

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

Michael T. Dirnberger

Max Planck Institute for Informatics

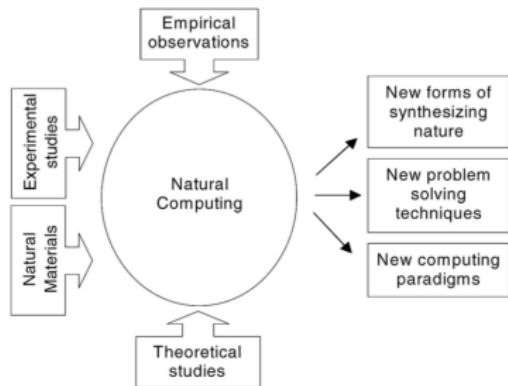
PhD Defense, 31.07.2017, Saarbrücken



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.



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Natural Computing is a highly interdisciplinary field!

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Ant Colony Optimization,
M. Dorigo, 2004

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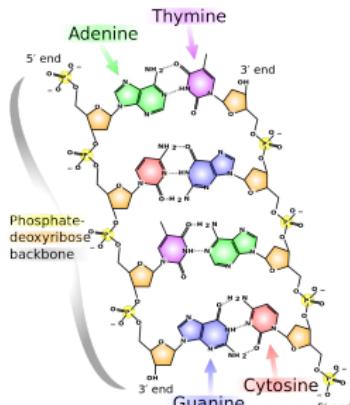


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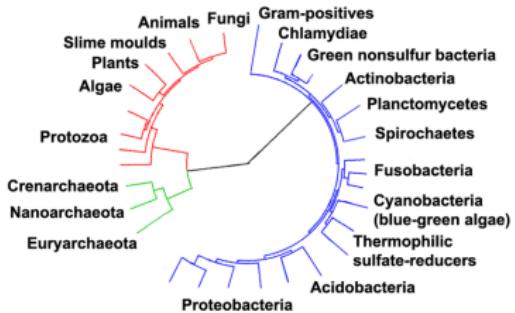
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Natural Computing is a highly interdisciplinary field!

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 behavior.

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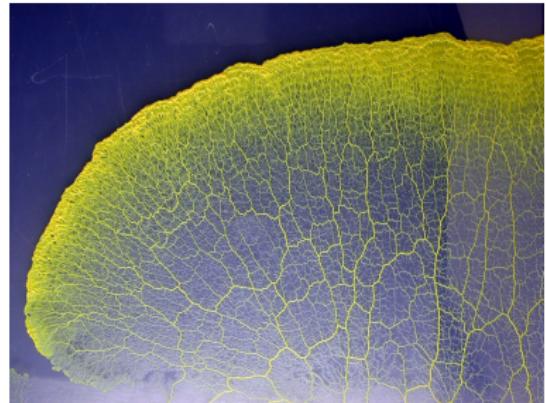
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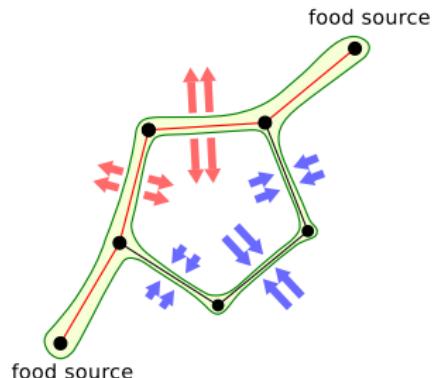
Key Properties:

Distributed dynamics, Min and Max behavior.

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

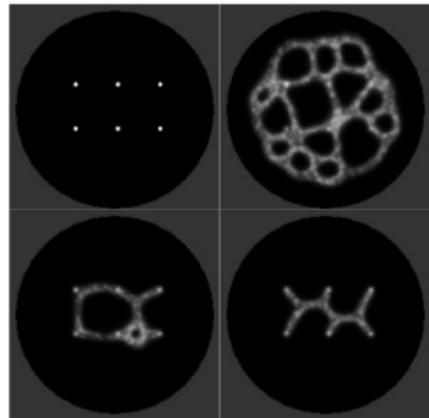
Caveat:

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

Natural Computing with *P. polycephalum*

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see J. Jones 2010

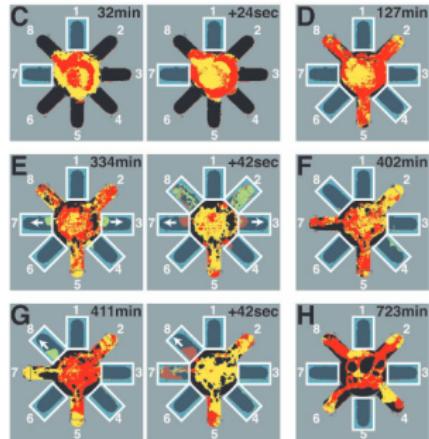
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Natural Computing with *P. polycephalum*

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see M. Aono et al. 2007

Caveat:

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

What about the flows?

Observation:

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

Our aim:

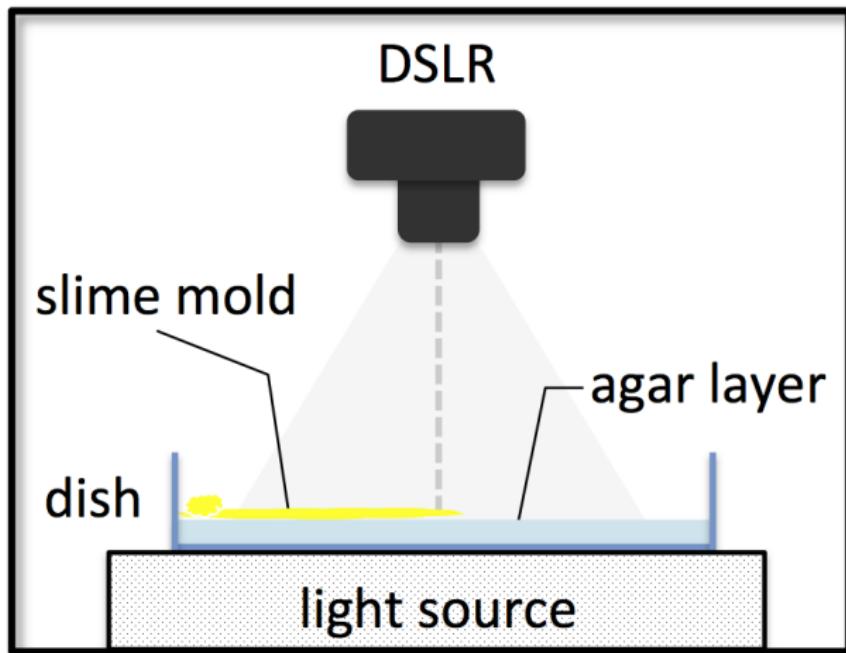
Study the networks formed by *P. polycephalum* in order to drive the development of a distributed model of its dynamic flows.

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



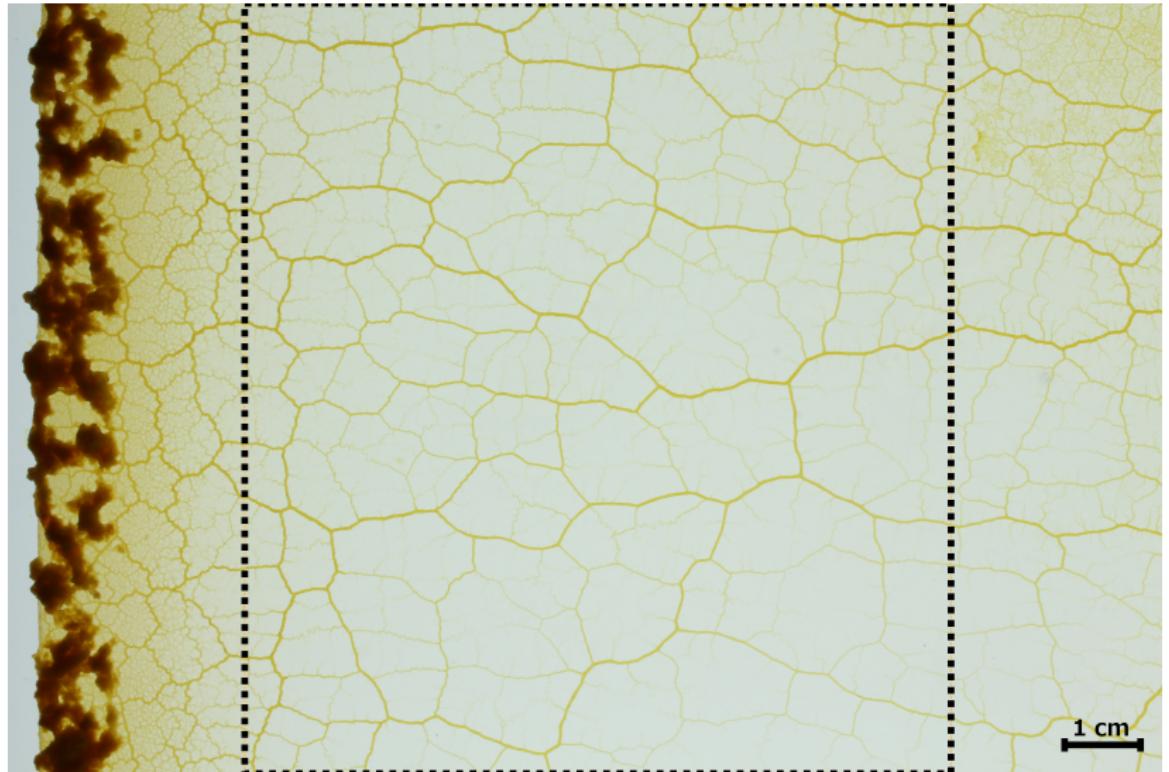
The exploring front moves on.

Experiments



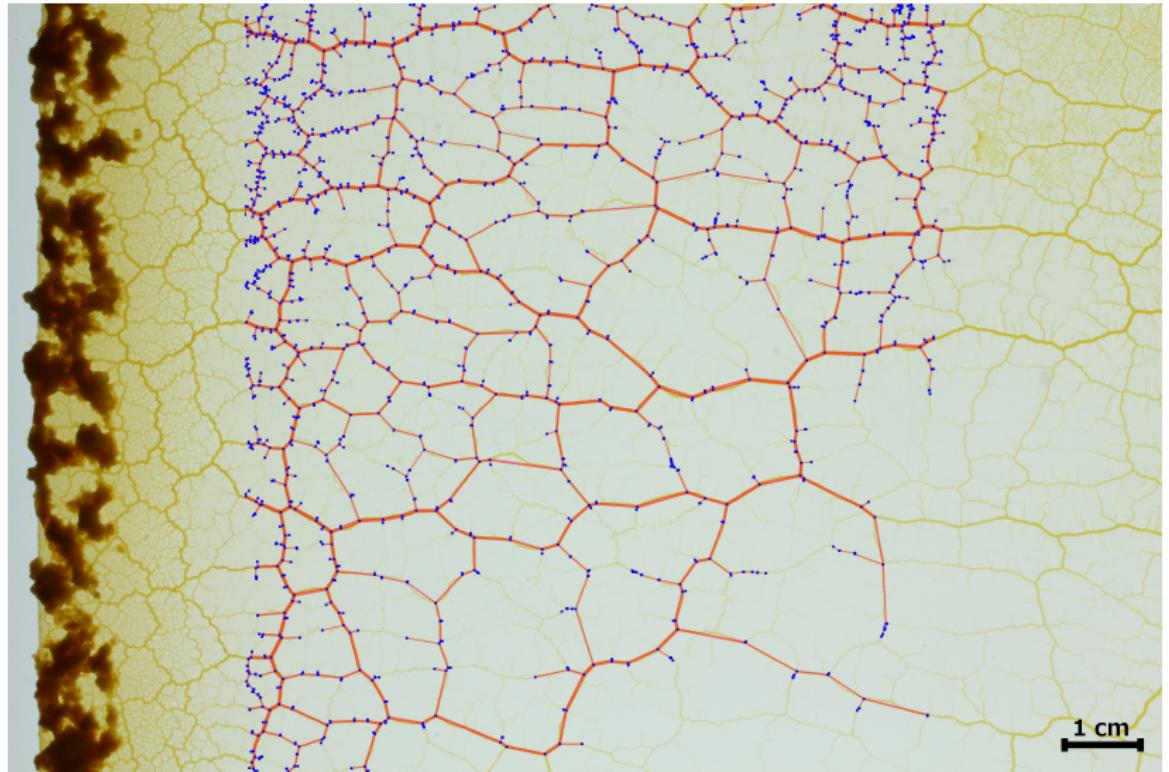
A intricate network supports the front.

Experiments



A region of interest is defined.

Experiments

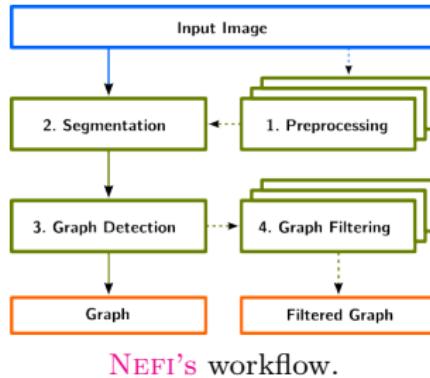


A graph representation of the network is computed.

Network Extraction From Images

Dirnberger et al., 2015

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



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, totaling 1998 weighted planar graphs.

Goal:

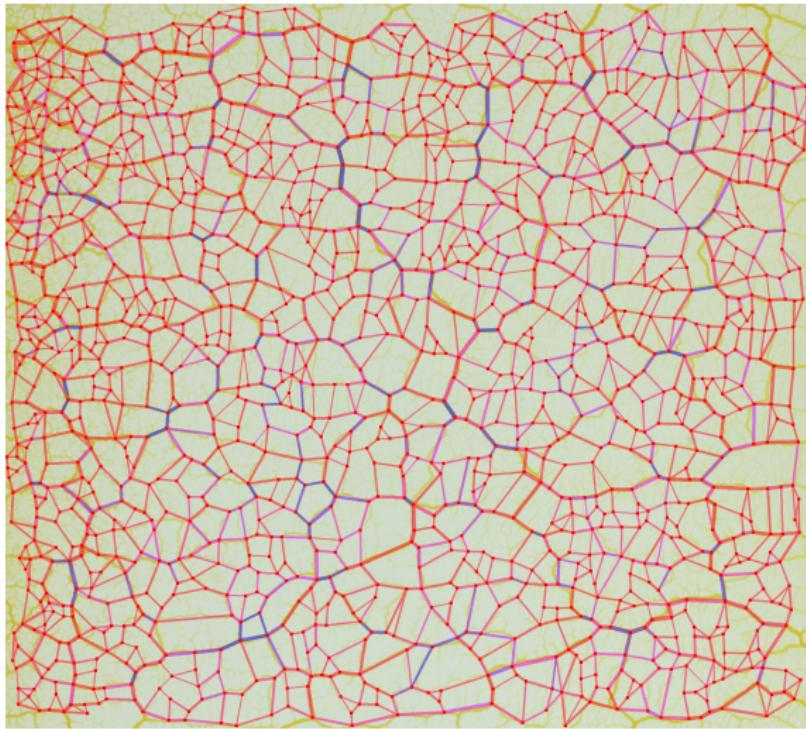
Obtain a catalogue of Observables that sheds light on various aspects of *P. polycephalum* structures.

Scope:

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

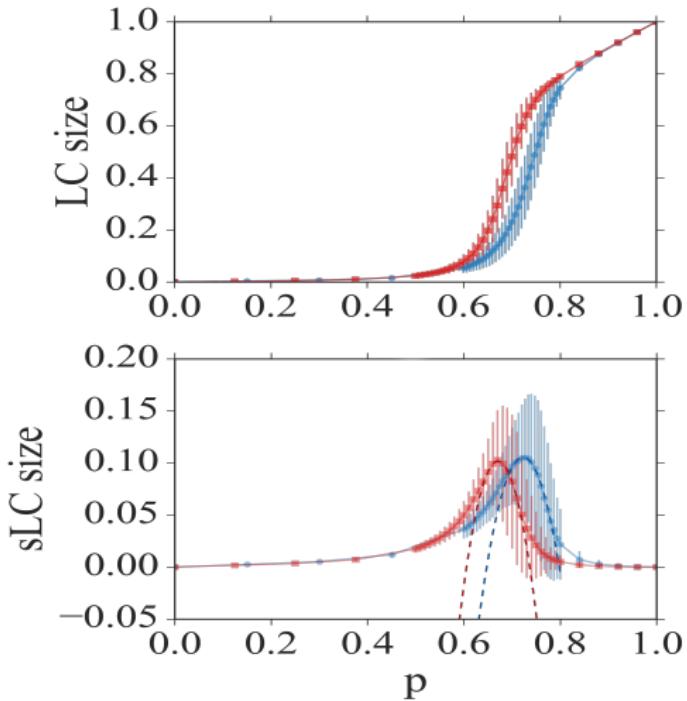
Robustness of *P. polycephalum* networks

Dirnberger et al., 2016



Cleaned graph on-top of original image.

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



$p_c = 0.7118 \pm 0.0544$ 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*

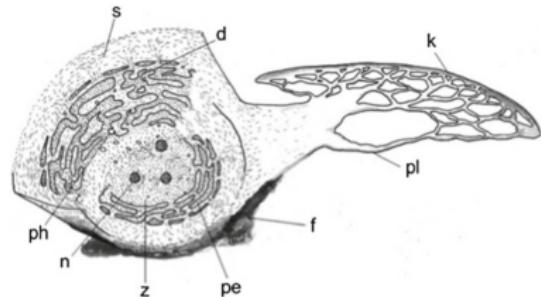
The goal:

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:

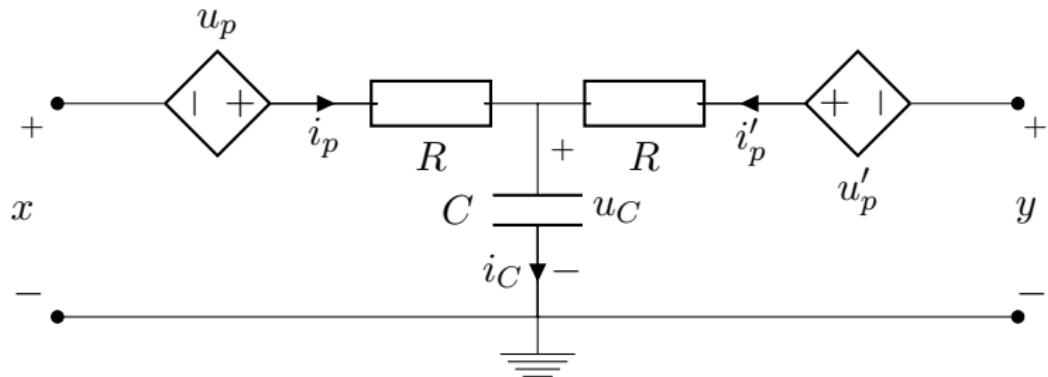
- ▶ Peristaltic pumps replaced by current controlled voltage sources.
- ▶ Emergent oscillatory dynamics mimics real flow patterns.



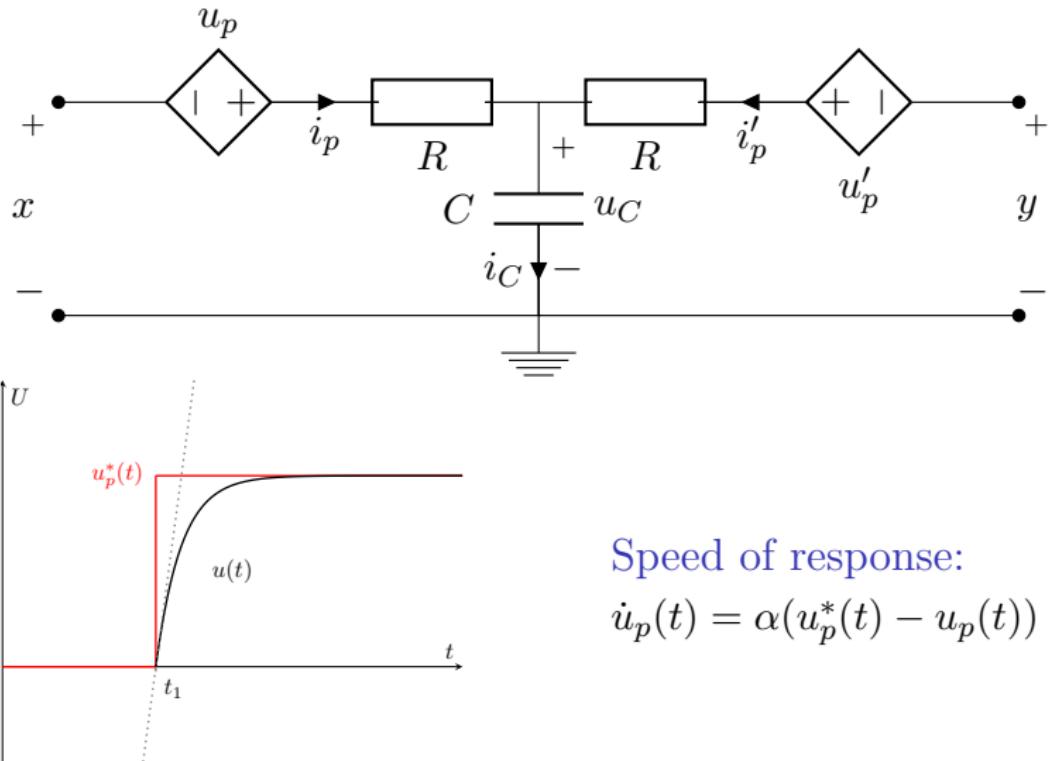
Courtesy of Prof. M. Grube.

Modelling vein segments - *Physarum* elements

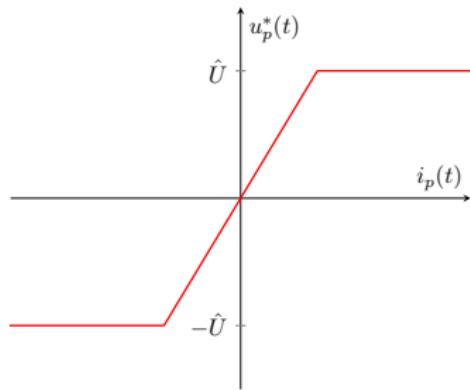
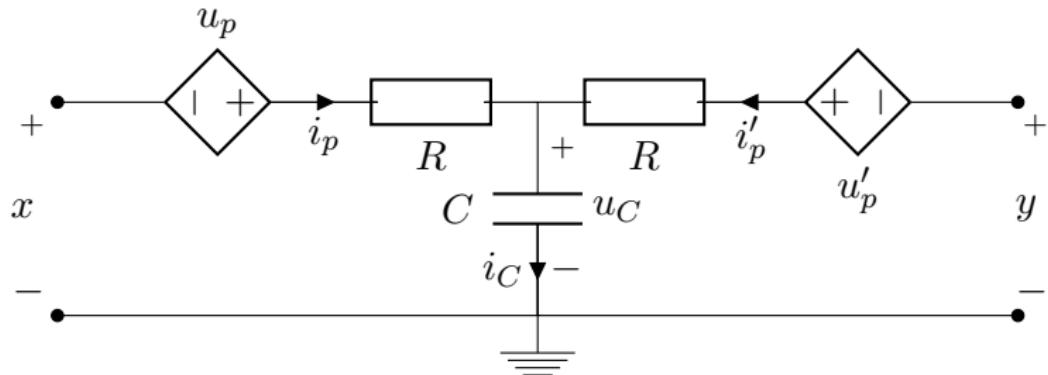
Hydrodynamic System	Electrical analogue
Fluid	Charge
Fluid flow	Current
Pressure	Potential
Pressure difference	Voltage
Viscosity	Resistance
Distensibility	Capacitance
Pump	Voltage source



Modelling vein segments - *Physarum* elements



Modelling vein segments - *Physarum* elements



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.

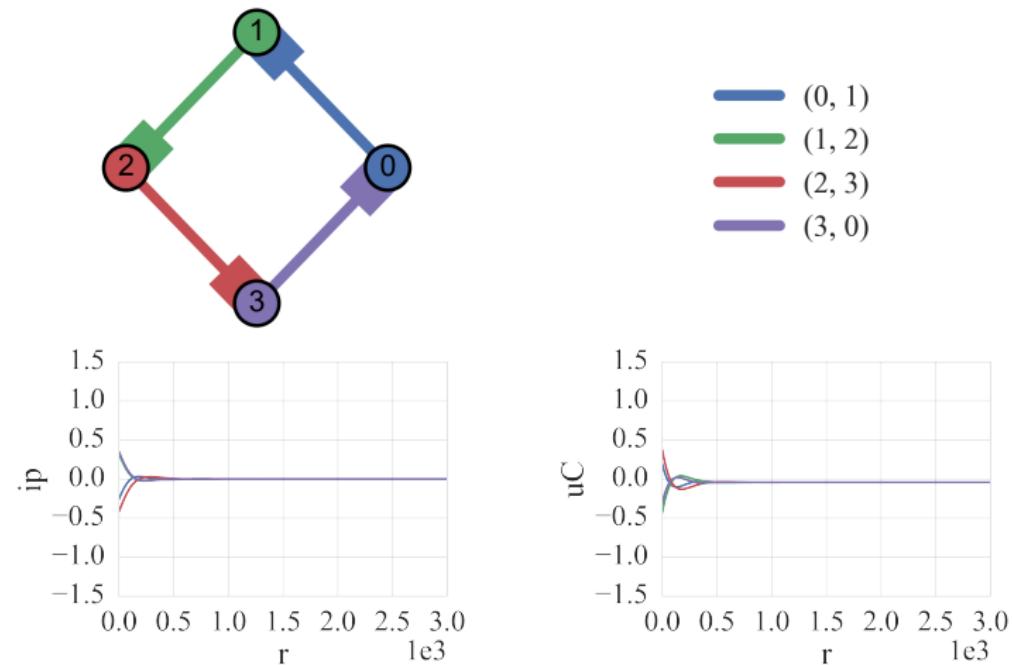
Exploration of *Physarum* networks:

- ▶ Continuous version
- ▶ Discretized version (Forward-Euler)

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

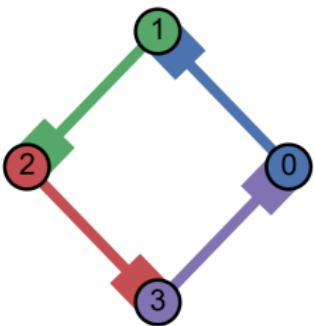
A *Physarum* network G *converges* if all $u_{C,e}$ converge. It *dies* if it converges, and for all edges $i_{p,e} = 0$ holds.

Example: The death of a cycle

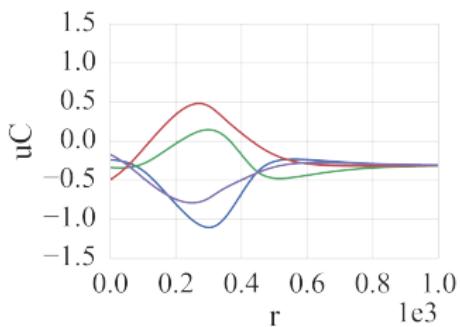
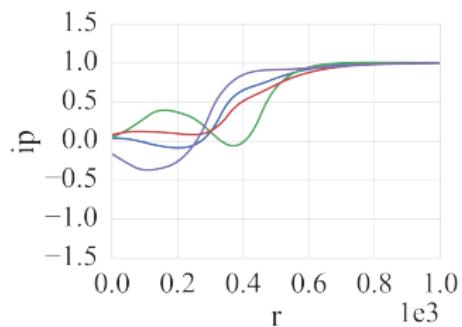


Lemma: If a cycle converges it either a) dies ...

Example: Counter-clockwise flow

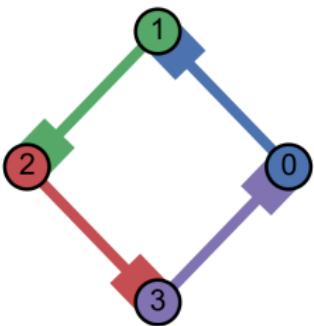


- (0, 1)
- (1, 2)
- (2, 3)
- (3, 0)

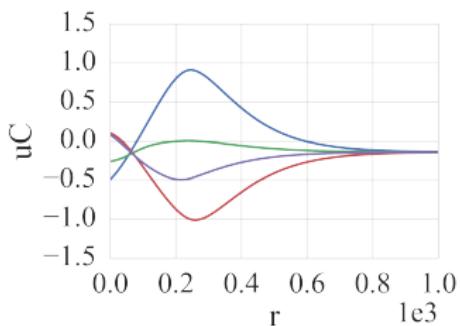
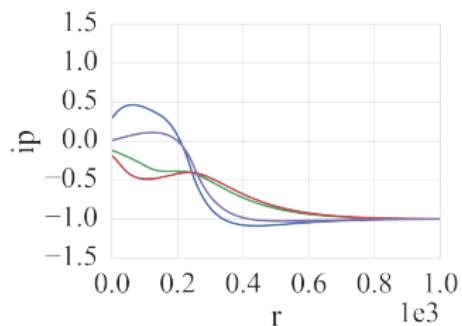


... it b) shows constant counter-clockwise flow or ...

Example: Clockwise flow

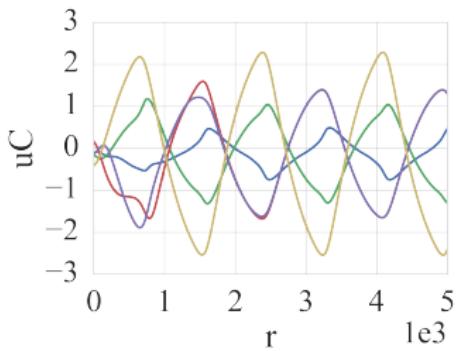
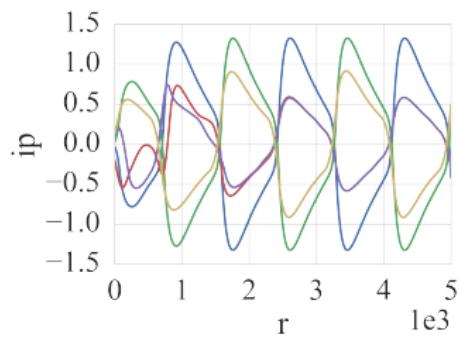
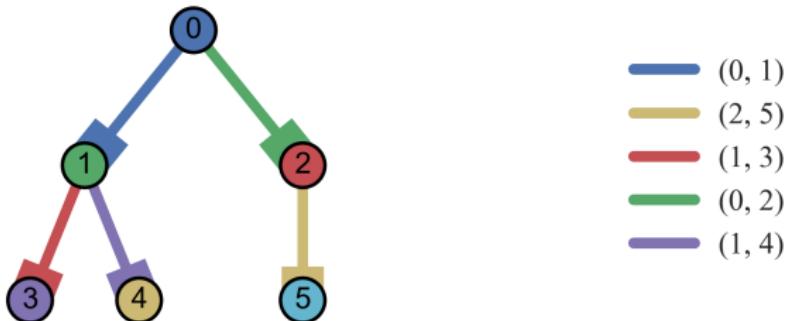


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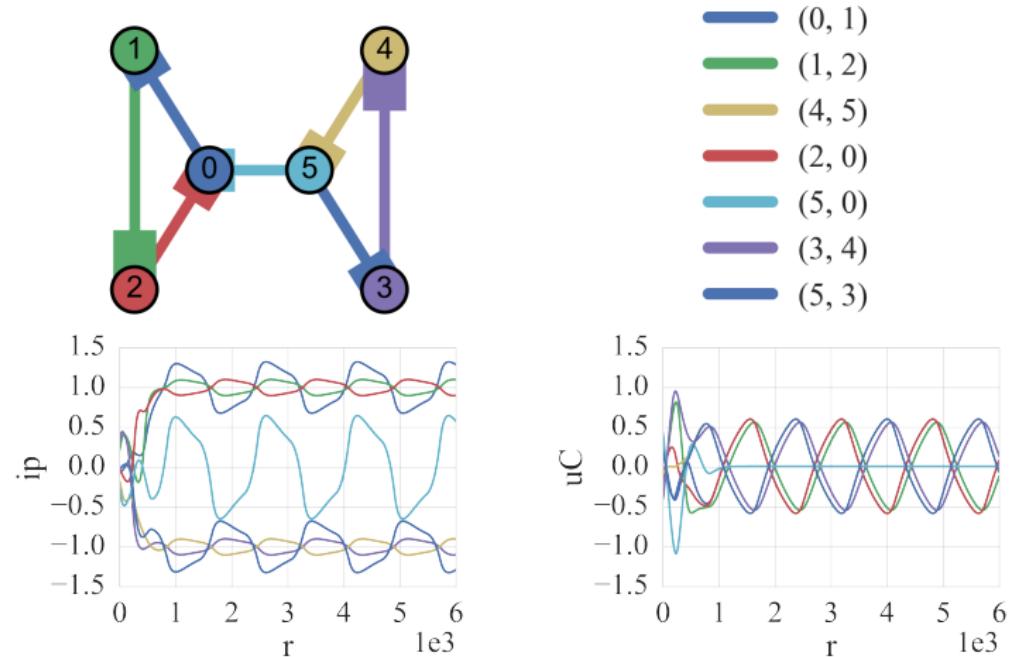
... it c) shows constant clockwise flow.

Example: Synchronisation on a tree



Lemma: If a tree converges it dies.

Example: Two coupled cycles



Model behavior is reminiscent of experimental findings 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?

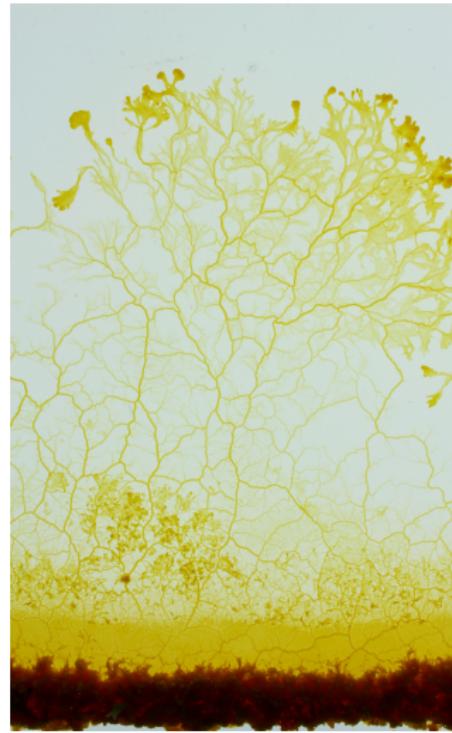
- ▶ Try to use the flow reversals exhibited in the model to solve a problem (M. Függer, M. Grube).
- ▶ Try to improve the realism of the model to obtain a more physical description.

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

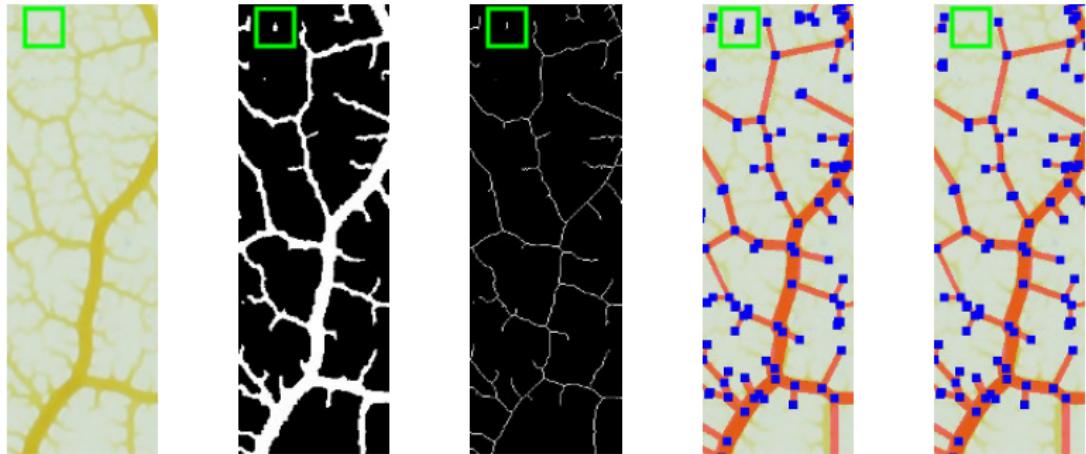
Summary

- ▶ 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 modeling attempts and demonstrated the validity of the approach.
- ▶ Briefly discussed possible avenues for future developments.

Thank you.

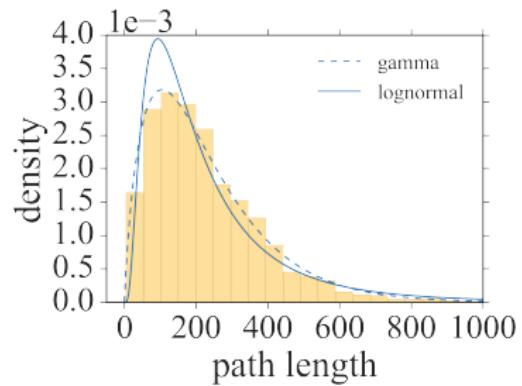
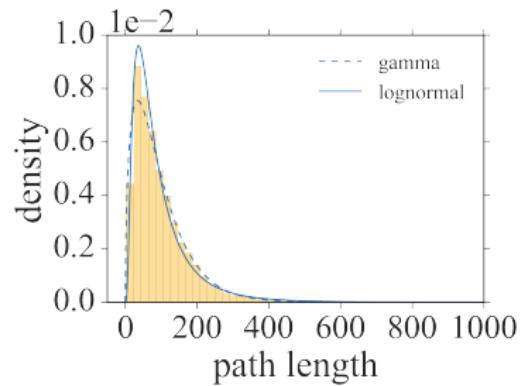


NEFI's pipeline



NEFI's pipeline steps.

NEFI's pipeline



Path length distributions for `data series 22.`