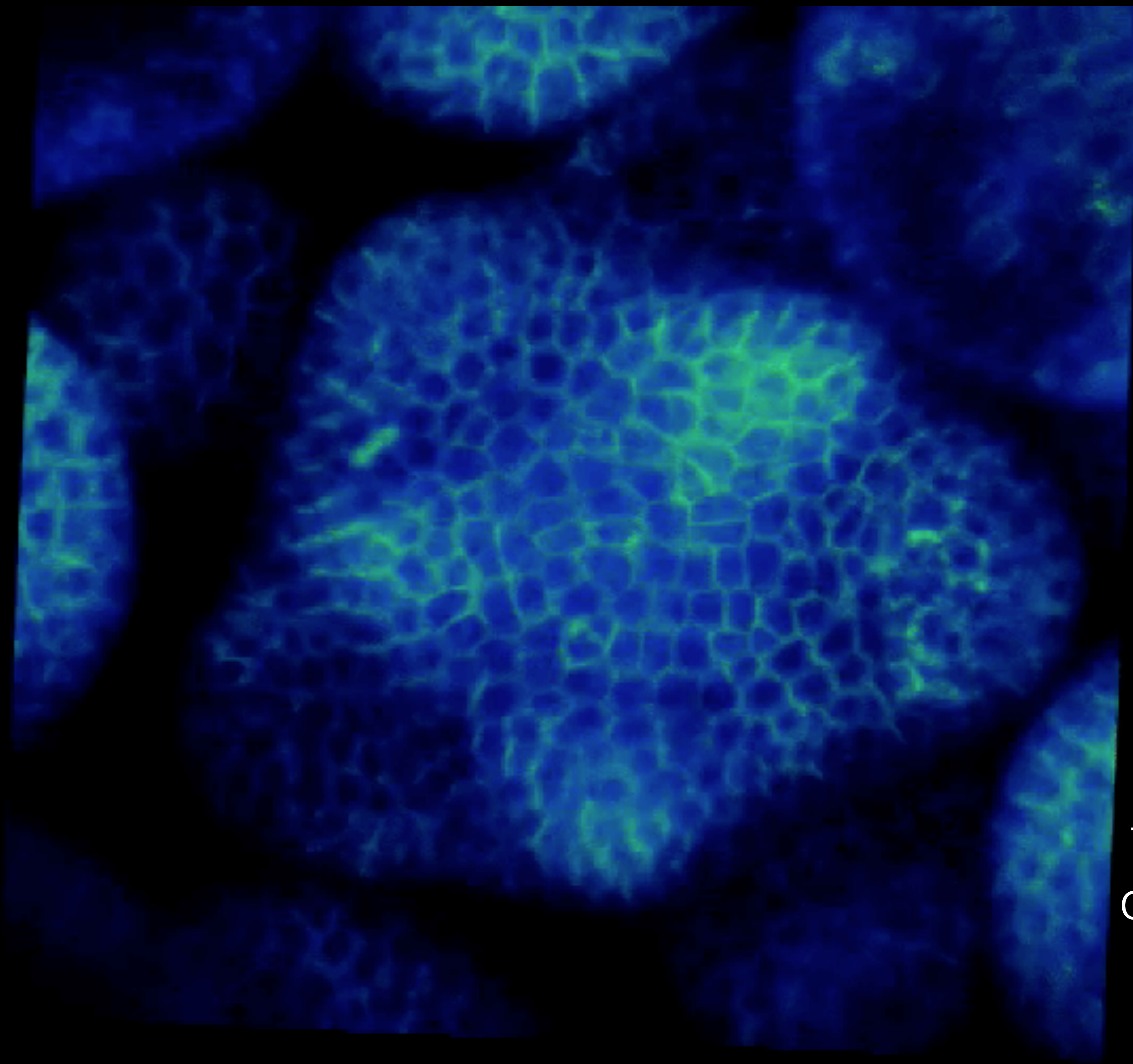
Heisler lab interest: Plant lateral organs - periodicity and a flattened shape



The Arabidopsis shoot meristem

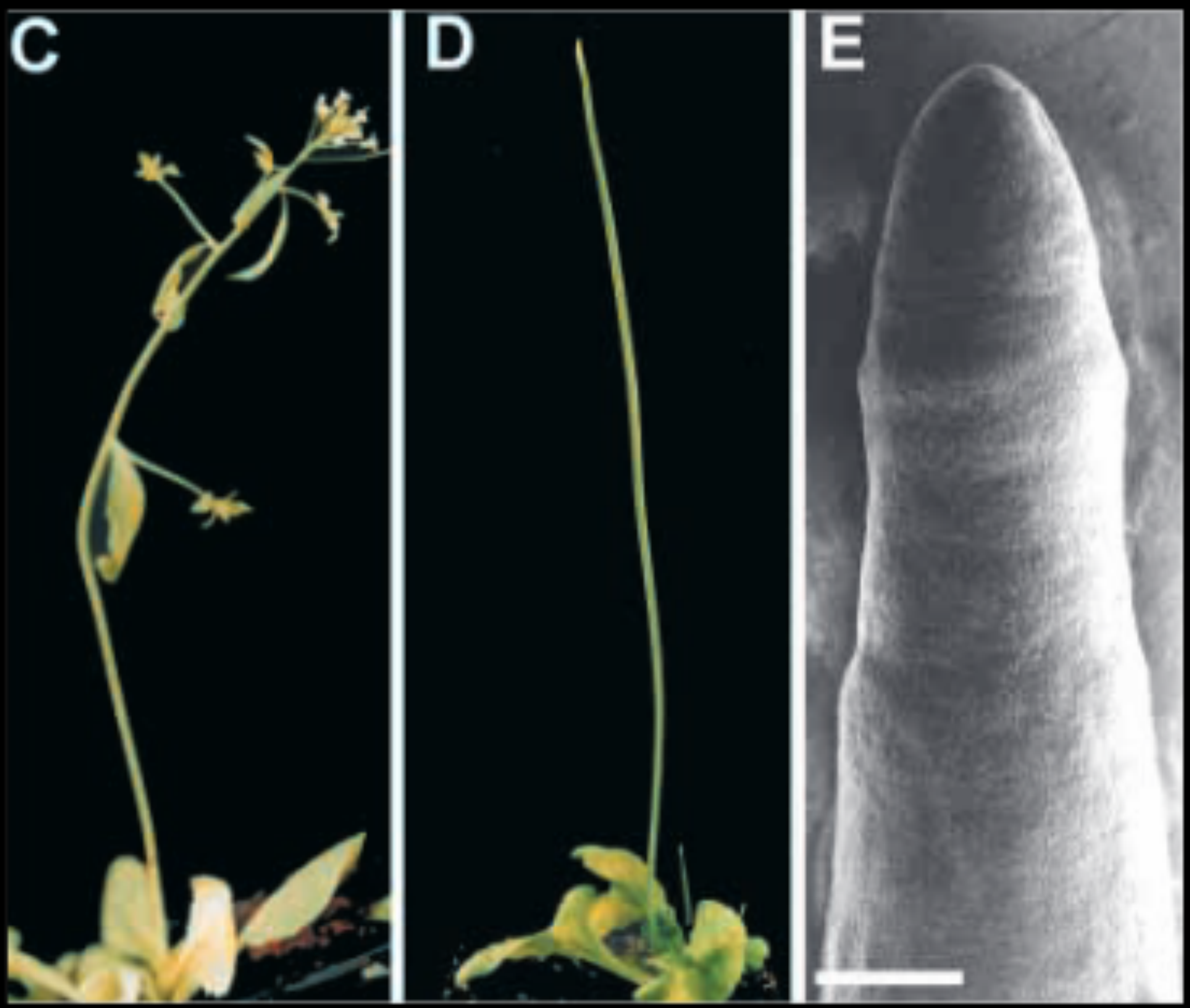
Organogenesis at the shoot meristem



time lapse
over 40 hrs

Heisler et al. 2005

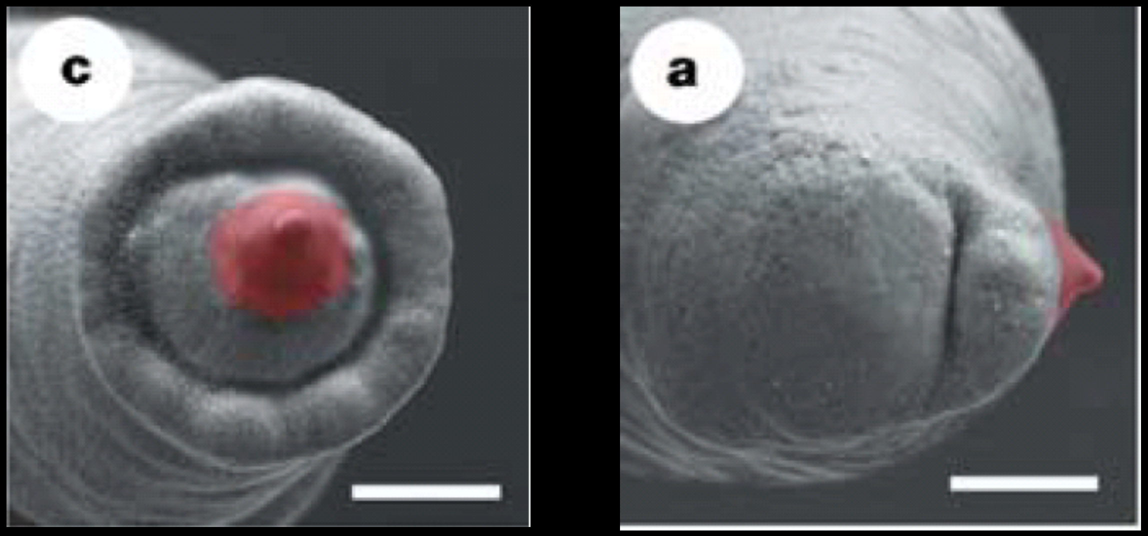
Cell-to-cell transport of a hormone is required for organ formation



Wild type apex

pin1 mutants fail to form flowers

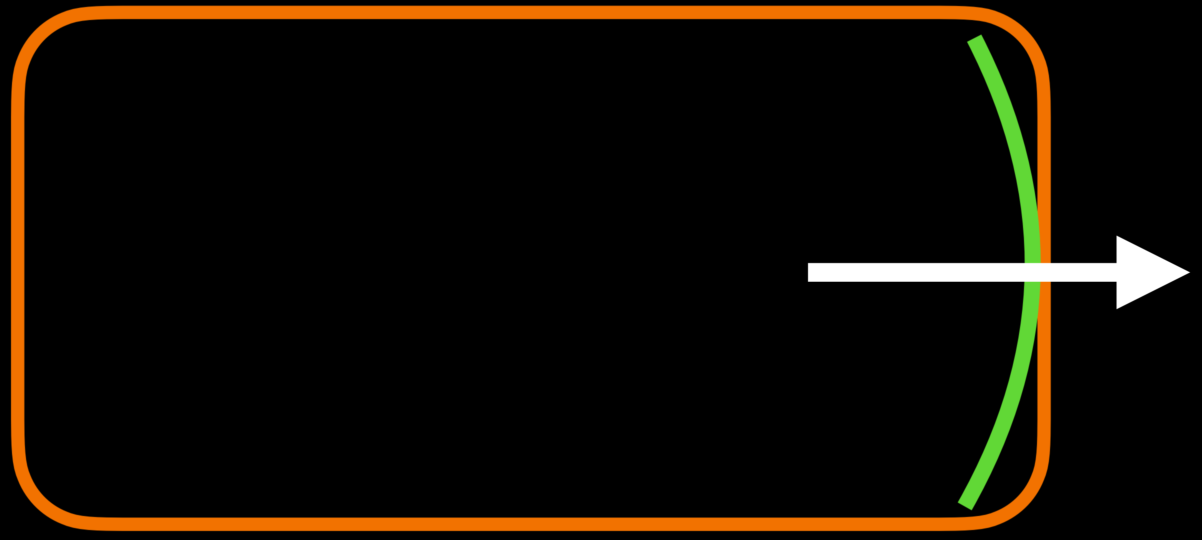
Vernoux et al., 2000.

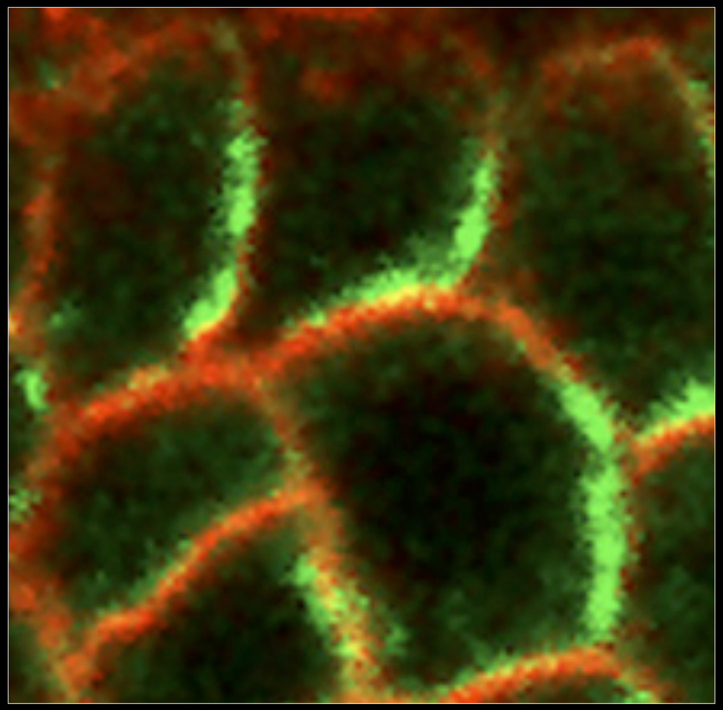


Hormone application can rescue organ formation

Reinhardt et al (2003) *Nature*

Hormone is transported directionally





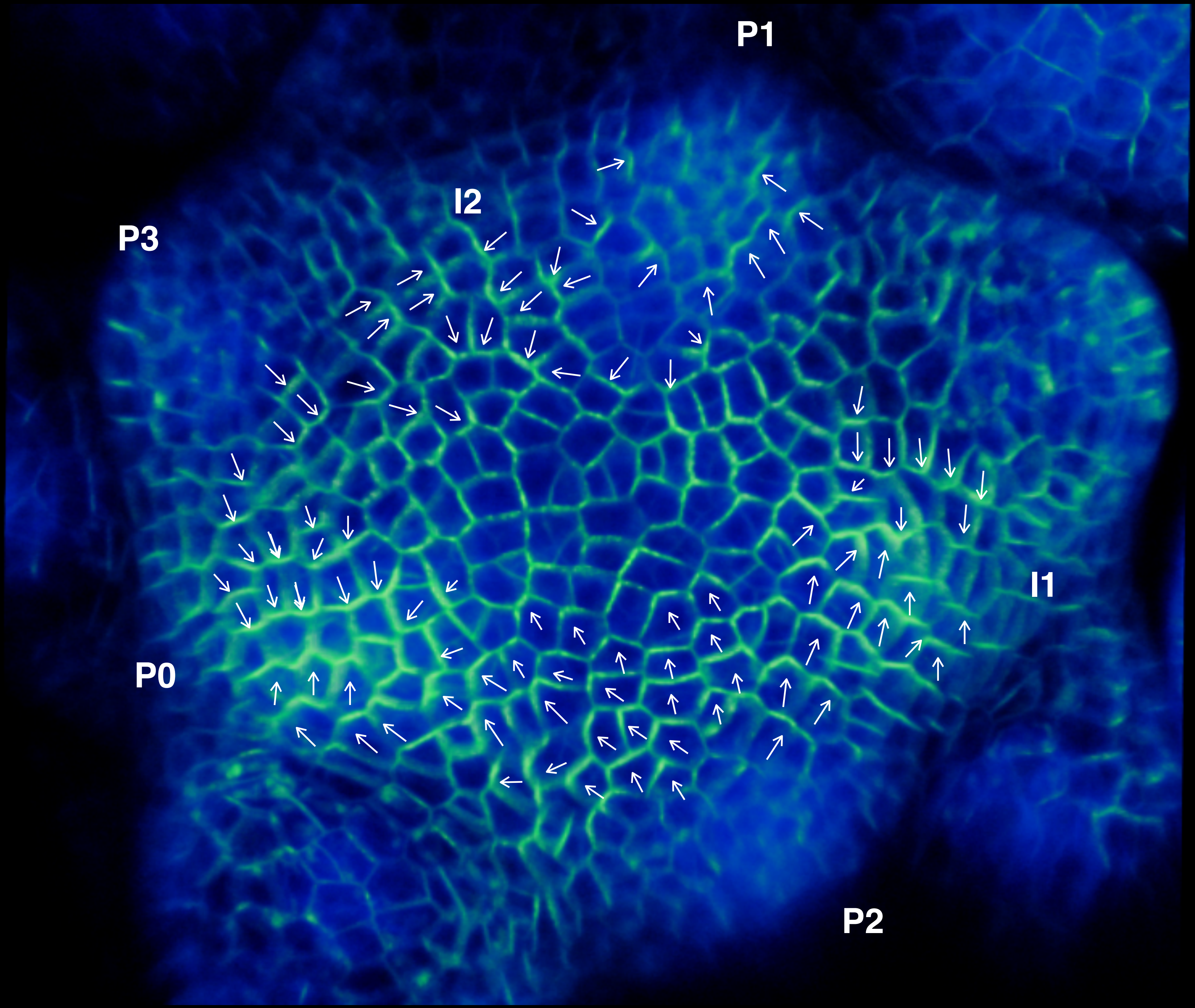
Cell

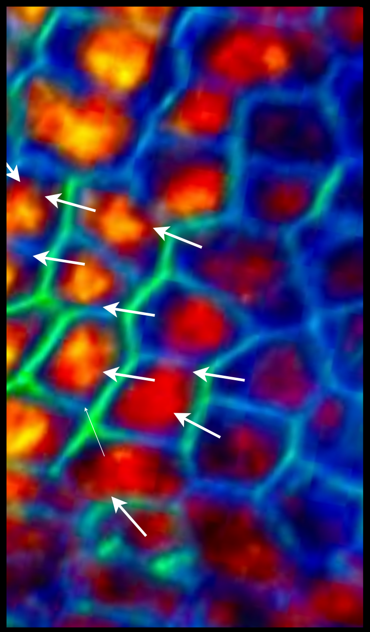
Hormone transporter

Cell

Hormone transporter

Transporter directs hormone toward sites of organ formation





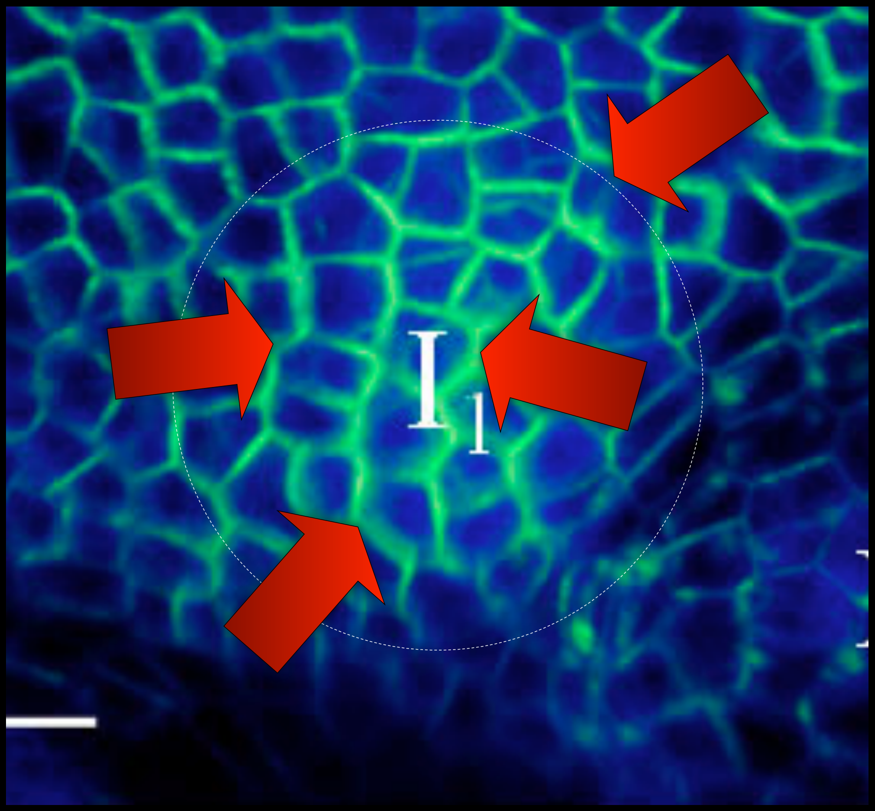
e sensor

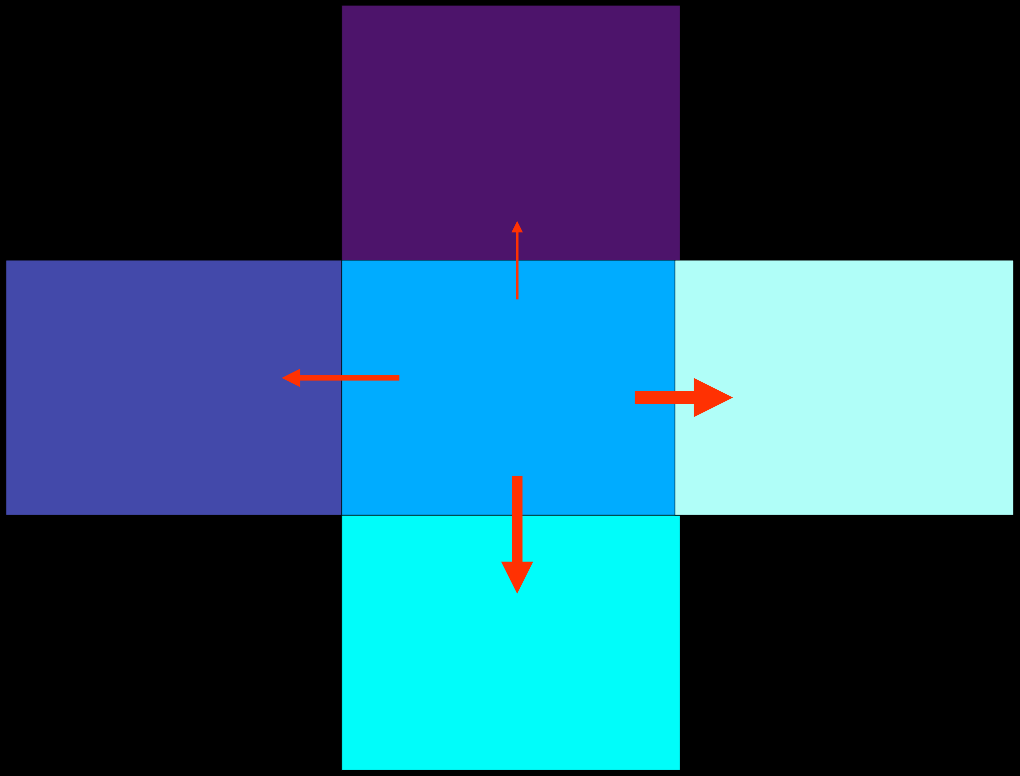
2016

How are transport directions determined?

Does signalling go both ways?

Feedback between PIN1 and auxin can generate periodic patterns

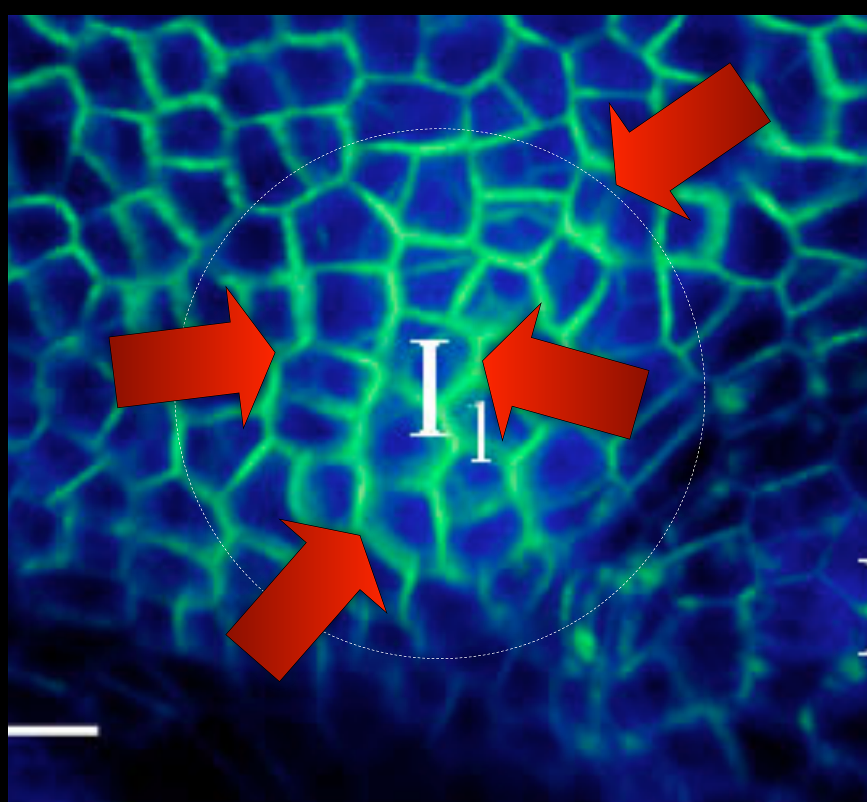


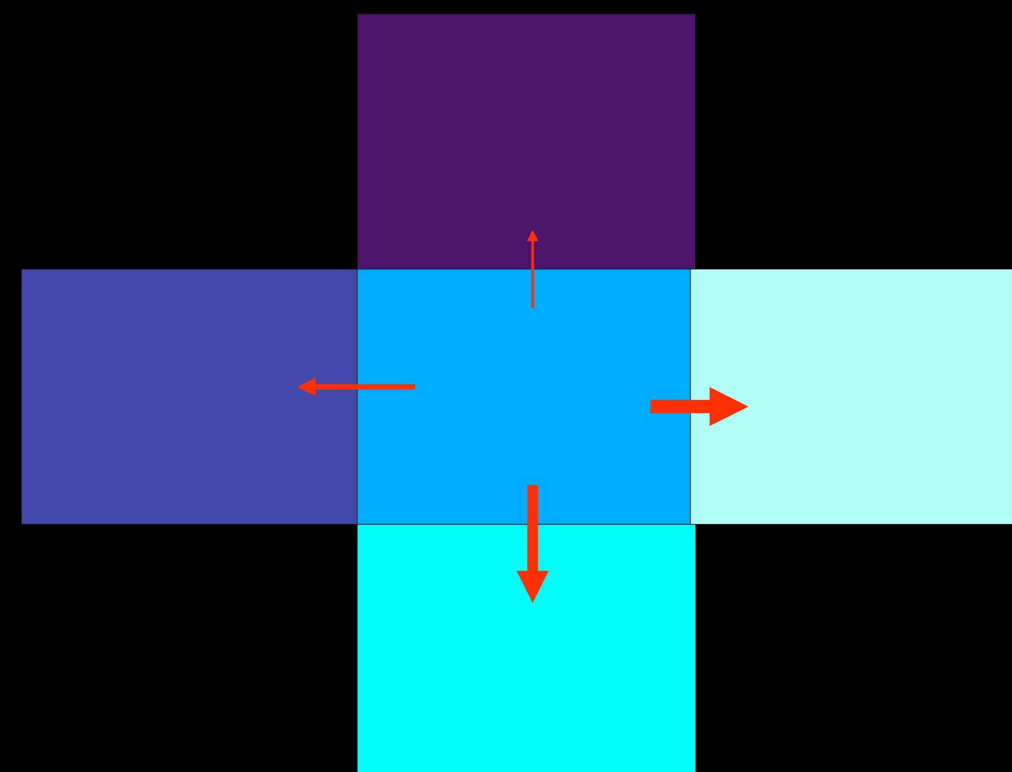


A cell polarises its PIN1 towards its neighbours with the most auxin

Jonsson and Heisler et al., 2006, *PNAS*

Feedback between transporter and hormone can generate periodic patterns



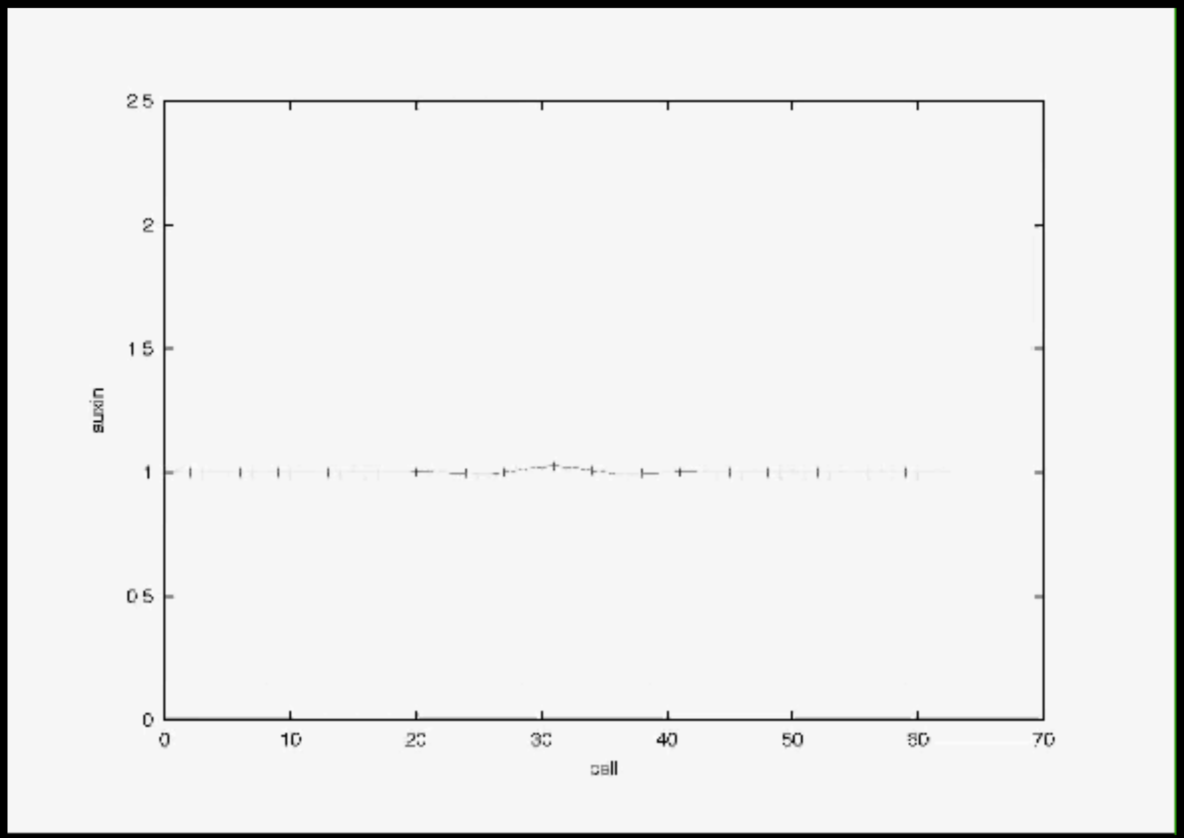


$$P_{ij} = P_i \frac{a_j}{\sum_k^{N_i} a_k} \propto P_i a_j$$

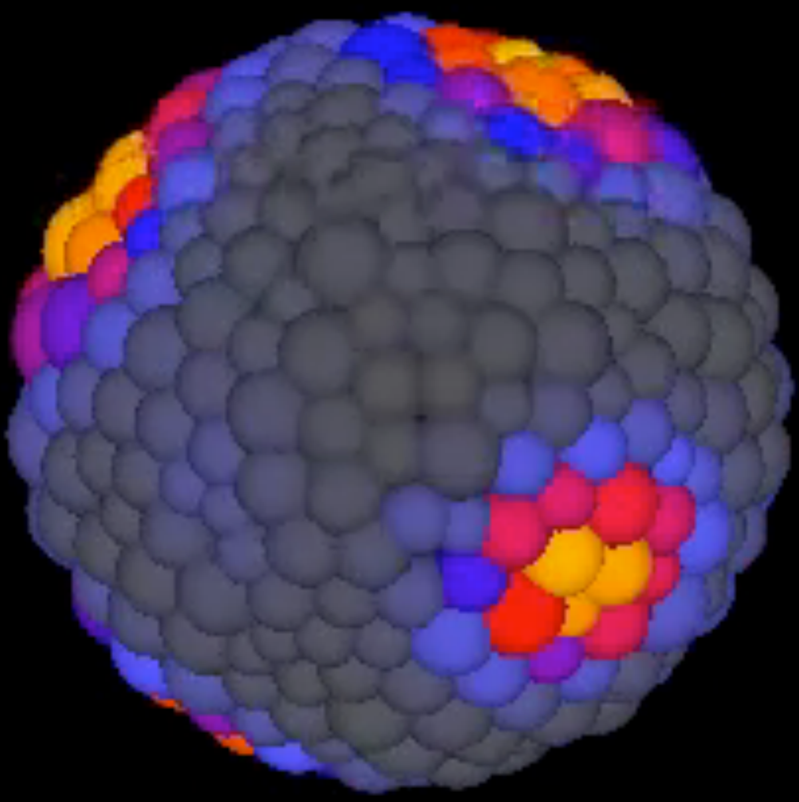
Jonsson and Heisler et al., 2006, *PNAS*

Feedback between PIN1 and auxin can generate periodic patterns

auxin conc.



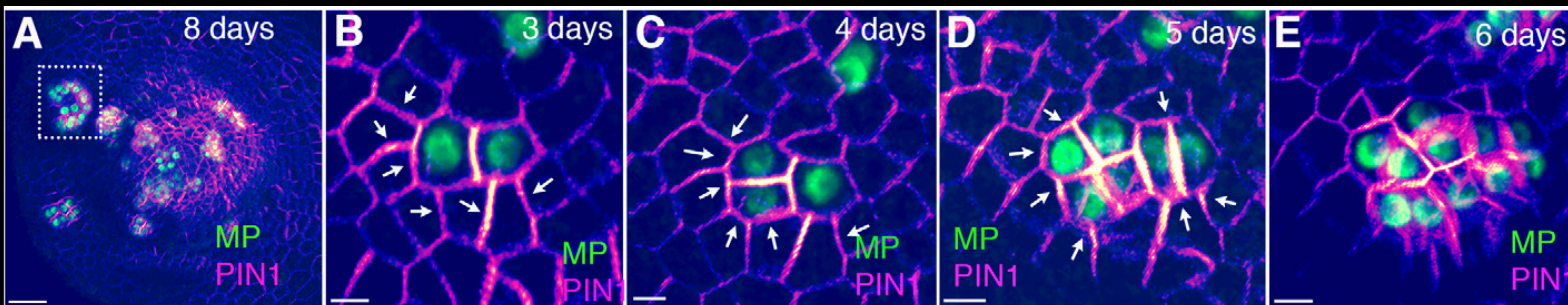
cells



Jonsson and Heisler et al., 2006, *PNAS*

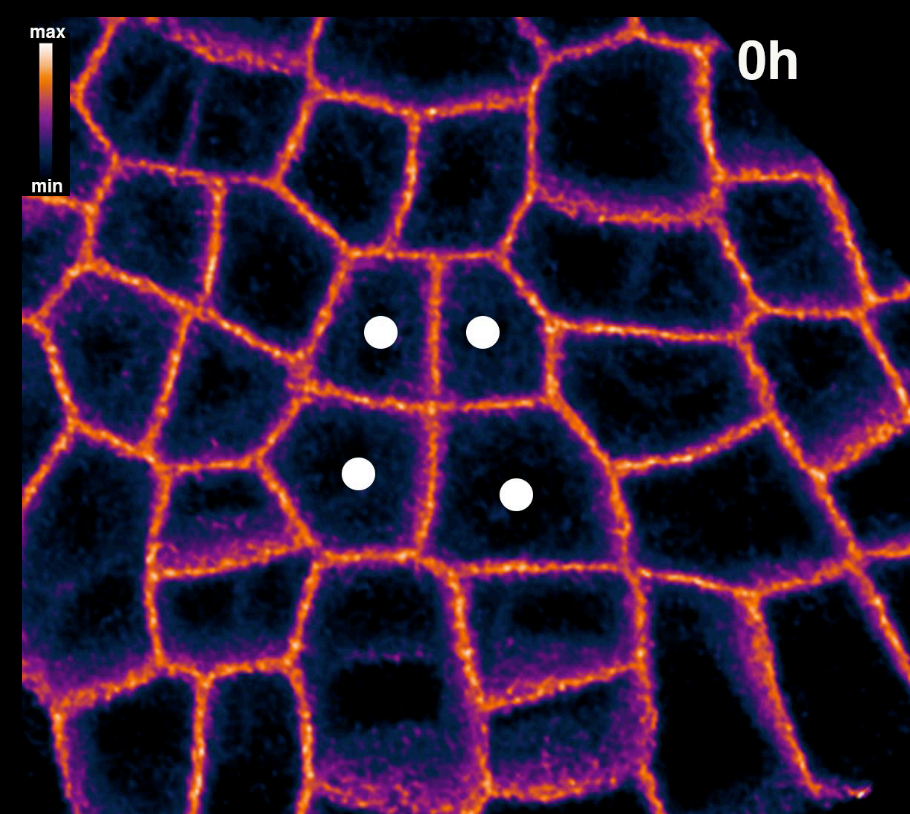
EMBL

Local hormone levels orient transport direction



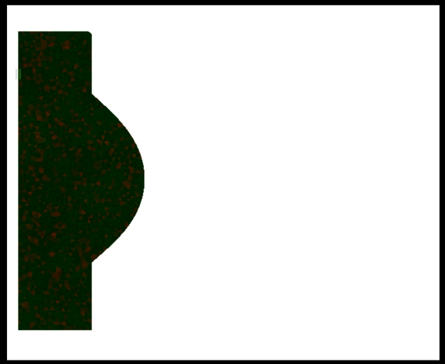
Transporter

Hormone

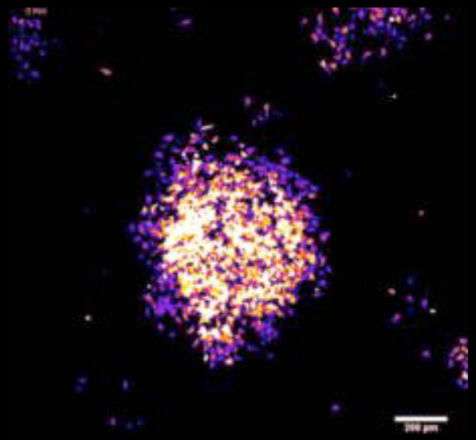


Bhatia et al., 2016, *PNAS*

Examples of emergent patterning

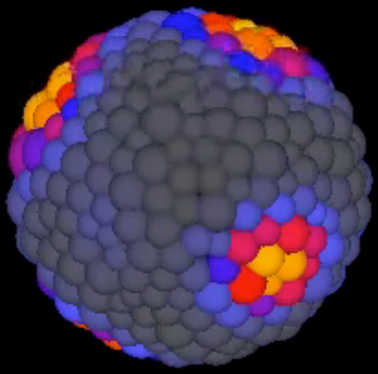


- Reaction-diffusion - Digit patterning

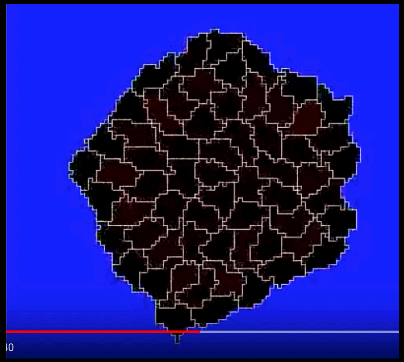


- Spontaneous traveling waves - Somatogenesis

Hubaud et al (2018) Cell



- Polarized transport - Plant phyllotaxis



- Lateral inhibition

Greenwald and Rubin (1982) Cell

- Organanoids/regeneration

Werner et al (2016) Curr Op Cell Biol

Acknowledgments

Heisler Lab

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