# Preliminaries for Distributed Natural Computing Inspired by the Slime Mold Physarum Polycephalum

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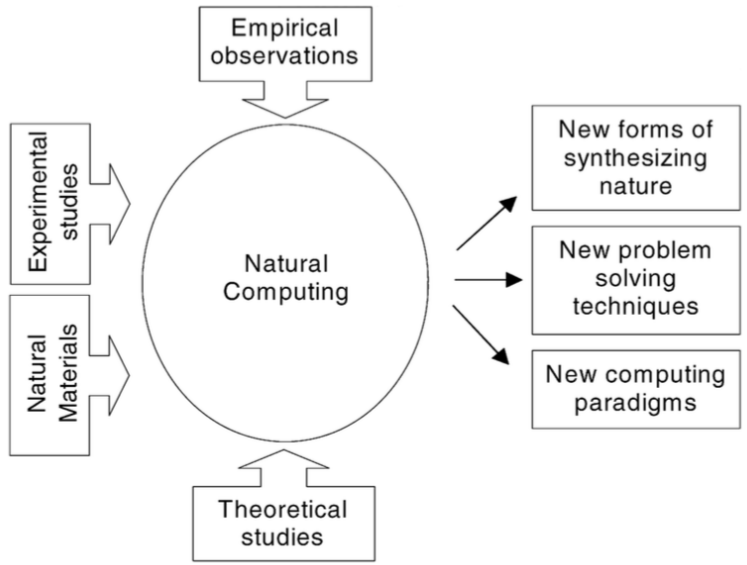
# Part I: Natural Computing with P. polycephalum

# Natural Computing in a Nutshell

- Design novel nature-inspired algorithms.
- Synthesize natural phenomena using computers.
- Use natural materials to do computations.






Natural Computing is a highly interdisciplinary field!

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Ant Colony Optimization, M. Dorigo, 2004

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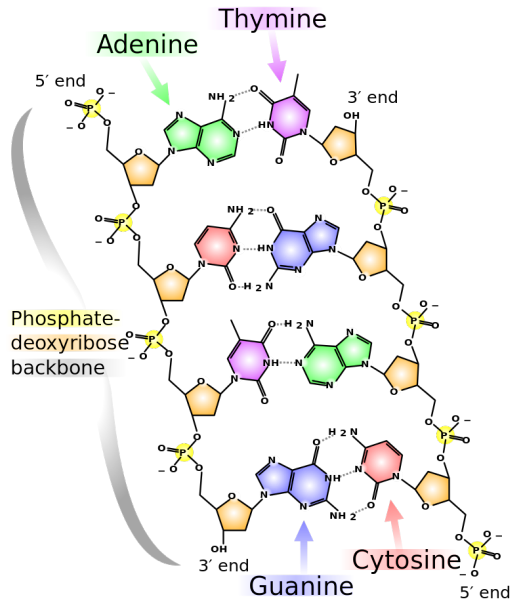




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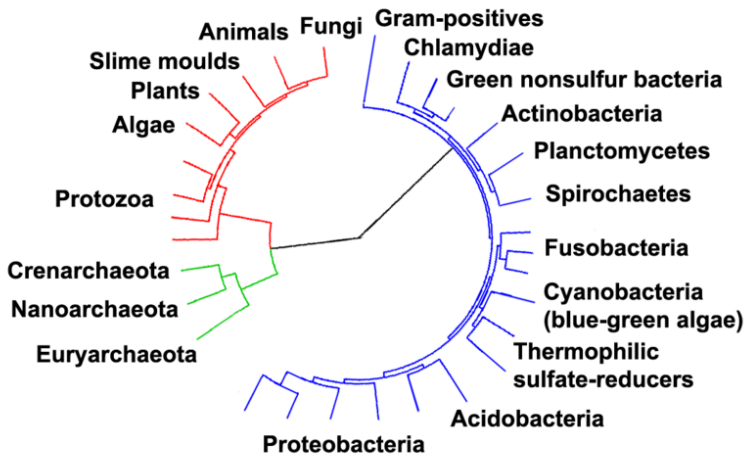
# A Magnificent Mold

*Physarum polycephalum*:

- Unicellular organism with many nuclei.
- Intricate foraging strategy.
- Networks circulate protoplasm.




Courtesy of Prof. T. Ueda

## Key Properties:

Distributed dynamics, Min and Max capabilities

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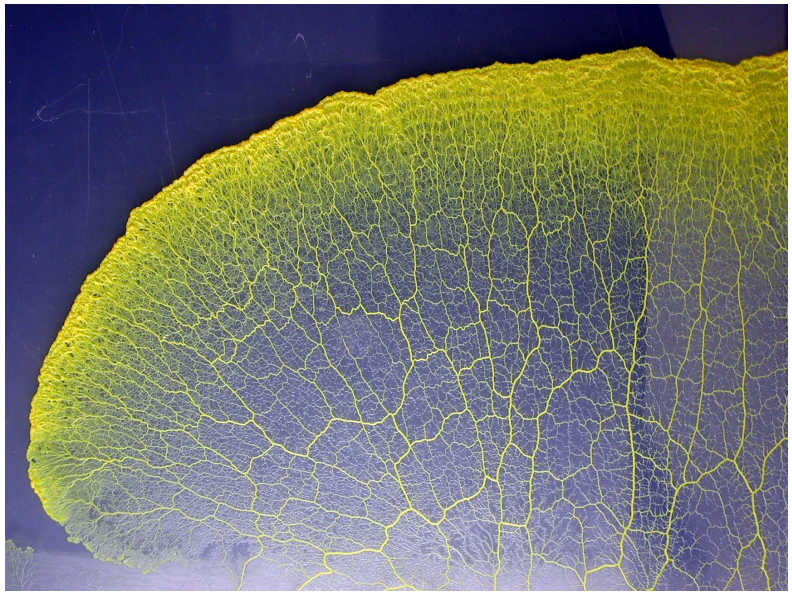

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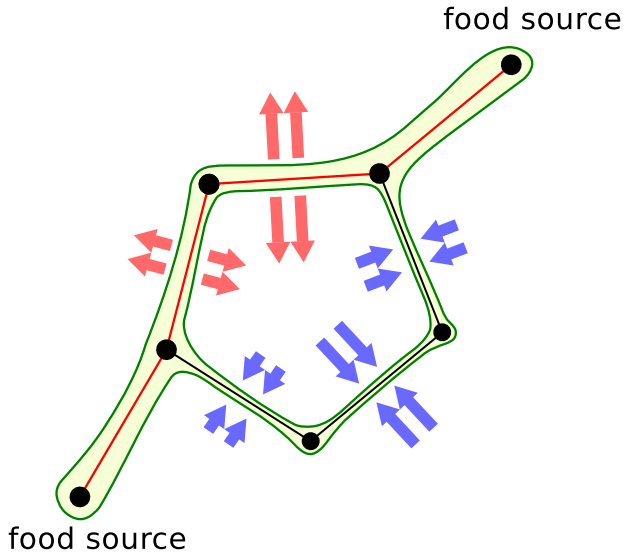
# Natural Computing with *P. polycephalum*

## Successful approaches:

- Positive feedback models/algorithms.
- Many particle simulations/cellular automata.
- Steering with light.




see T. Nakagaki et al. 2006

## Caveat:

Existing work is focused on morphological changes in *P. polycephalum*. Flow dynamics have largely been ignored.

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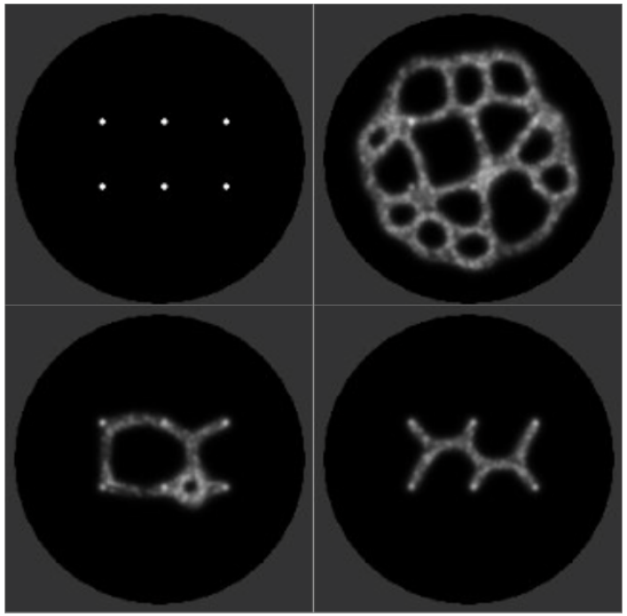

see J. Jones 2010

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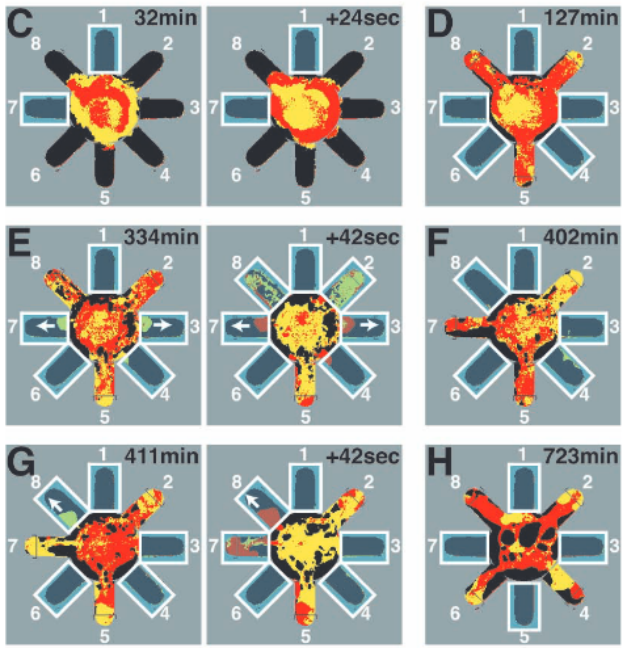


see M. Aono et al. 2007

## Caveat:

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# What about the flows?

## Observation:

*P. polycephalum* maintains some type of dynamic flow circulation on a changing graph in a distributed manner.

## Our aim:

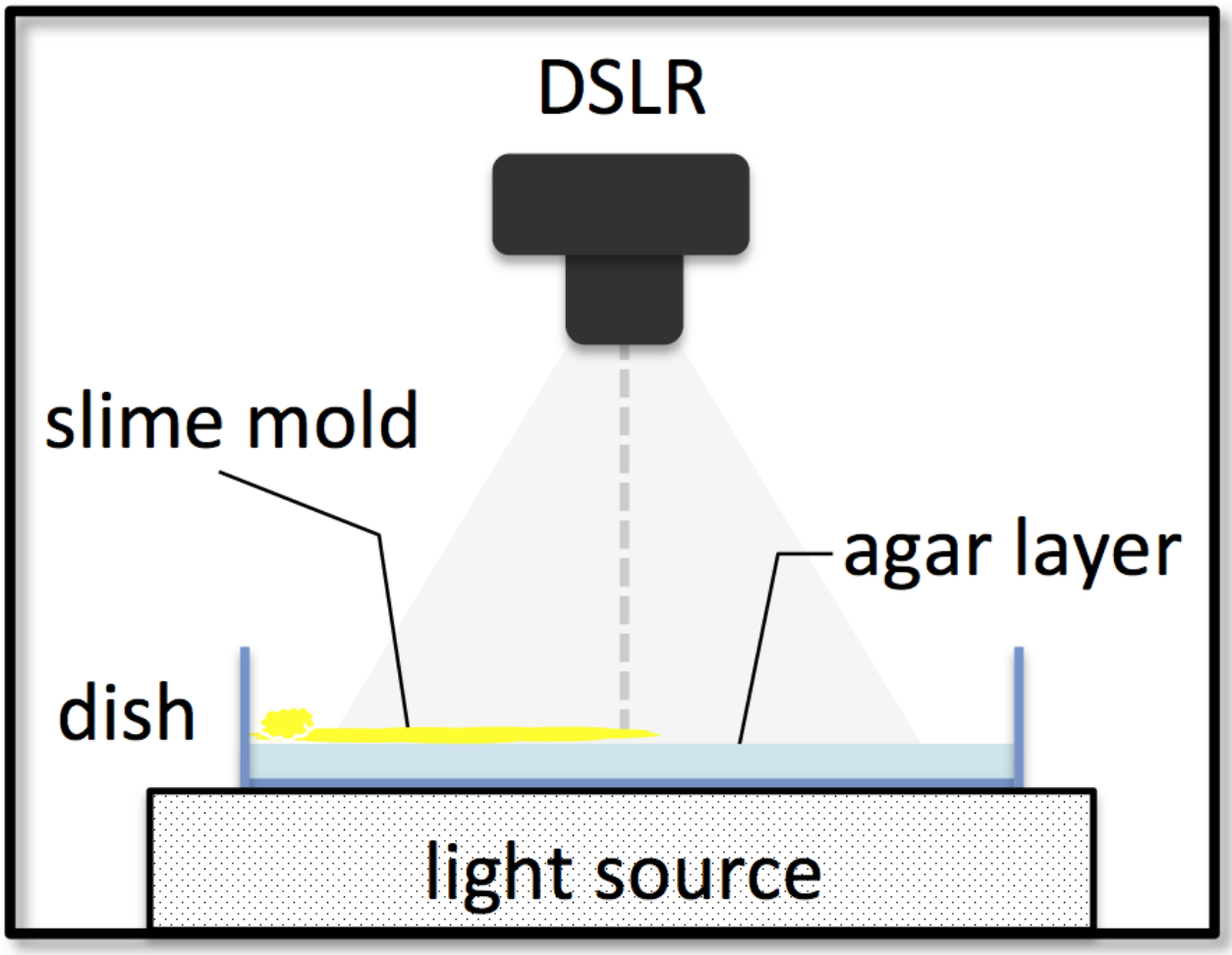
Study the networks formed by *P. polycephalum* in order to drive the development of a distributed model of its dynamic flows.

## Our approach:

- Obtain a large body of experimental data.
- Study network properties.
- Model the dynamics exhibited by *P. polycephalum*.

# Part II: Studying the networks formed by P. polycephalum

# Experiments

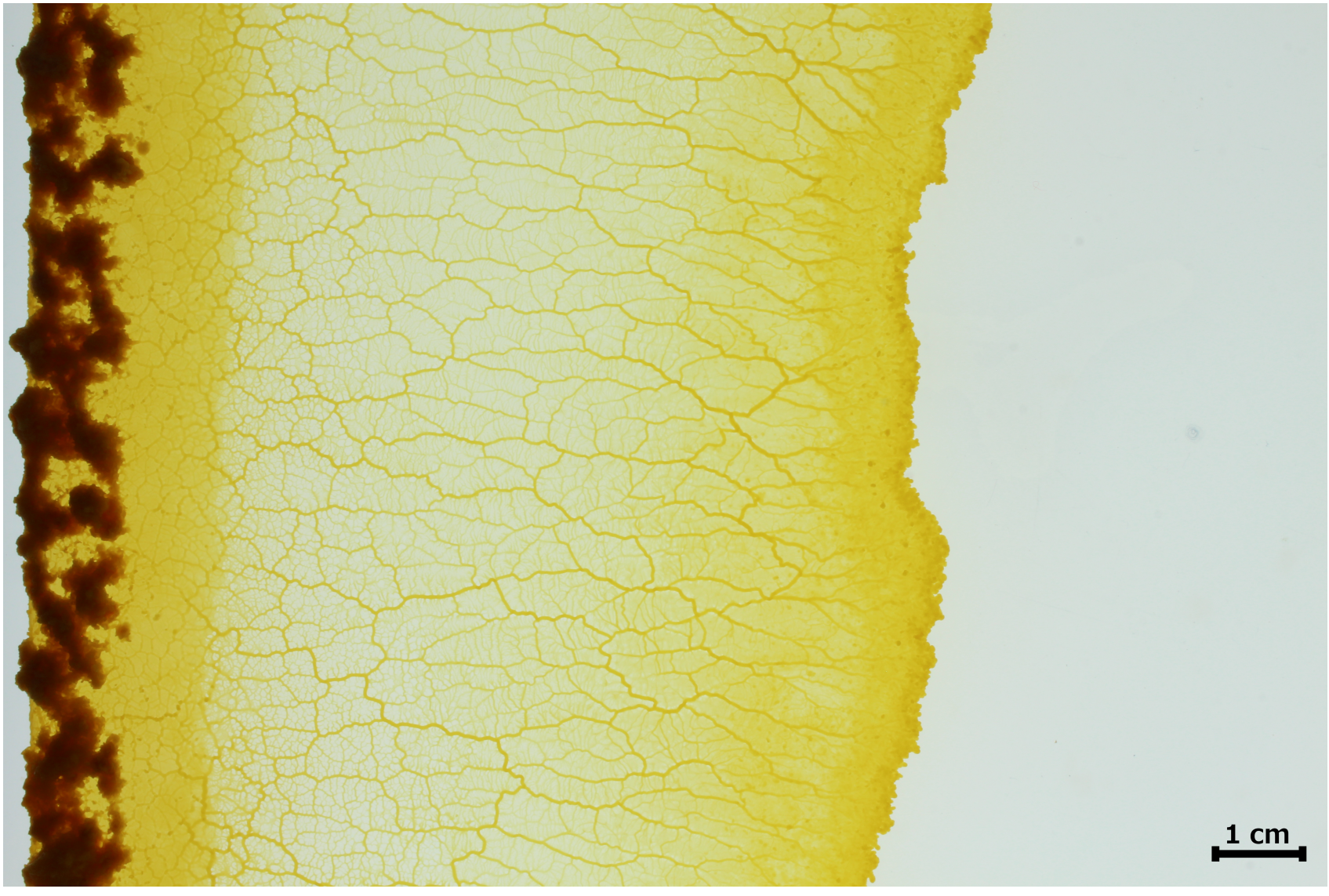



Schematic of experimental setup.

# Experiments

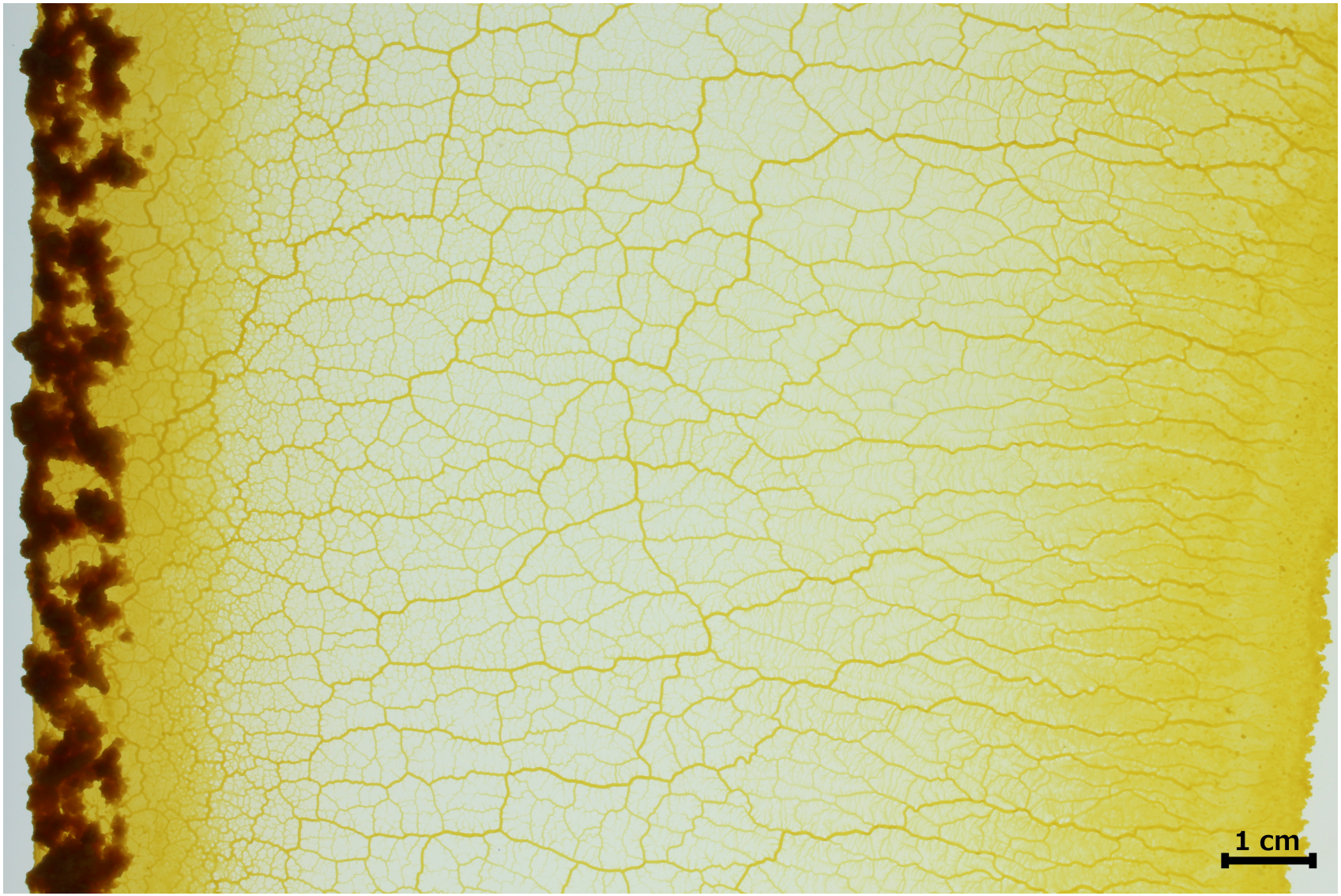

Sclerotia placed in the container.

# Experiments



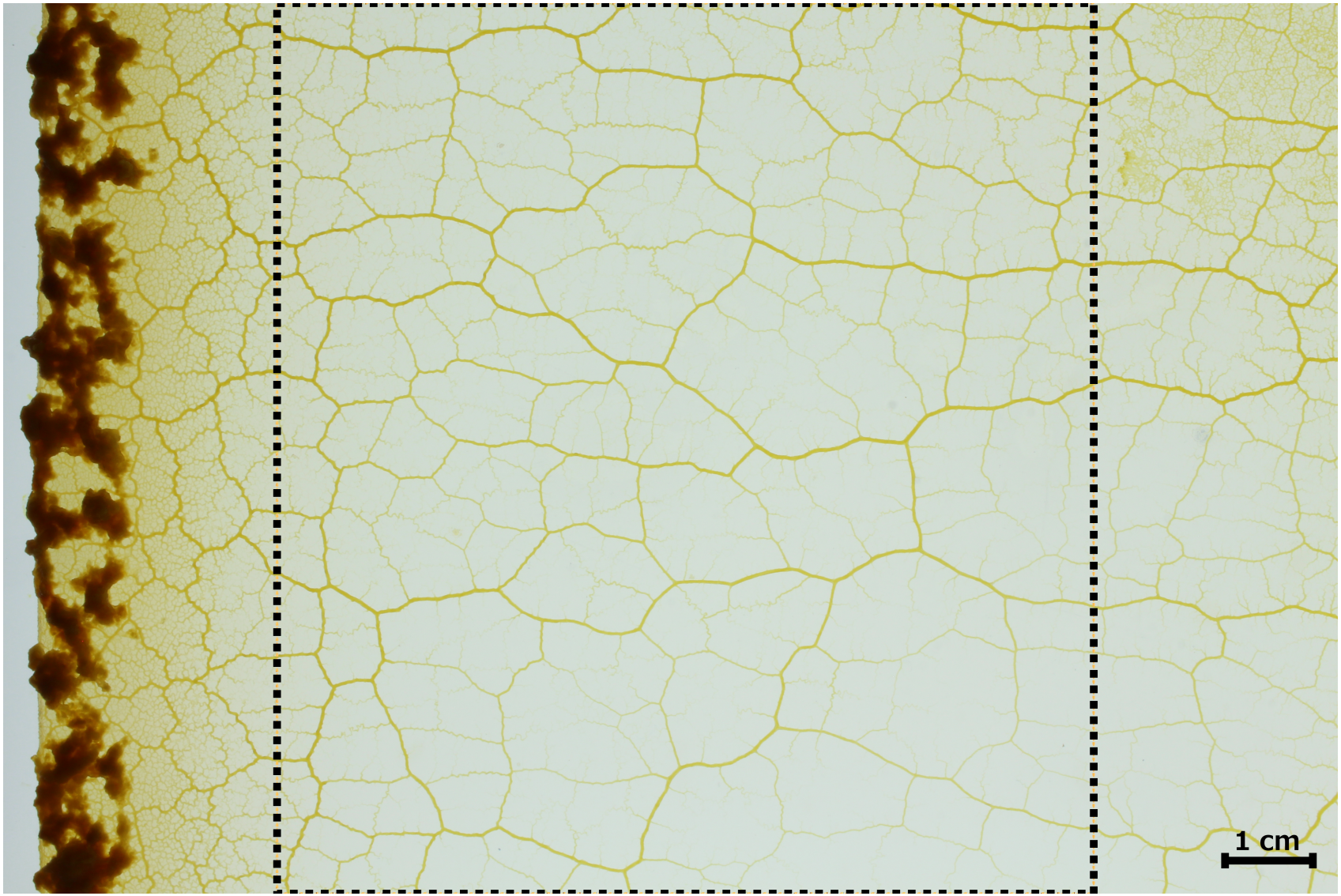

The exploring front moves on.

# Experiments



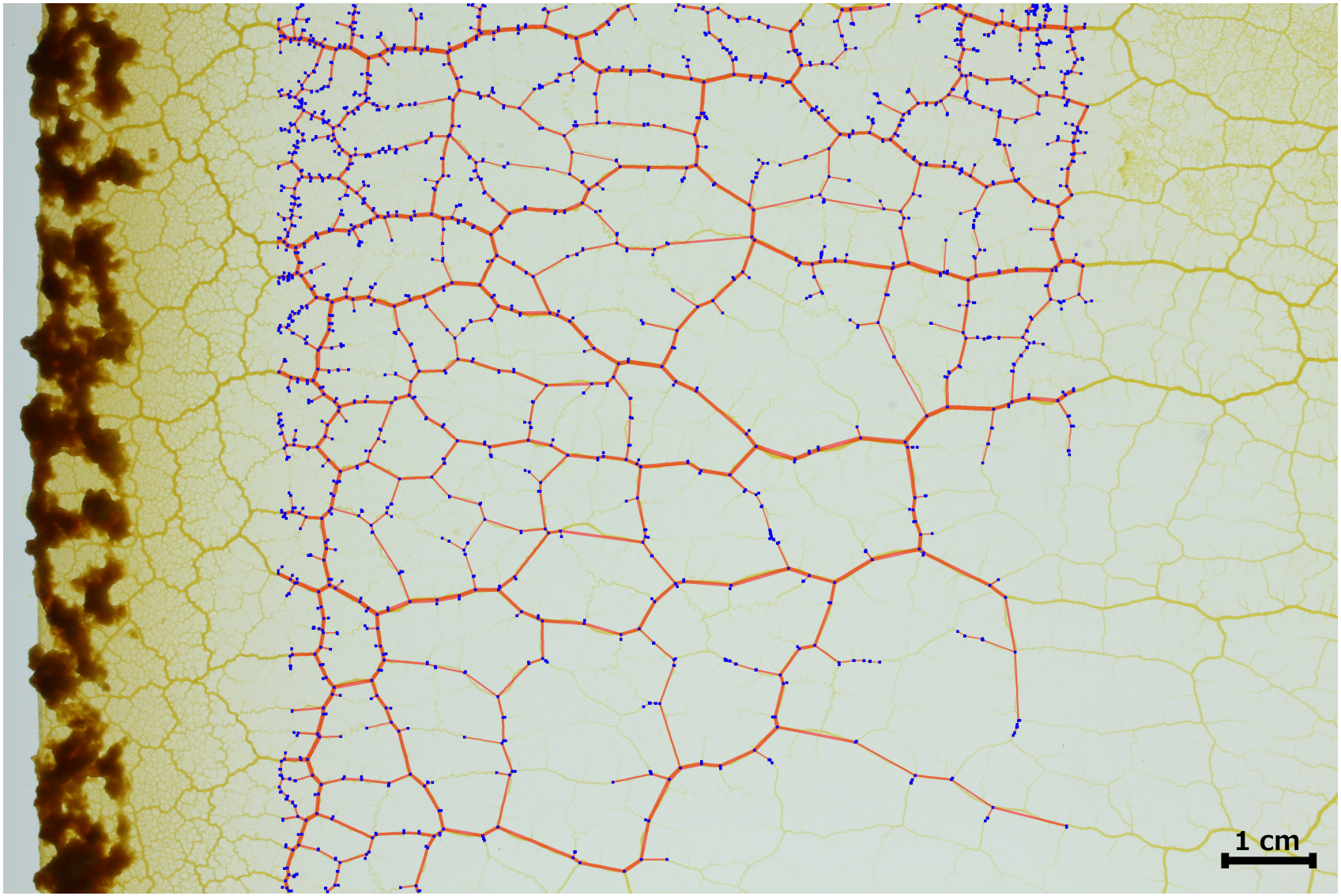

A intricate network supports the front.

# Experiments




A region of interest is defined.

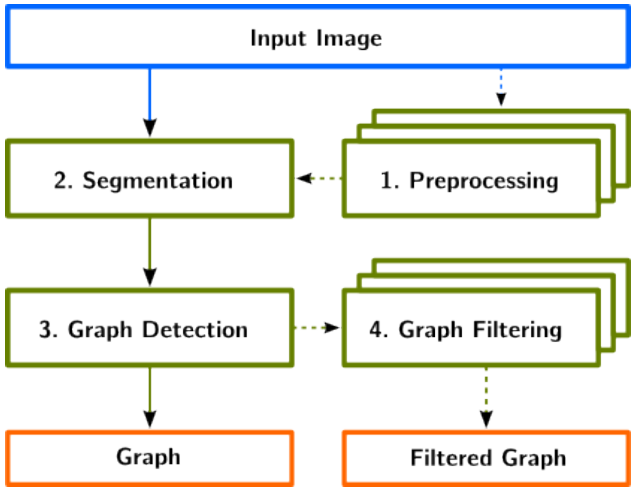
# Experiments




A graph representation of the network is computed.

# Network Extraction From Images Dirnberger et al., 2015

- Input: High quality image of a network.
- Output: Graph representation of depicted structure.




NEFI's workflow.

## Design goals:

- Combine well-known and well-implemented algorithms to obtain a new modular tool.
- Make it accessible for others (e.g. non-experts).

# Analysis of *P. polycephalum* networks

## KIST Europe data set:

Consists of 38 distinct time series of *P. polycephalum* graphs, totalling 1998 weighted planar graphs.

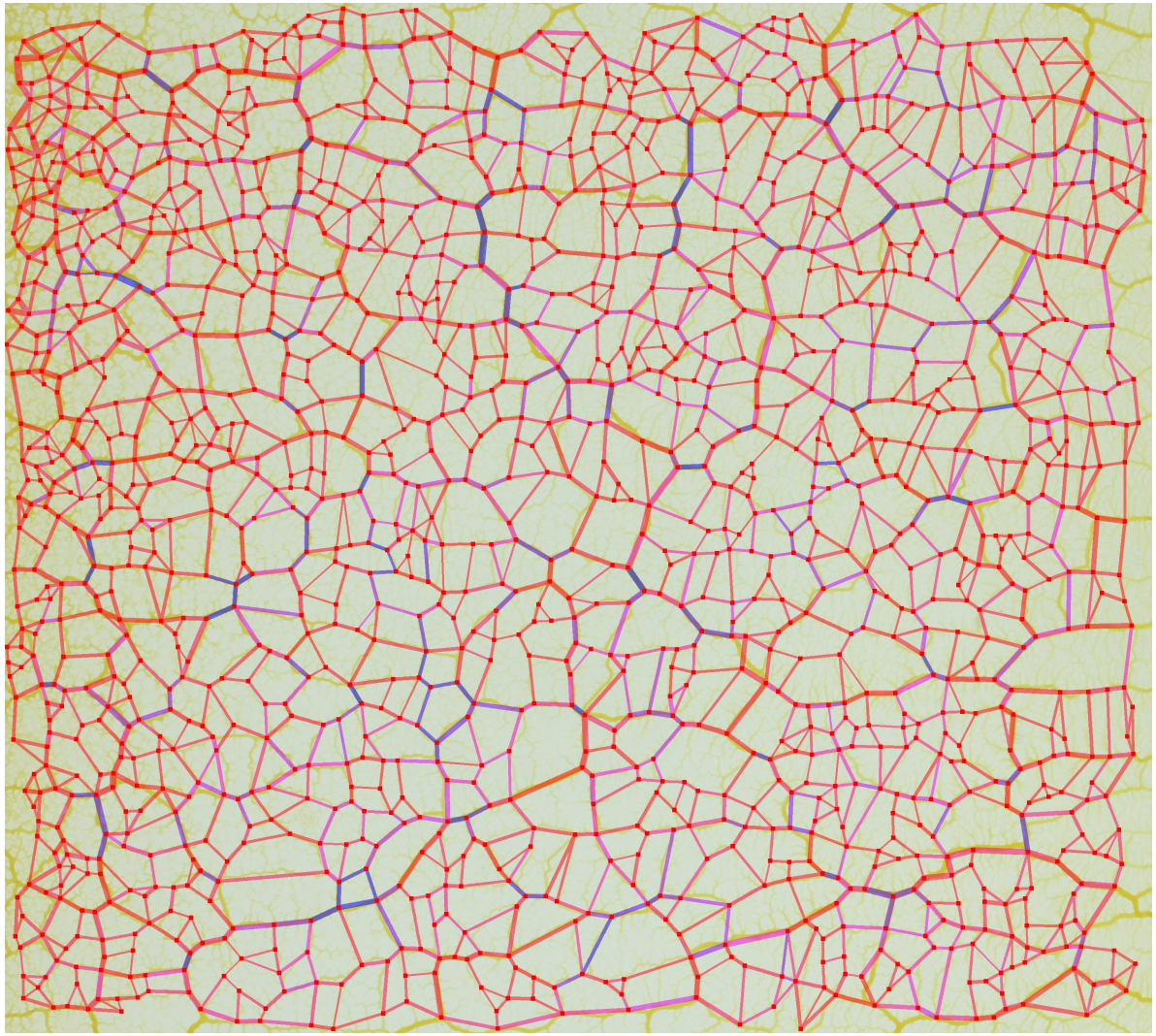
## Goal:

Obtain a catalogue of Observables that sheds light on various aspects of *P. polycephalum* structures.

## Scope:

- Distributions of observables and their time development.
- Examples: Edge lenghts/widths, Face area/circumference and various other properties.

# Robustness of *P. polycephalum* networks Dirnberger et al., 2016



Cleaned graph on-top of original image.

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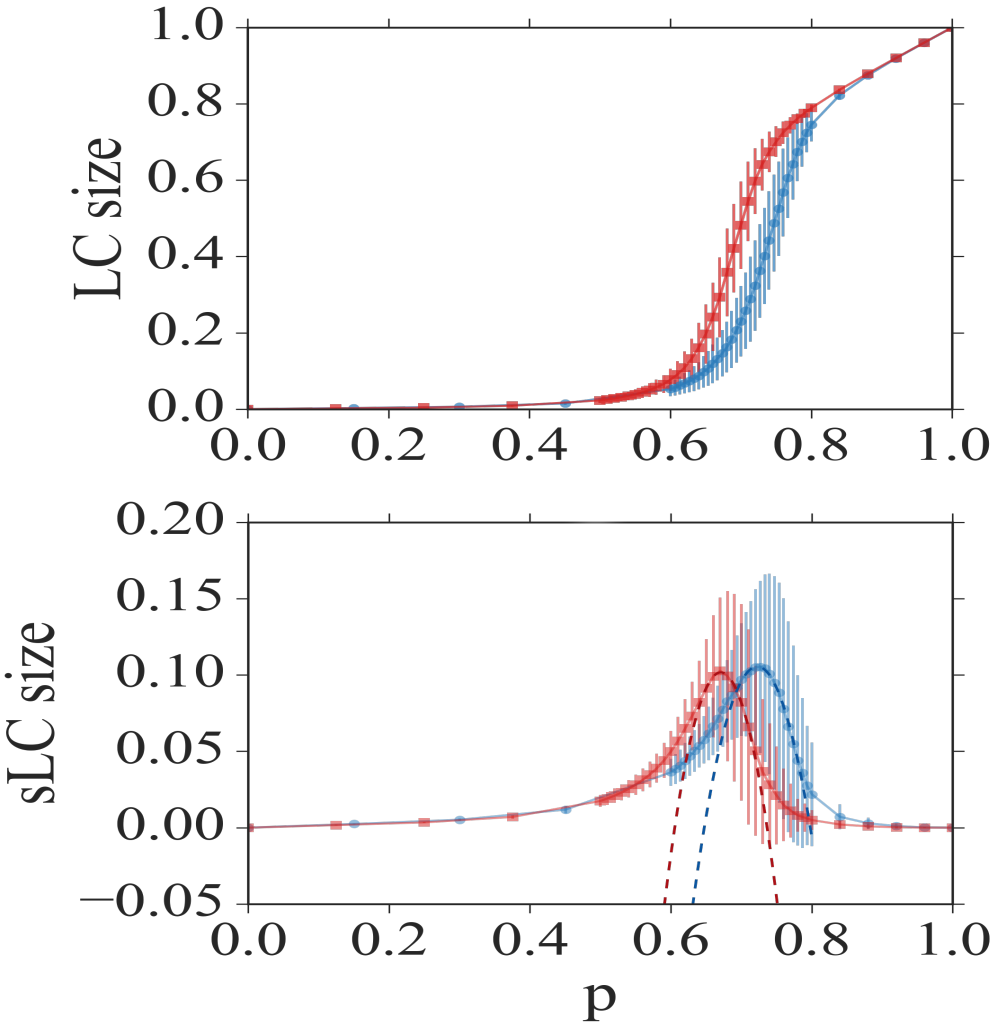



$p_c = 0.7118 \pm 0.0544$ for node percolation
$p_c = 0.6584 \pm 0.0217$ for edge percolation.

# Part III: A distributed model of P. polycephalum

# What we know about *P. polycephalum*

Desirable properties:

- The **organism** operates in a fully distributed manner and requires no central control.
- The **organism** maintains a dynamic circulation of flow including flow reversals.
- The **organism** is robust against changes in topology.
- The **organism** has a degree of efficiency.

# What we want from a model of *P. polycephalum*

Desirable properties:

- The **model** operates in a fully distributed manner and requires no central control.
- The **model** maintains a dynamic circulation of flow including flow reversals.
- The **model** is robust against changes in topology.
- The **model** has a degree of efficiency.

# Modelling the dynamics of *P. polycephalum*

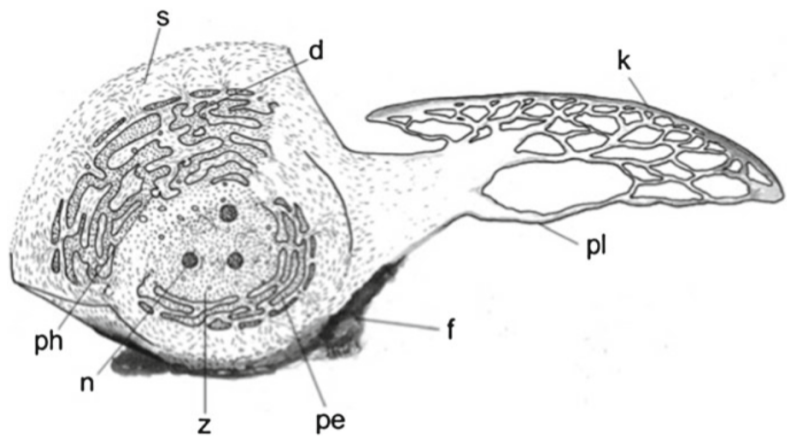
## The goal:

Model the peristaltic pumping and obtain dynamic fluid flows similar to what is observed in *P. polycephalum*.

The problem: Hydrodynamics is extremely difficult analytically!

Solution:

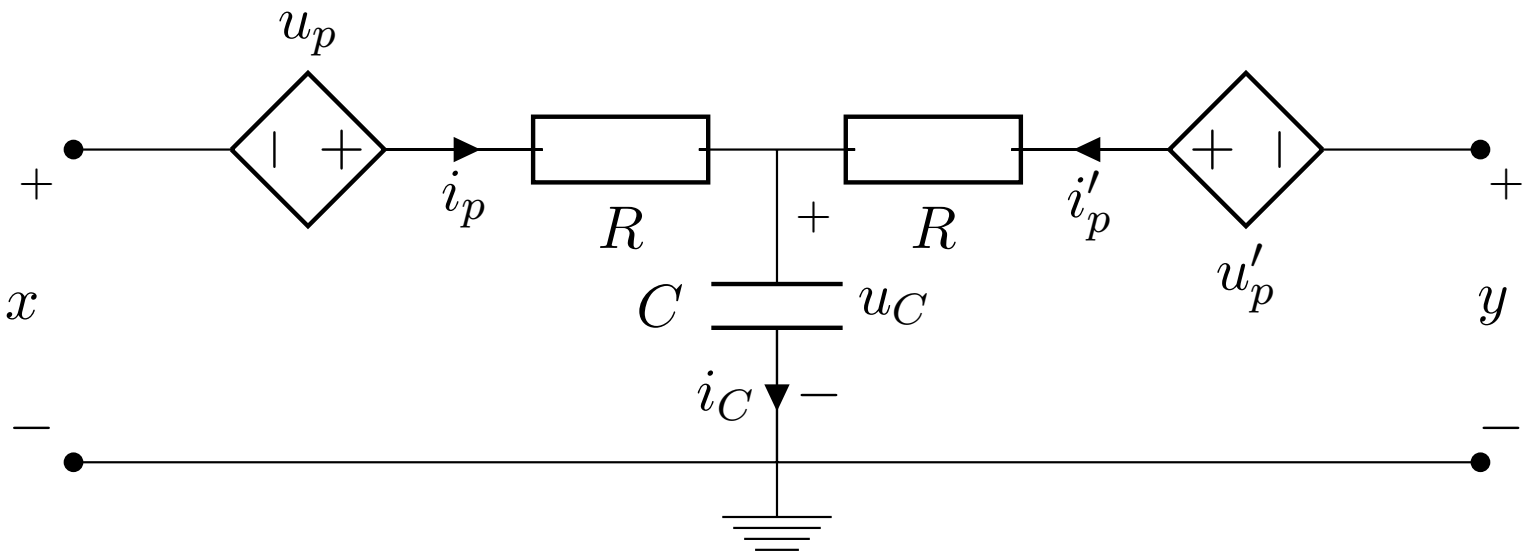
- Peristaltic pumps replaced by current controlled voltage sources.
- Emergent oscillatory dynamics mimics real flow patterns.




Courtesy of Prof. M. Grube.

# Modelling vein segments - *Physarum* elements

| Hydrodynamic System | Electrical analogue |
|---|---|
| Fluid | Charge |
| Fluid flow | Current |
| Pressure | Potential |
| Pressure difference | Voltage |
| Viscosity | Resistance |
| Distensibility | Capacitance |
| Pump | Voltage souce |



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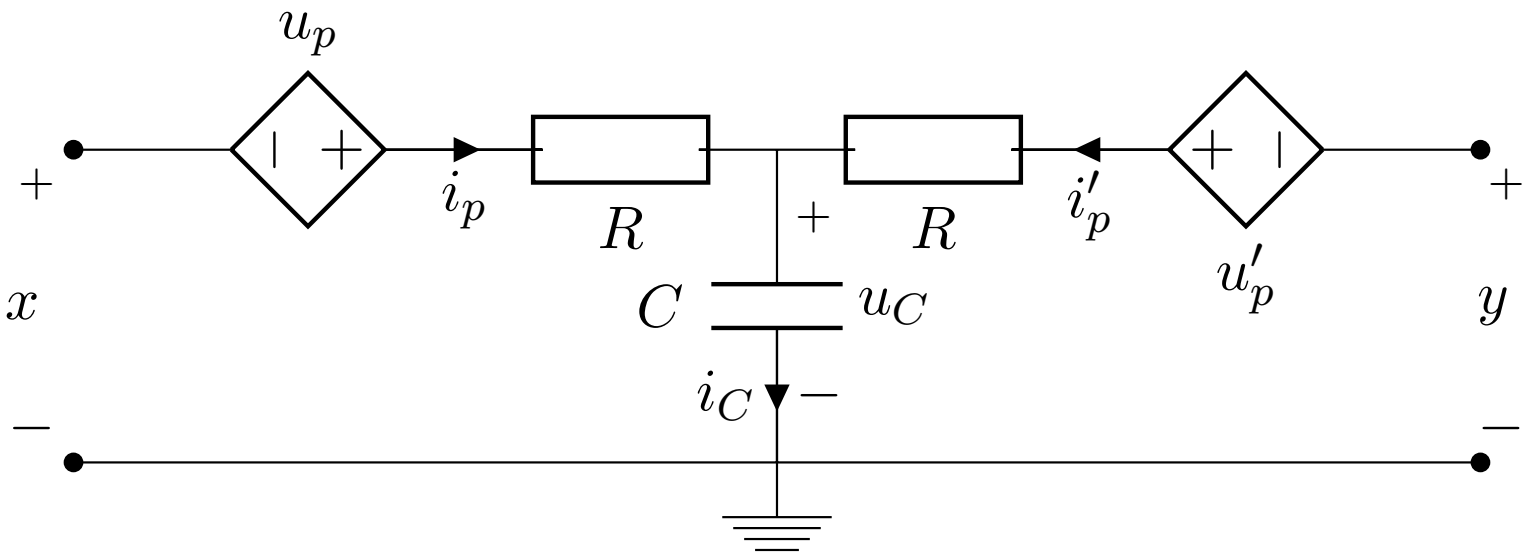


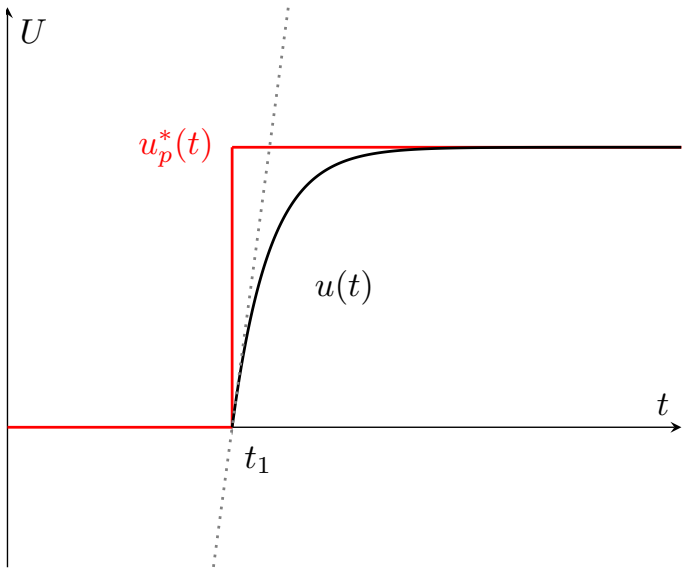


Speed of response:

$$\dot{u}_p(t) = \alpha(u_p^*(t) - u_p(t))$$

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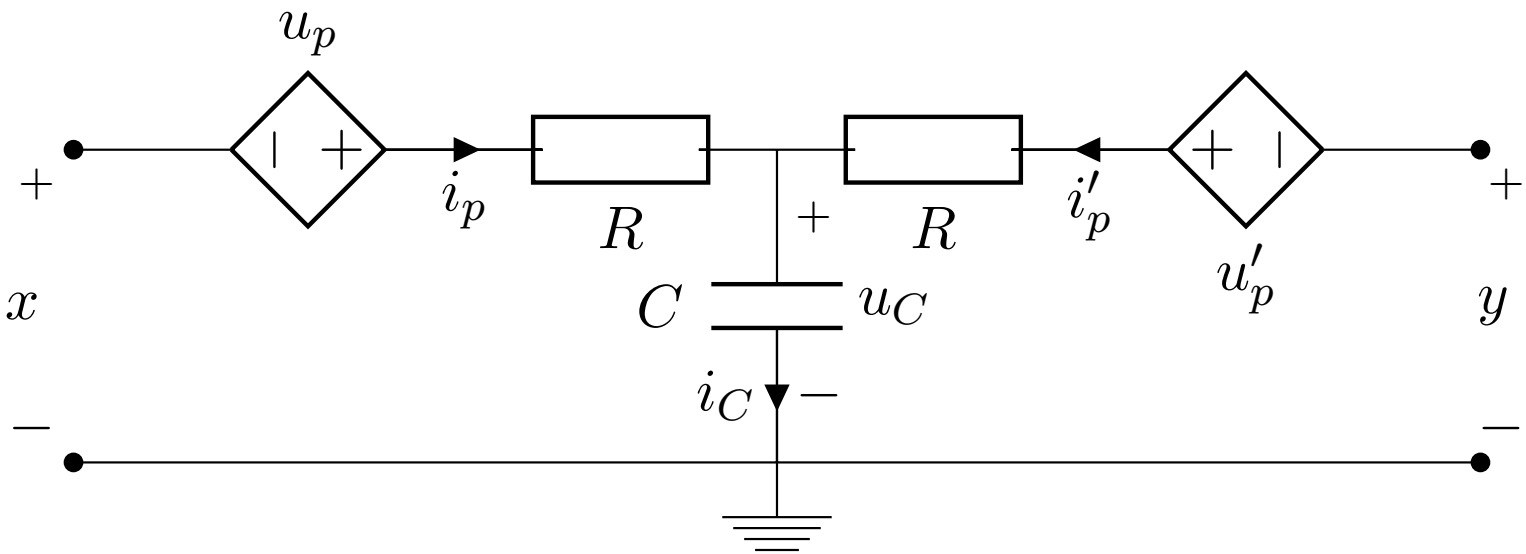
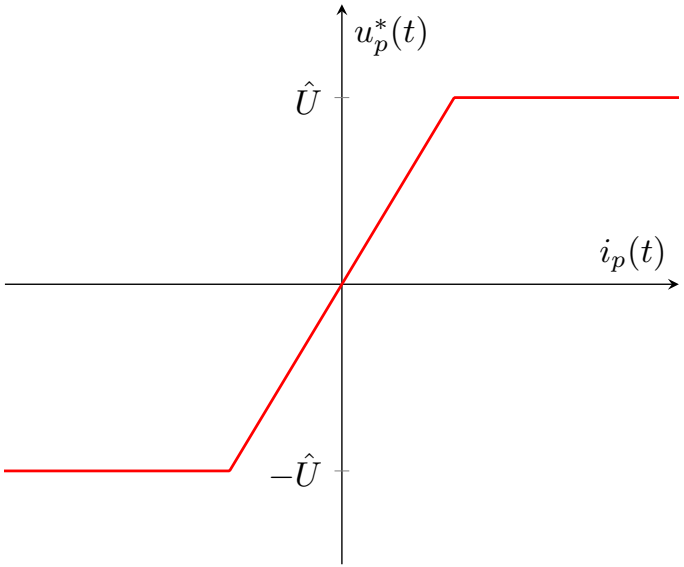



Magnitude of response:

$$u_p^*(t) = \max(\min(\beta \cdot i_p(t), \hat{U}), -\hat{U})$$

# *Physarum* networks

A *Physarum* network is a directed graph $G$ where each edge represents a *Physarum* element. For now, all *Physarum* elements are identical.

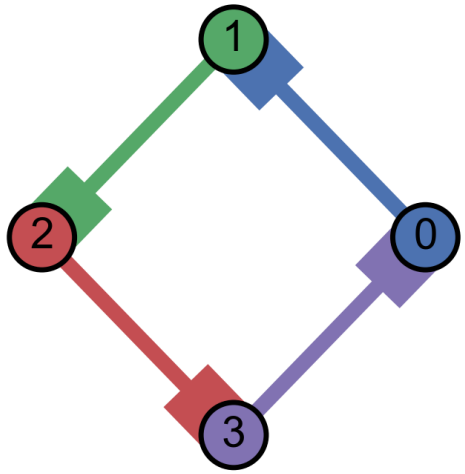
Exploration of *Physarum* networks:

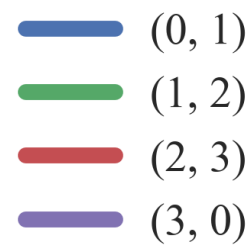
- Continuous version
- Discretized version (Forward-Euler)

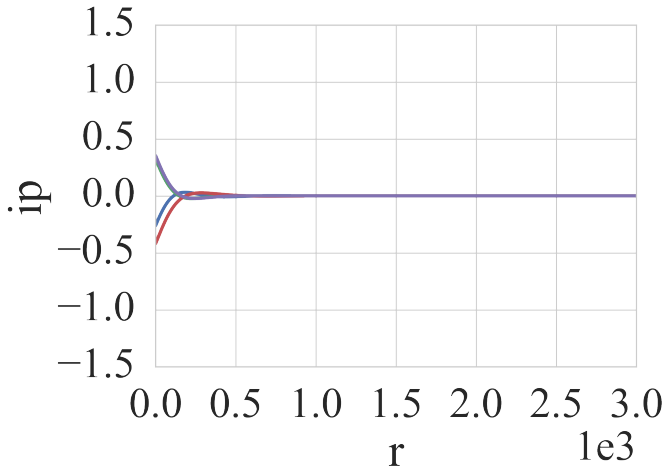
An *execution* of a *Physarum* network is a function that maps each edge in $G$ to a signal $t \mapsto u_C(t)$.

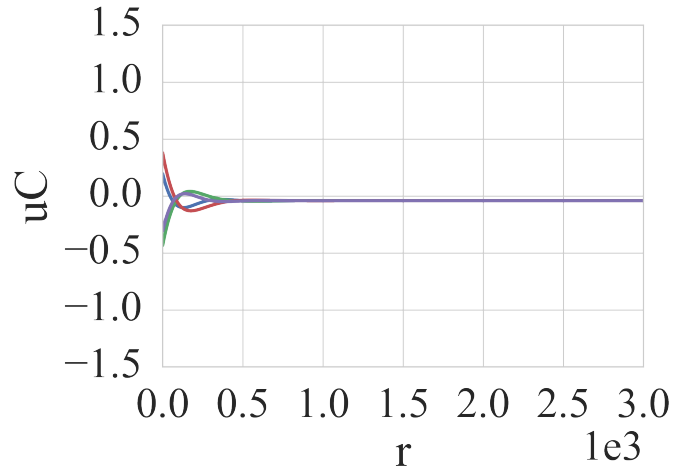
A *Physarum* network $G$ *converges* if all $u_{C,e}$ converge. It *dies* if it converges, and for all edges $i_{p,e} = 0$ holds.

# Example: The death of a cycle



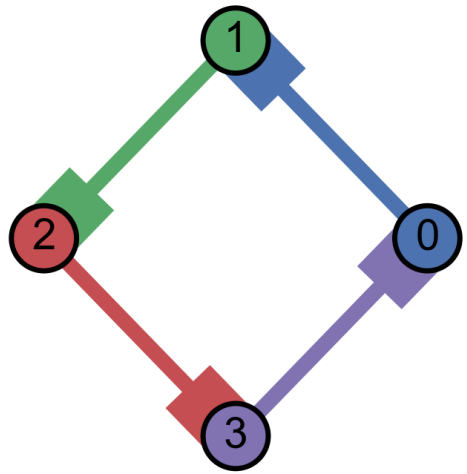



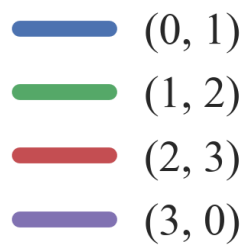



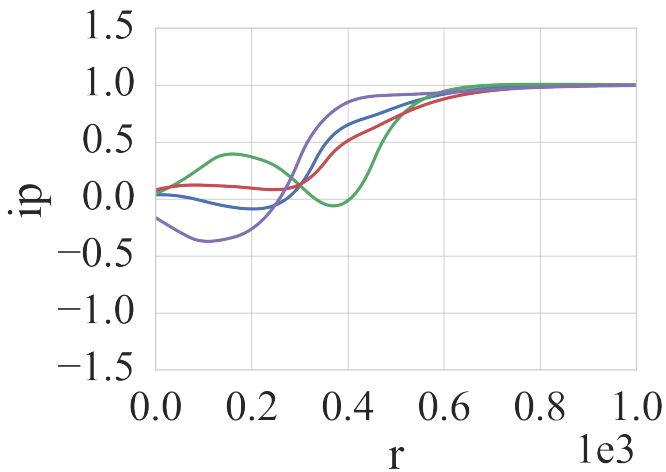



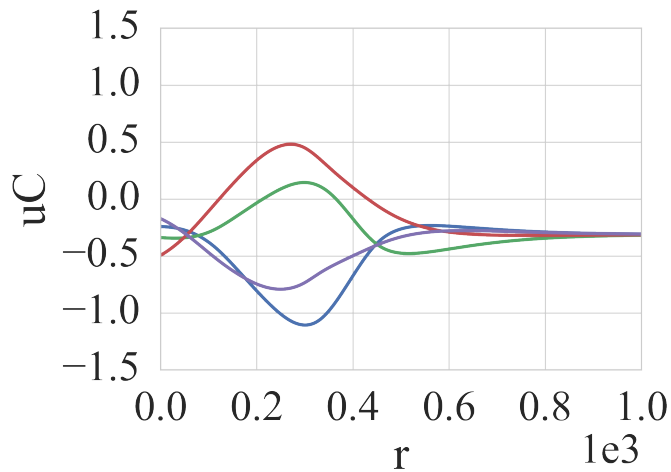

Lemma: If a cycle converges it either a) dies . . .

# Example: Counter-clockwise flow



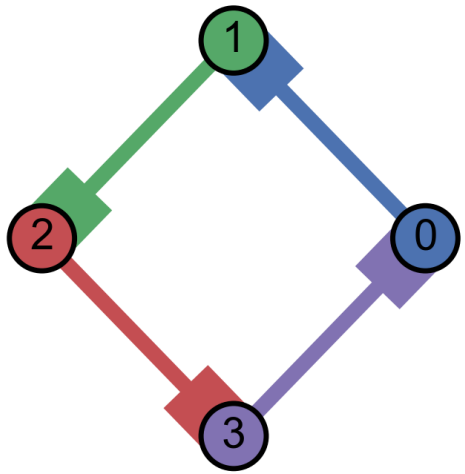



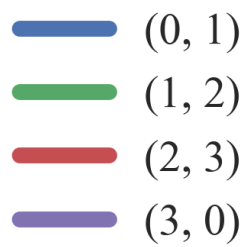



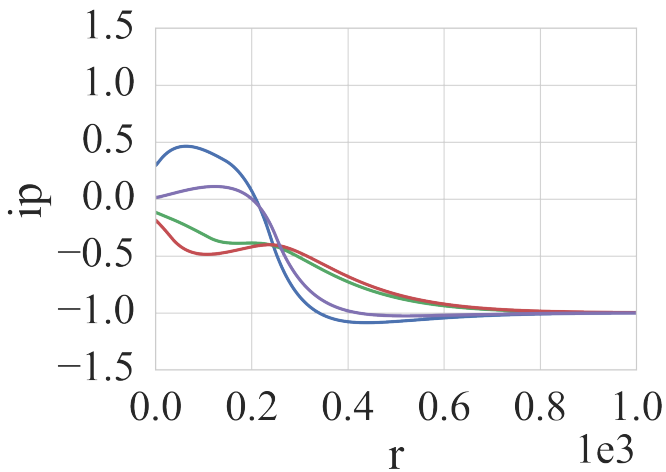



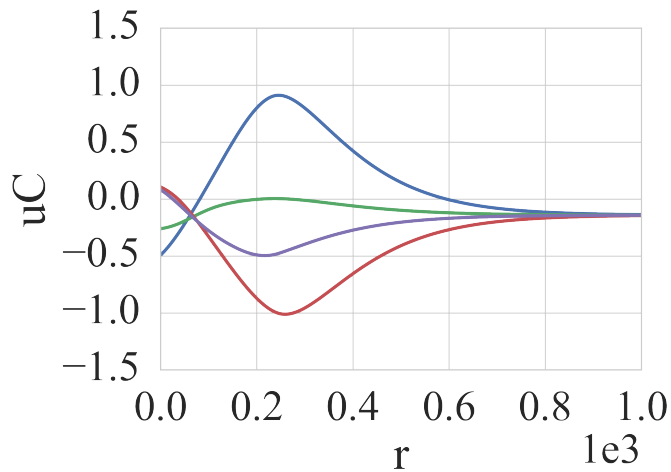

. . . it b) shows constant counter-clockwise flow or . . .

# Example: Clockwise flow



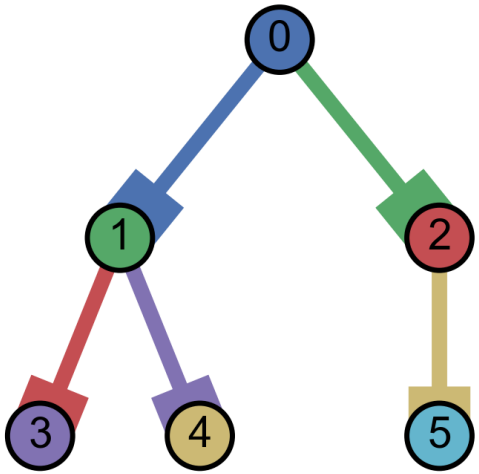



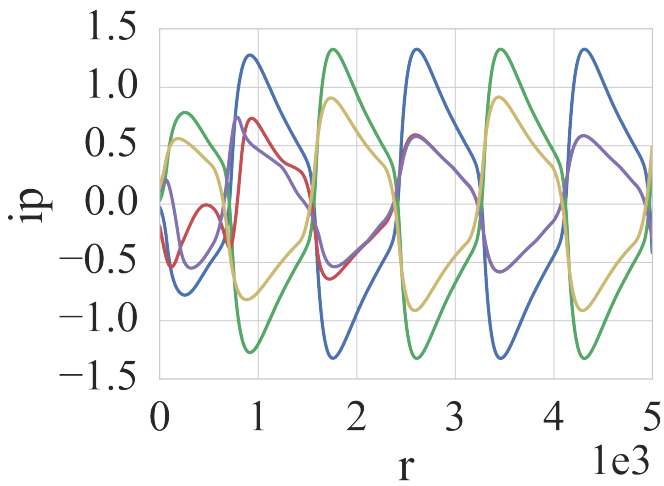



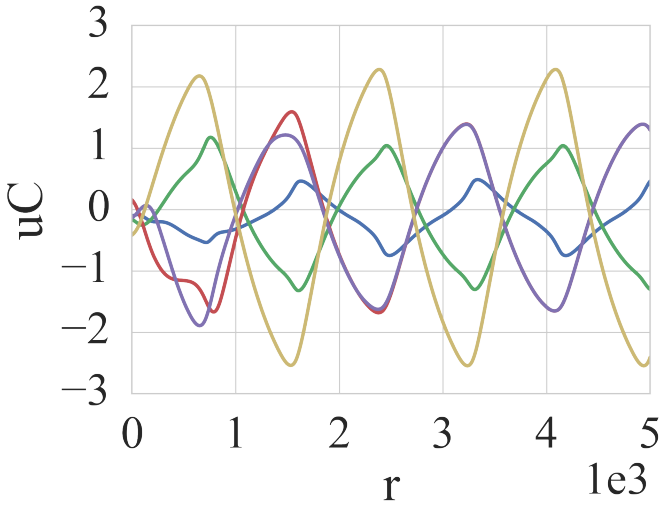

. . . it c) shows constant clockwise flow.

# Example: Synchronisation on a tree



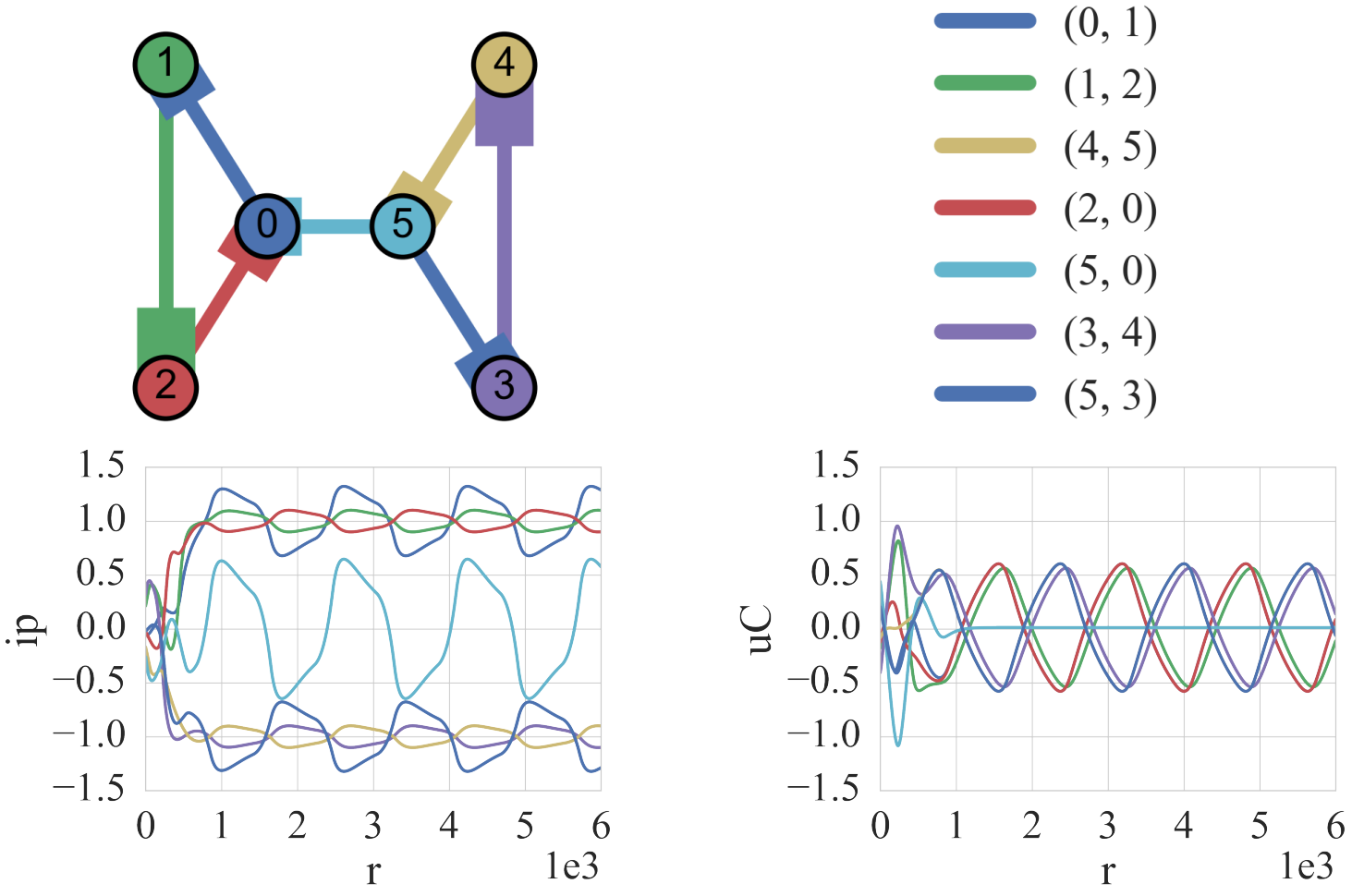





Lemma: If a tree converges it dies.

# Example: Two coupled cycles




Model behaviour mimics experimental observations of A. Takamatsu et al., 2000.

# A model at the cross-roads

## Status Quo:

We have obtained a novel distributed model that mimics the flow dynamics of *P. polycephalum*!

## How to proceed?

- Try to use the flow reversals exhibited in the model to solve a problem (M. Függer, M. Grube).
- Try to improve the realism of the model to obtain a more physical description.

Both approaches are worthwhile, require specialist input and continued interdisciplinary effort.

# Summary

- Illustrated how the distributed nature of *Physarum polycephalum* renders it a promising candidate for Natural Computing.
- Presented our efforts to better understand the networks formed by the organism.
- Sketched our modelling attempts and demonstrated the validity of the approach.
- Briefly discussed possible avenues for future developments.

Thank you.