Neuroevolution of Collective Systems

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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.

(Alonso 2015)

(Hajer 2015)

(Thomas 2023)

Coevolution of Intelligent Systems

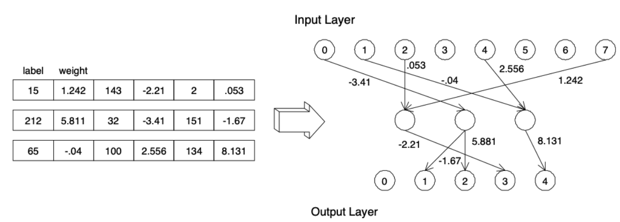
- Coevolution: Multiple populations evolve together.
- Cooperative: Populations evolve to achieve common goals.
- Competitive: Populations compete for resources, driving innovation.
- Neuroevolution can utilize both processes.

(https://images.app.goo.gl/QaJz76hZyghCEgXk6)

(https://i.ytimg.com/vi/edvARkLhc58/maxresdefault.jpg)

Cooperative Coevolution of a Single Neural Network

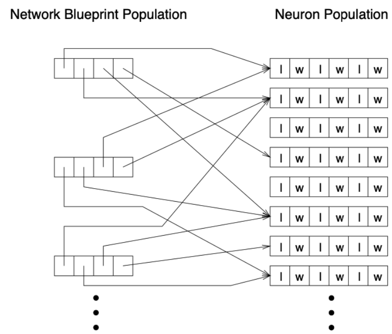
- Cooperative coevolution applied to individual components, such as neurons or connections.
- Neurons are evolved to work together to solve a task.
- How to form a network intelligently?



(Moriarty & Miikkulainen 1997)

SANE: Symbiotic Coevolution of Networks and Blueprints

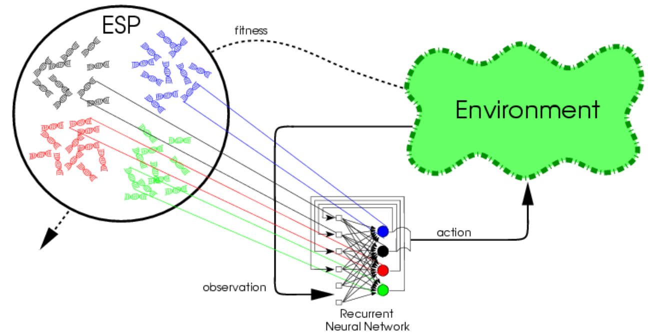
- Networks are created based on a blueprint that selects neurons.
- Neurons and blueprints coevolve based on the network's fitness.
- Neurons evolve to cooperate; blueprints to combine.
- Tends to evolve general neurons, not specializations.



(Moriarty & Miikkulainen 1997)

ESP: Enforced Subpopulations

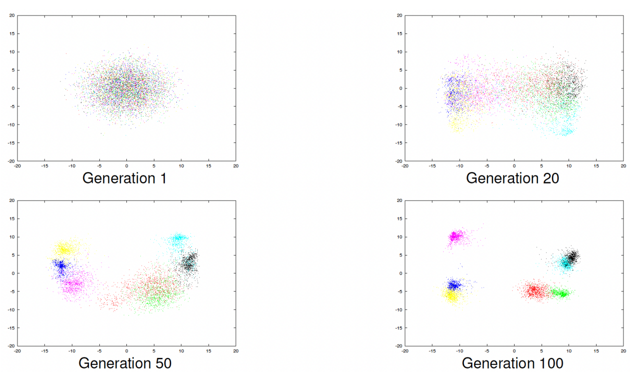
- ESP enhances SANE by evolving neurons in separate subpopulations.
- Each neuron specializes in a specific location within the network.
- Fully connected network; only weights evolved.
- This approach helps the network discover differentiated roles for each neuron.



(Gomez 2003)

Example: Maze Navigation with Khepera

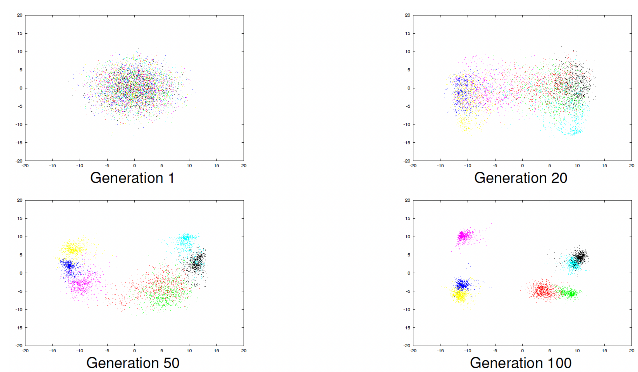
- Subpopulations start random but specialize over time.
  - Some slow the robot down with obstacle up front; others veer left when obstacle on the right, etc.
- Evolution discovers compatible subtasks.
  - Neurons optimized for each subtask.
  - Avoids the competing conventions problem by assigning neurons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



(Gomez 2003)

Maintaining Diversity in Cooperative Coevolution

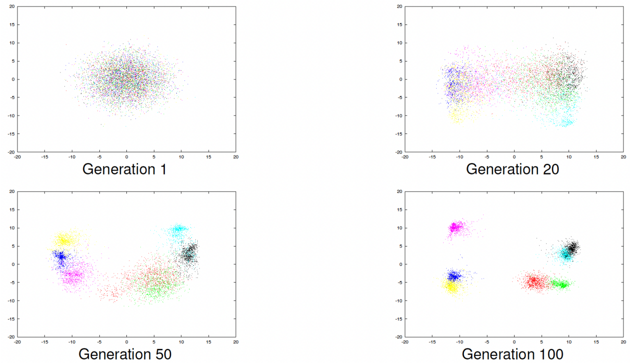
- Maintaining diversity in the population is essential to prevent premature convergence.
- Neurons must specialize in different tasks, preventing the population from becoming too similar.
- ESP helps maintain diversity through subpopulation specialization.



(Gomez 2003)

Robust Search for Subtasks

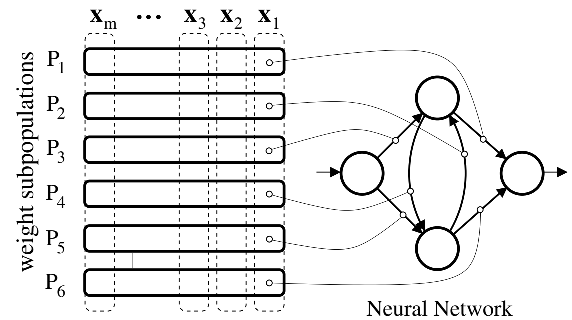
- Subpopulations evolve multiple subtasks, leading to redundancy.
- Redundancy ensures that even suboptimal neurons are compensated by others.
- Redundance makes the search robust: Necessary subtasks usually included.



(Gomez 2003)

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 permutated.
- Instead of unrestricted search, exploration of new combinations.

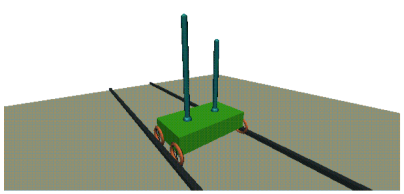


(Gomez et al. 2008)

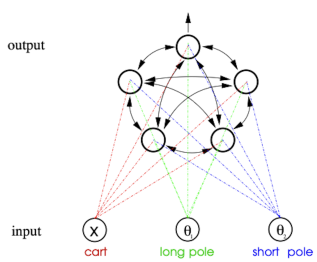
Example: POMDP Double Pole Balancing

- 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.

Embedded Demo:



(https://nn.cs.utexas.edu/?dpb-esp)



(Gomez 2003)

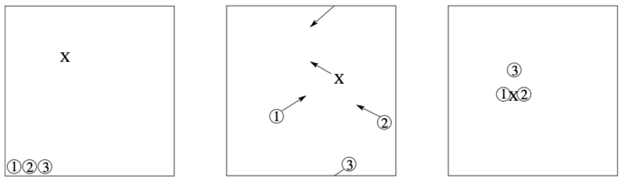
Evolving a Team

- 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.

(Londolozi Images 2019)

Cooperative Strategy in Predator-Prey Task

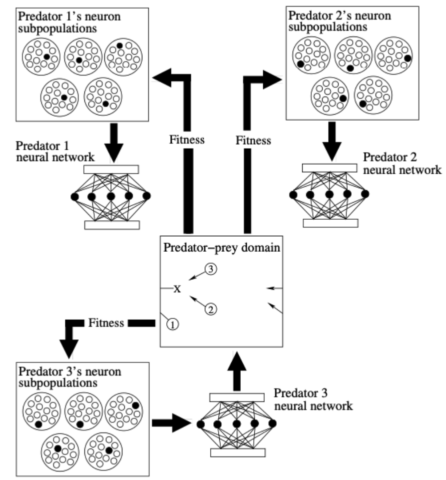
- In a predator-prey task, three predators evolve to cooperate in capturing a prey (in a toroidal environment).
- The prey runs away from the nearest predator (stochastically).
- The team is rewarded based on the success of the capture.



(Yong & Miikkulainen 2010)

Multi-Agent ESP

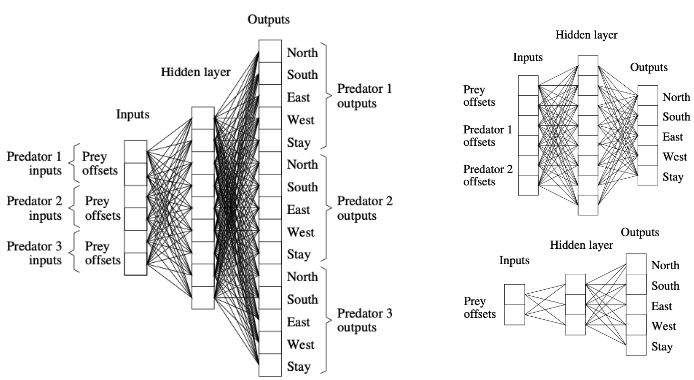
- Extend ESP to multiple networks: one for each predator.
- Hierarchical structure: each neuron subpopulation evolves one nueron for one network.
- The neurons inherit the fitness of the entire team.



(Yong & Miikkulainen 2010)

To Communicate or Not to Communicate?

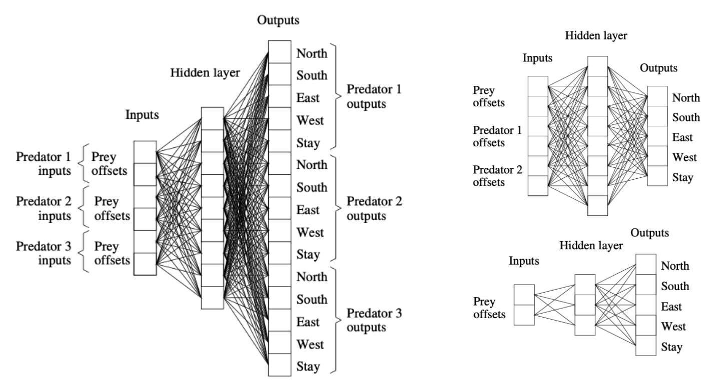
- For comparison, a central controller can be evolved in one population.
- In Multi-agent ESP, each agent may see each other.
- Or they may see only the prey.



(Yong & Miikkulainen 2010)

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?

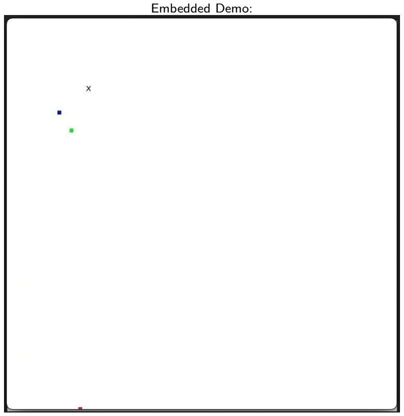


(Yong & Miikkulainen 2010)

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.

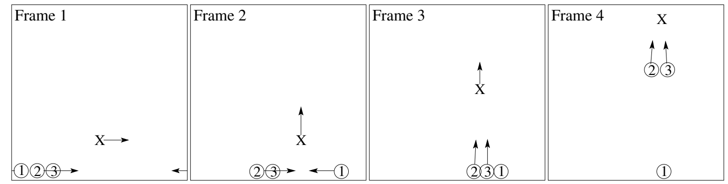
Embedded Demo:



(https://nn.cs.utexas.edu/?multiagent-esp)

Discovering Compatible Behaviors

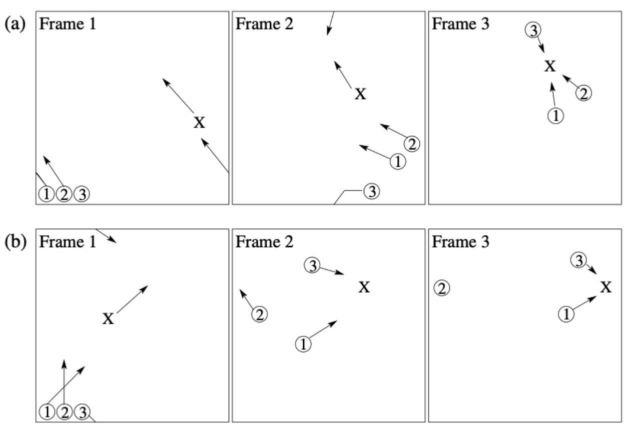
- Evolution discovers role-based behaviors more easily than flexible team strategies.
- Each behavior compensates for inaccuracies in other agents.
- Cooperation based on roles often leads to robust solutions.



(Yong & Miikkulainen 2010)

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:



(Yong & Miikkulainen 2010)

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:

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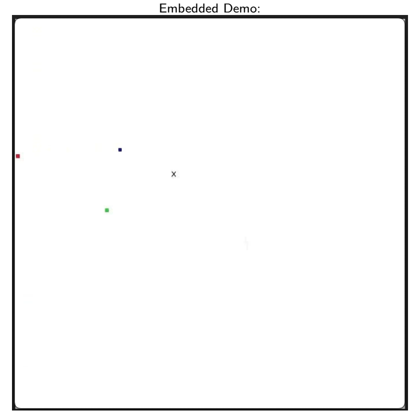
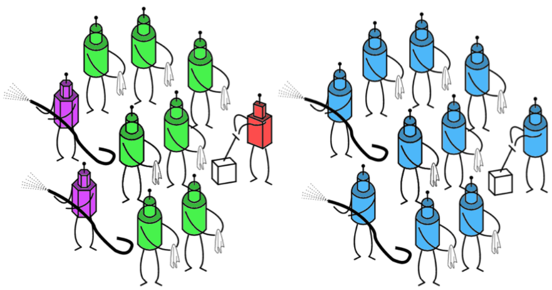


(https://nn.cs.utexas.edu/?multiagent-esp)

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.



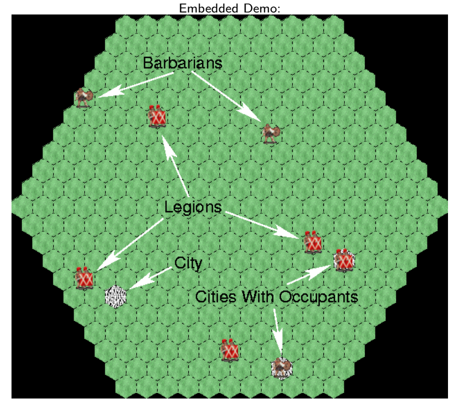
(Bryant & Miikkulainen 2018)

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.

Embedded Demo:



(https://nn.cs.utexas.edu/?Legion2)

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.

(Williams 2024)

Toxin vs. resistance to it in garter snakes and newts

Fitness Definition in Competitive Coevolution

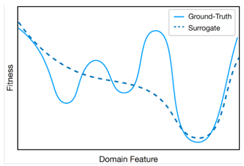
- Fitness is defined in relation to the performance of other agents in the population.
- As individuals improve, fitness becomes harder to achieve, ensuring continuous adaptation.
- Competitive coevolution automatically shapes the fitness function.

(Williams 2024)

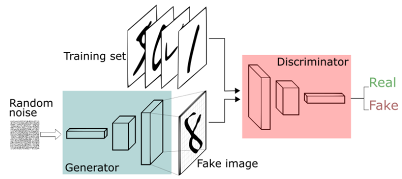
Toxin vs. resistance to it in garter snakes and newts

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.



(Francon et al. 2020)



(Thalles 2017)

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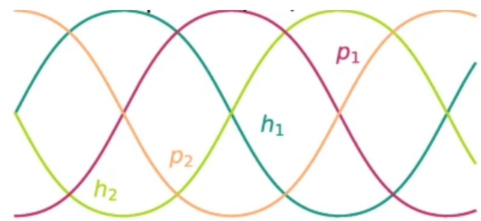
Challenges in Competitive Coevolution

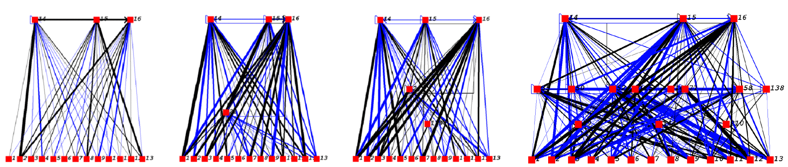
- Progress is not always guaranteed; fitness improvement may only be relative (Red Queen dynamics).
- Possible to exploit weaknesses in current candidates without true improvement.
- Maintaining a collection of previous candidates helps track absolute progress.



(Schenk et al. 2020)

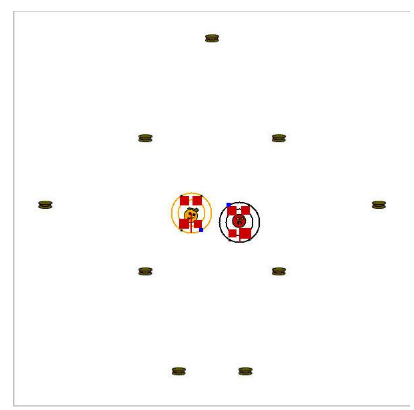
Competitive Coevolution with NEAT

- 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.


(Stanley 2004)

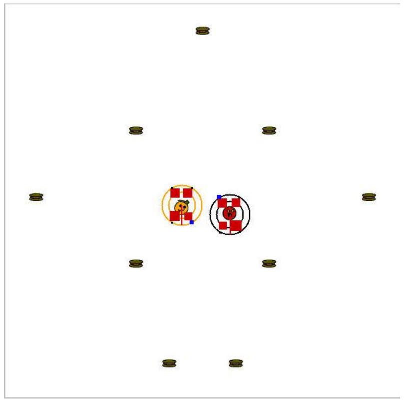
Foraging, Pursuit, and Evasion Task

- 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.


(Stanley 2004)

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.



(Stanley 2004)

Early Strategies

- Rest and let opponent waste energy
- Mainly forage, occasionally crash by accident
- Difficult to switch between tasks

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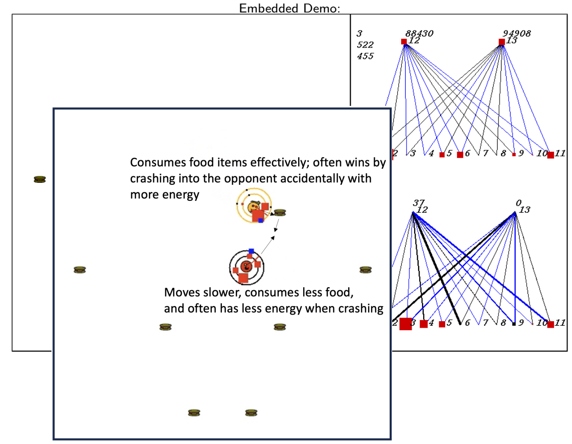

(Stanley 2004)

Mature Strategies

- Recurrent hidden node allows switching between tasks
- Collect food to gain energy; rest to save energy
- Difficult to predict energy at contact

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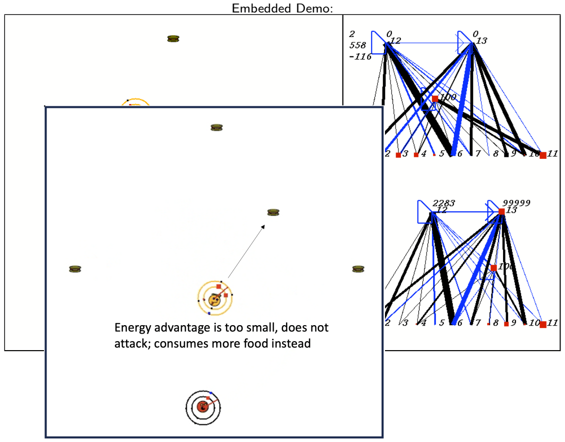

(Stanley 2004)

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

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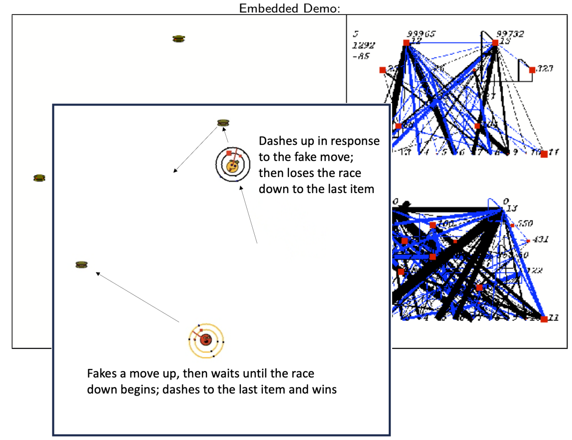
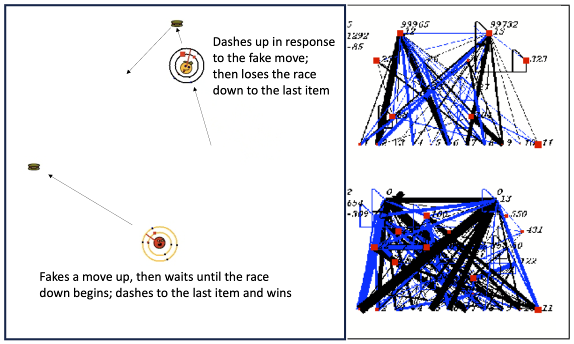


(Stanley 2004)

Coevolution of Complex Strategies

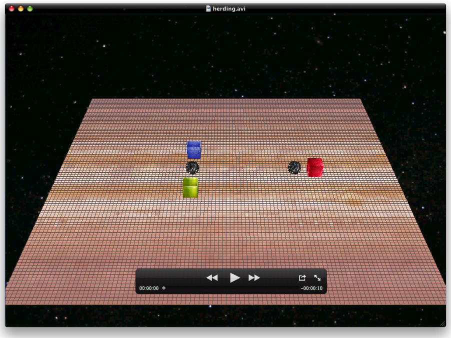
- Competitive coevolution is a powerful approach for discovering increasingly complex behaviors.
- Strategies such as faking moves and forcing opponents into energy-depleting mistakes are discovered.
- These behaviors would be difficult to discover without competitive coevolution, or without complexification.



(Stanley 2004)

Evolving Multiple Teams

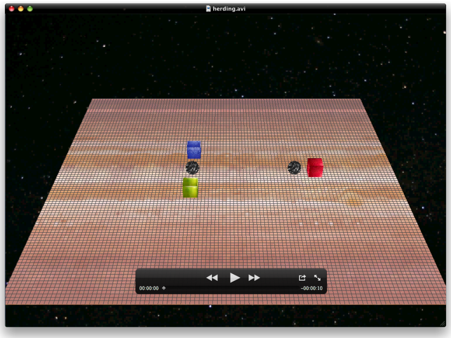
- Multiple cooperative teams can evolve in a competitive environment.
- Teams challenge each other, leading to increasingly complex behaviors.
- This process is called an evolutionary arms race.



(https://nn.cs.utexas.edu/?armsrace)

Challenges in Establishing Absolute Improvement

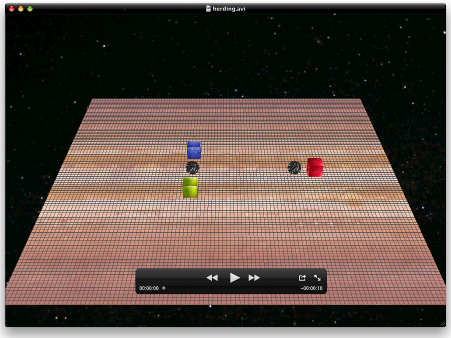
- Absolute improvement is not always guaranteed.
- Teams may evolve strategies that exploit weaknesses in others but fail in the long run.
- However, in natural tasks, more complex behaviors often subsume simpler ones, leading to real progress.



(https://nn.cs.utexas.edu/?armsrace)

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.



(https://nn.cs.utexas.edu/?armsrace)

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.

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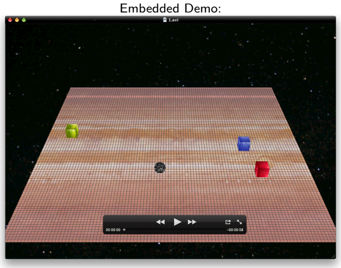

50-75: Single predator catches prey

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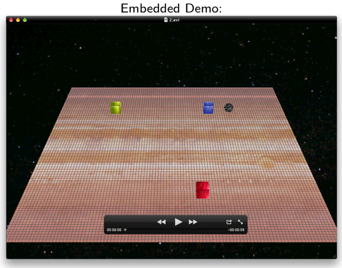

75-100: Prey evades by circling

(https://nn.cs.utexas.edu/?armsrace)

Cooperation and Escape

- Predators evolve a cooperative strategy of approaching from two directions.
- Prey evolves to lure them close and then escapes between them.

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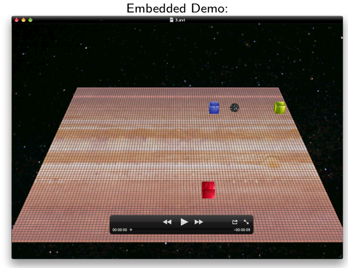

100-150: Two predators cooperate

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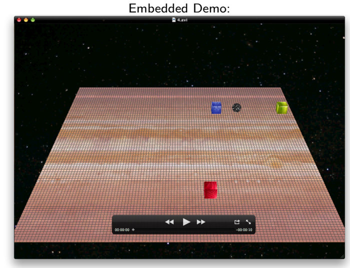

150-180: Prey baits and escapes

(https://nn.cs.utexas.edu/?armsrace)

Herding Multiple Preys

- Predators evolve to approach from three different directions.
- This strategy works also for two preys.

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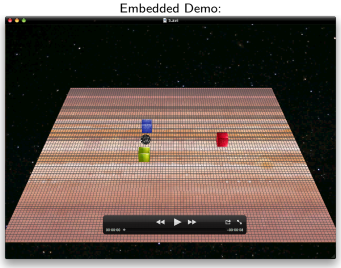

180-200: All predators cooperate

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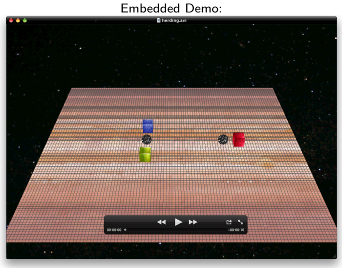

200-250: Predators herd two prey

(https://nn.cs.utexas.edu/?armsrace)

Confusing the Predators

- The prey team evolves to confuse the predators by splitting their directions.
- This mirrors natural behavior seen in prey!

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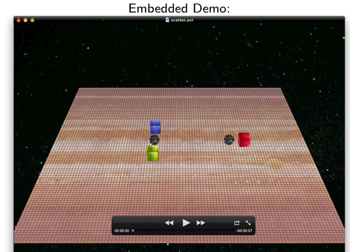
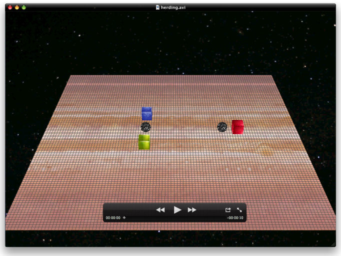


250-300: Prey evade by scattering

(https://nn.cs.utexas.edu/?armsrace)

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.



(https://nn.cs.utexas.edu/?armsrace)

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.