

INFORMATION & CONTROL

Network Optimisation: Topology and Resilience from Biological Systems

How biological networks optimise for efficiency and failure tolerance simultaneously

5	2	1–3	5
convergent strategies	principle clusters	TRL range	featured strategies

PROBLEM FRAMING

Communication, logistics, and power distribution networks face a multi-objective optimisation: efficiency (short paths, low total length) versus robustness (failure of any node/edge has minimal impact). Biological networks solve this without centralised control or global information.

Application domains: energy, architecture, transportation

Principle cluster: self organization, fluid dynamics

Physics & Mechanism

Underlying physics

[DRAFT] Biological networks implement a local reinforcement rule: flow channels that carry more material expand; channels with low use contract. This produces global optimisation without global information, through a mechanism mathematically equivalent to gradient descent on a transport cost function. Physarum polycephalum (slime mold) implements this rule through actomyosin-driven oscillatory flow: tubes experiencing higher flow develop thicker walls and lower hydrodynamic resistance (Hagen-Poiseuille: $R \propto 1/r^4$), attracting more flow. Steady state: a minimum spanning tree with additional redundant links providing robustness — identical topology to the Tokyo metro system (Tero et al., Science 2010). Leaf venation networks implement two distinct topological modes: dicotyledon reticulate venation (redundant loops for damage tolerance) versus monocotyledon parallel venation (high efficiency, lower robustness). Leonardo's rule: at each branching point in a tree network, the sum of daughter branch cross-sectional areas equals the parent cross-sectional area (Murray's Law for vascular networks). This minimises total volume while maintaining constant flow velocity throughout the network — derivable from minimum-entropy-production principles. [END DRAFT]

Biological Strategies

Compute Red harvester ant · TRL 3/9 · 2 genera

Pogonomyrmex barbatus coordinates foraging and information flow via decentralized local interactions rather than central command. Individual ants vary in their spatial location and movement patterns, creating natural interaction hubs near critical zones like nest entrances. When foragers return with food or recruitment information, they make brief antennal contact with nestmates in these high-traf...

Design principle: Design distributed information systems that leverage natural variation in node connectivity rather than imposing uniform architecture. Instead of forcing all processors or agents into identical roles

Coordinate by Self-Organization African termite · TRL 3/9 · 19 genera ♦ Evidence File

Swarms are groups of robots that can coordinate, cooperate, and communicate to achieve tasks that may be impossible for a single robot. These systems exhibit complex dynamical behavior, similar to those observed in physics, neuroscience, finance, biology, social and communication networks, etc. For instance, in Biology, schools of fish, swarm of bacteria, colony of termites exhibit flocking behavi...

Design principle: We usually only can observe the individual trajectories of the agents. A technique to learn how to discover and understand the underlying governing dynamics of these systems and how they interact from

What's actually hard: The single deepest engineering obstacle is structural integration. This biomimetic strategy cannot be applied as a retrofit to standard, lightweight glass-curtain-wall skyscrapers. It requires immense, heavy thermal mass and specifically calculated i...

Attach Permanently Slime mold · TRL 1/9 · 24 genera

With the "many-headed" slime mold Physarum polycephalum having been voted the unicellular organism of the year 2021 by the German Society of Protozoology, we are reminded that a large part of nature's huge variety of life forms is easily overlooked - both by the general public and researchers alike. Indeed, whereas several animals such as mussels or spiders have already inspired many scientists t...

Design principle: Here, we provide an overview of naturally occurring slimy substances with adhesive properties and categorize them in terms of the main chemical motifs that convey their stickiness, i.e., carbohydrate

Respond to Signals Slime mold

Collective navigation and swarming have been studied in animal groups, such as fish schools, bird flocks, bacteria, while slime molds. Computer modeling has shown that collective behavior of simple agents can result from simple interactions between the agents, which include short range repulsion, intermediate range alignment, while long range attraction. More specifically, each agent adjusts its i...

Design principle: Here we study collective navigation of bacteria-inspired smart agents in complex terrains, with adaptive interactions that depend on performance. More specifically, each agent adjusts its interactions

Learn Slime mold · TRL 3/9 · 19 genera ◆ Evidence File

Neither animal nor plant, the slime mold *Physarum polycephalum* is a large-scale single-celled organism which lives in damp forests. At a glance it may look like a splash of paint, but patient observation reveals it creeping across surfaces by oozing forward in fingerlike projections. Even though it doesn't have a brain, the slime mold exhibits a simple form of learning by changing its behavior bas...

Design principle: Adaptive network algorithms mimicking *Physarum*'s tube reinforcement rule solve minimum-cost network design problems: (1) rail and road network planning (Tero et al. 2010 algorithm generates Tokyo-equivalent)

Active: Multiple logistics SaaS providers (undisclosed) (ACO/*Physarum* hybrid routing optimisation)

What's actually hard: The *Physarum* algorithm optimises for a specific trade-off between cost (total tube length) and fault-tolerance (redundant paths). This trade-off is hardwired into the biological original by the organism's fitness function. For engineering networks wh...

Quantitative Performance Parameters

Performance benchmarks from peer-reviewed literature. Copy directly into design specs.

Strategy / Organism	Parameter	Value
Learn (Slime mold)	Vs Minimum Spanning Tree	<i>Physarum</i> network: 0.5–3% higher total cost, but 20–30% higher fault tolerance (single-node removal connectivity)
	Vs Tokyo Rail Network	<i>Physarum</i> network matches efficiency within 1%, matches fault-tolerance within 5%, at comparable cost metric
	Computational Complexity	$O(n^2)$ per iteration, typically converges in 50–200 iterations for networks of 100–1,000 nodes
	Real World Network Size Tested	Up to 50,000 nodes in power grid applications

State of Commercialisation

Commercial implementations for strategies on this challenge page, drawn from the Atlas Evidence Files.

Function	Product	Company	Year	Status / Notes
Learn	ACO/Physarum hybrid routing optimis	Multiple logistics SaaS provid	2015	Active Physarum-inspired flow allocation combined with ant colony optimisation for vehicle routing. Not marketed as bio-inspire...
Learn	Physarum-inspired power grid topolo	NEDO (New Energy and Industria	2012	Other Applied Physarum algorithm to optimise Japanese regional power grid topology after 2011 Fukushima event. Used to identif...

EXPLORE THE INTERACTIVE VERSION

This report is a static synthesis. The interactive version includes live strategy cards, the Design Brief generator, Combination Intelligence engine, and filtering by TRL, scale, and principle.

<https://atlasofnature.org/challenge/network-optimisation-biological>

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