Can Global Intelligence Emerge Without a Global Plan?

Micro-Swarm is a C++-based artificial life system that explores how complex, adaptive behavior can arise from simple, local rules.

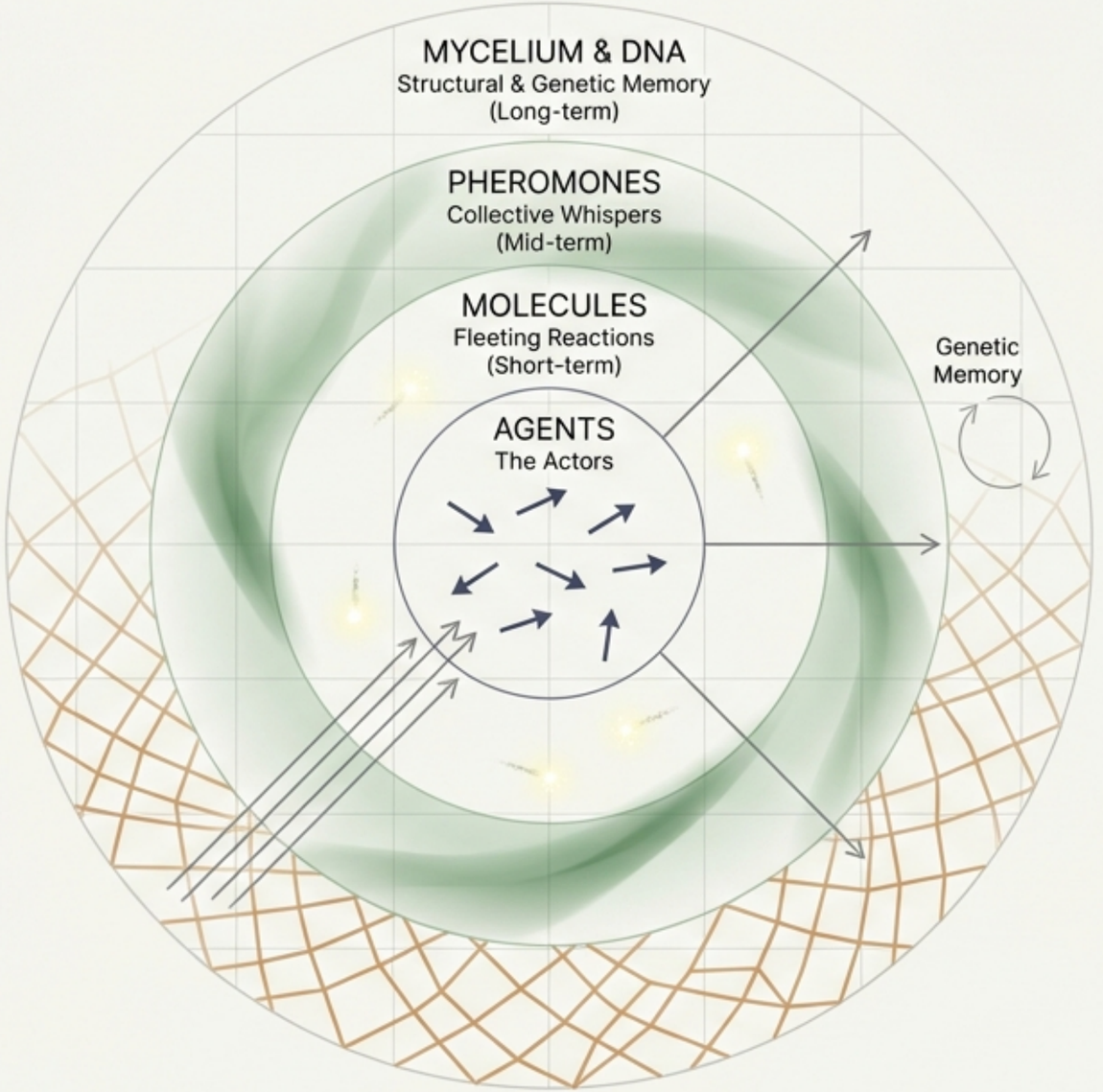
It achieves this without conventional AI tools:

- No Neural Networks
- No Backpropagation
- No Reinforcement Learning Frameworks

The focus is on emergence over optimization, and on creating systems with complete mechanistic transparency.

Intelligence as a Function of Layered Memory

In Micro-Swarm, collective behavior is not centrally directed. It emerges from the interplay of four distinct, interacting memory layers, each operating on a different timescale.

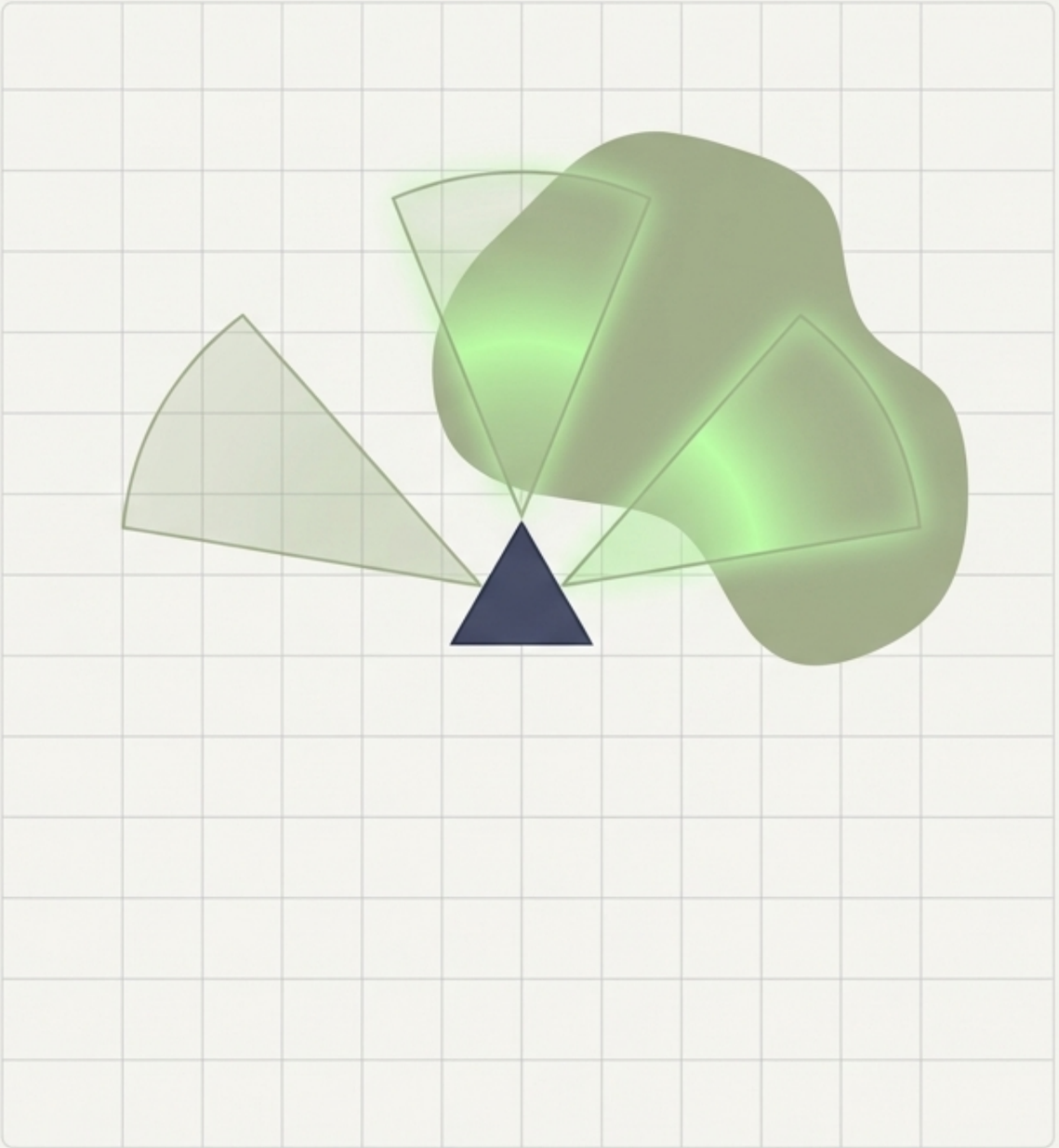


The Actors: Agents with Purely Local Knowledge

Agents are mobile units with a simple state (position, direction, energy) and a genome (a vector of parameters). Their behavior is governed by a strict local loop:

1. **Sense**: Sample environmental fields (resources, pheromones) in three forward directions (left, center, right).
2. **Act**: Make a stochastic choice of direction based on weighted sensor inputs. There is no global goal.
3. **Interact**: Consume resources, gain energy, and emit molecules or pheromones as a side effect of their actions.

Key Principle: Agents possess zero global awareness. All coordination is indirect.

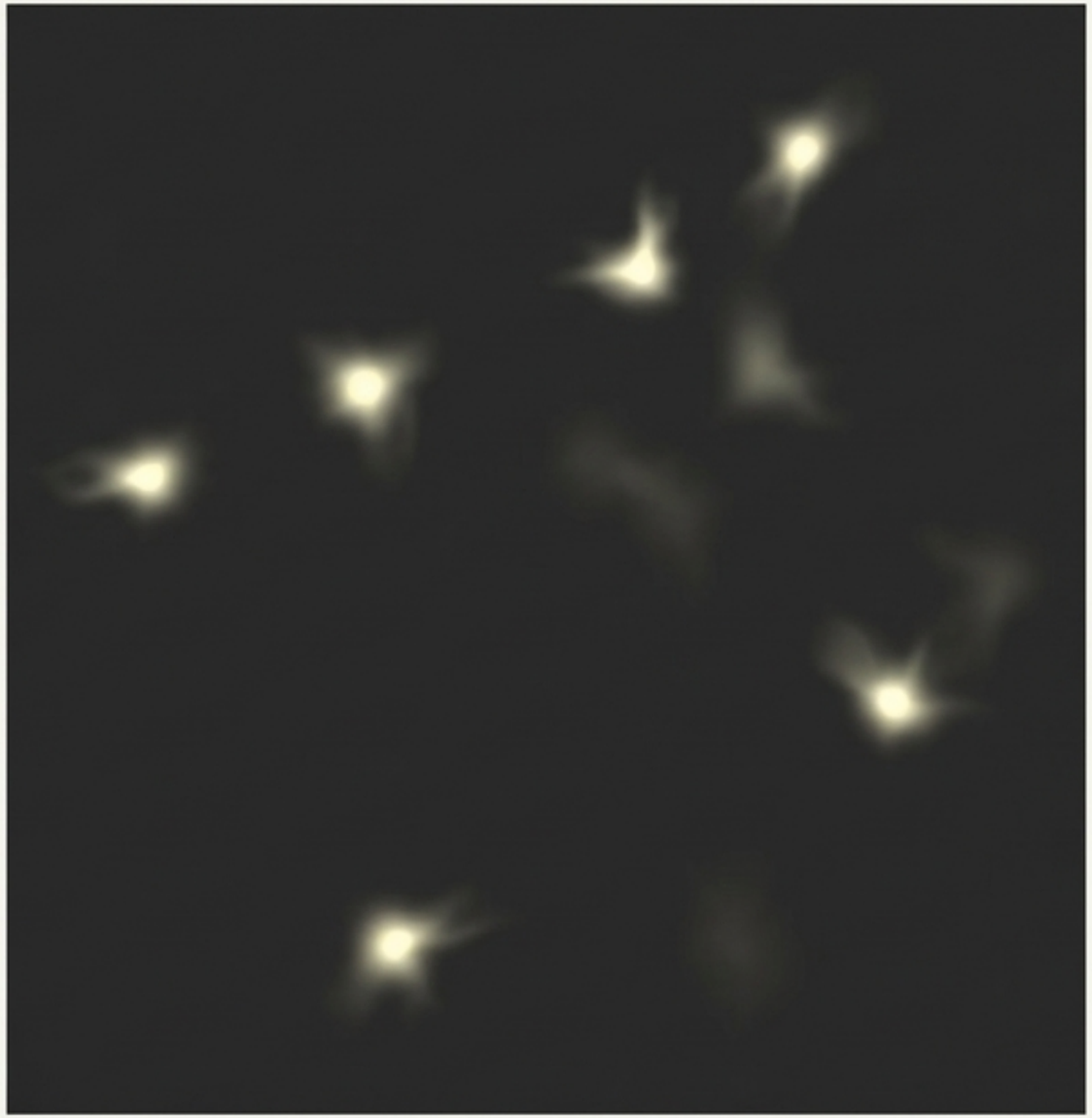


Layer 1: Molecules, the Short-Term Reactive Memory

Visual Metaphor: “Fleeting Reactions”

Molecules are a highly volatile information layer. They are emitted by agents in response to specific events and evaporate almost instantly.

- **Function:** Encodes immediate, transient information like “an agent was just here.” epnamation.
- **Dynamics:** High evaporation rate, minimal diffusion.
- **Purpose:** Creates a very short-term “recency” signal, preventing agents from immediately turning back on themselves and encouraging local dispersal.



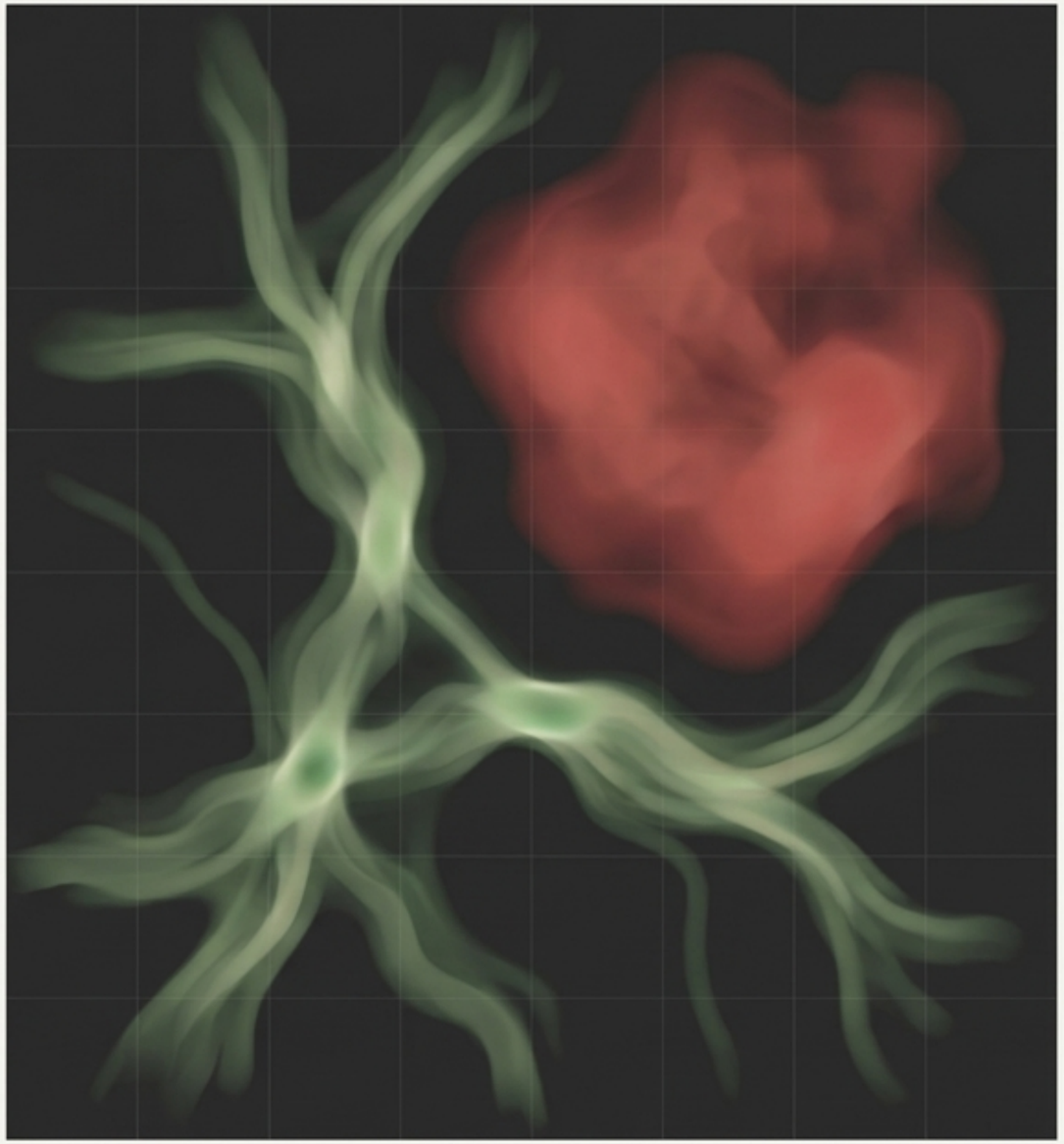
Layer 2: Pheromones, the Mid-Term Collective Whispers

Visual Metaphor: “Collective Whispers”

Pheromones are a diffusive, slowly evaporating field that enables stigmergic communication. Agents influence each other’s behavior by modifying a shared environment, leaving trails that aggregate over time.

- **Dual Channels**: The system uses two independent pheromone fields:
  - **Food Pheromone**: Attracts other agents, reinforcing paths to resources.
  - **Danger Pheromone**: Repels agents, marking depleted or hazardous areas.

- **Dynamics**: Moderate diffusion and evaporation.



Layer 3: Mycelium, the Long-Term Structural Memory

Visual Metaphor: 'Structural Memory'

The Mycelium is a slow-growing density field that reinforces and stabilizes pathways that have sustained, high activity (from resources and pheromones). It acts as the system's structural long-term memory.

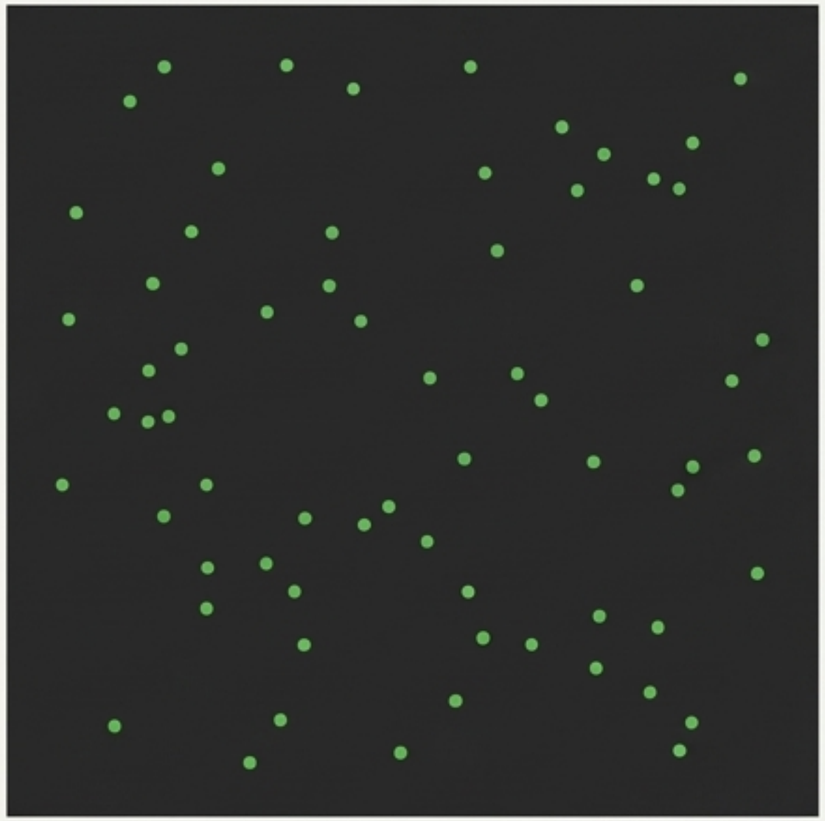
****Growth Dynamics****

- Grows only where activity exceeds a threshold.
- Logistic growth and Laplacian transport prevent global saturation and explosive feedback loops.
- Explicit decay ensures the structure can slowly ‘forget’ unused paths.

From Chaos to Order: Emergence in Action (t=0 to t=50)

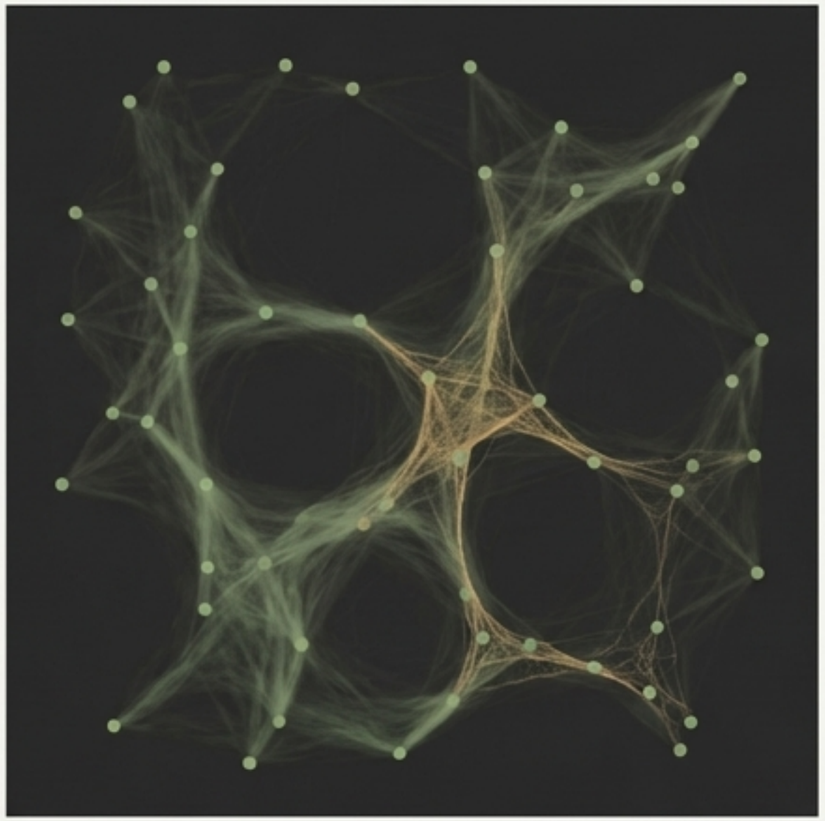
At the start of a simulation, the world is random. Agents move without direction, and the memory fields are empty. Early exploration is chaotic but quickly lays the groundwork for structure.

Step 0



phero_food mean: 0.0000
mycel mean: 0.0000
mycel nonzero_ratio: 0.0000

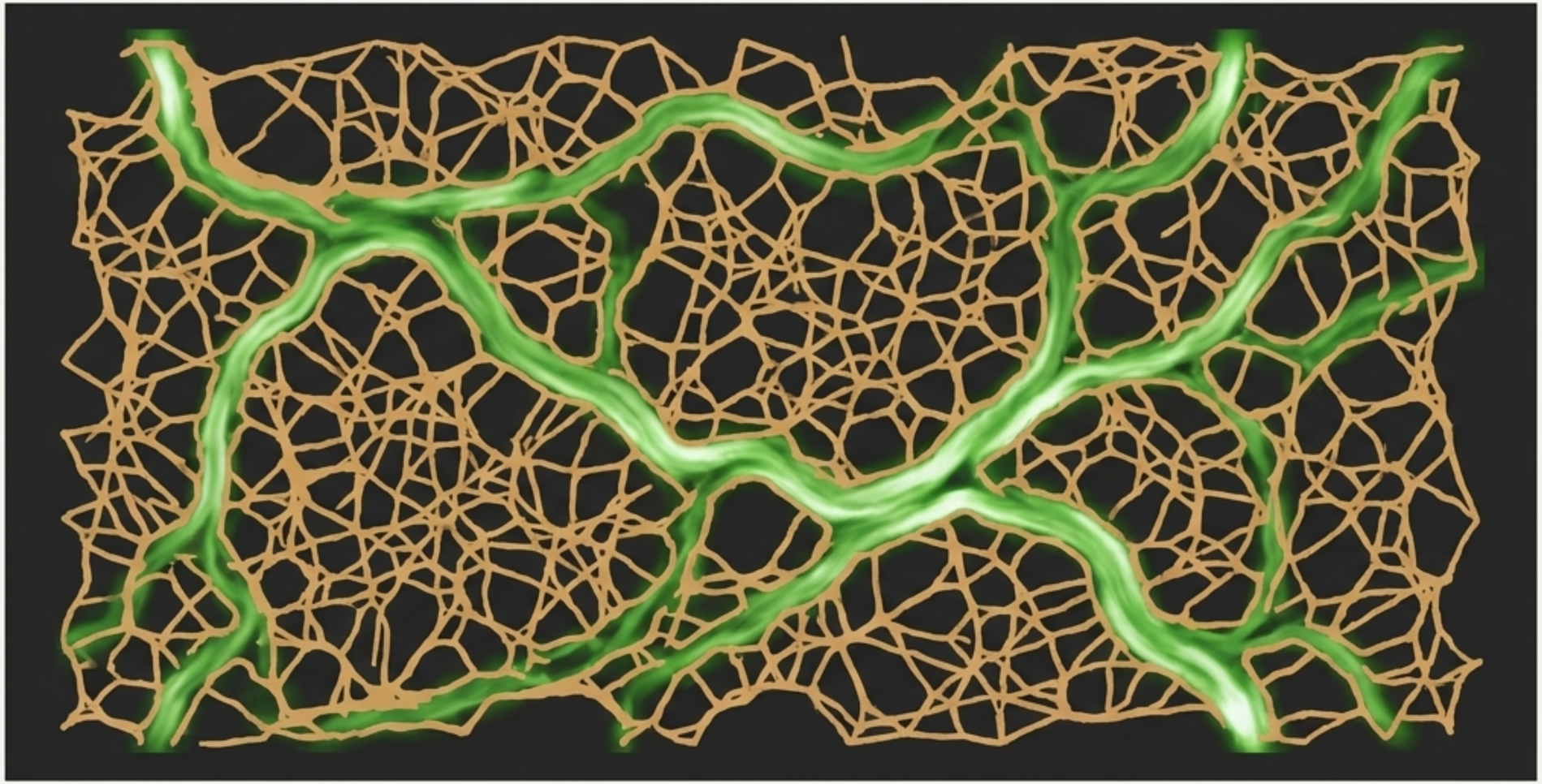
Step 50



phero_food mean: 0.0162
mycel mean: 0.0043
mycel nonzero_ratio: 0.5417

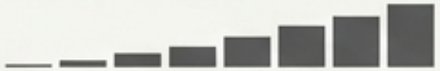
The Result: A Stable, Self-Organized Network (t=450)

After 450 steps, the system has self-organized. Pheromone trails have coalesced and been “fossilized” by the mycelium network, creating efficient, stable highways for resource exploitation. The swarm has created a persistent, shared map of its world.

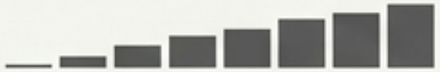


Key Metrics (t=450)
mycel mean: 0.0831
mycel nonzero_ratio: 1.0000
mycel norm_entropy: 0.8772

Mycelium Mean Growth



Food Pheromone Mean Growth



Functional Intelligence: A Division of Labor

The swarm is not monolithic. It is composed of four distinct species, each with a fixed role and strategy defined by its innate preferences. This specialization creates a balanced and adaptive collective.

Species 0: The Explorator

High curiosity, low pheromone binding. Seeks out new resource gradients.

Species 1: The Integrator

High pheromone attraction, low exploration. Reinforces and stabilizes existing paths.

Species 2: The Regulator

High sensitivity to danger signals. Provides negative feedback and prevents overcrowding.

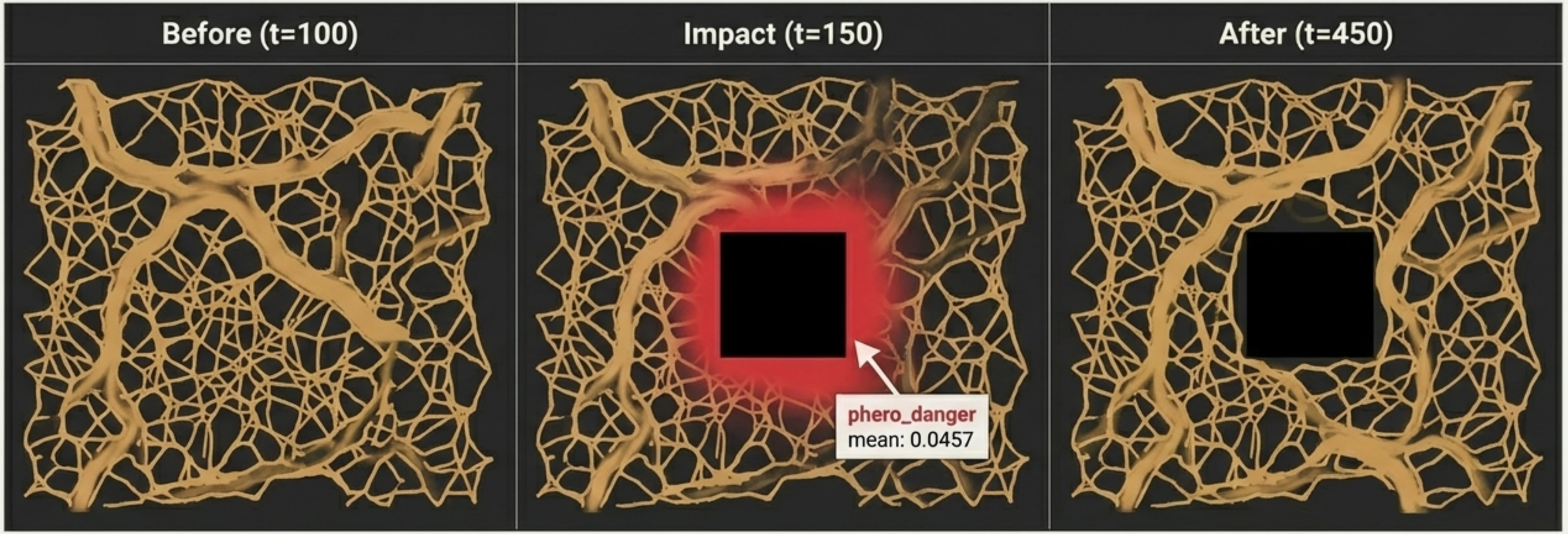
Species 3: The Innovator

Increased mutation rates, weak DNA binding. Tests new strategies, preferring areas of high entropy.

Proving Resilience: Adaptation Under Stress

The system's intelligence is not static. When faced with a sudden environmental block and continuous pheromone noise (introduced at step 120), the swarm dynamically reroutes its pathways, demonstrating true adaptation.

Scenario (from `Stress-Test` report):
At Step 120, a 30x30 resource area is blocked, and **`pheromone_noise=0.004`** is injected.

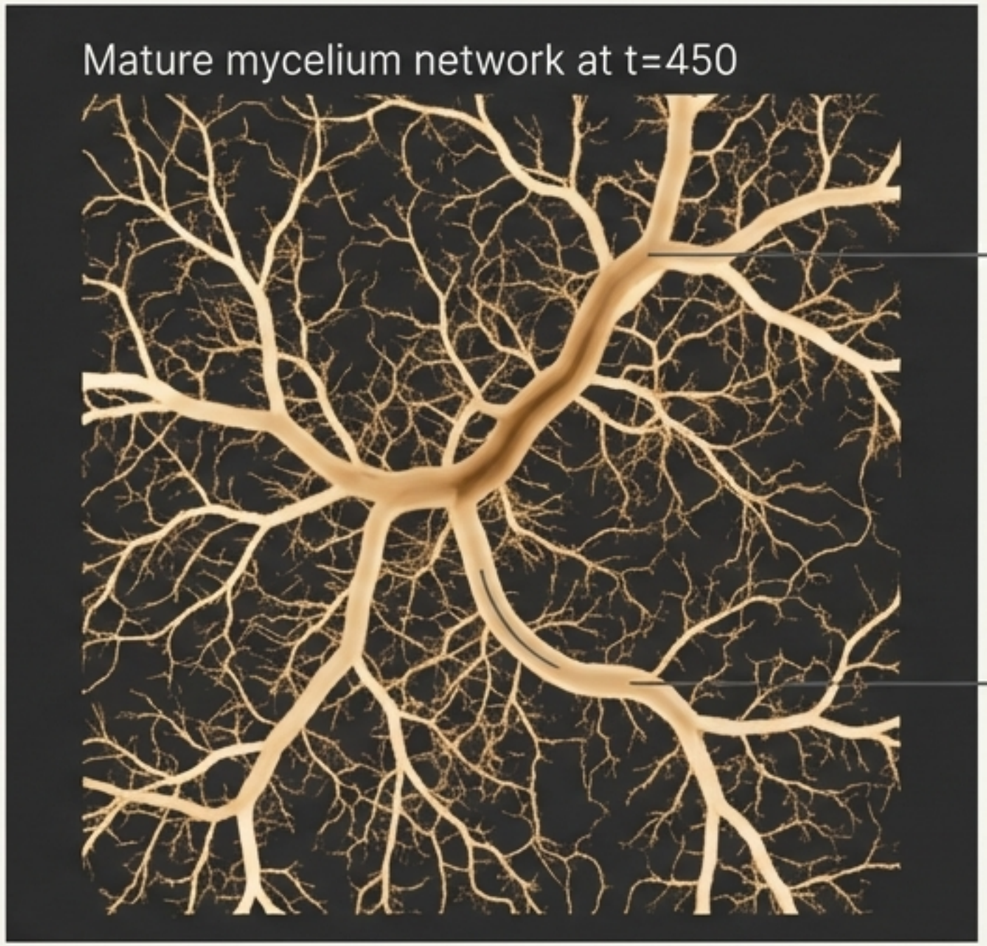


No Black Boxes: Every Pattern is Explainable

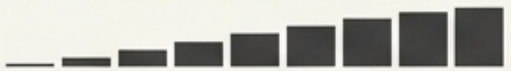
Every emergent structure in Micro-Swarm is the direct, measurable result of its underlying rules. There is no hidden layer, no inscrutable black box. The ‘why’ behind every pattern can be traced, measured, and understood.

Mycelium Mean over time

(0.0000 .. 0.0831)



Mycelium Entropy over time

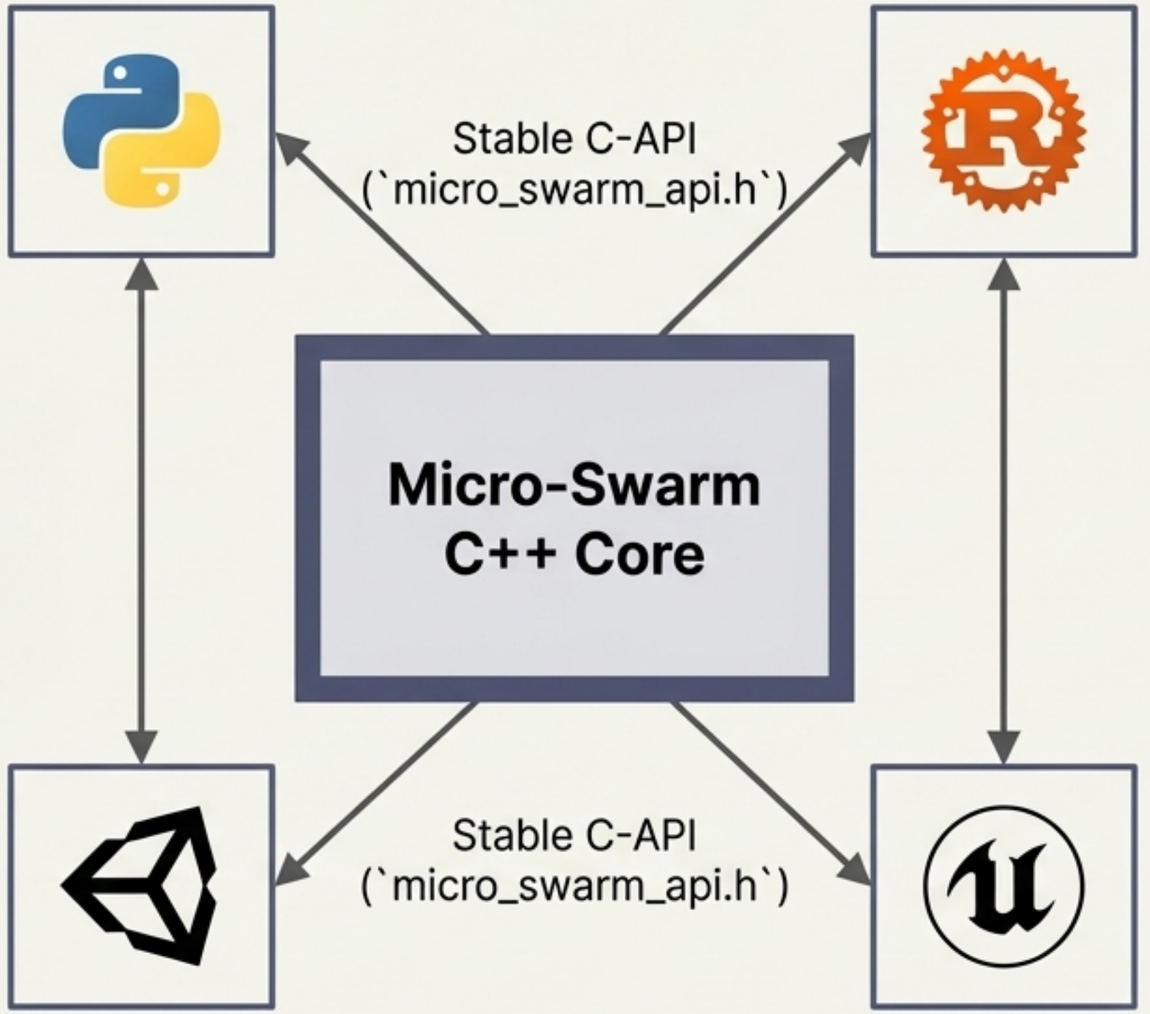


(0.0000 .. 0.8772)

An Engine for Experimentation

Micro-Swarm is built on a performant C++17 core, designed for deterministic, repeatable simulations. A stable C-API allows the simulation engine to be embedded anywhere.

- **High Performance**
  Thousands of steps per second, with optional GPU-accelerated diffusion via OpenCL.
- **Fully Embeddable**
  Native integration into Python, Rust, Unity, and Unreal Engine for visualization and interaction.
- **Repeatable Science**
  A headless batch pipeline enables systematic, scriptable experiments and automated report generation.



Micro-Swarm: Intelligence from the Ground Up

By combining simple agents, local rules, and a multi-layered memory system, Micro-Swarm demonstrates that sophisticated, adaptive, and transparent intelligence can emerge without centralized control or complex optimization algorithms. It serves as a fully instrumented laboratory for exploring the fundamental principles of self-organization and artificial life.

Future Directions: The architecture enables further research through controlled experiments like:

- Ablation tests (disabling Pheromone or Mycelium layers).
- Introducing novel Pheromone channels.
- Evolving agent roles and strategies.