Unexpected Cleverness in Unicellular Organisms: The Slime Mold Case

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OUTLINE

- Physarum Polycephalum
- Physarum Cleverness
- Physarum Model
- Physarum-Inspired Networking
- Physarum-Driven Networking
- Physarum-Driven Molecular Communications

WHAT ARE WE TALKING ABOUT?

A. Tero, S. Takagi, T. Saigusa, and others, "Rules for biologically inspired adaptive network design", Science, vol. 327, issue 5964, p. 439, 2010.

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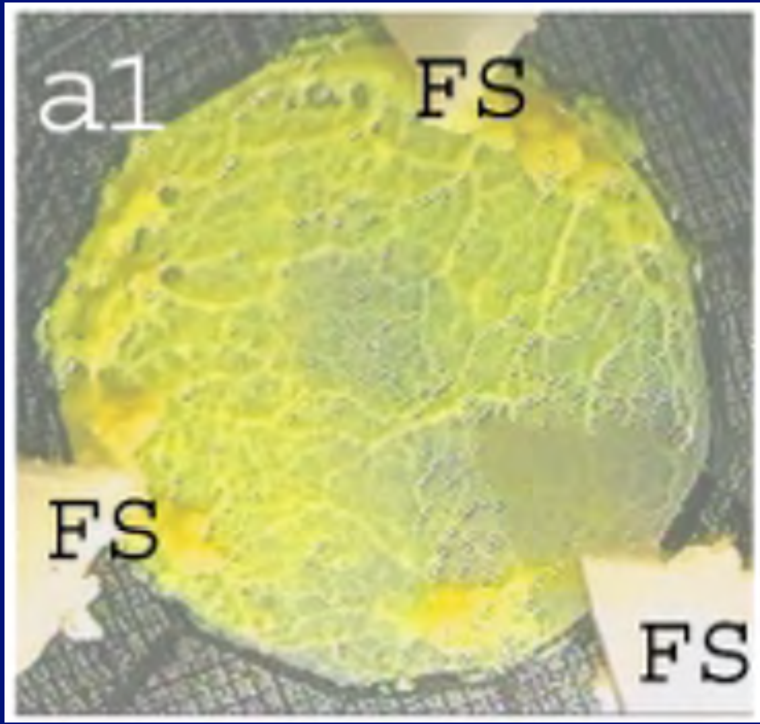
PHYSARUM POLYCEPHALUM

Large multinucleated unicellular amoeboid organism
- mobile and no chitin, unlike fungi
- no chlorophyll, unlike plants
- large, unlike bacteria

Different forms:
- spore stage
- amoeba stage
- plasmodium stage (active)
- sclerotium stage (dormant)

PLASMODIUM STAGE: SHEET-LIKE FORM

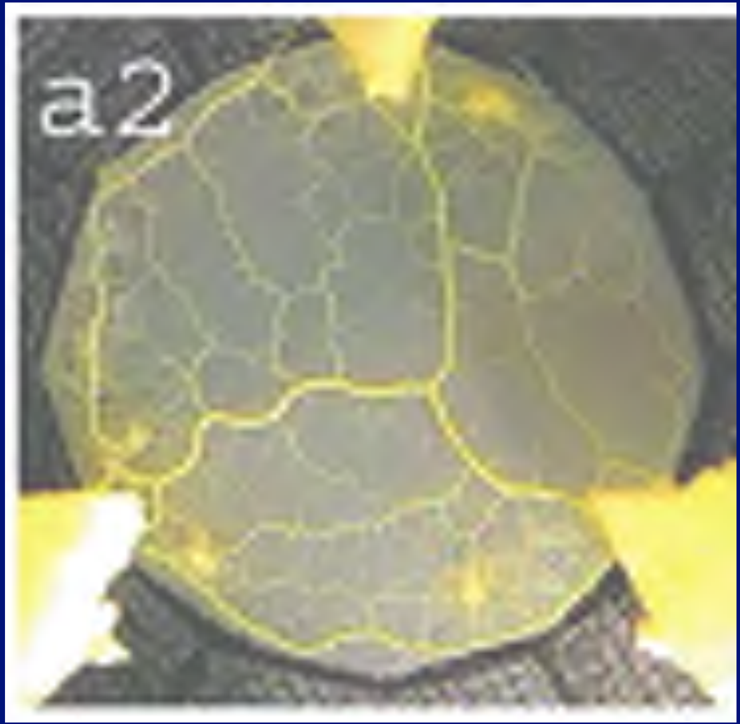
- contiguous foraging margin
  - to maximize the searched area for feeding
- tubular network
  - for transporting nutrients and physical/chemical signals
  - formed by hydrostatic pressure of flowing protoplasm (1 mm/s) due to rhythmic contractions



T. Nakagaki, H. Yamada, M. Hara, "Smart network solutions in an amoeboid organism", Elsevier Biophysical Chemistry, vol. 107, issue 1, pp. 1-5, 2005\

PLASMODIUM STAGE: FEEDING FORM

- **efficiency**
  - food sources are connected with direct connections
  - intermediate junctions (Steiner points) reduce the overall network length
- **reliability**
  - occasional cross-links that improve overall transport resilience



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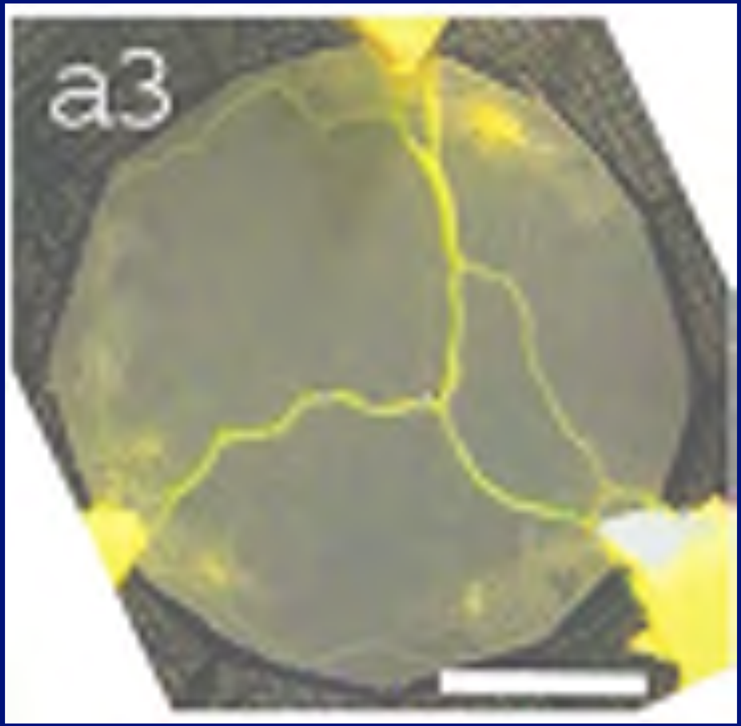

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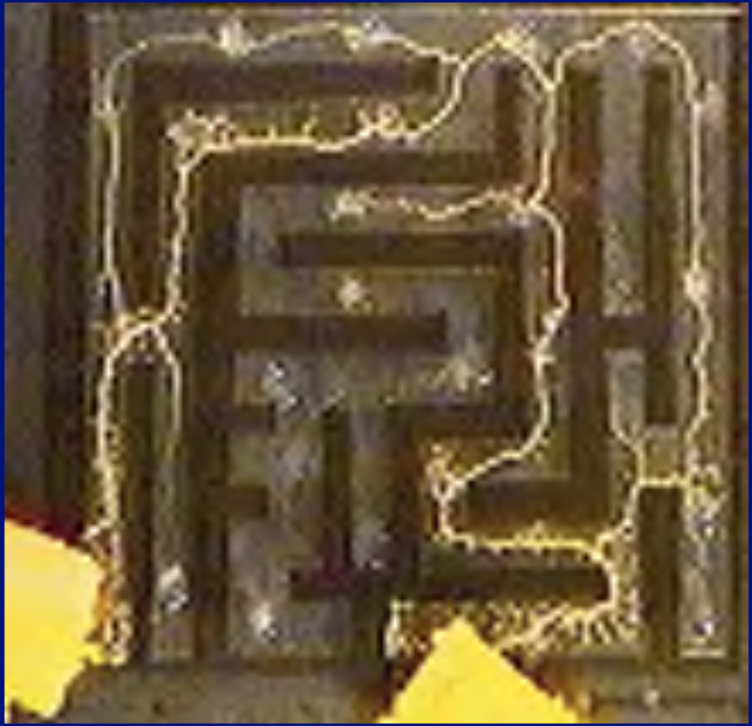
PHYSARUM CLEVERNESS

Physarum has been applied to:

- Maze-solving

  The Physarum is able to navigate a maze using the shortest route.



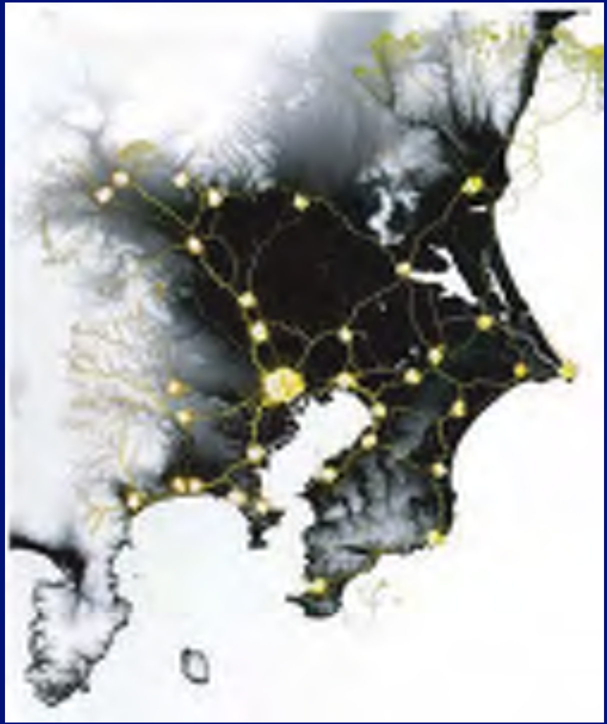
T. Nakagaki, H. Yamada, A. Toth, "Intelligence: Maze-solving by an amoeboid organism", Nature, vol. 407, issue 6803, p. 470, 2000.

PHYSARUM CLEVERNESS

Physarum has been applied to:

- Maze-solving
- Network Design

  The Physarum can form a network with efficiency/ resilience comparable or better than those of existing rail networks.



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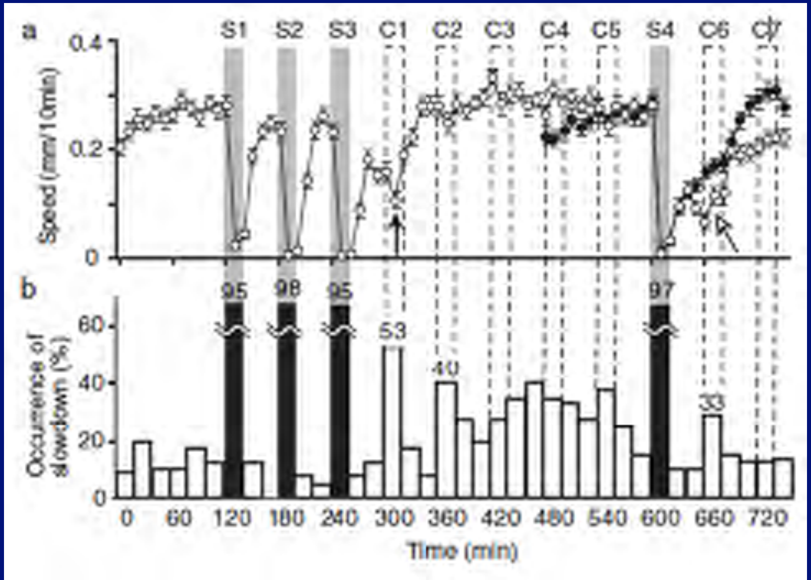
PHYSARUM CLEVERNESS

Physarum has been applied to:

- Maze-solving
- Network Design
- Event Anticipation

  The Physarum can anticipate a 1 hour cold-dry pattern previously applied.



T. Saigusa, A. Tero, T. Nakagaki, Y. Kuramoto, "Amoebae anticipate periodic events", APS Physical Review Letters, vol. 100, issue 1, p. 18101, 2008.

PHYSARUM CLEVERNESS

Physarum has been applied to:

- Maze-solving
- Network Design
- Event Anticipation
- Computing

The Physarum can be used to form logical gates.

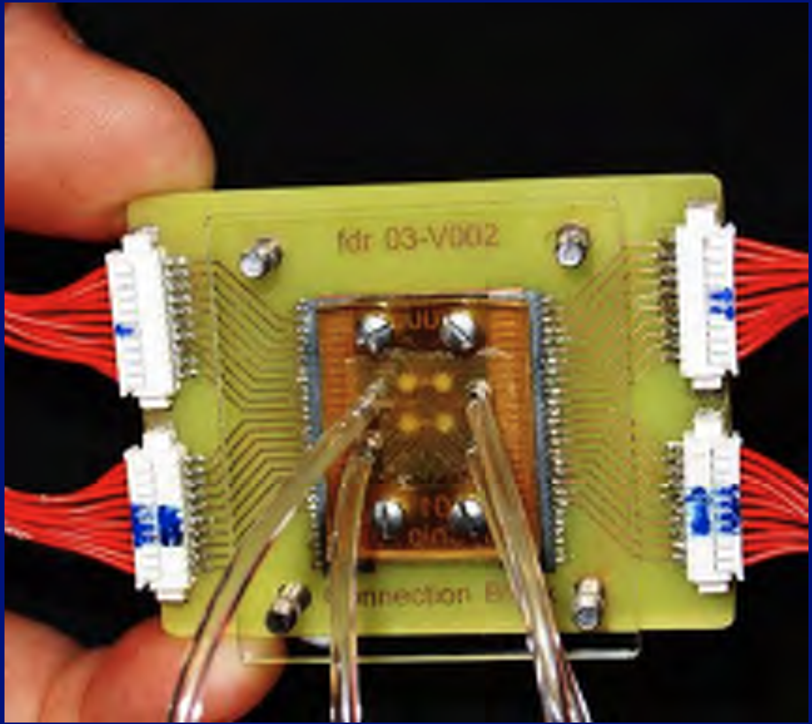
A. Adamatzky, "Slime mould logical gates: exploring ballistic approach", Arxiv preprint arXiv:1005.2301, 2010.

PHYSARUM CLEVERNESS

Physarum has been applied to:

- Maze-solving
- Network Design
- Event Anticipation
- Computing

The Physarum can be used to control a robot.



J. Gough, G. Jones, G. and others, "Integration of Cellular Biological Structures Into Robotic Systems", European Space Agency Acta Futura, vol. 3, pp. 43-49, 2009.

PHYSARUM CLEVERNESS

Is this cleverness really unexpected?

biological organisms

- successive rounds of evolutionary selection
- cost, efficiency, and resilience of their communication/ computation tasks are appropriately balanced

Physarum Polycephalum's tasks:

- movement for food discovering
- <u>nutrients and physical/chemical signals transport</u>

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PHYSARUM MODEL

Physiological Aspects

- tube dynamic is controlled by flux (protoplasm hydrostatic pressure)
- flux is generated by rhythmic contractions
- contractions are out of phase when food is available

Simple empirical rules

- open-ended tubes (not connected to food) tend to disappear
- longer tubes tend to disappear
- hydrostatic equilibrium

A. Tero, R. Kobayashi, T. Nakagaki, "A mathematical model for adaptive transport network in path finding by true slime mold", Journal of Theoretical Biology, vol. 244, issue 4, pp. 553-564, 2007

PHYSARUM MODEL

Mathematical Model

$$Q_{ij}(t) = \frac{D_{ij}(t)}{L_{ij}}(p_i(t) - p_j(t))$$

$$\sum_i Q_{ij}(t) = \begin{cases} -I & \text{if } j = source \\ I & \text{if } j = destination \\ 0 & \text{if } j \neq source, destination \end{cases}$$

$$\frac{dD_{ij}(t)}{dt} = f(Q_{ij}(t)) - D_{ij}(t)$$

Q_{ij}	flux for link l_{ij}
D_{ij}	conductivity for link l_{ij}
L_{ij}	length of link l_{ij}
p_i	pressure at node i
I	flux flowing from the source node
f	monotonically increasing continuous with $f(0) = 0$

T. Miyaji, I. Ohnishi, "Physarum can solve the shortest path problem on riemannian surface mathematically rigourously", International Journal of Pure and Applied Mathematics, vol. 47, issue 3, pp. 353-369, 2008.

K. Ito, A. Johansson, and others, "Convergence Properties for the Physarum Solver", Arxiv preprint arXiv: 1101.5249, 2011.

PHYSARUM MODEL

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The model

- assures the optimal solution for the shortest path problem
- converges with an exponential rate to the optimal solution of a flow problem

PHYSARUM MODEL

Applications of the model

- Maze Navigation
- Road Navigation
- Flow Network Adaption
- Graph Theory

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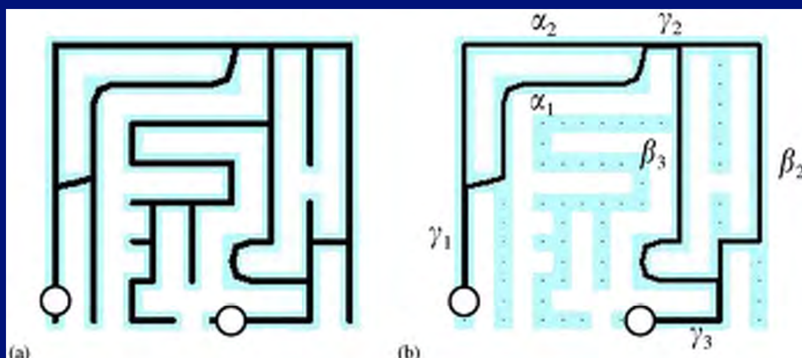

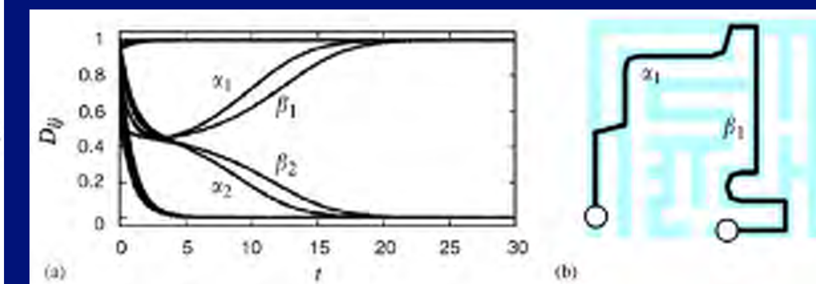

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PHYSARUM MODEL

Applications of the model

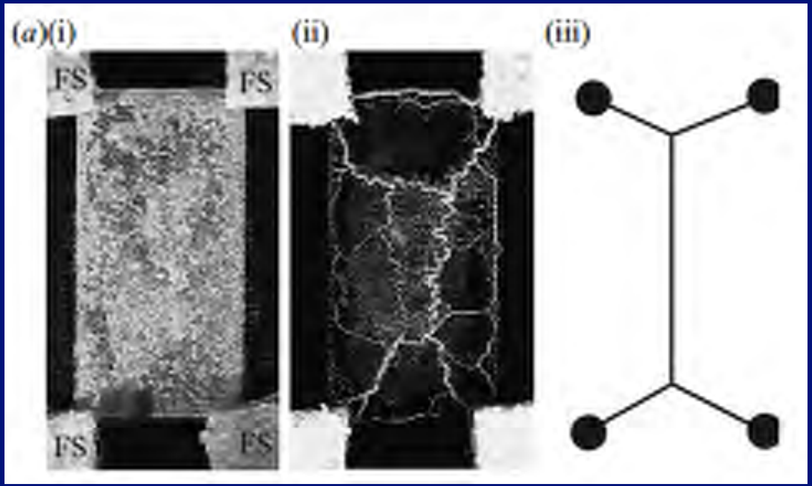
- Flow Network Adaptation

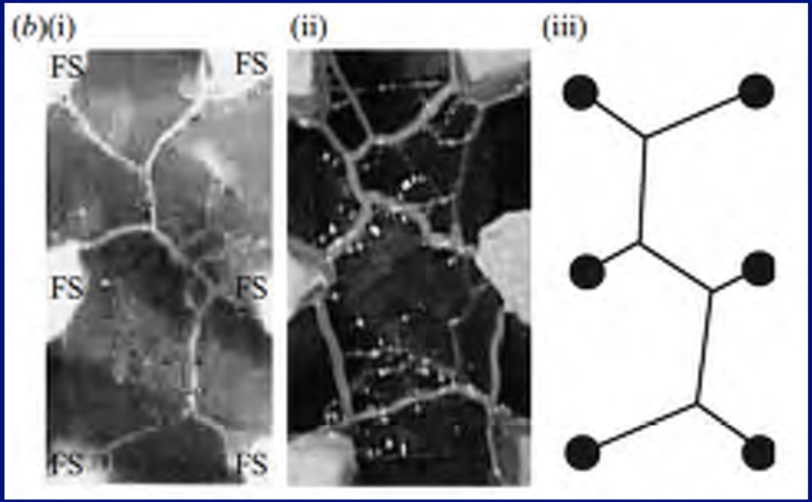
A. Tero, K. Yumiki, and others, "Flow-network adaptation in Physarum amoebae", Springer Theory in Biosciences, vol. 127, issue 2, pp. 89-94, 2008.

PHYSARUM MODEL

Applications of the model

- Graph Theory (Steiner minimum trees)





T. Nakagaki, R. Kobayashi, R. and others, "Obtaining multiple separate food sources: behavioural intelligence in the Physarum plasmodium", in Proc. of the Royal Society of London, vol. 271, issue 1554, p. 2305, 2004.

SO WHAT?

PHYSARUM CLEVERNESS

Physarum-Inspired Networking

Physarum-Driven Networking

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PHYSARUM-INSPIRED NETWORKING

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Advantages

- simple model
- effective network representation
- adaptive (through reinforce)
- can find
  - efficient solutions
  - resilience solutions
  - hybrid solutions

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Applications

- network design
- routing
  - path discovery
- QoS
  - optimization problems
- graph theory
  - NP-hard problems

PHYSARUM-INSPIRED NETWORKING

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Drawbacks

- convergence time
- global knowledge
  - can be avoided, but with larger convergence times
- solutions depending on the initial data
- oscillation effects?

PHYSARUM-INSPIRED NETWORKING

Research Challenges

- accurate equilibrium analysis
  - we can benefit from an adaptive behavior
  - but we cannot have chaotic evolution
- dynamic network
  - mobility issues
  - scalability issues

PHYSARUM-INSPIRED NETWORKING

Research Challenges

- cross-layer design
  - **physical layer?**

    continuous flows vs "impulsive" communications
  - **mac layer?**

    point-to-point flows vs broadcast communications

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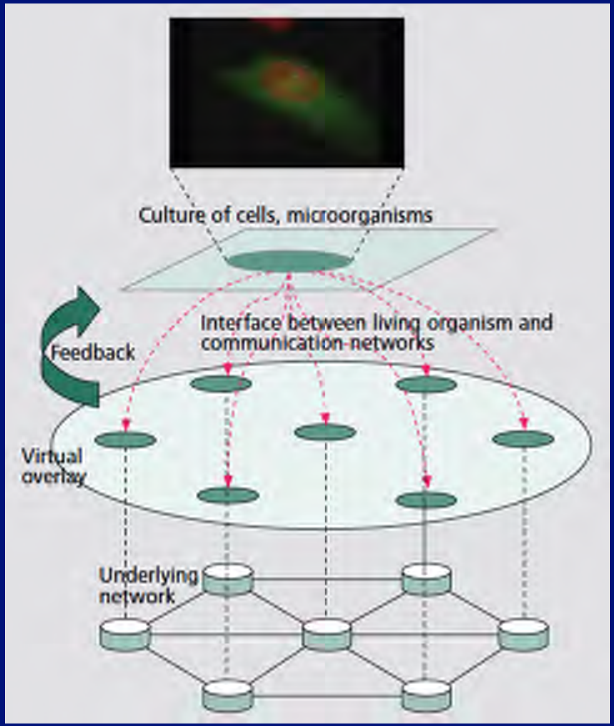
BIOLOGICAL-DRIVEN NETWORK DESIGN

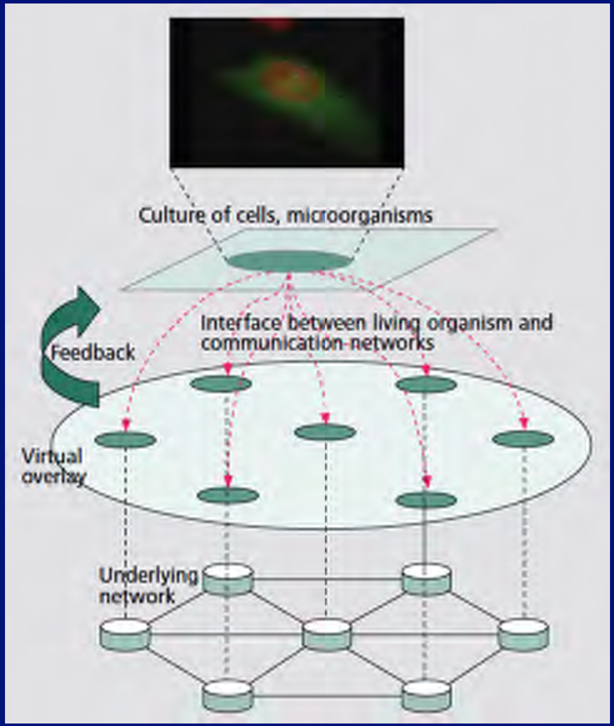


The biological culture models the overlay network

- changes in the underlying network trigger feedbacks in the biological culture
- the culture drives the behavior of virtual overlay

S. Balasubramaniam, K. Leibnitz, and others, "Biological principles for future internet architecture design," IEEE Communications Magazine, vol.49, issue 7, pp.44-52, 2011.

BIOLOGICAL-DRIVEN NETWORK DESIGN



Centralized Design:

the biological culture models the whole network

- the *stimuli* must be collected from the whole underlying network
  - communication bottleneck
- the underlying network connections must be mapped in the culture
  - biological bottleneck

BIOLOGICAL-DRIVEN NETWORK DESIGN

Our Proposal:

Distributed Design based on the Physarum:

Physarum cells are used to model nodes

- the stimuli are local
  - communication scalability
- the underlying network neighborhood is mapped on the cell
  - biological scalability

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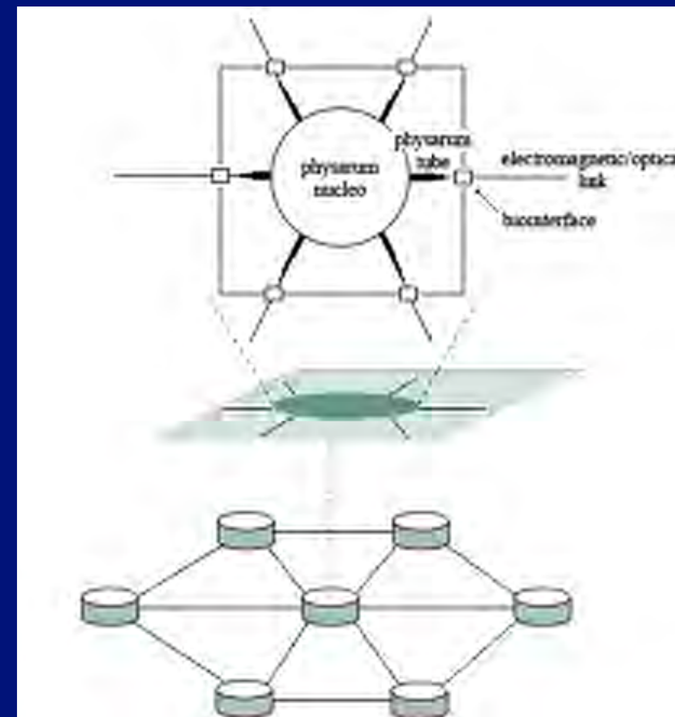


BIOLOGICAL-DRIVEN NETWORK DESIGN

<u>Our Proposal</u>:

Stimuli

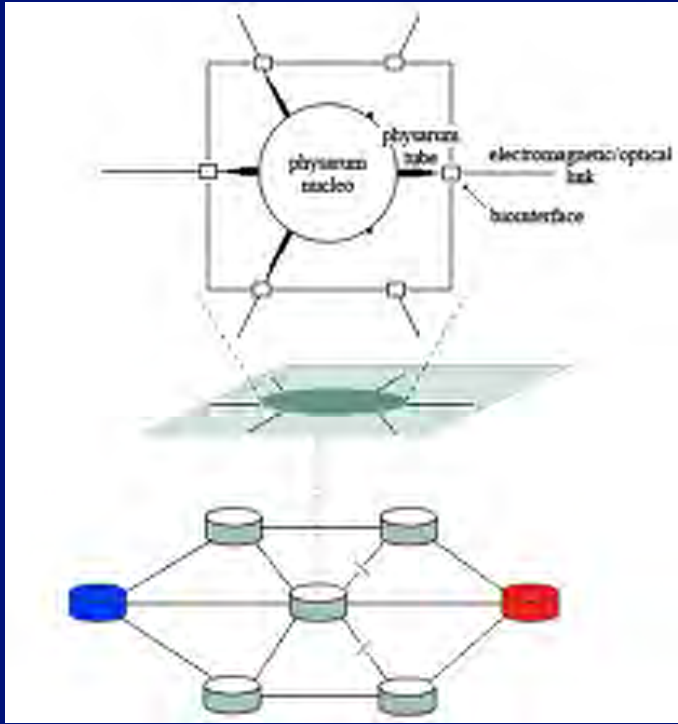
- variation of food
- protoplasm flow
- environmental conditions

Underlying link

- mapped on food presence
- mapped on flow/oscillation

Biological Feedback

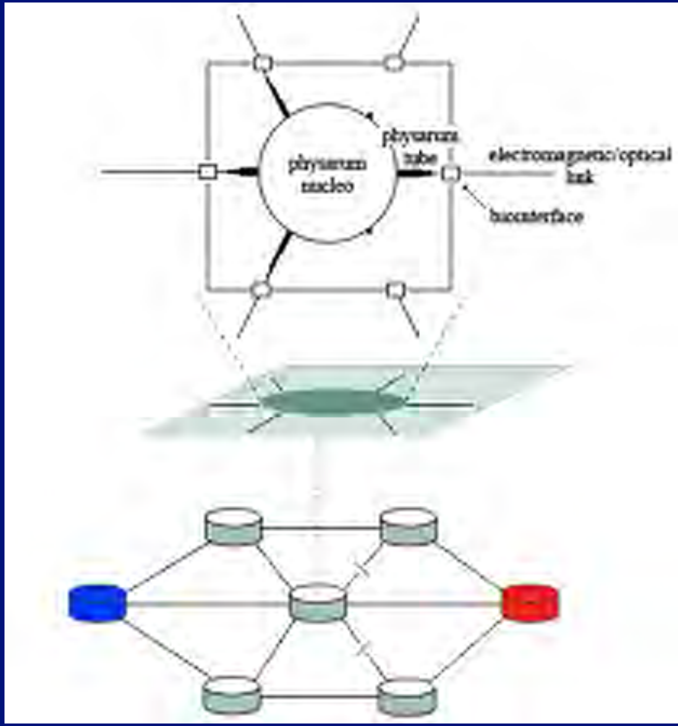
Tubular network



BIOLOGICAL-DRIVEN NETWORK DESIGN

Drawbacks

- plasmodium initialization
- convergence time
- unpredictable behavior
- foraging/mortality



BIOLOGICAL-DRIVEN NETWORK DESIGN

Research Challenges

- biointerface design
  - stimuli
  - information encoding
  - broadcast channels
- biological feedback
  - how to map it on the underlying network

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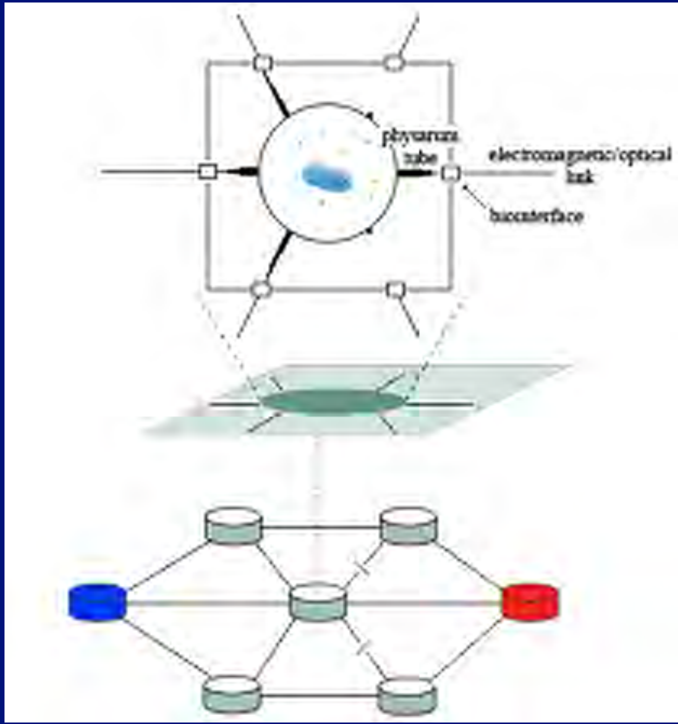
PHYSARUM-DRIVEN MOLECULAR COMMUNICATIONS

Problem duality

Physarum networking vs Molecular Nanonetworks

- Broadcast Messages
- Multi-attractant Receivers for Longer Distance
- Network deployment:
  - Address assignment
  - Neighbor discovery
  - Multi-hop path creation.



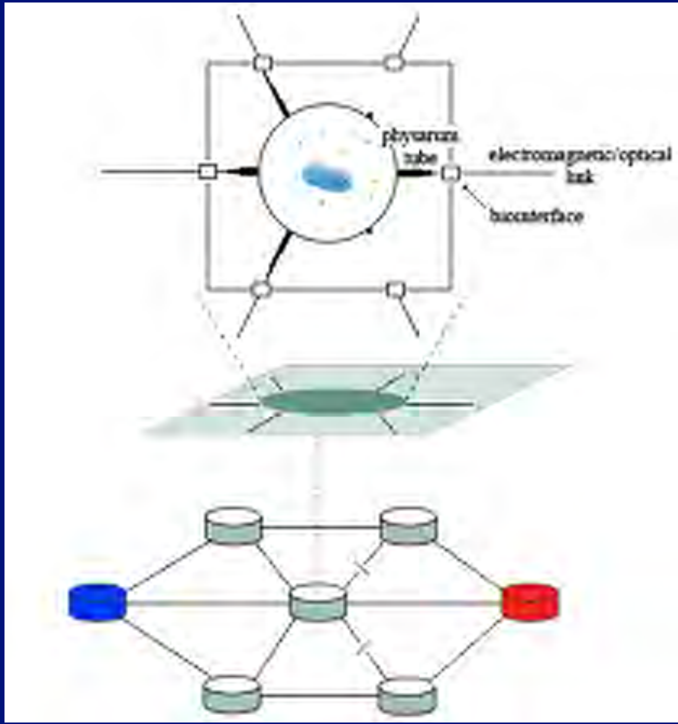
I. F. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A New Communication Paradigm," Elsevier Computer Networks, vol. 52, issue 12, pp. 2260-2279, 2008.

PHYSARUM-DRIVEN MOLECULAR COMMUNICATIONS

Our Proposal:

Physarum-Driven Molecular Nanonetworks

- Carriers for long-range molecular communications
  - Range 1μm-1m
  - Speed 1mm/s
  - Reliable



PHYSARUM-DRIVEN MOLECULAR COMMUNICATIONS

Research Challenges

Physarum-Driven Networking Challenges

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Molecular Communications Challenges