Slime Molds and Cognitive Maps

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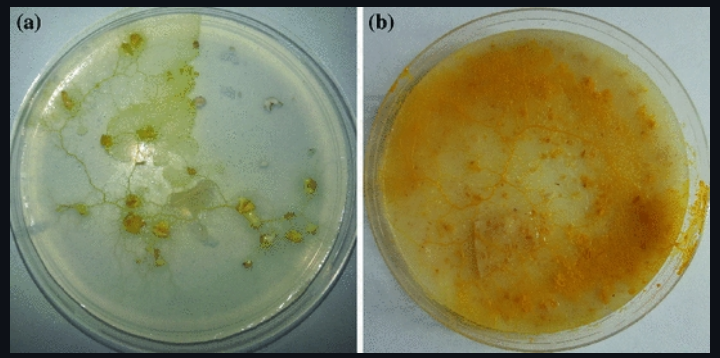
- World of the Slime Mold
  - The slime itself: *Physarum polycephalum*
  - Mapping the world with/of the slime mold
  - To err is ~~human~~ slime mold
- Computational Models
  - Analyticaly derived models
  - Monte Carlo-based models
  - Shortcomings of the current models
- Results and Outcomes
- Future directions

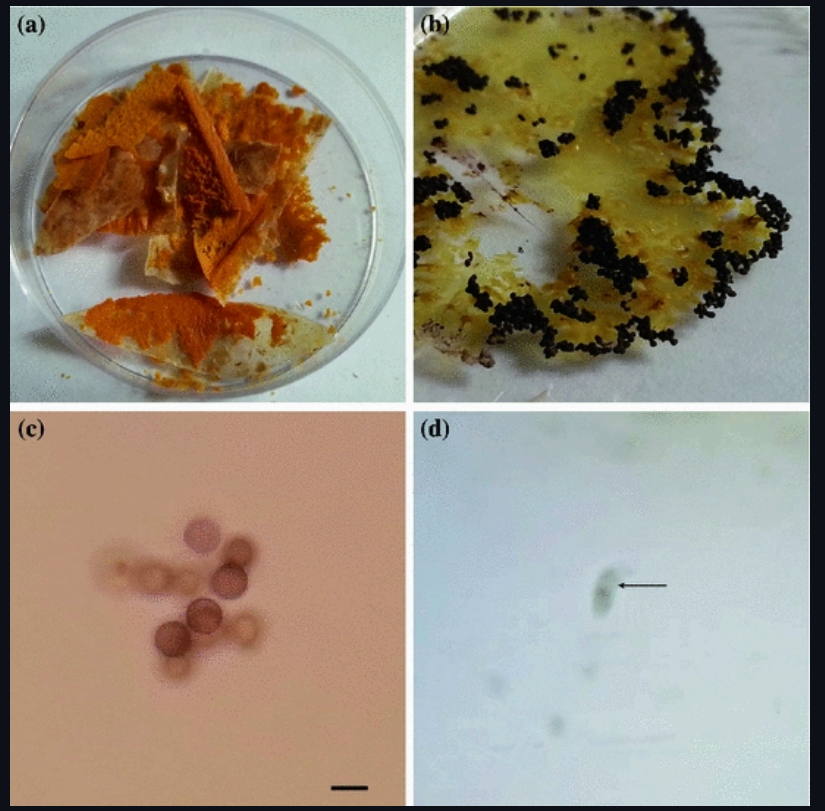
World of the Slime Mold

The slime itself: *Physarum polycephalum*

- eukaryote but not a fungus!
  - amoeboid protist
- "syncytium:" one cell, *millions* of nuclei!



- plasmodium: mobile form
  - few mm^2 to over half a m^2
  - can move up to 1cm/h
- has inspired many work, including an optimization algorithm



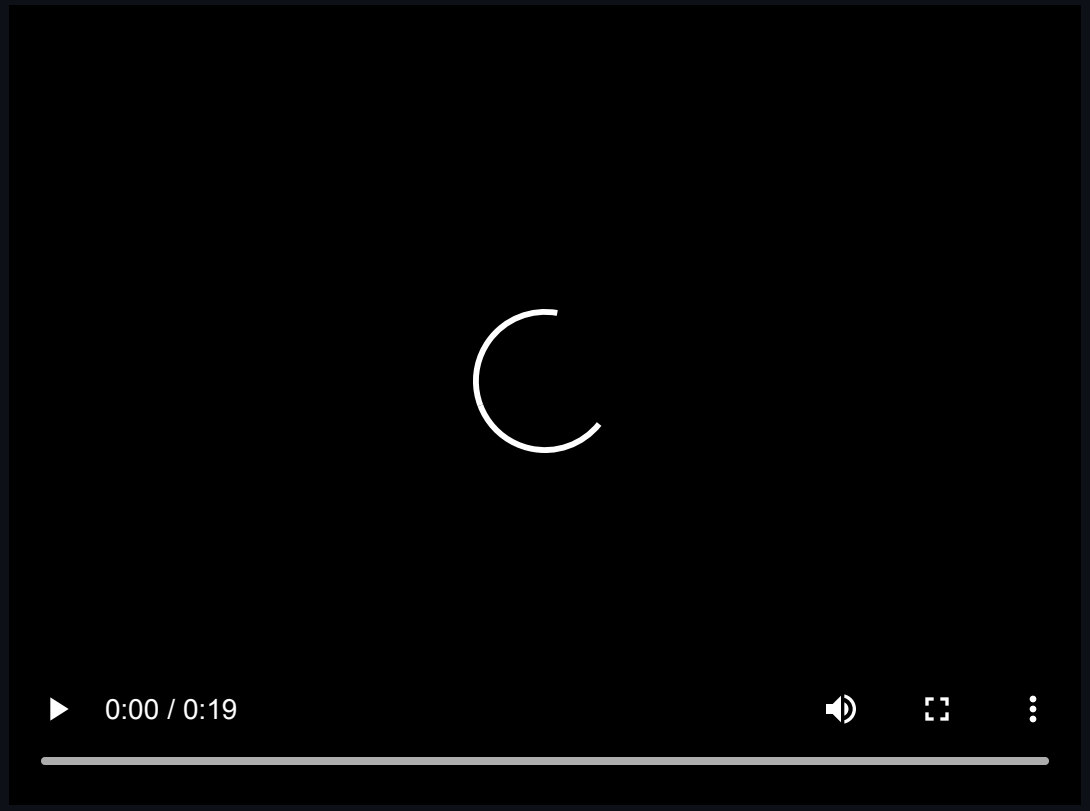
(a) Fragments of sclerotium. (b) Sporangia. (c) Spores. (d) Swarm cell (arrowed). c, d Scale bar = 10μ m

Adamatzky (ed.) (2016) "Advances in Physarum Machines," https://doi.org/10.1007/978-3-319-26662-6
Mayne (2016). "Biology of the Physarum polycephalum Plasmodium: Preliminaries for Unconventional Computing," In: Adamatzky, A. (eds) Advances in Physarum Machines. https://doi.org/10.1007/978-3-319-26662-6_1
Li et al. (2020) "Slime mould algorithm: A new method for stochastic optimization," https://www.sciencedirect.com/science/article/pii/

Mapping the world with/of the slime mold

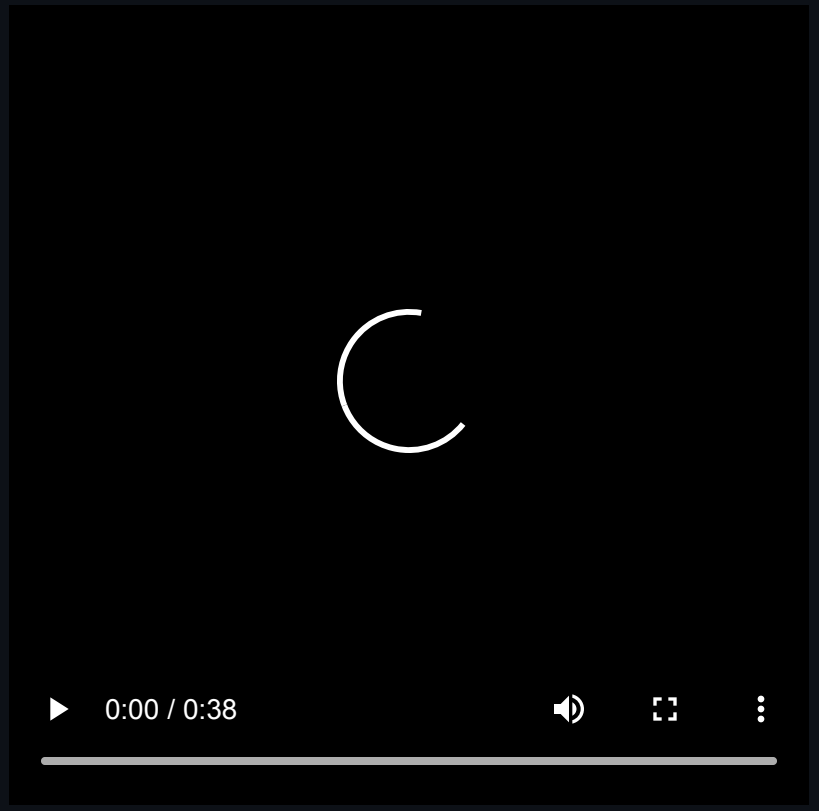
Slime molds as path finders

- Maze solving



Youtube: Slime mold solving a maze in the lab

- Tokyo subway map



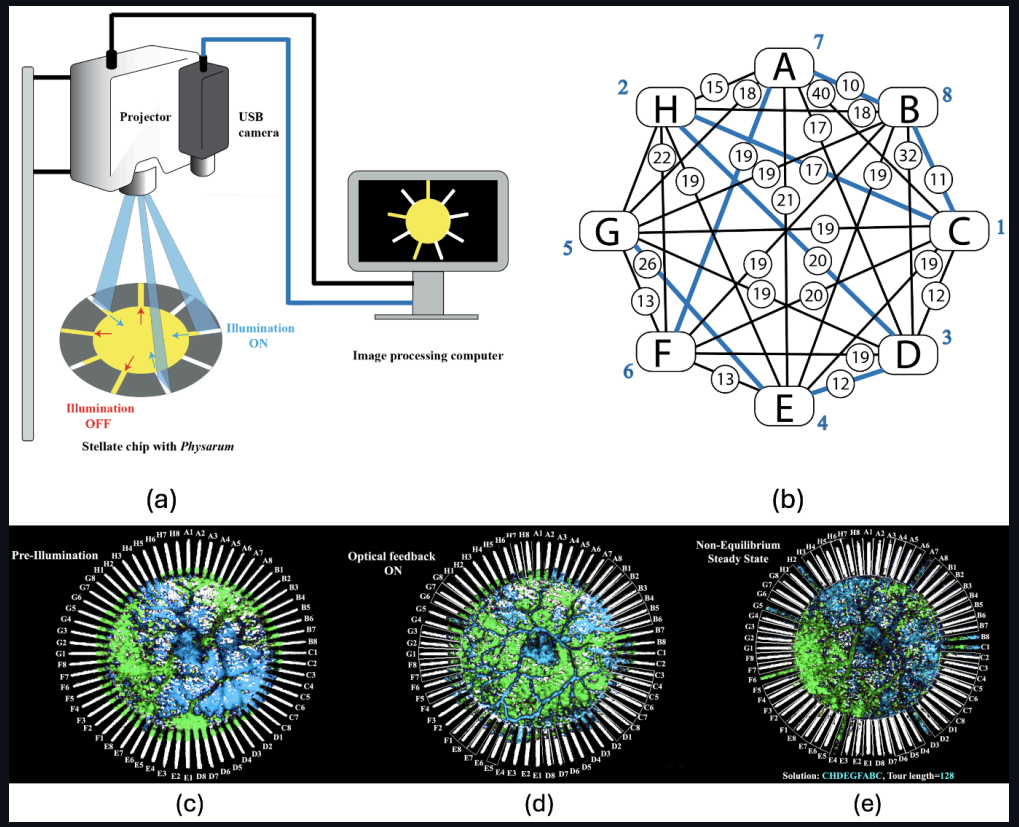
Youtube: Slime mold form a map of the Tokyo-area railway system

Nakagaki et al. (2000) “Maze-solving by an amoeboid organism,” https://www.nature.com/articles/35035159
Tero et al. (2010), “Rules for Biologically Inspired Adaptive Network Design,” https://www.science.org/doi/10.1126/science.1177894

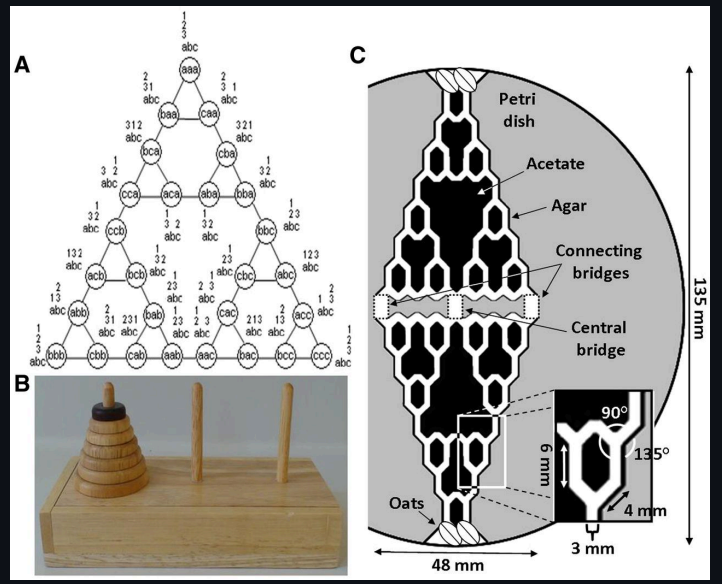
Mapping the world with/of the slime mold - 2

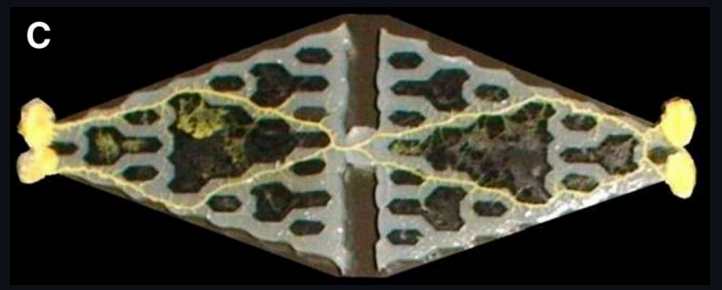
Slime molds as "problem solvers"

- Traveling salesperson problem



- Towers of Hanoi puzzle



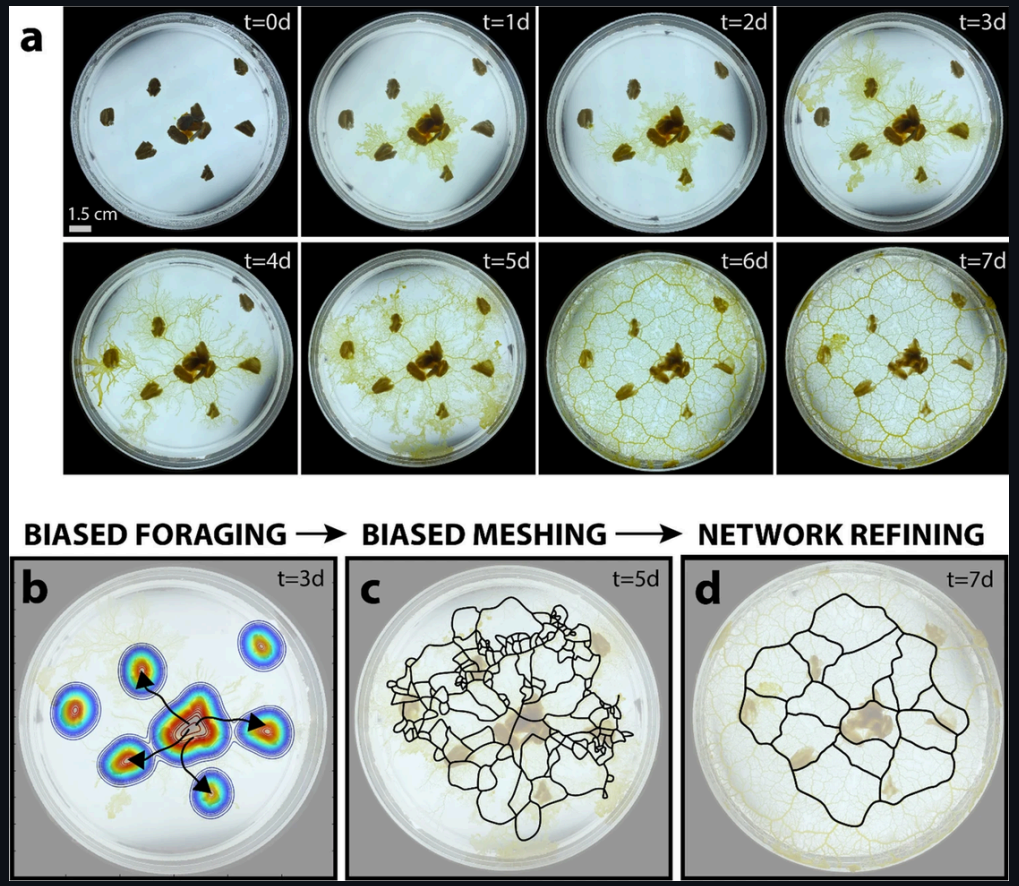


Bajpai et al. (2026) "Tracking and distinguishing slime mold solutions to traveling salesperson problems through synchronized amplification in the non-equilibrium steady state," http://arxiv.org/abs/2504.03492
Reid and Beekman (2013) "Solving the Towers of Hanoi – how an amoeboid organism efficiently constructs transport networks," https://doi.org/10.1242/jeb.081158

Mapping the world with/of the slime mold - 3

Slime molds as ???

- Urban designers?



- Romans??



- Colonizers???

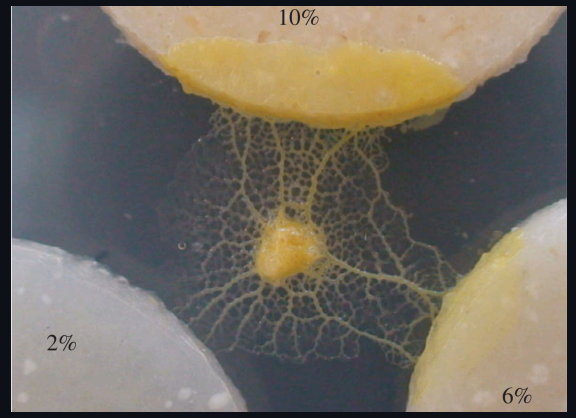


Kay et al., (2022) "Stepwise slime mould growth as a template for urban design," https://www.nature.com/articles/s41598-022-05439-w
Evangelidis et al., (2017) "Physarum machines imitating a Roman road network: the 3D approach," https://www.nature.com/articles/s41598-017-06961-y
Adamatzky, (2012) "The World's Colonisation and Trade Routes Formation as Imitated by Slime Mould," https://arxiv.org/abs/1209.3958v1

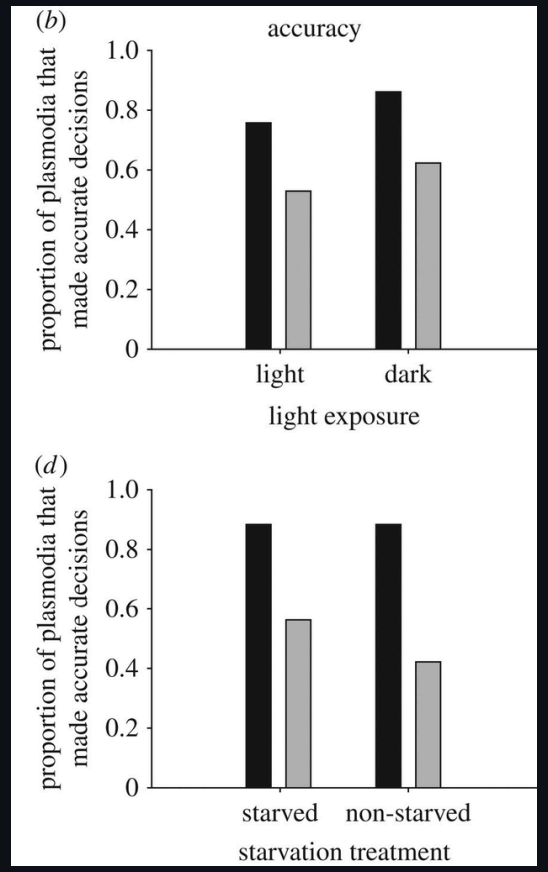
To err is ~~human~~ slime mold

Speed-accuracy trade-off

when having to choose between food sources, adding stressors reduce accuracy of choosing the larger one

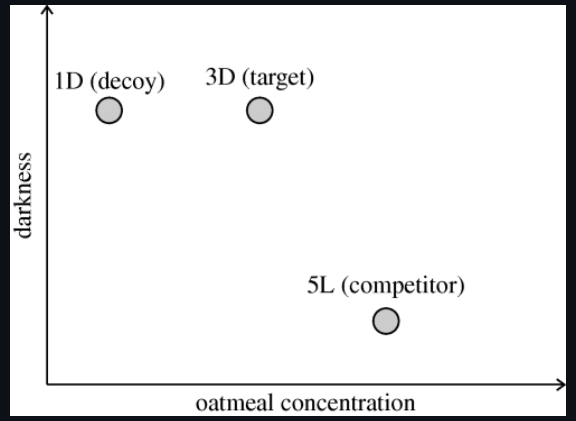


dark: easy
gray: difficult

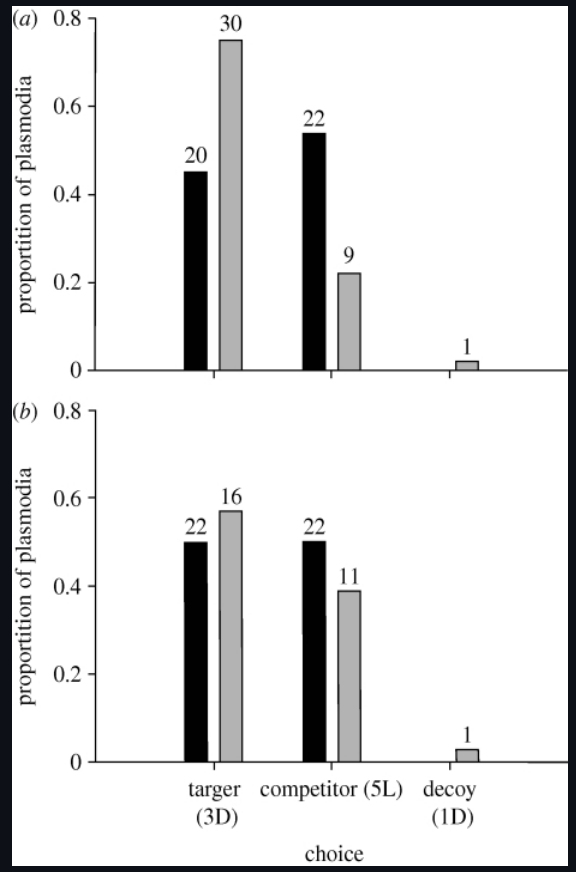


Independence of Irrelevant Alternatives

when an overall worse option is introduced into a choice among two, slime molds sometimes choose it



dark: two-choice setup
gray: three-choice setup



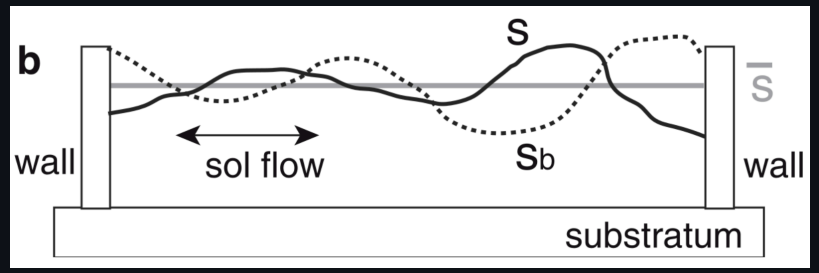
Latty and Beekman (2011) "Speed-accuracy trade-offs during foraging decisions in the acellular slime mould Physarum polycephalum," https://dx.doi.org/10.1098/rspb.2010.1624
——, (2011) "Irrational decision-making in an amoeboid organism: transitivity and context-dependent preferences," https://pmc.ncbi.nlm.nih.gov/articles/PMC3013386/

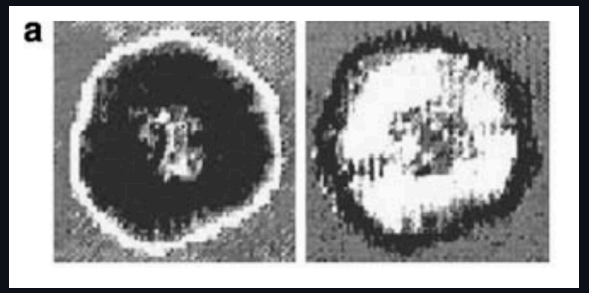
Computational Models

Analytically derived

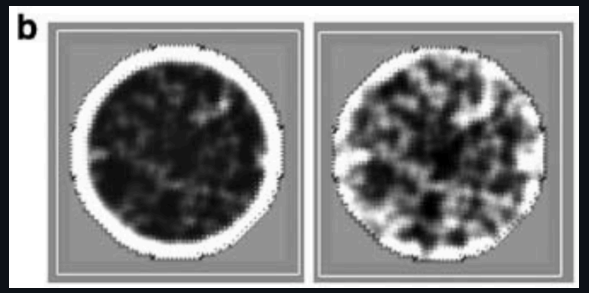
- the slime mold's thickness is assumed to be/approximated by a mathematical rule

$$\frac{\partial s}{\partial t} = \nabla \cdot (sM\nabla p)$$





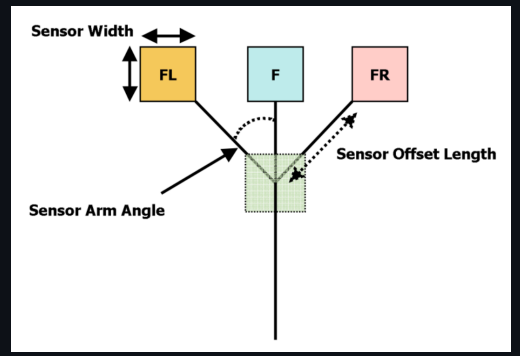
real slime mold patterns

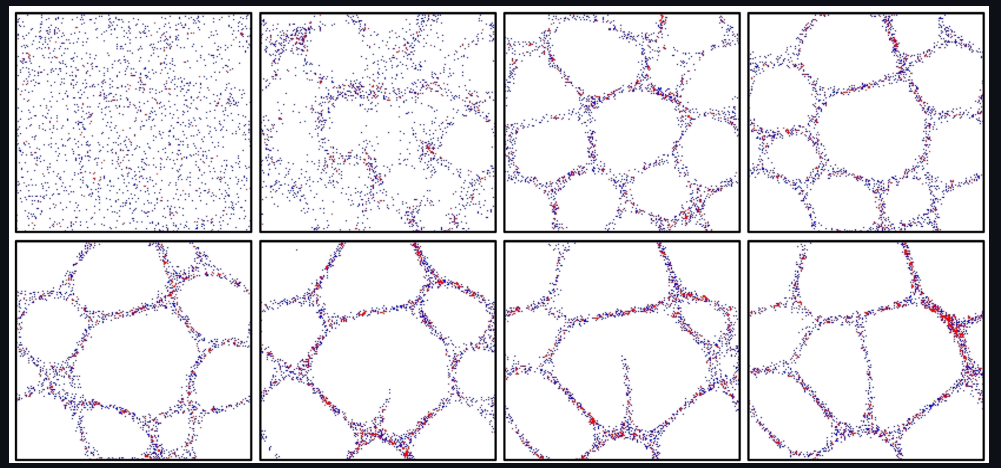


simulation results

Monte Carlo-based

- lots of small particles make small decisions to generate overall behavior





Kobayashi et al. (2006) "Mathematical Model for Rhythmic Protoplasmic Movement in the True Slime Mold," https://doi.org/10.1007/s00285-006-0007-0
Jones (2010) "The emergence and dynamical evolution of complex transport networks from simple low-level behaviours," https://www.scopus.com/pages/publications/77949441365

Analyticaly derived models

Tero et al (2007) adapted Kobayashi et al. (2006)'s model to graphs

- flux Q_{ij} from node i to j:

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

  where D_{ij} is the conductivity of the edge, p_i are pressures at nodes

- two nodes are special: one is source, one is sink

  flux *conserved* at regular node i

$$\sum_j Q_{ij} = 0$$

  flux *generated* at source node

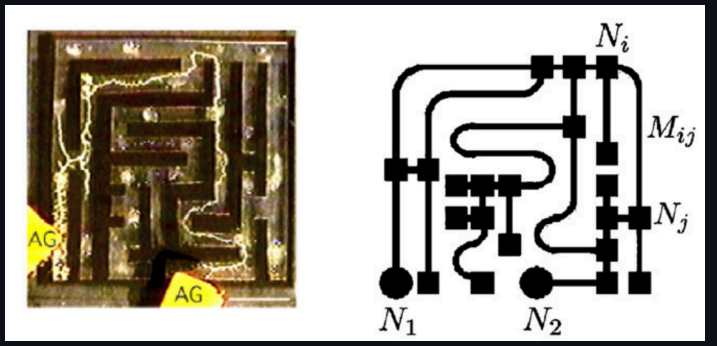
$$\sum_j Q_{\text{source},j} = I_0$$

  flux *consumed* at sink node

$$\sum_j Q_{\text{sink},j} = -I_0$$

- adapt the conductivities according to

$$\frac{d}{dt} D_{ij} = f(|Q_{ij}|) - rD_{ij}$$



- **this is just a lumped circuit model!**
  - p_i is node voltages,
  - Q_{ij} is the current,
  - $G_{ij} = \frac{D_{ij}}{L_{ij}}$ is the conductance



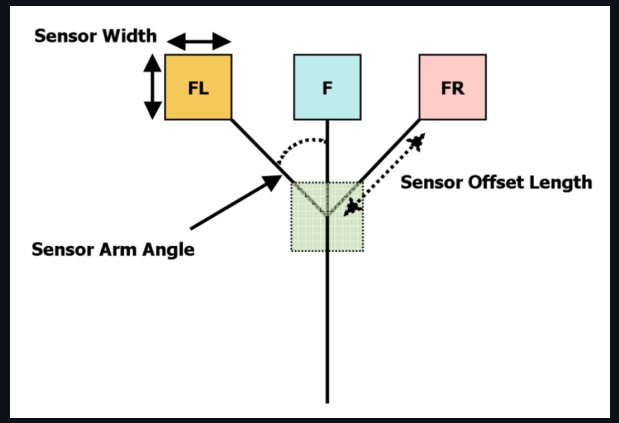
Tero et al. (2007) "A mathematical model for adaptive transport network in path finding by true slime mold," https://www.sciencedirect.com/science/article/pii/S002251930600289X

Monte Carlo-based models

simple actions of little particles can give rise to complex behavior at the population level...

Jones (2010)'s model:

```
[Motor stage]
- Attempt move forwards in current direction
- If (moved forwards successfully)
        Deposit trail in new location
- Else
        Choose random new orientation
[Sensory stage]
- Sample trail map values
- if (F > FL) && (F > FR)
        - Stay facing same direction
        - Return
- Else if (F < FL) && (F < FR)
        Rotate randomly left or right by RA
- Else if (FL < FR)
        Rotate right by RA
- Else if (FR < FL)
        Rotate left by RA
- Else
        Continue facing same direction
```



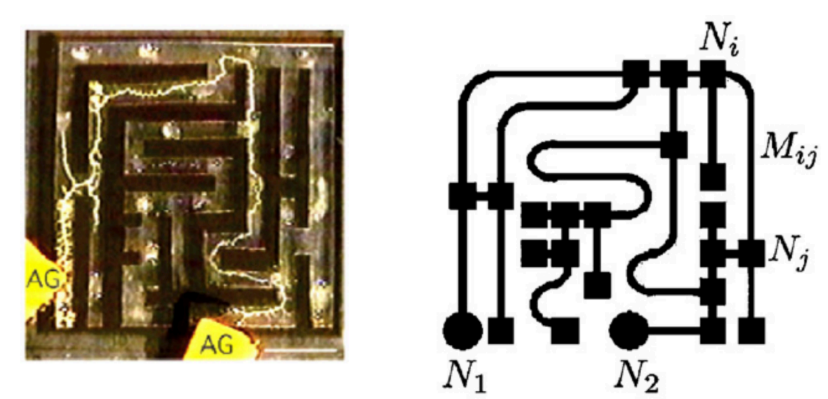
can we build on this?

- say each particle "looks" at all the nodes it can travel to and assigns a positive "score" to each of them
  - softmax decision:
    - sample the next node proportional to these scores
  - Metropolis-Hastings decision:
    - sample a candidate next node
      - if better, move there
      - if worse, move or stay probabilistically

Jones (2010) "The emergence and dynamical evolution of complex transport networks from simple low-level behaviours," https://www.scopus.com/pages/publications/77949441365

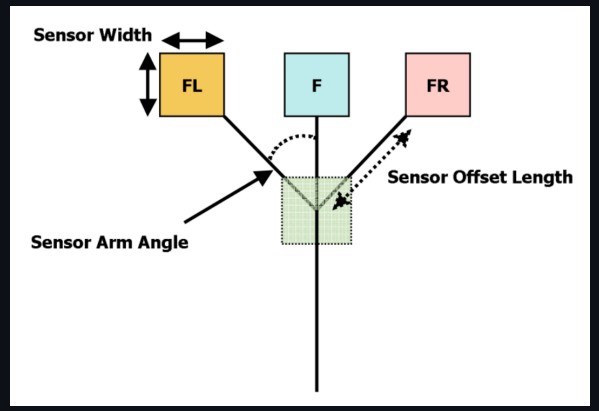
Shortcomings of the current models

Tero et al. (2007):



- biologically undesirable model
  - the function $f(|Q_{ij}|)$ is not as interpretable
  - food sources are modeled asymmetrically
- no repulsion term: light or slime
- no "exploration"

Jones (2010):

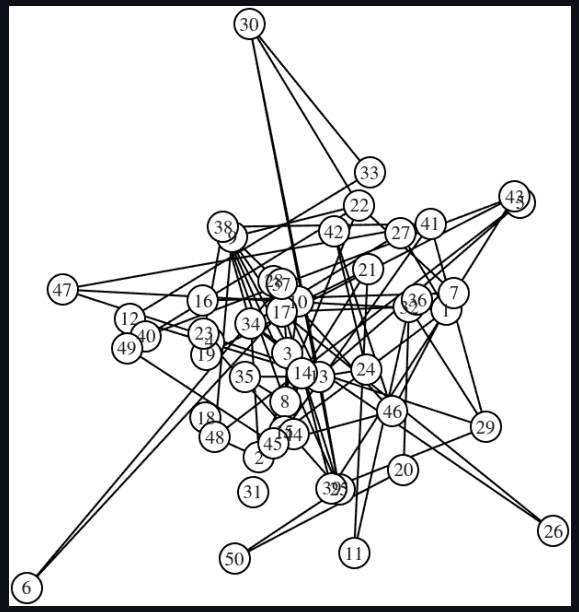


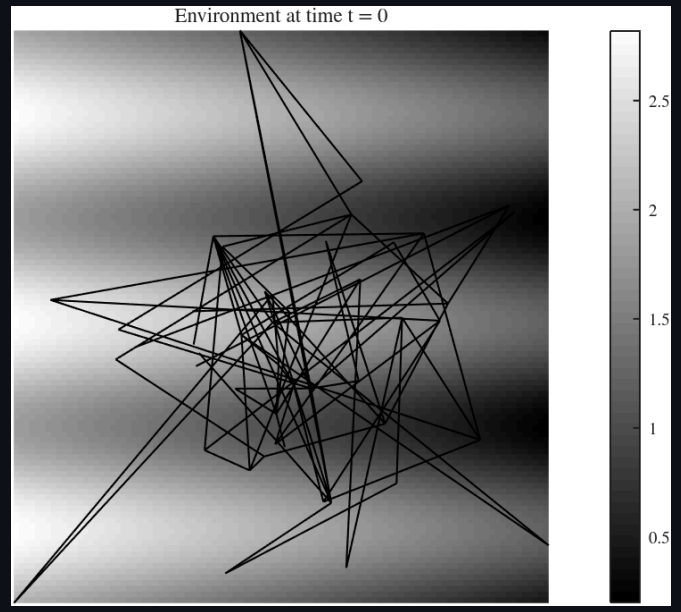
- no accounting of the path-finding effects
- no food, no light, just slime

Tero et al. (2007) "A mathematical model for adaptive transport network in path finding by true slime mold," https://www.sciencedirect.com/science/article/pii/S002251930600289X
Jones (2010) "The emergence and dynamical evolution of complex transport networks from simple low-level behaviours," https://www.scopus.com/pages/publications/77949441365

Results and Outcomes

- a `ratinabox`-style toolbox emerges!
  - `world = slimeWorld(node_locs, C_, light, slime, opts)`
  - `slime = circuitSlime(world, options)`
  - `slime = softmaxSlime(world, options)`
  - `slime = MHslime(world, options)`
- example:

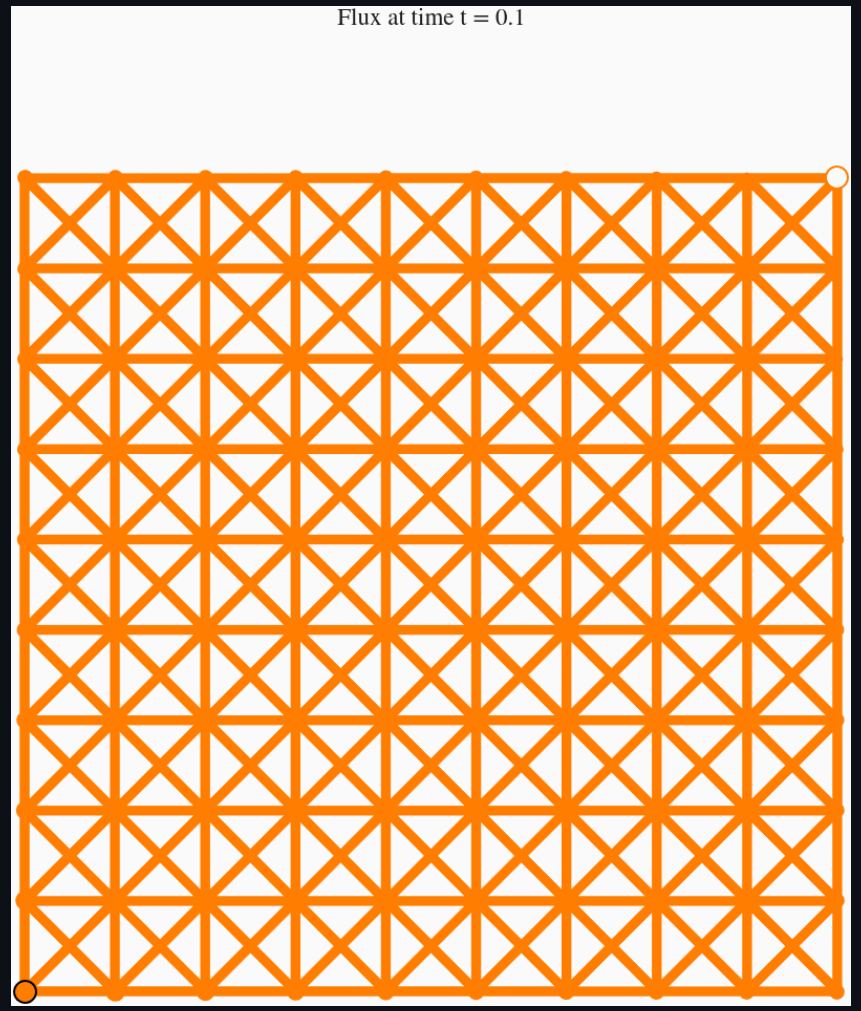


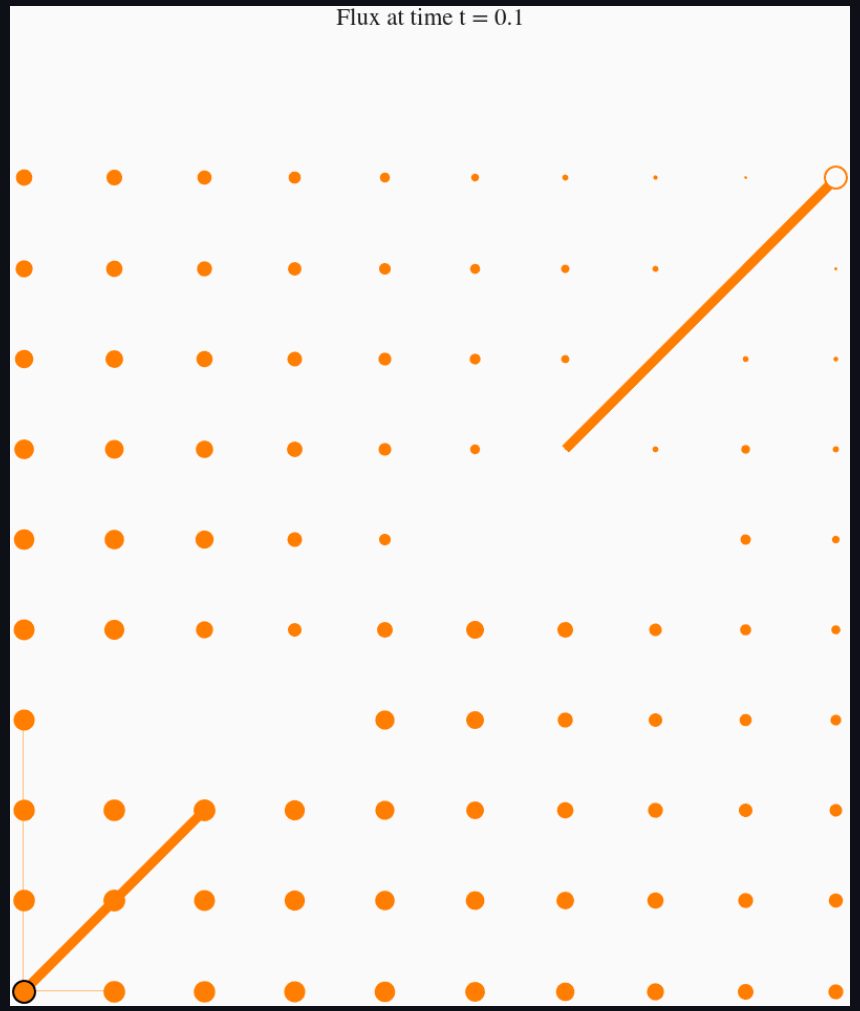




Results and Outcomes

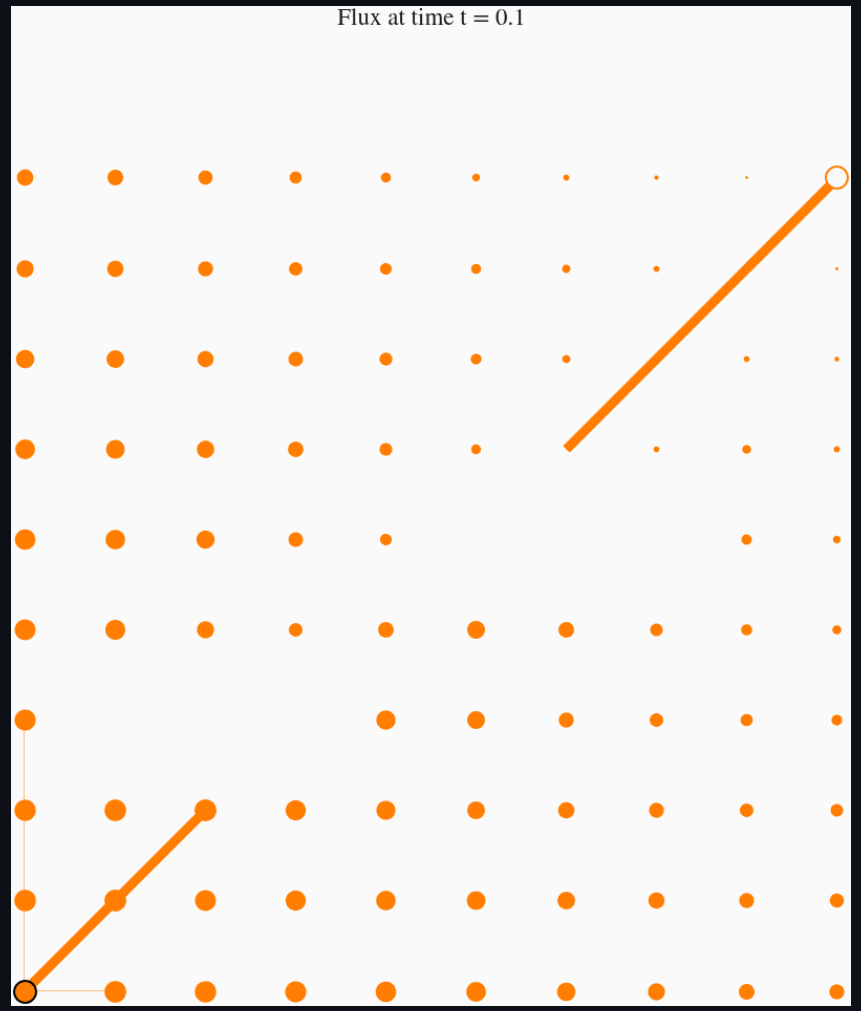
Path-finding and detours

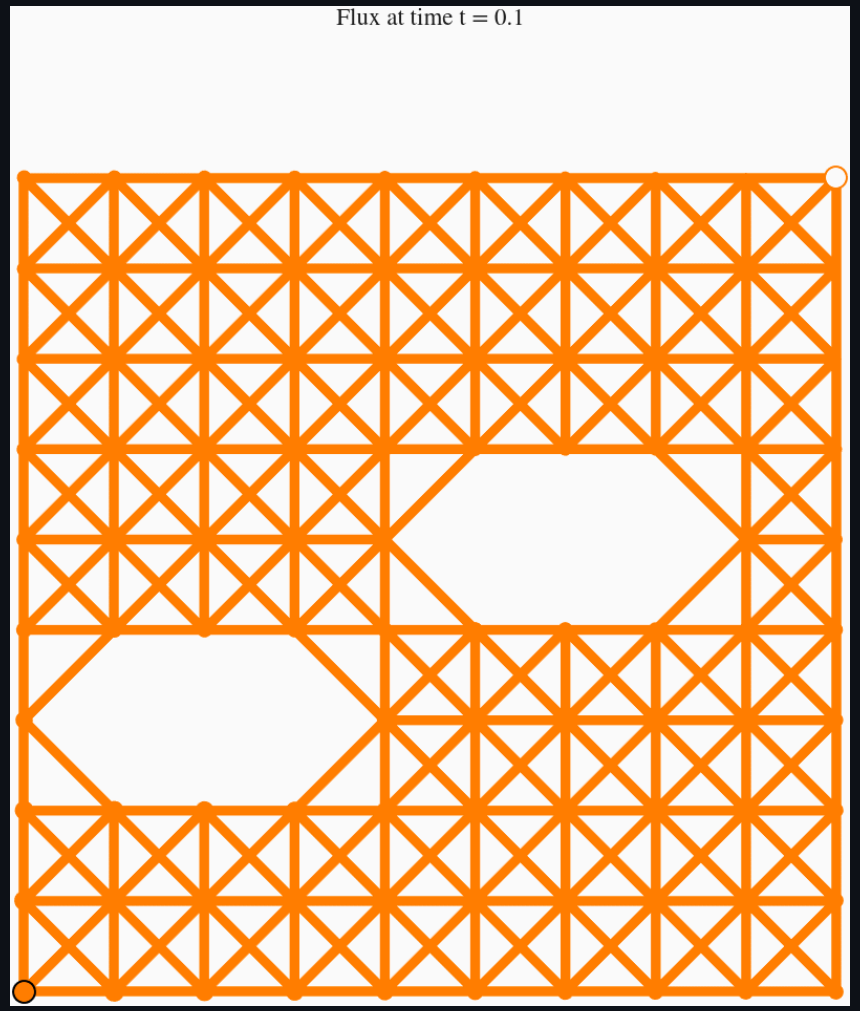




Results and Outcomes

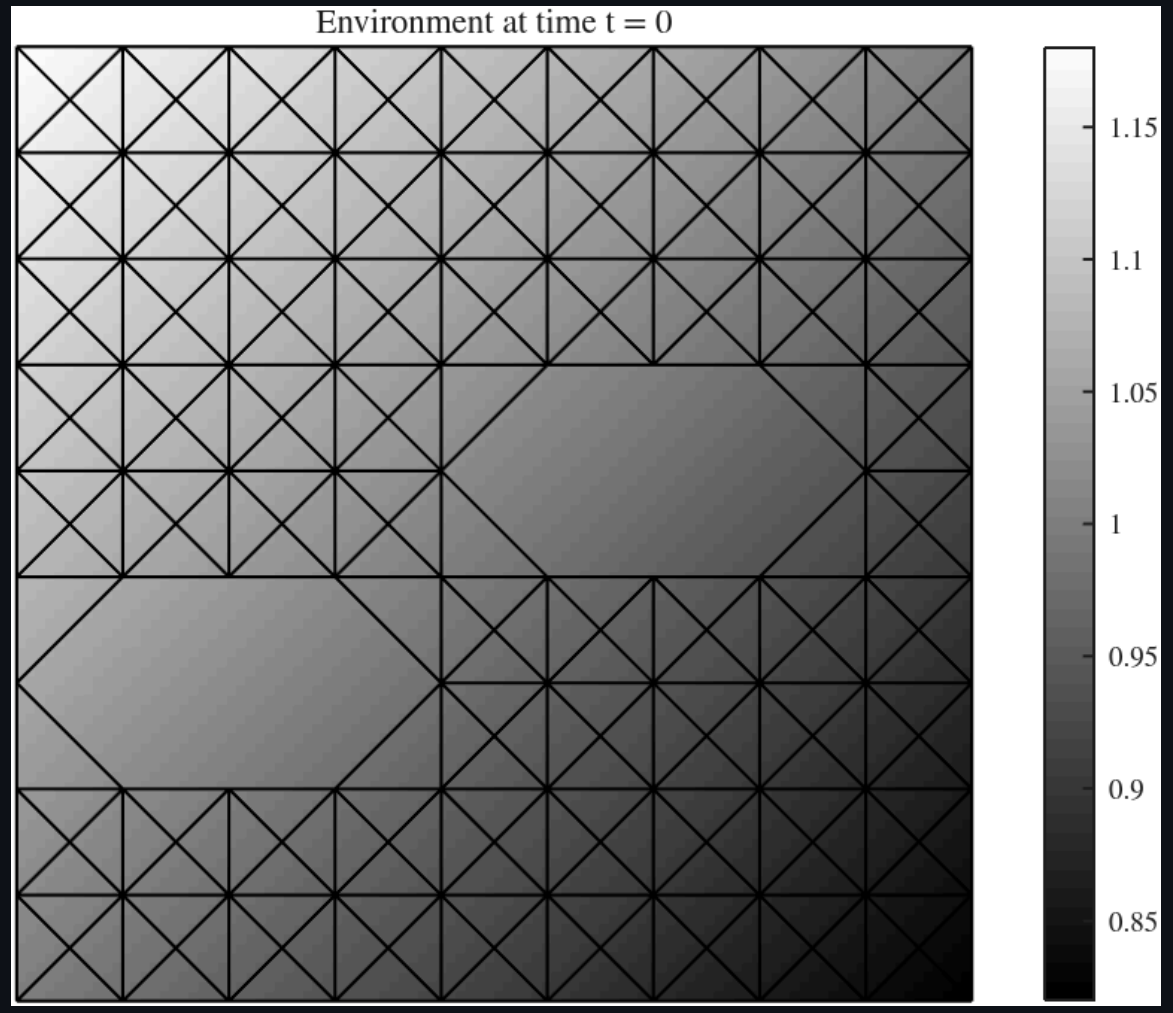
Path memory

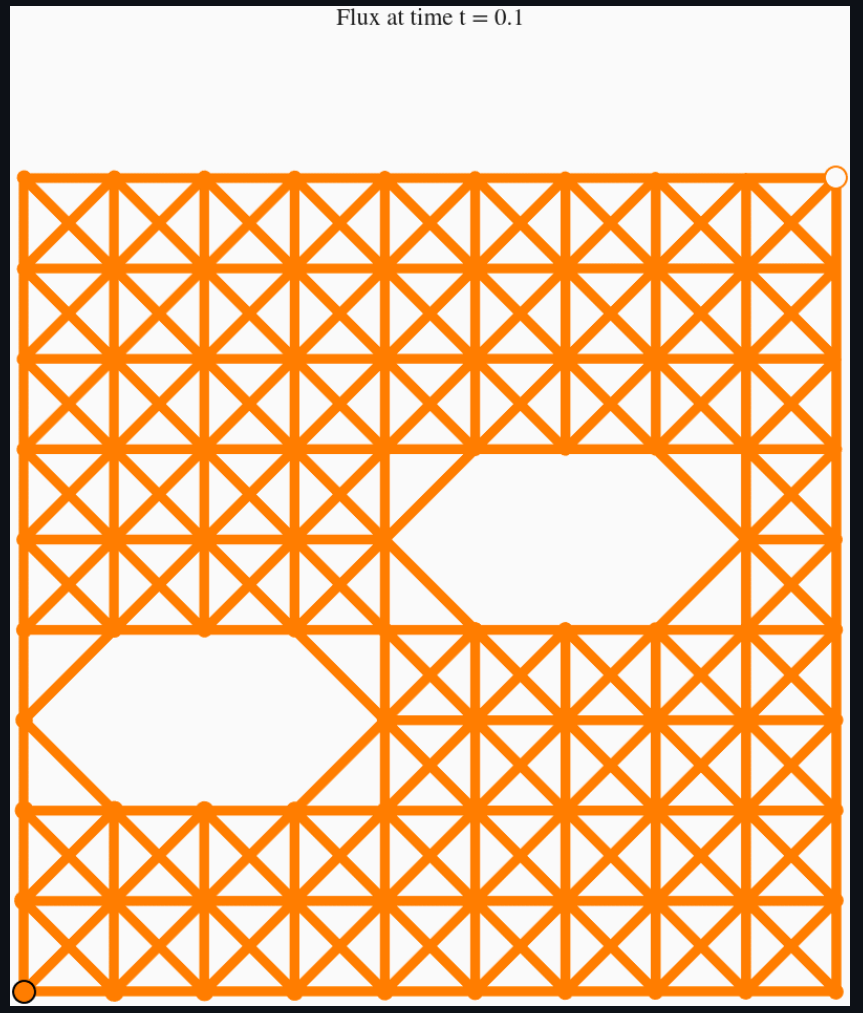




Results and Outcomes

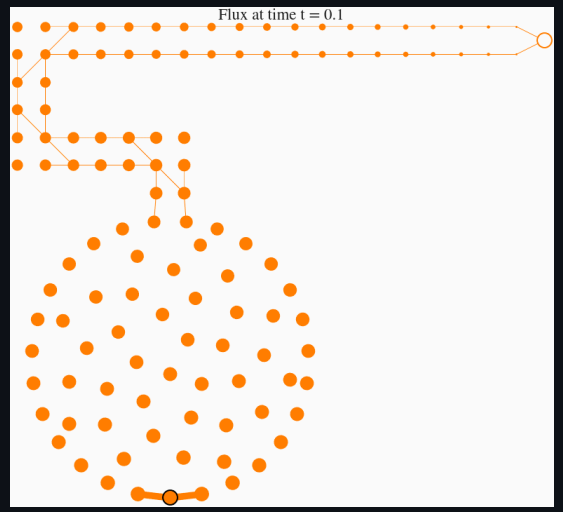
Undesirable paths

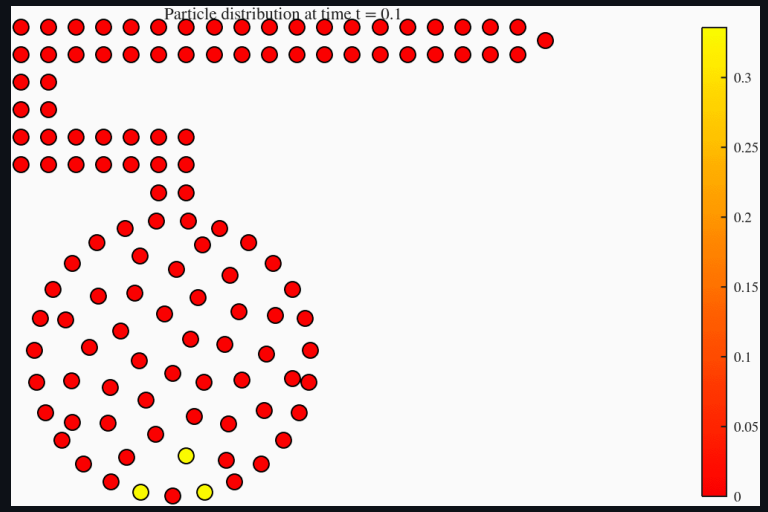




Future directions

- Tolman's sun maze: Latent learning in slime molds?





- Spatial memory
- Temporal memory: accommodation to repeated stimuli
- Foraging experiments
- Memory sharing in slime molds in contact
- ...

Thank you!