Neuroevolution of Collective Systems

Risto Miikkulainen

September 29, 2024

Collective Intelligence

- ▶ Groups self-assemble into complex forms based on local interactions.
- ▶ Examples: Ants building bridges, termites constructing nests, and bees making foraging decisions.
- ▶ These complex collective behaviors emerge from simple individual behaviors discovered through evolution.


Coevolution of Intelligent Systems

- ▶ Coevolution: Multiple populations evolve together.
- ▶ Cooperative: Populations evolve to achieve common goals.
- ▶ Competitive: Poluations compete for resources, driving innovation.
- ▶ Neuroevolution can utilize both processes.

Cooperative Coevolution of a Single Neural Network

- ▶ Cooperative coevolution applied to individual components, such as neurons or connections.
- ▶ Neurons are evolved to work together to solve a task.
- ▶ How to form a network intelligently?
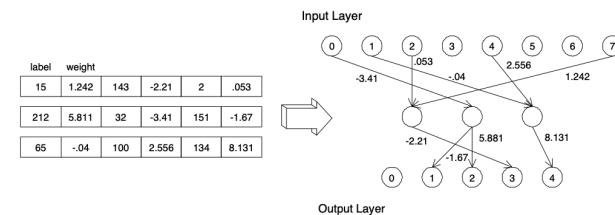
## SANE: Symbiotic Coevolution of Networks and Blueprints

- ▶ Networks are created based on a blueprint that selects neurons.
- ▶ Neurons and blueprints coevolve based on the network's fitness.
- ▶ Neurons evolve to cooperate; blueprints to combine.
- ▶ Tends to evolve general neurons, not specializations.

Network Blueprint Population   Neuron Population
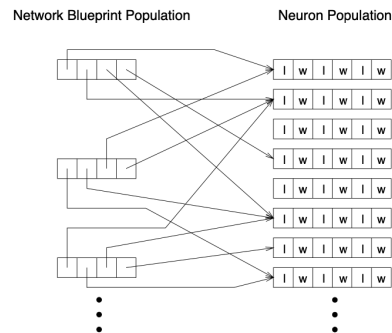
ESP: Enforced Subpopulations

- ▶ ESP enhances SANE by evolving neurons in separate subpopulations.
- ▶ Each neuron specializes in a specific location within the network.
- ▶ Fully connected network; only weights evolved.
- ▶ This approach helps the network discover differentiated roles for each neuron.
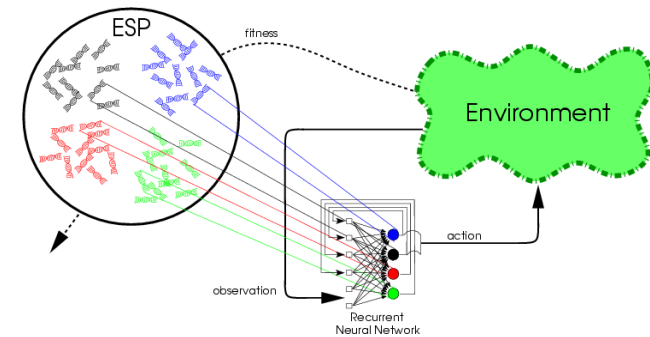
## Example: Maze Navigation with Khepera

- ▶ Subpopulations start random but specialize over time.
  - ▶ Some slow the robot down with obstacle up front; others veer left when obstacle on the right, etc.
- ▶ Evolution discovers compatible subtasks.
  - ▶ Neurons optimized for each subtask.
  - ▶ Avoids the competing conventions problem by assigning neurons to distinct roles.
  - ▶ Reduces search space by evolving neurons individually instead of optimizing the entire network at once.

Generation 1   Generation 20

Generation 50   Generation 100
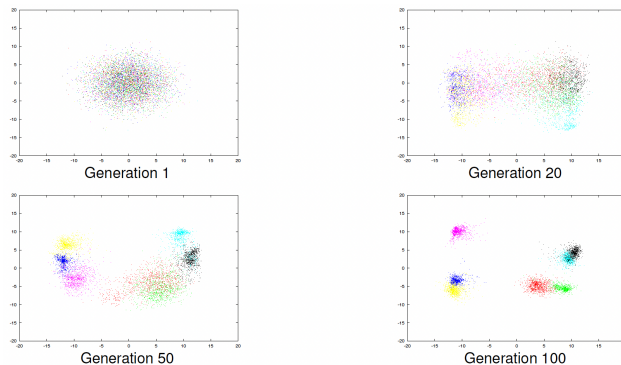
## Maintaining Diversity in Cooperative Coevolution

- ▶ Maintaining diversity in the population is essential to prevent premature convergence.
- ▶ Neurons must specialize in different tasks, preventing the population from becoming too similar.
- ▶ ESP helps maintain diversity through subpopulation specialization.

Generation 1   Generation 20

Generation 50   Generation 100
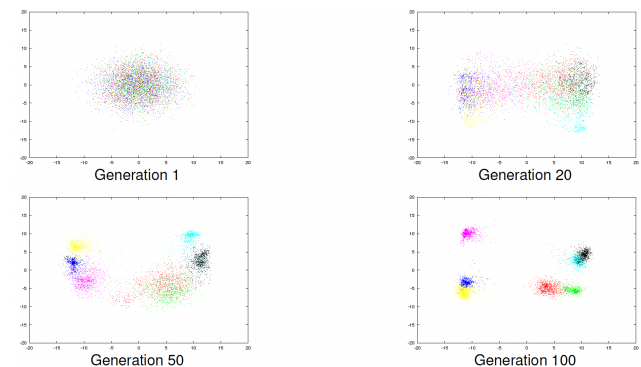
Robust Search for Subtasks

- Subpopulations evolve multiple subtasks, leading to redundancy.
- Redundancy ensures that even suboptimal neurons are compensated by others.
- Redundance makes the search robust: Necessary subtasks usually included.

Generation 1 Generation 20 Generation 50 Generation 100
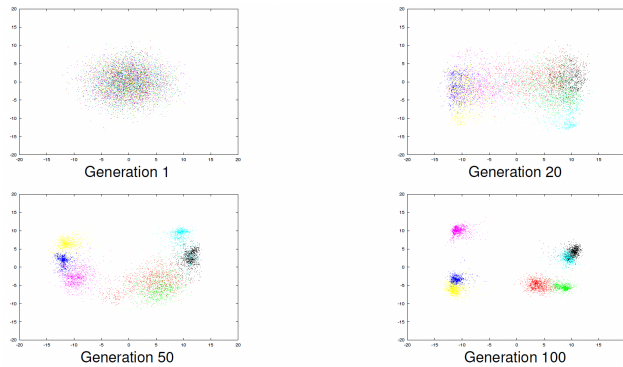
CoSyNE: Cooperative Coevolution of Weights

- Extend the idea of evolving partial solutions to weights.
  - Each weight evolved in a separate subpopulation.
  - Networks formed by combining neurons with the same index.
  - Networks mutated and recombined; indices permuted.
- Instead of unrestricted search, exploration of new combinations.

Neural Network
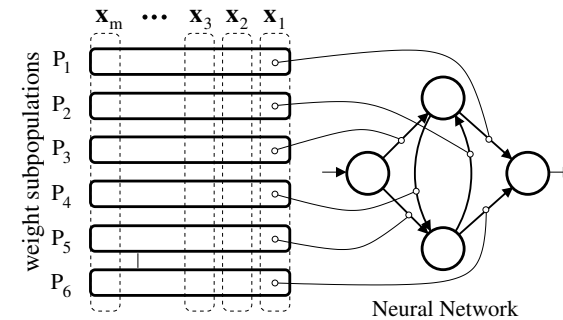
Example: POMDP Double Pole Balancing

- Two poles with different lengths respond differently.
  - Nonlinear interactions make it difficult.
  - Without velocities requires a recurrent network.
- CoSyNE state of the art; RL could not solve.

Demo:

output

input

x   θ   θ
cart   long pole   short pole
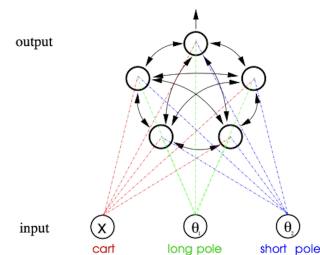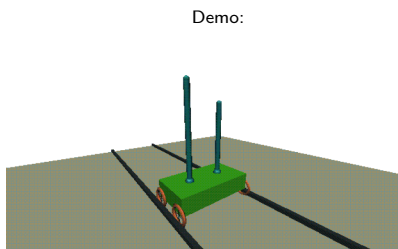
Evolving a Team

- Neuroevolution can be extended to construct teams of agents.
- Agents evolve separately but are evaluated based on the success of the entire team.
- Predator-prey scenarios provide a classic example of this approach.

Cooperative Strategy in Predator-Prey Task

▶ In a predator-prey task, three predators evolve to cooperate in capturing a prey (in a toroidal environment).

▶ The prey runs away from the nearest predator (stochastically).

▶ The team is rewarded based on the success of the capture.
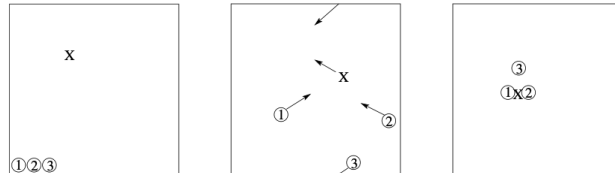
Multi-Agent ESP

▶ Extend ESP to multiple networks: one for each predator.

▶ Hierarchical structure: each neuron subpopulation evolves one nueron for one network.

▶ The neurons inherit the fitness of the entire team.
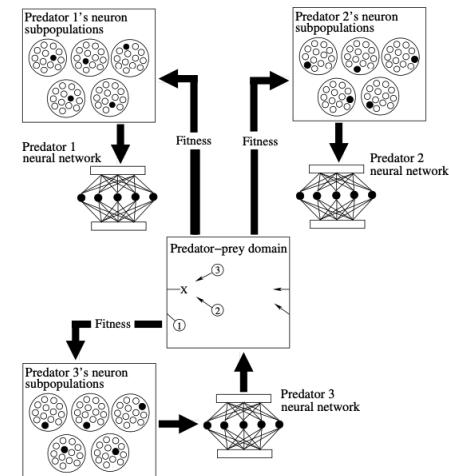

To Communicate or Not to Communicate?

▶ For comparison, a central controller can be evolved in one population.

▶ In Multi-agent ESP, each agent may see each other.

▶ Or they may see only the prey.
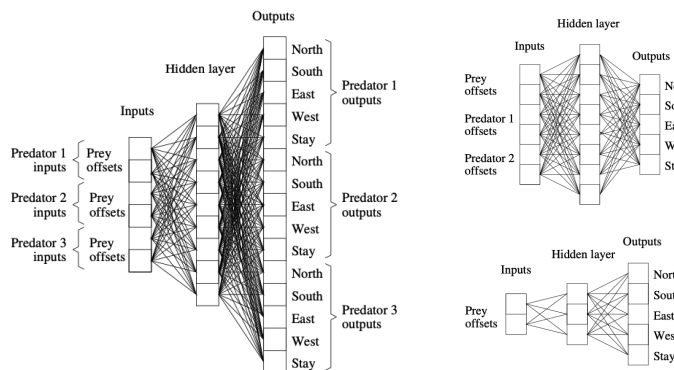
To Communicate or Not to Communicate?

▶ Central controller takes twice as long to evolve than a communicating team.

▶ A communicating team takes twice as long as non-communicating team.

▶ How can less information be more effective?
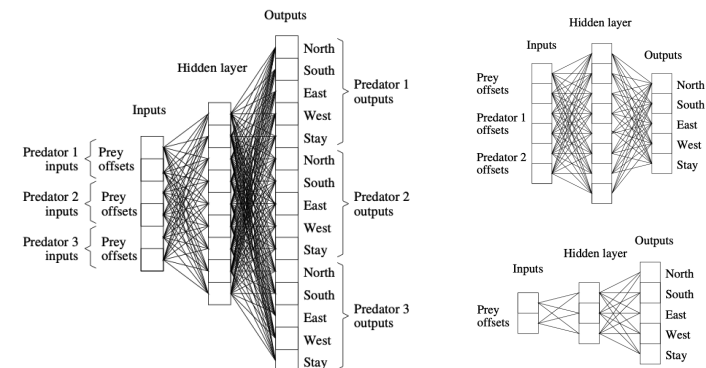
Role-based Cooperation Through Stigmergy

- Without communication, team members evolve distinct roles.
- Cooperation emerges through stigmergy—coordination through interaction with the environment, i.e. the prey.
- For instance, two chasers driving the prey to a blocker.

Demo:
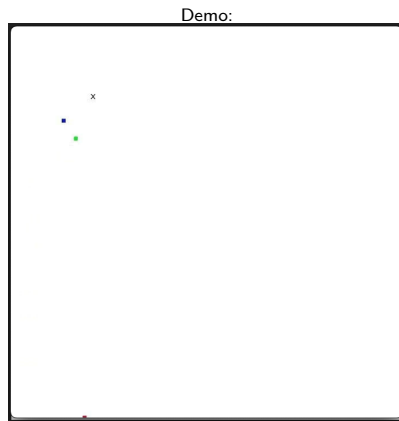
Discovering Compatible Behaviors

- Evolution discovers role-based behaviors more easily than flexible team strategies.
- Each behavior compensates for inaccuracies in other agents.
- Cooperation based on roles often leads to robust solutions.
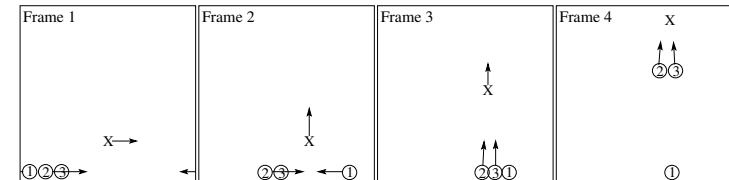
Adaptive Communication-based Cooperation

- In some cases, agents may need to change their behavior based on changing situations.
- E.g. changing roles, changing direction of the chase:
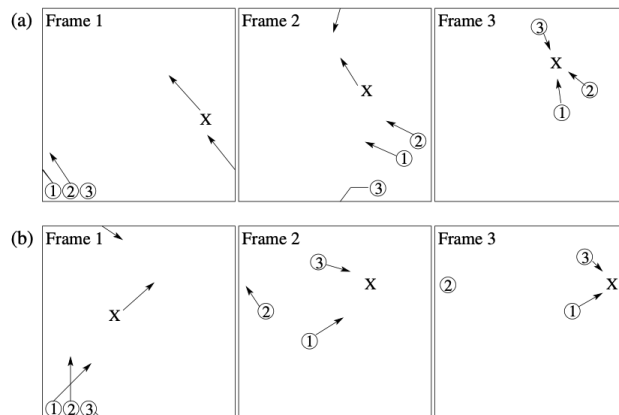
Role vs. Communication-based Cooperation

- The contrast is similar to well-practiced vs. pick-up soccer.
- Communication-based is less effective, more reactive, more general.
 - E.g. changing direction of the chase:

Demo:
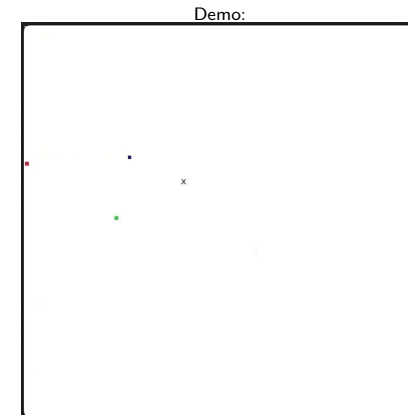
Evolving Generalists

- Evolving specialists is not always effective.
- The required number or kind of specialists may change.
- Generalists adapt to perform different roles when needed.
- This approach requires evolving homogeneous teams:
  - Single agent cloned to form a team.

Specialists   Generalists
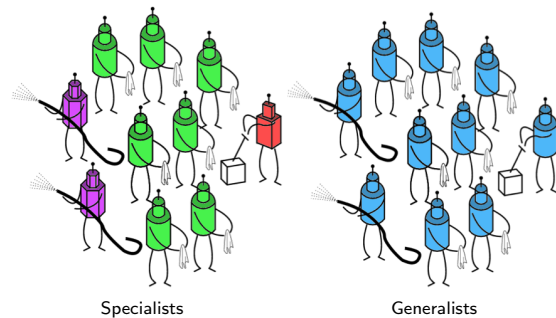
Example: Legions Strategy Game

- Agents need to defend the cities and chase barbarians in the countryside.
- These roles are required at different numbers at different times.
- The team evolves to allocate roles dynamically.
- Heterogeneous vs. homogeneous teams better? Still an open question.

Demo:
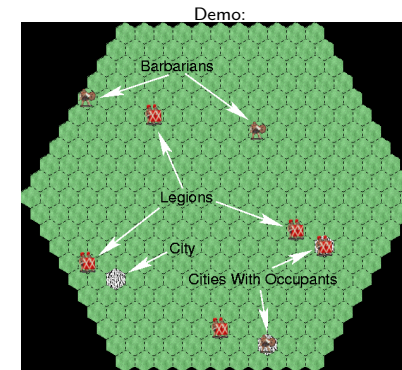
Competitive Coevolution

- Competition between agents drives the discovery of increasingly complex behaviors.
- Open-ended fitness: Agents continuously evolve to outdo each other in an evolutionary arms race.
- Evolutionary dynamics similar to curricular learning in machine learning.

Toxin vs. resistance to it in garter snakes and newts

Fitness Definition in Competitive Coevolution

- Fitness is defined in relation to the performance of other agents in the population.
- As individuals improve, fitness becomes harder to achieve, ensuring continuous adaptation.
- Competitive coevolution automatically shapes the fitness function.

Toxin vs. resistance to it in garter snakes and newts

Sound Familiar?

- ▶ Dynamics similar to curricular learning.
- ▶ GANs (Generative Adversarial Networks) employ competitive coevolution between generator and discriminator.
- ▶ Similar mechanisms are seen in self-play systems like AlphaZero.
- ▶ Early neuroevolution systems like Blondie24 pioneered competitive coevolution in checkers and chess.
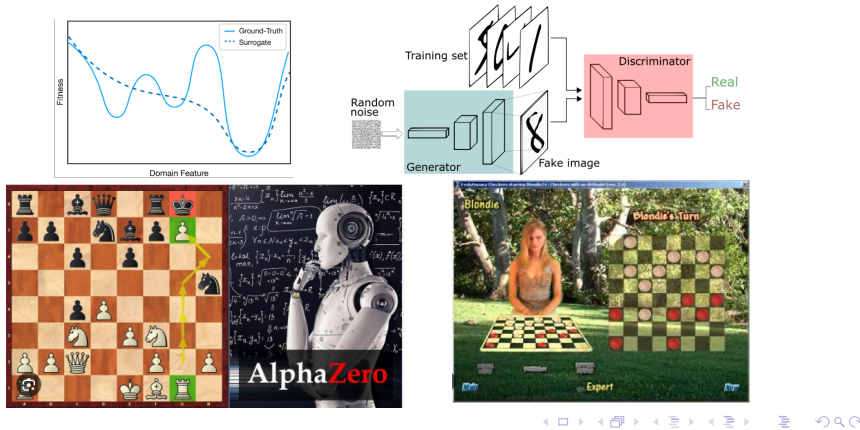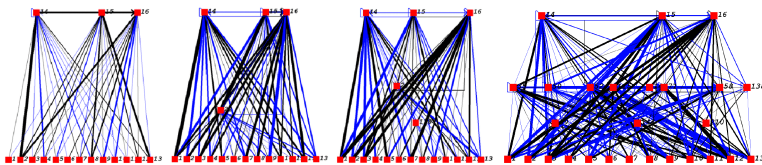

Challenges in Competitive Coevolution

- ▶ Progress is not always guaranteed; fitness improvement may only be relative (Red Queen dynamics).
- ▶ Possible to exploit weaknesses in current candidates without true improvement.
- ▶ Maintaining a collection of previous candidates helps track absolute progress.
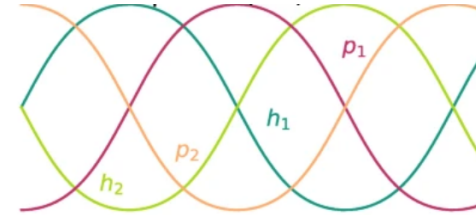
Competitive Coevolution with NEAT

- ▶ NEAT supports competitive coevolution by complexifying networks incrementally.
- ▶ Networks grow in complexity while preserving earlier behaviors, ensuring absolute progress.
- ▶ Mutation and crossover add nodes and connections to existing structures.

Foraging, Pursuit, and Evasion Task

- ▶ Simulated Khepera robots evolve through competitive coevolution to forage, pursue, and evade.
- ▶ Robots sense distance to opponents, food items, and walls.
- ▶ They gain energy by eating, lose energy by traveling.
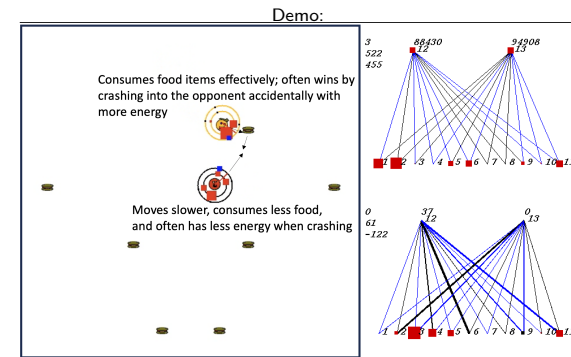- ▶ Win when bumping into the opponent while more energy.
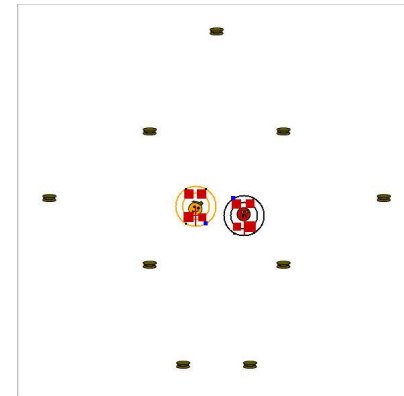
Discovering Complex Behavior

▶ Competitive coevolution discovers complex strategies through incremental improvements.

▶ Robots evolve foraging and attack strategies, learning to predict and exploit opponent energy levels.

▶ Energy management becomes crucial for winning encounters.
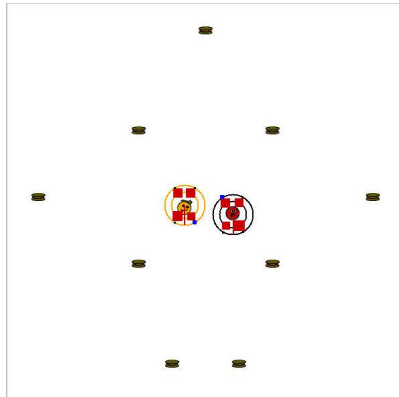
Early Strategies

▶ Rest and let opponent waste energy

▶ Mainly forage, occasionally crash by accident

▶ Difficult to switch between tasks

Demo:

Consumes food items effectively; often wins by crashing into the opponent accidentally with more energy

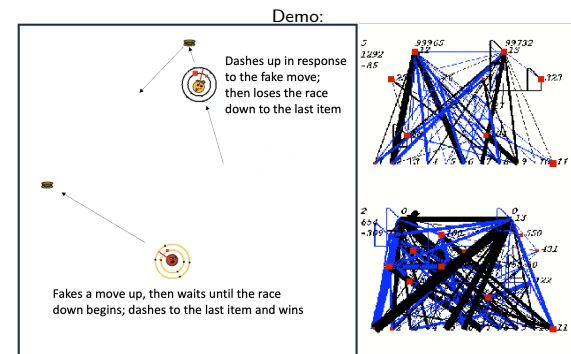Moves slower, consumes less food, and often has less energy when crashing

Mature Strategies

▶ Recurrent hidden node allows switching between tasks

▶ Collect food to gain energy; rest to save energy

▶ Difficult to predict energy at contact

Demo:

Energy advantage is too small, does not attack; consumes more food instead
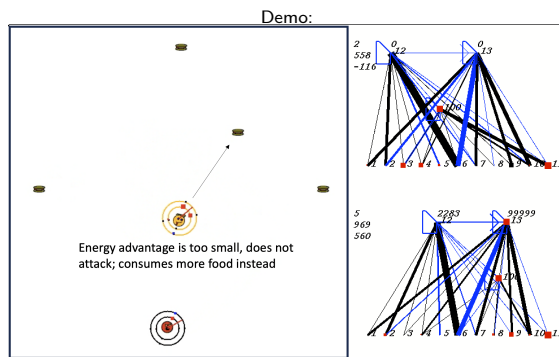
A Sophisticated Strategy

▶ Split & recurrent connections predict crash outcome

▶ Complex structure to anticipate opponent behavior

  ▶ "Fake" a rest; entice opponent to forage far away
  ▶ Win by making a dash to last piece

Demo:

Dashes up in response to the fake move; then loses the race down to the last item

Fakes a move up, then waits until the race down begins; dashes to the last item and wins

Coevolution of Complex Strategies

- ▶ Competitive coevolution is a powerful approach for discovering increasingly complex behaviors.
- ▶ Strategies such as faking moves and forcing opponents into energy-depleting mistakes are discovered.
- ▶ These behaviors would be difficult to discover without competitive coevolution, or without complexification.
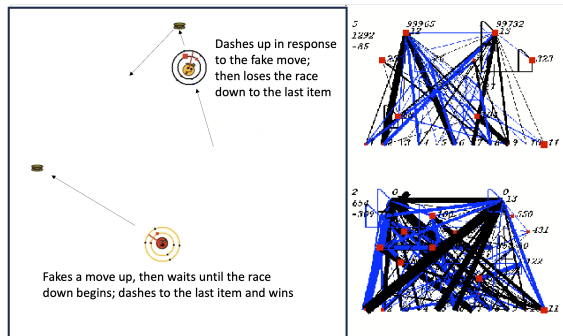

Evolving Multiple Teams

- ▶ Multiple cooperative teams can evolve in a competitive environment.
- ▶ Teams challenge each other, leading to increasingly complex behaviors.
- ▶ This process is called an evolutionary arms race.
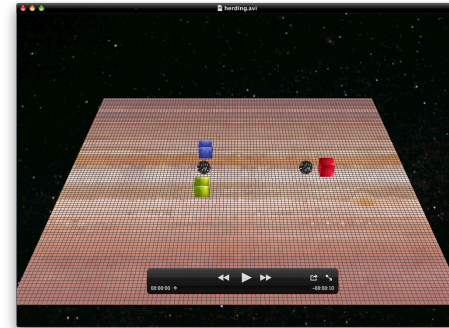
## Challenges in Establishing Absolute Improvement

- ▶ Absolute improvement is not always guaranteed.
- ▶ Teams may evolve strategies that exploit weaknesses in others but fail in the long run.
- ▶ However, in natural tasks, more complex behaviors often subsume simpler ones, leading to real progress.
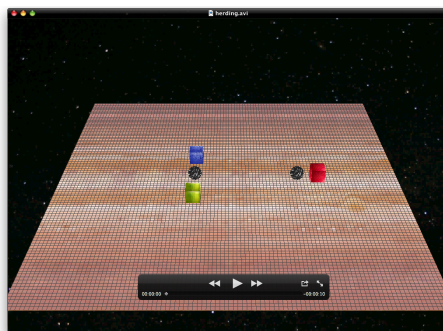

Predator-Prey Coevolution Example

- ▶ A good example of competitive-cooperative dynamics is the predator-prey task.
- ▶ Predator (hyenas) and prey (zebras) populations evolve together in a toroidal world.
- ▶ Predators evolve strategies to catch prey, while prey evolve strategies to escape.
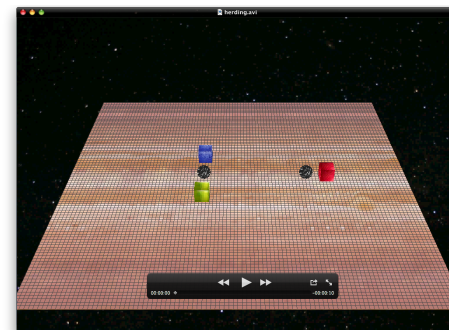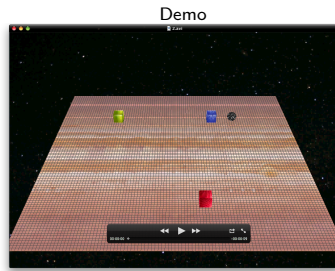
Initial Behaviors

▶ Initially, prey evolves to run away from the nearest predator, and predators towards the prey. The prey is captured increasingly often.

▶ In response, the prey evolves to circle the predator.
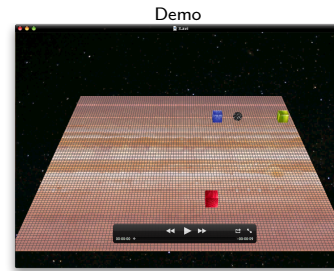

Demo

Demo
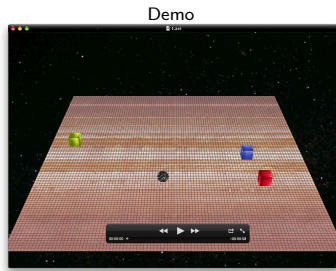
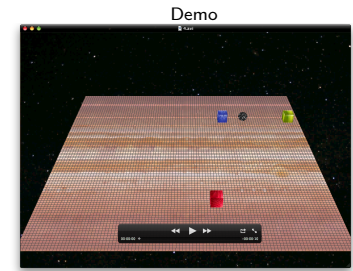50-75: Single predator catches prey

75-100: Prey evades by circling

Cooperation and Escape

▶ Predators evolve a cooperative strategy of approaching from two directions.

▶ Prey evolves to lure them close and then escapes between them.
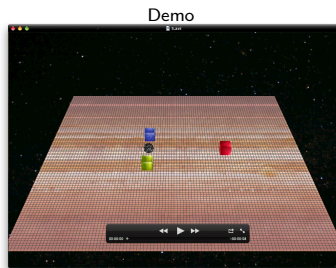

Demo

Demo

100-150: Two predators cooperate

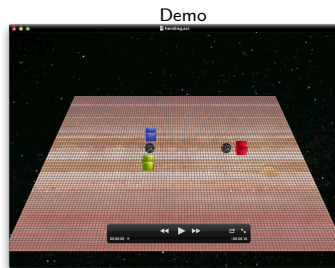150-180: Prey baits and escapes

Herding Multiple Preys

▶ Predators evolve to approach from three different directions.

▶ This strategy works also for two preys.
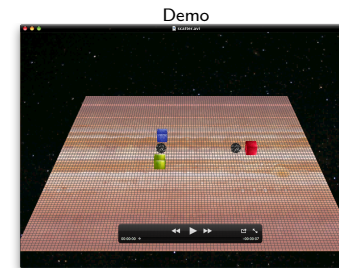

Demo

Demo

180-200: All predators cooperate

200-250: Predators herd two prey

Confusing the Predators

▶ The prey team evolves to confuse the predators by splitting their directions.

▶ This mirrors natural behavior seen in prey!

Demo

250-300: Prey evade by scattering

Insights from the Predator-Prey Simulation

- ▶ Complex behaviors do not evolve in a vacuum, but in response to a changing environment.
- ▶ The competitive+cooperative coevolution arms race leads to increasingly complex interactions over multiple generations.
- ▶ Simulations shed light on the evolution of real-world animal behaviors.
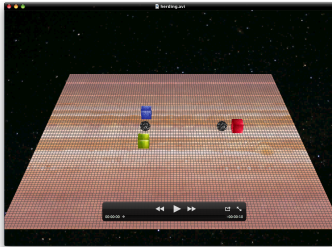
Conclusion on Collective Systems

- ▶ **Cooperative Coevolution:**
  - ▶ Individual networks as well as teams can be evolved cooperatively by sharing overall fitness.
  - ▶ Role-based cooperation can be effective; communication-based flexible.
  - ▶ Homogeneous teams of generalists can adapt dynamically.

- ▶ **Competitive Coevolution**
  - ▶ Competition can drive the emergence of highly complex behaviors.
  - ▶ The arms race forces each population to innovate in response to the other.
  - ▶ This process may be crucial in open-ended evolution and the emergence of major evolutionary transitions.