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

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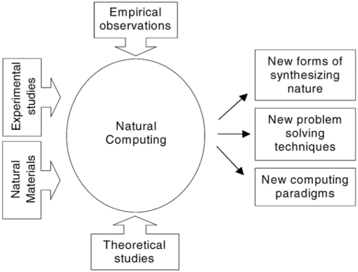
Part I: Natural Computing with P. polycephalum

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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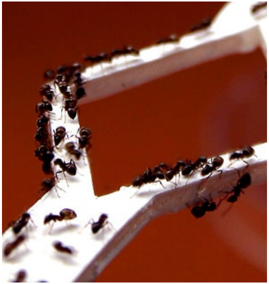

Ant Colony Optimization, M. Dorigo, 2004

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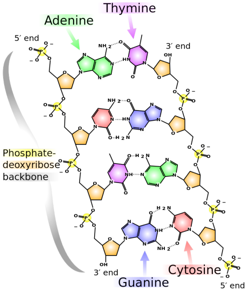

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A Magnificent Mold

Physarum polycephalum:

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

Courtesy of Prof. T. Ueda

Key Experiments show:

Distributed dynamics, Min and Max capabilities

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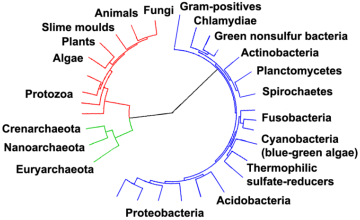

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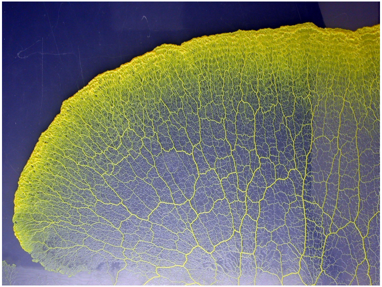

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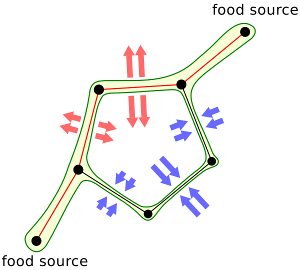
Key Experiments show:

Distributed dynamics, Min and Max capabilities

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:

Distributed nature of *P. polycephalum* has largely been ignored in the context of Natural Computing.

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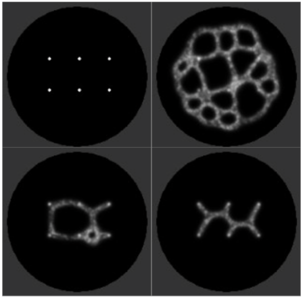

see J. Jones 2010

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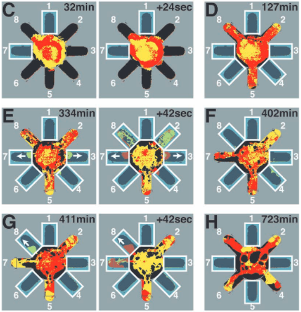

see M. Aono et al. 2007

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Distributed nature of *P. polycephalum* has largely been ignored in the context of Natural Computing.

Towards distributed Natural Computing

Our aim:

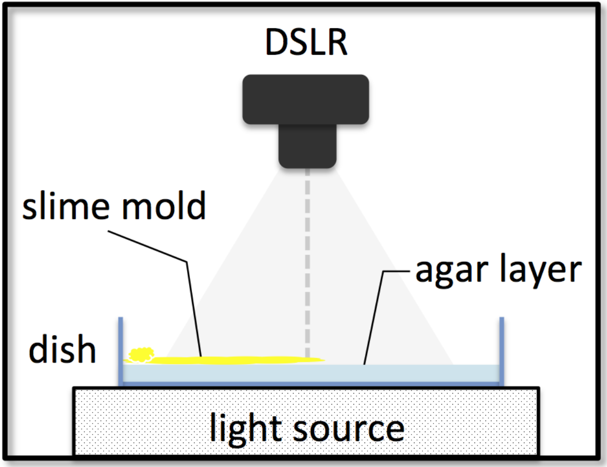
Study the networks formed by *P. polycephalum* in order to drive the development of a distributed model of its dynamic flows.

Our approach:

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

Part II: Studying the networks formed by P. polycephalum

Experiments

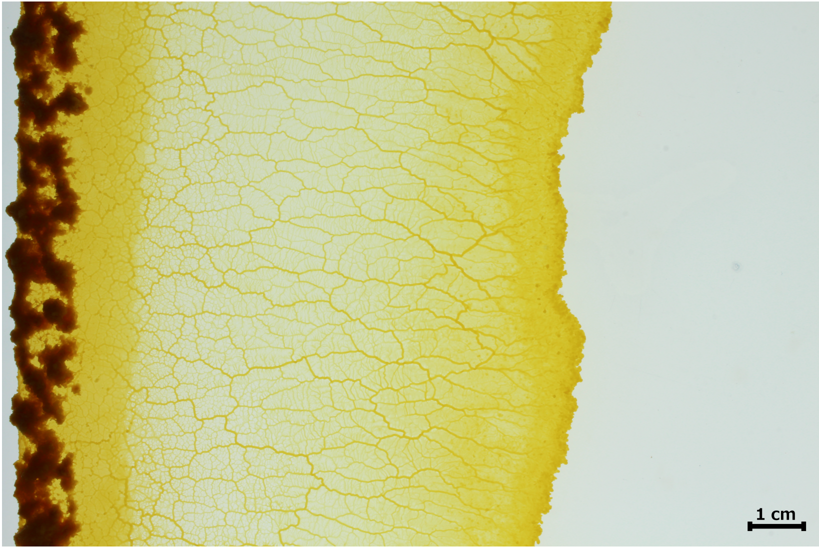


Schematic of experimental setup.

Experiments

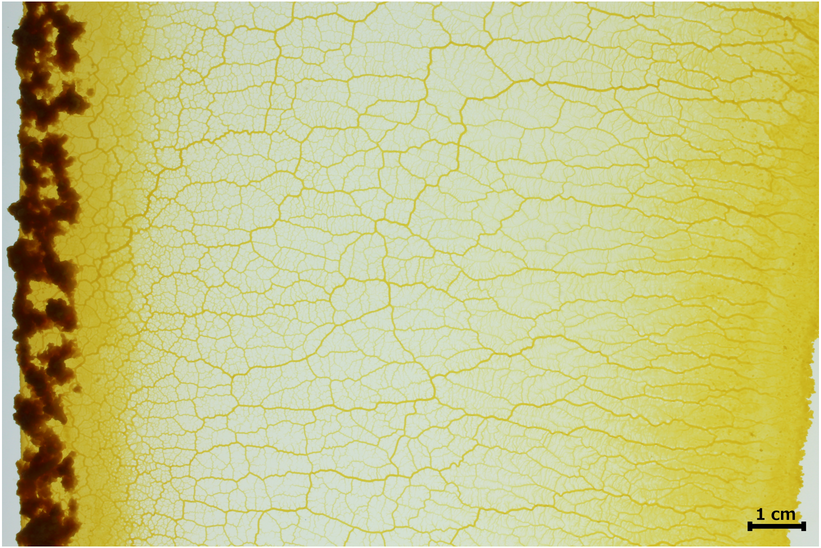
Sclerotia placed in the container.

Experiments



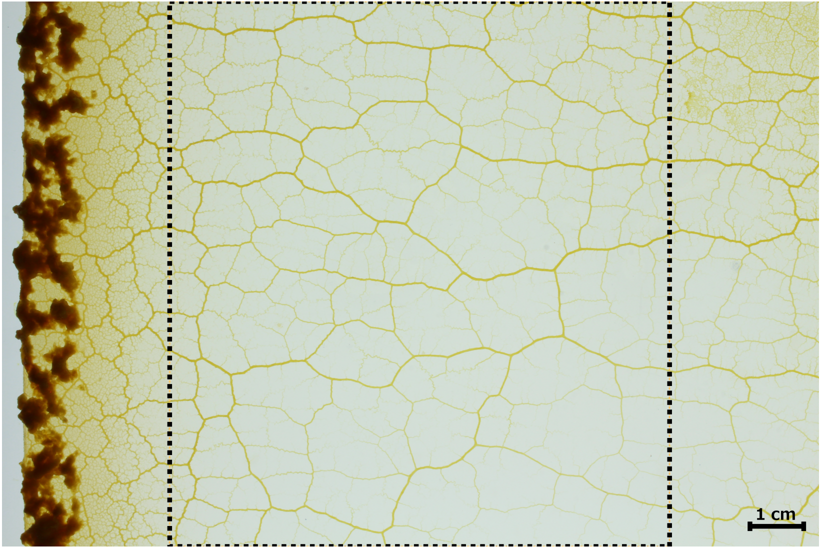
The exploring front moves on.

Experiments



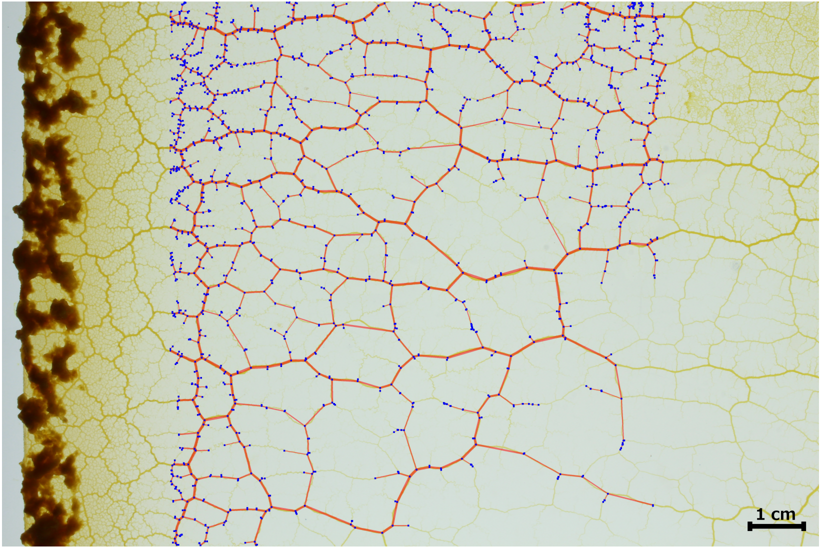
A intricate network supports the front.

Experiments



A region of interest is defined.

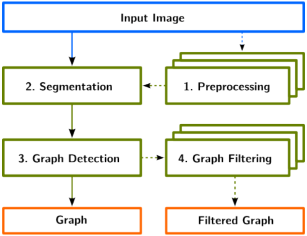
Experiments



A graph representation of the network is computed.

Network Extraction From Images

- 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.

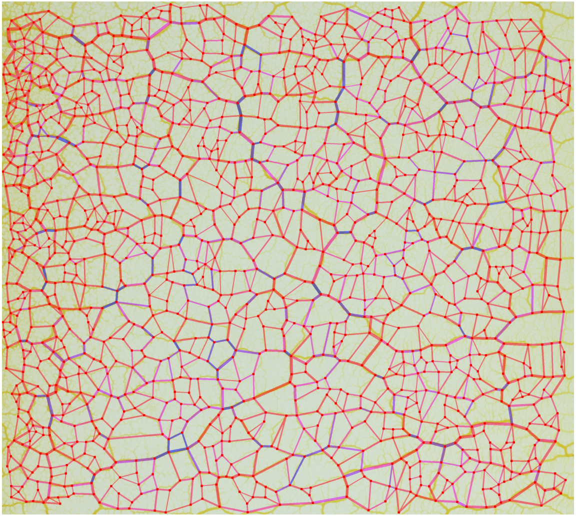
Goal:

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

Key components:

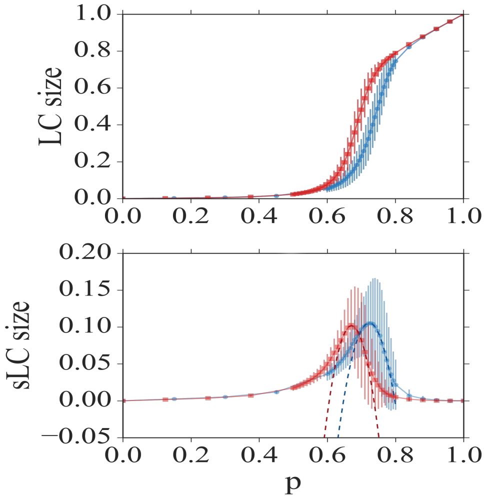
- Distributions of observables and their time development.
- Examples: Edge lenghts/widths, Face area/circumference and various other properties.

Robustness of *P. polycephalum* networks



Cleaned graph on-top of original image

Robustness of *P. polycephalum* networks



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

Sharing is caring Dirnberger et al., 2016

Slime Mold Graph Repository:

Collects raw experimental data, graphs, results and useful tools.

Motivation:

- Facilitate exchange and reuse of data.
- Make data available to everyone.
- Drive and evaluate modelling attempts.

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.
- 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.
- The **model** is robust against changes in topology.
- The **model** has a degree of efficiency.

Modelling the dynamics of *P. polycephalum*

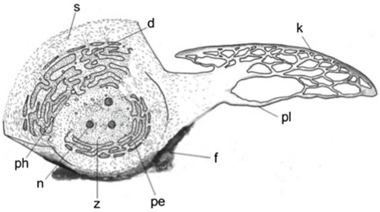
The goal:

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

The problem: Hydrodynamics is extremely difficult analytically!

Solution: Go electric!

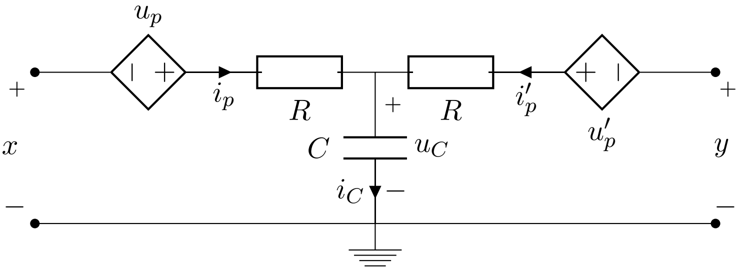
- Windkessel model.
- Peristaltic pumps replaced by current controlled voltage sources.
- Emergent oscillatory dynamics mimics real flow patterns.



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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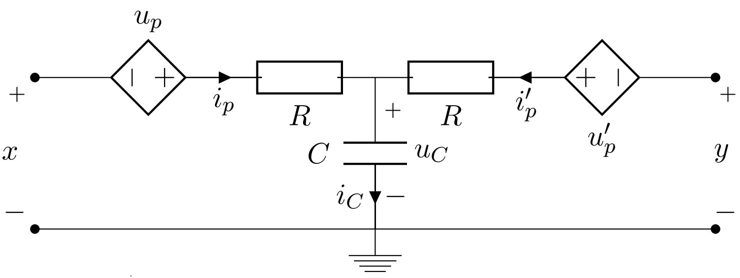
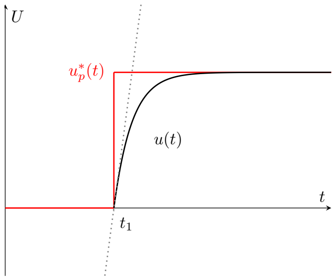
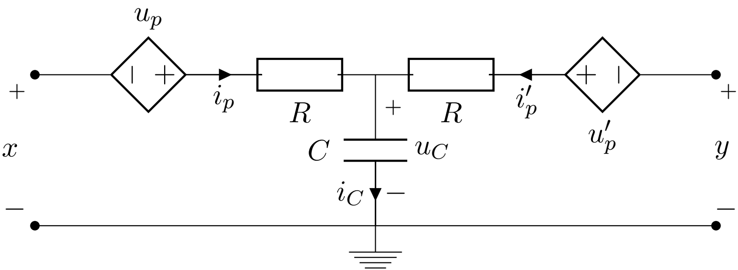


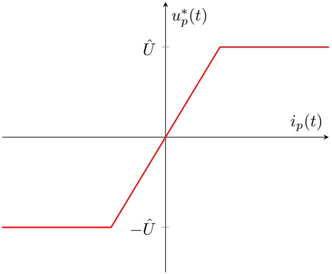


Speed of response:

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

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.

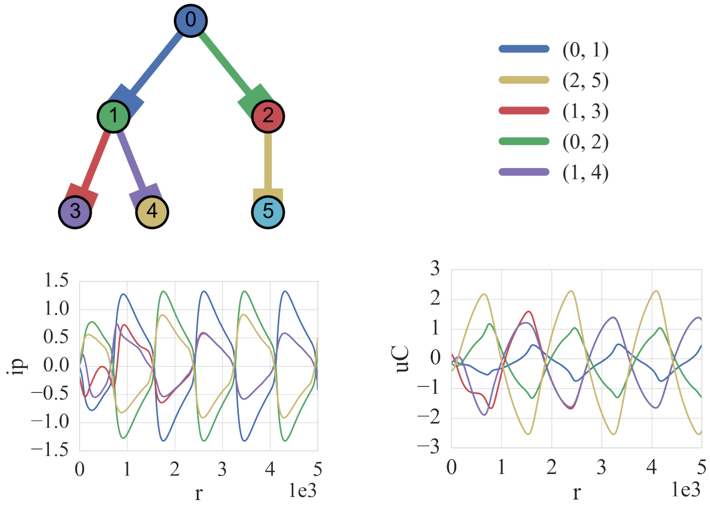
Exploration of *Physarum* networks:

- Continuous version
- Discretized version (Forward-Euler)

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

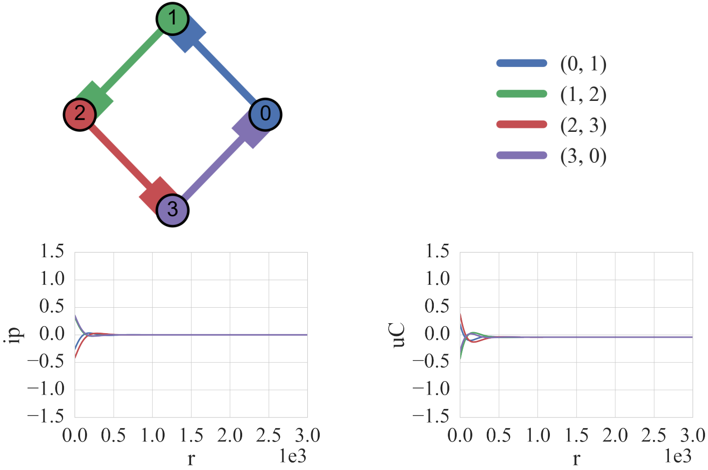
A *Physarum* network G *converges* if all $u_{C,e}$ converge. It *dies* if it converges, and for all edges $i_{p,e} = 0$ holds.

Example: Synchronisation on a tree



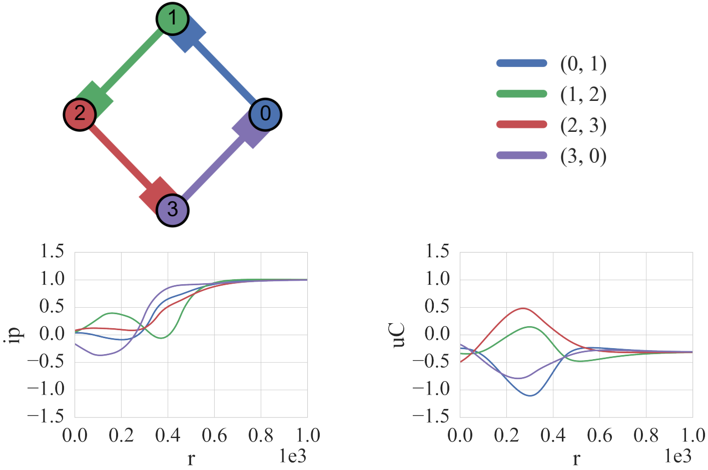
Lemma: If a tree converges it dies.

Example: The death of a cycle



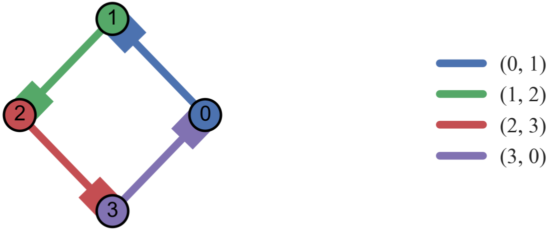
Lemma: If a cycle converges it either a) dies . . .

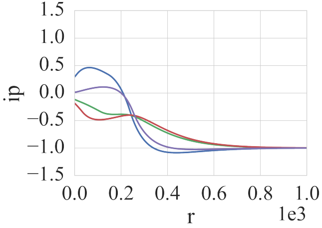
Example: Counter-clockwise flow

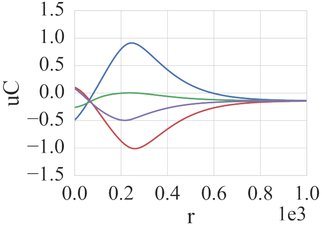


… it b) shows constant counter-clockwise flow or …

Example: Clockwise flow

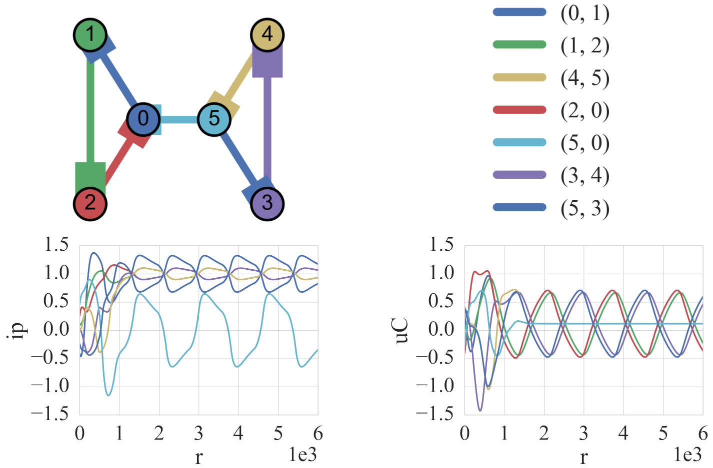






. . . it c) shows constant clockwise flow.

Example: Two coupled cycles



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

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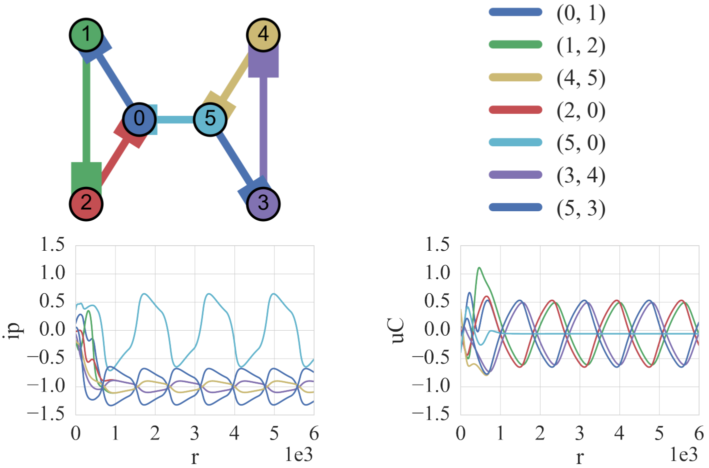

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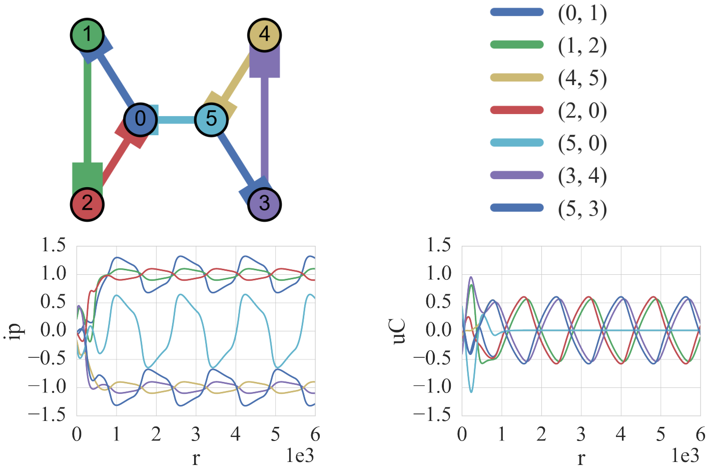

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A model at the cross-roads

Status Quo:

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

How to proceed?

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

Both approaches are worthwhile and 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.