RULES FOR BIOLOGICALLY INSPIRED ADAPTIVE NETWORK DESIGN

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TRANSPORT SYSTEMS

- Used to transport resources.
- Examples:
  - Railways (large physical goods)
  - Blood flow (small materials)
  - The Internet (information)
- Can conceptually be applied to non-physical quantities such as energy and information.

EXAMPLE: UNITED STATES HIGHWAY NETWORK

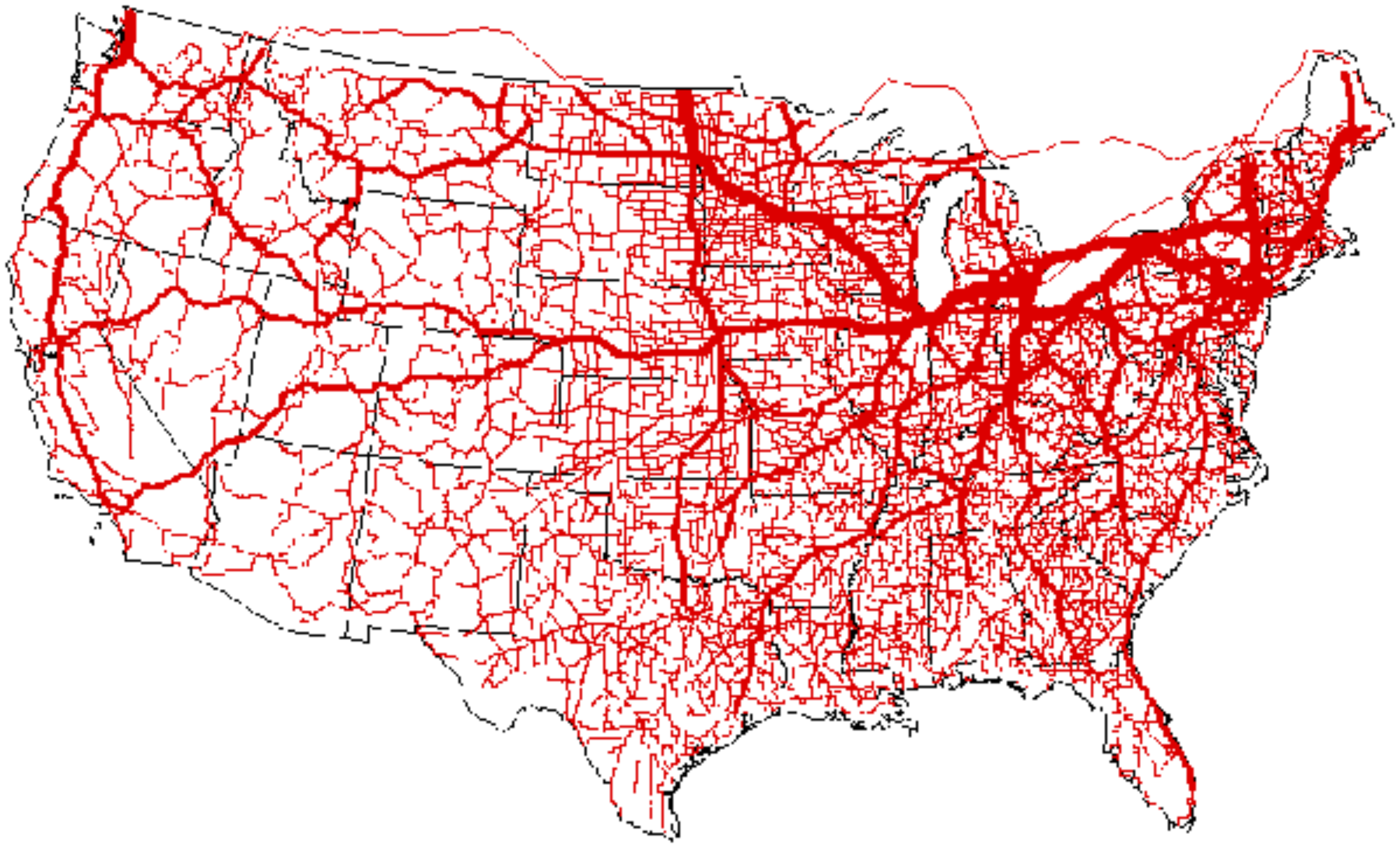


Image courtesy of the U.S. Department of Transportation
Retrieved from https://ops.fhwa.dot.gov/freight/presentations/images/faf_17.gif

STRUCTURE AND CONSTRAINTS

- Typically form an interconnected network between destinations.
- Efficiency vs. Cost vs. Resilience
  - More efficiency means higher throughput.
  - Lower cost usually requires sacrificing either efficiency or resilience.
  - Higher resilience is a **long-term** strategy to retard failure over a significant period of time.

LEARNING FROM BIOLOGY

- Some organisms grow into an interconnected network as part of their foraging strategy.
- Evolutionary constraints have, in theory, optimized these networks to be:
  - **Adaptive**, as competition has forced them to respond to a changing environment.
  - **Resilient**, a single local failure does not imply whole organism death.
  - **Balanced**, in terms of the trade-offs between efficiency, cost, and resilience.
- All of this happens without a central authority or explicit information.
- Can these dynamic networks be used to create a general model of adaptive network development?

PHYSARUM POLYCEPHALUM (SLIME MOLD)

Stinson, L. (2015). Listen to Slime Mold Sing a Song, *Wired.*
Retrieved from https://assets.wired.com/photos/w_582/wp-content/uploads/2015/10/SciSource_7Z3597.jpg

EWW! WHY SLIME MOLD?!

- As it grows and explores for food, slime molds form an interconnected network between discovered sources.
  - **Direct connections** connect from one food source to another.
  - **Steiner points** are intermediate junctions that reduce the overall length of the network.
  - **Cross-links** improve both transport efficiency and resilience.
- These networks can allow slime molds to find the shortest path through a maze or connect many different food sources in an optimal configuration.
- Can be easily manipulated for experimental purposes by physical barriers and light.

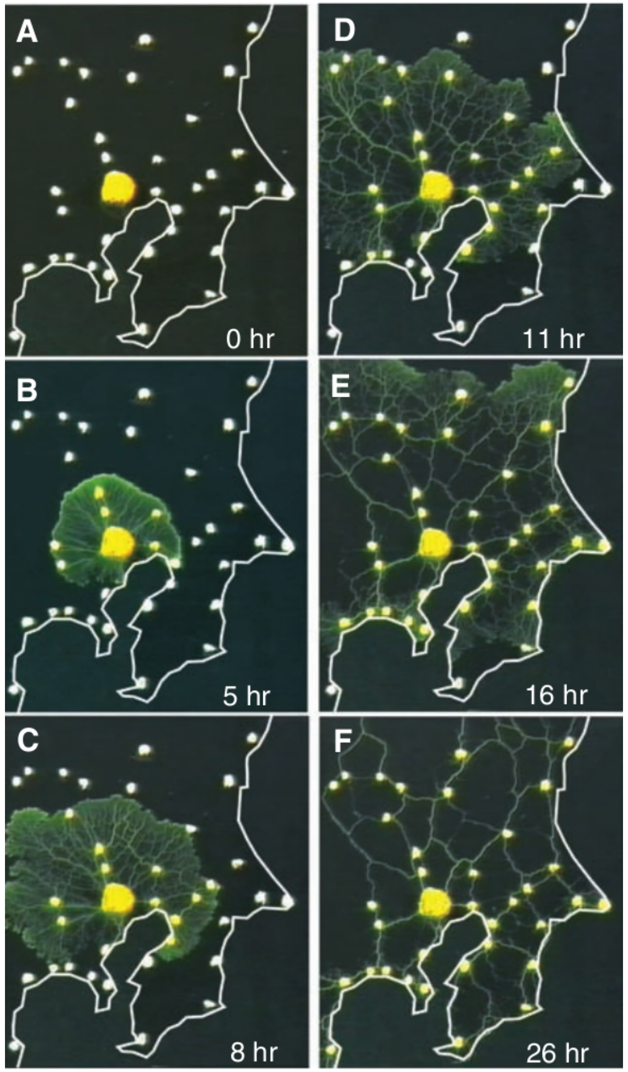
THE EXPERIMENT

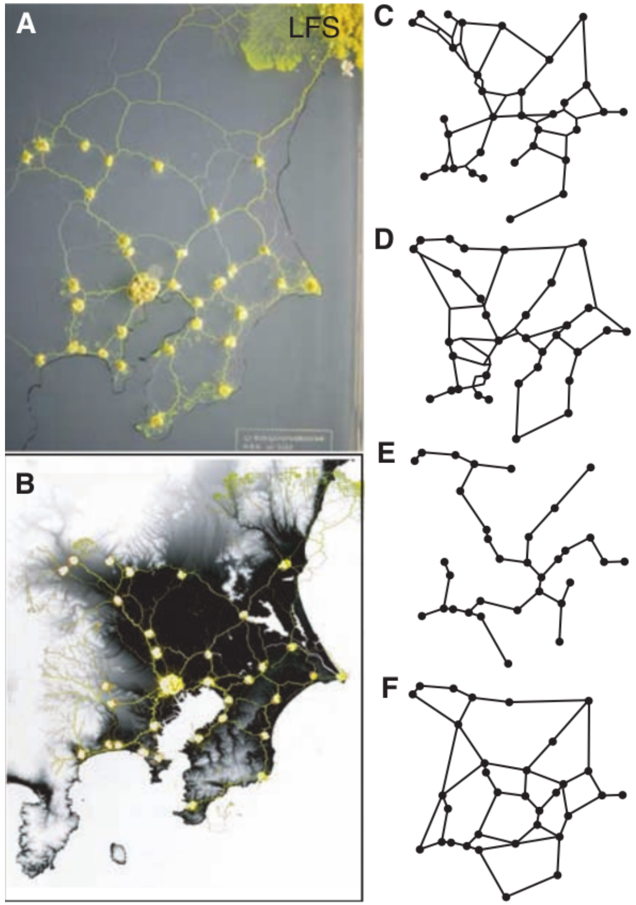
- The purpose is to try and see if slime mold can produce a similar structure to a human railway system.
- 36 food sources corresponding to the geographical position of cities around Tokyo, Japan.
- Two different types of experiments:
  - The slime mold was allowed to explore and grow around food sources before being trimmed to leave a subset of network features.
  - The slime mold was allowed to fully expand before all food sources were introduced simultaneously.
- Geographical constraints such as mountainous terrain or lakes were introduced using illumination.

METRICS

- Performance analysis uses the following metrics:
  - **Cost** (TL) is defined as the total length of a network.
  - **Transport efficiency** (MD) is computed as the minimum distance between all pairs of nodes.
  - **Robustness** (FT) is determined as the probability of disconnecting a substantial part of the network due to the failure of a single link.
- These are normalized against the minimum spanning tree (MST) to produce TL_{MST}, MD_{MST}, and FT_{MST} respectively.
- The experiment was performed using pre-determined locations for food sources so the MST could be computed in advance (i.e. has no relation to the slime mold).
- Final metric **α** represents the **benefit to cost ratio** defined as the robustness of a network divided by the normalized transport efficiency.

PROGRESSION OF NETWORK FORMATION





- Tero, A. (2009). Rules for biologically inspired adaptive network design. *Science*, 327, p. 439-442.

RESULTS

- The resulting networks created by the slime mold did an impressive job of mimicing the Japanese railway system. The slime mold:
  - Closely matched both the costs and transport performance of the railway system.
  - Used only **30%** of the maximum possible number of links.
- In contrast, the railways system was far more resilient. Only **4%** of faults in the system could lead to isolation, whereas **14%** of failures in the slime mold's network would result in disconnection **(20%** when unconstrained by illumination).
- The benefit to cost ratio was similar for both, although the railway's was slightly better due to its improved resilience.

MATHEMATICAL MODEL

- Mimic the expansion of slime mold by modeling its network construction as the result of variable flow through a connected set of tubes.
- The model begins with a fine mesh of tubes and each iteration a source and destination are chosen, forcing fluid to find a path from one to the other.
- Using the equation on the next page to describe the flux of plasmodium through each edge in the network, each edge either expands or constricts in response. Edges that constrict repeatedly are eventually deleted, causing the network's topology to evolve over time.

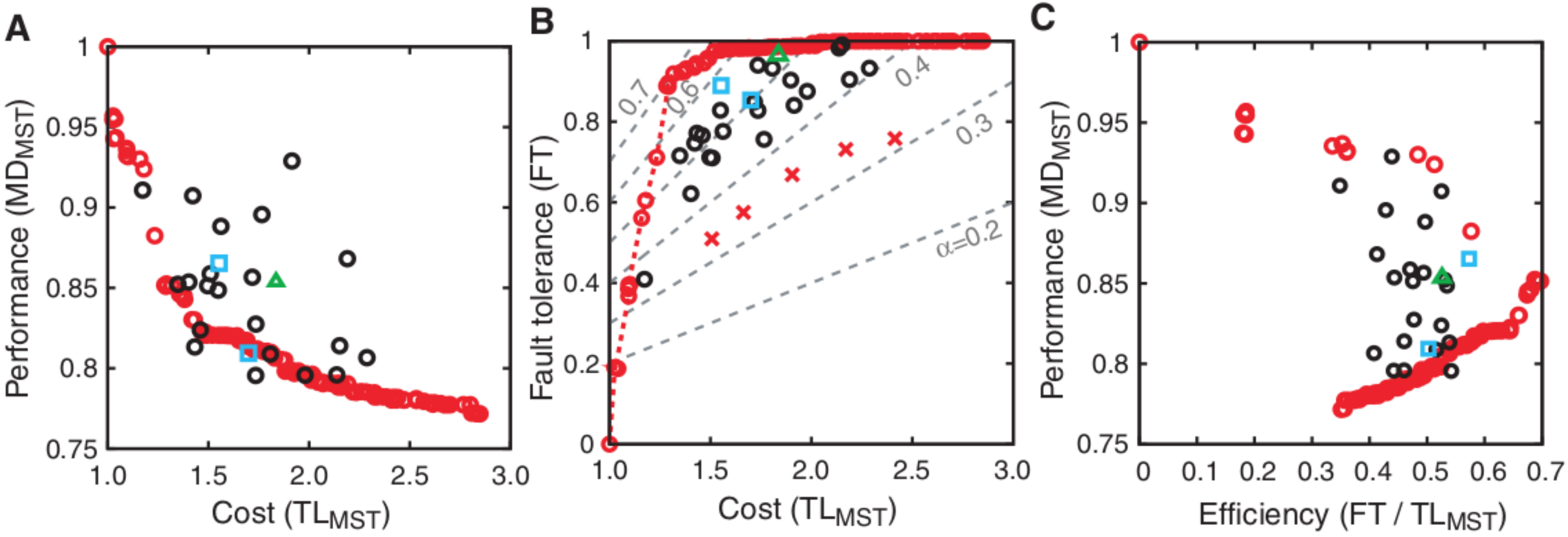
EQUATION OF FLUX

$$Q_{ij} = \frac{\pi r^4 (p_i - p_j)}{8\eta L_{ij}} = \frac{D_{ij}(p_i - p_j)}{L_{ij}}$$

n is the viscosity of the fluid
$\mathbf{L_{ij}}$ is a constant

The behavior of the network revolves around the quantities $\mathbf{D_{ij}}$ that represent measures of conductivity.

SIMULATION RESULTS AND COMPARISON



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FURTHER WORK

- Model by Zhang et. Al (2015) expands on the ideas of this paper by:
  - Applying a gravity model in order to incorporate different factors into edge weighting. Of primary importance is a city's gross domestic product (GDP), as other research has shown that GDP – a comprehensive metric that includes population size - can offset the cost of distance.
  - The gravity model makes use of real-world data in order to generate the traffic demand between all cities (which may be between nationalities). Afterwards, the slime mold algorithm is applied to shape the network topology.
  - In addition to a traditional slime mold model, this paper compares the new algorithm to a simple cellular automata implementation that uses an attractant diffusion equation to model foraging behavior.
- The two data sets used to explore the performance characteristics of this algorithm were based on the Mexican Highway and the Chinese Motorway networks.
- Initial results show that this new algorithm generates networks that are capable of being balanced in terms of cost, transport efficiency, and resilience compared to similar research given a variety of different parameters.

QUESTIONS?

REFERENCES

- Tero, A. (2009). Rules for biologically inspired adaptive network design. *Science*, 327, p. 439-442.
- Zhang, X. (2015). A biologically inspired network design model. *Scientific Reports*, 5.