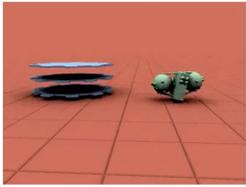


Neuroevolution Under Constraints

- ▶ Evolution of behavior is guided by constraints from the body, environment, and other agents.
- ▶ Evolution under realistic constraints leads to natural, believable, human-like behavior.
- ▶ Simulations can be used to understand biological determinants of behavior.



(<https://nn.cs.utexas.edu/?evcdemo>)



(Schrum & Karpov 2012)

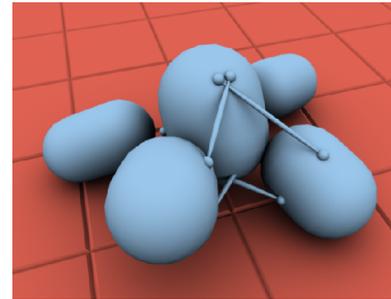


(<https://nn.cs.utexas.edu/?mobbingfactors>)

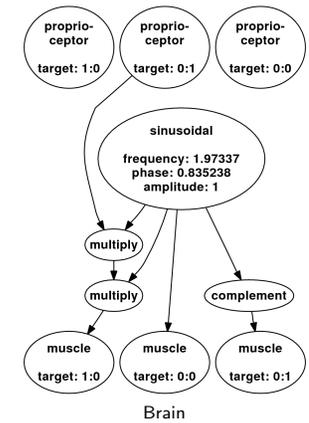


Emergence of Intelligence

- ▶ Origins of intelligence: Embodied optimization
- ▶ Body-Brain Coevolution.
 - ▶ Body: Blocks, muscles, joints, sensors
 - ▶ Evolved together in a physical simulation



Body

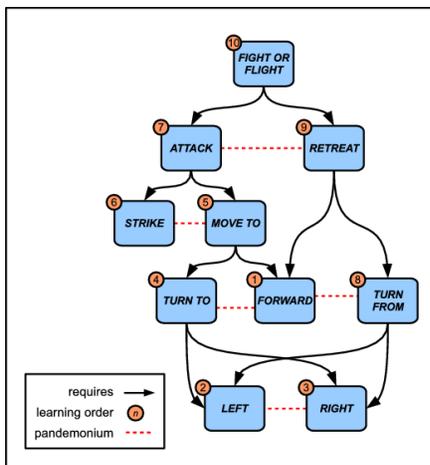


(Lessin et al. 2013)



Syllabus

- ▶ Step-by-step construction of complex behavior
- ▶ Primitives and three levels of complexity
- ▶ Constructed by hand; body and brain evolved together

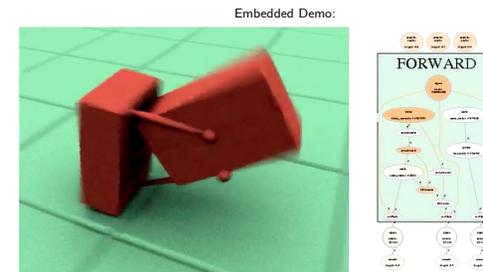


(Lessin et al. 2013)



Encapsulation

- ▶ Once evolved, a trigger node is added

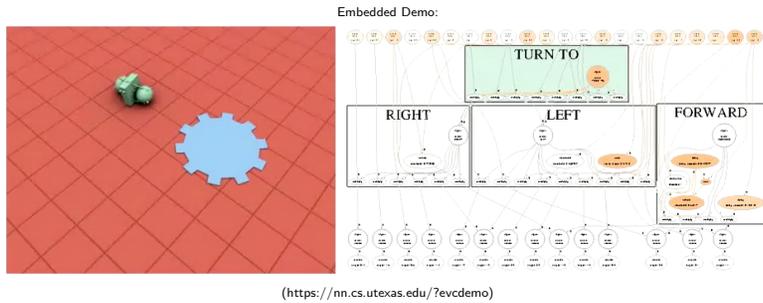


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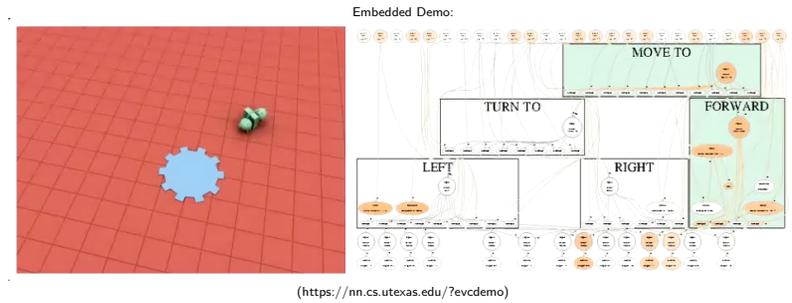
Turn to Light

- ▶ First level of complexity
- ▶ Selecting between alternative primitives



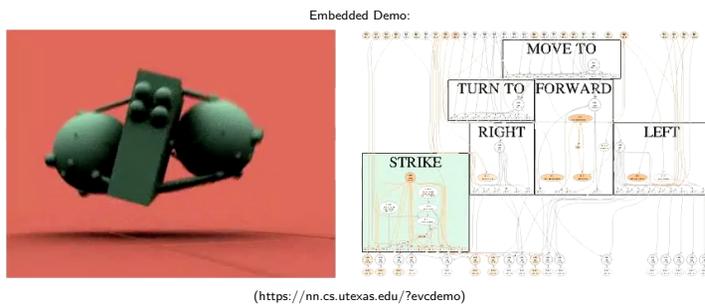
Move to light

- ▶ First level of complexity (Sims 1994)
- ▶ Selecting between alternative primitives



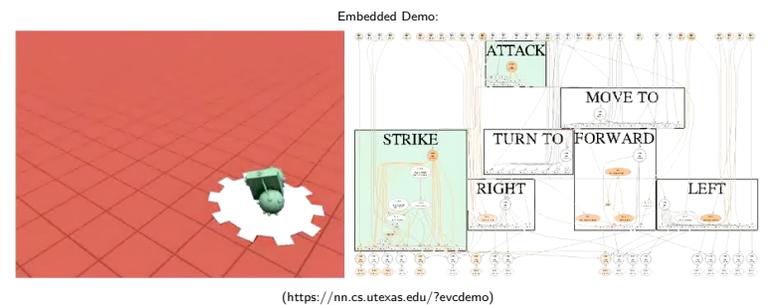
Strike

- ▶ Alternative behavior primitive



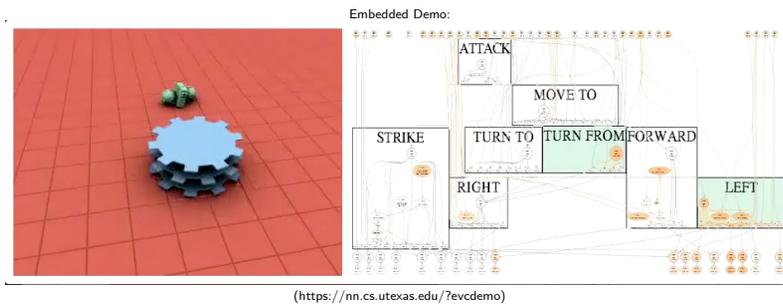
Attack

- ▶ Second level of complexity (beyond Sims and others)



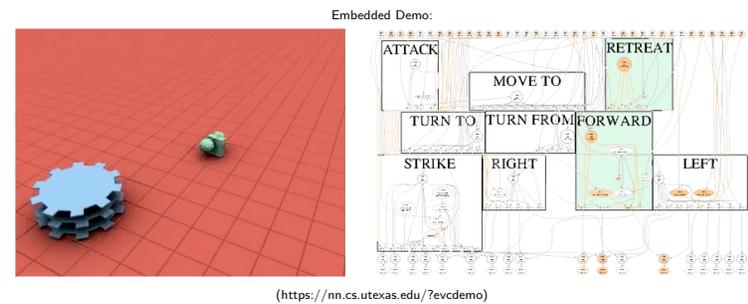
Turn from Light

- ▶ Alternative first-level behavior



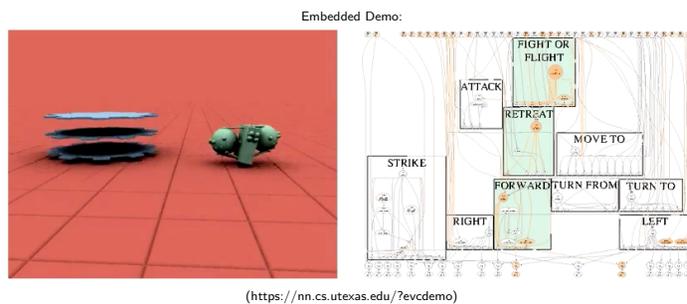
Retreat

- ▶ Alternative second-level behavior



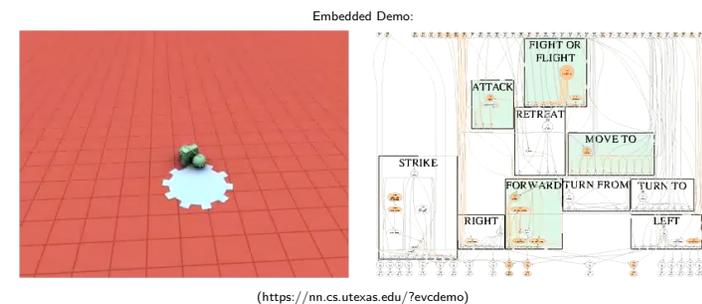
Fight or Flight

- ▶ Third level of complexity



Insight: Body/Brain Coevolution

- ▶ Evolving body and brain together poses strong constraints
 - ▶ Behavior appears believable
 - ▶ Worked well also in BotPrize (Turing test for game bots)
- ▶ Possible to construct innovative, situated behavior



Evolving Humanlike Behavior

- ▶ Botprize Competition 2007-2012: A Turing test for game bots.
- ▶ Three players in Unreal Tournament 2004:
 - ▶ Human confederate: tries to win
 - ▶ Software bot: pretends to be human
 - ▶ Human judge: tries to tell them apart!
- ▶ Success measured by bots being mistaken for human players.



(Schrum & Karpov 2012)



Evolving an Unreal Bot

- ▶ Wandering, unstuck etc. based on scripts & learning from humans
- ▶ Evolve effective fighting behavior
- ▶ Persistent gap: 30% vs. 80% human
 - ▶ Bots initially identified easily by mechanical and repetitive behavior.
 - ▶ Humans adapt to game lags and show varying performance, which bots lacked.
 - ▶ Effective but mechanical behavior was not human-like.



(Schrum & Karpov 2012)



Early Challenges and Findings

- ▶ Human subject experiment to understand what's missing.
- ▶ But human judges do not understand their expertise.



(Schrum & Karpov 2012)



Imposing Constraints on Bots

- ▶ Evolving to win results in unnatural behaviors.
- ▶ Constraints on multitasking, accuracy, and reaction times imposed during evolution.
- ▶ Bots performed inconsistently, similar to humans under stress.
- ▶ Result: Bots became more human-like and less predictable.

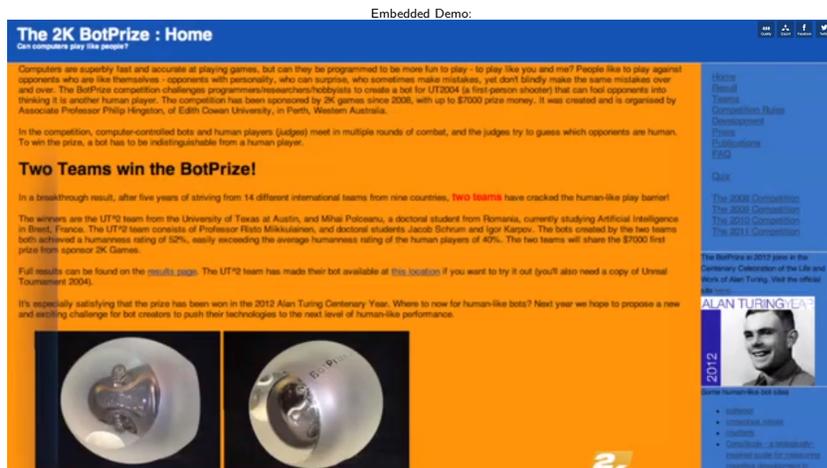


(Darthys1 2007)



After Five Years, Success!!!

- ▶ Bots judged as human more than 50% of the time.
- ▶ Best bot better than 50% of the humans!



(Hingston 2012)



Lessons from Botprize

- ▶ Complex behaviors emerge from constrained optimization.
- ▶ Constraints guide neuroevolution toward more human-like behavior.
- ▶ Fascinating further challenges:
 - ▶ Judges can still differentiate in seconds—how?
 - ▶ Judges lay cognitive, high-level traps.
 - ▶ Bots should learn from interactions and adapt to opponents.
 - ▶ Coordination in team play and communication.



(Schrum & Karpov 2012)



Emergence of Intelligence



(<https://msuhyenas.blogspot.com/2017/09/>)



(<https://directory.natsci.msu.edu/Directory/Profiles/Person/101358/>)

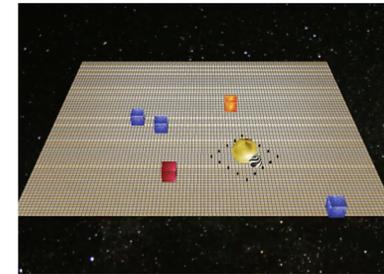
- ▶ Evolved Virtual Creatures
 - ▶ Neuroevolution of intelligent behavior
 - ▶ Useful e.g. for video games
- ▶ Can such experiments lead to insights in biology?
- ▶ Collaboration with Kay Holekamp's lab (MSU)
 - ▶ Studying hyenas in Masai Mara since 1982



Biological Insights from Simulations



(<https://www.holekamplab.org/>)
69,70,71,72



(<https://nn.cs.utexas.edu/?mobbingfactors>)

In simulation

- Manipulate constraints, observe outcomes, analyze trajectory of discovery

Computational support for hypotheses

- Reward structure: Emergence of cooperation in hunting
- Lethality of conflicts: Emergence of a hierarchical society
- Signaling in mate selection vs. hunting: Origins of communication



Example: Evolution of Intelligent Coordinated Behavior

Embedded Demo:



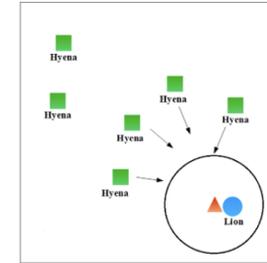
(<https://nn.cs.utexas.edu/?mobbingfactors>)

- ▶ Stealing a kill from lions
 - ▶ Succeeds in an otherwise impossible task (sometimes)
 - ▶ More sophisticated than other hyena behaviors
 - ▶ Highly rewarding compared to normal hunting
 - ▶ Largely genetically determined
 - ▶ A breakthrough in evolution of intelligence?

- ▶ Mobbing involves strategic positioning, vocalizations, and a synchronized attack.
- ▶ Hyenas must balance fear, aggression, and coordination to successfully mob lions.



Simulation Setup

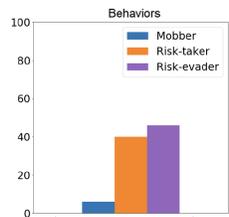


(Rajagopalan et al. 2020)

- Lion at a kill, with an interaction circle around it⁶⁹
 Ten hyenas chosen and placed randomly in the field
 If 4 or more hyenas enter the circle simultaneously, they get the kill
- Otherwise they die
- Does mobbing behavior evolve?
- What are the stepping stones for it?

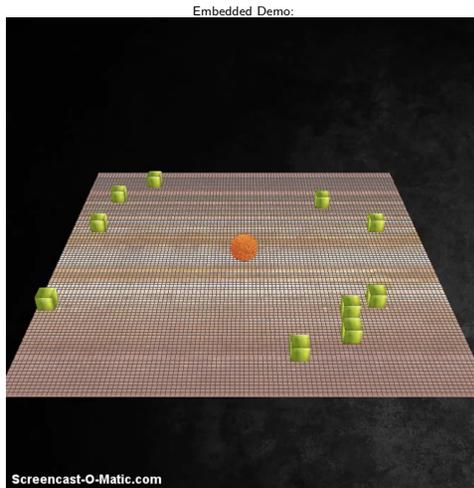


Initial Behaviors



(Rajagopalan et al. 2020)

- Risk evasion is common
- Never reach the circle; Medium fitness
- Risk taking is common
- Charge the circle; Frequent low fitness
 - Occasional high fitness by accident

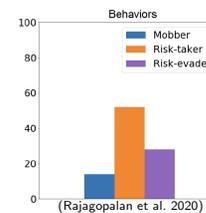


ScreenCast-O-Matic.com

(<https://nn.cs.utexas.edu/?mobbingfactors>)

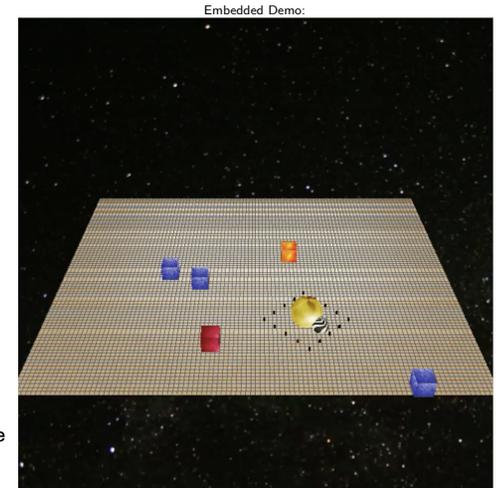


Early Behaviors



(Rajagopalan et al. 2020)

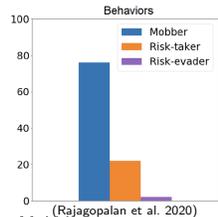
- Risk taking grows
- As long as it is successful often enough
- Risk evasion also persists
- Evasion at the circle starts to emerge
- Is mostly detrimental, but an important stepping stone



(<https://nn.cs.utexas.edu/?mobbingfactors>)

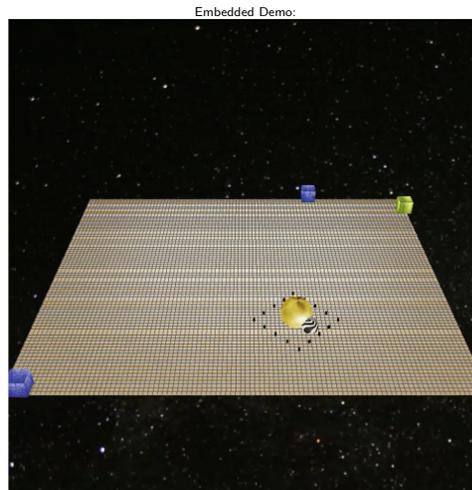


Later Behaviors



(Rajagopalan et al. 2020)
Mobbing emerges

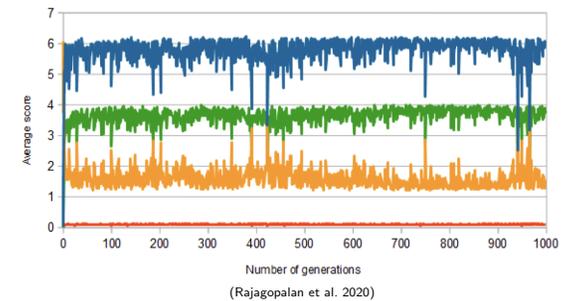
- Not just coincidence of risk takers
- Hyenas wait until there's enough of them
- Risk-evaders evolve into latecomers
- Simple risk-taking and risk-evasion still exist



(<https://nn.cs.utexas.edu/?mobbingfactors>)



These Behaviors Persist in Prolonged Evolution



Risk taking and risk evasion never go away completely

- They serve a role in maintaining the mobbing behavior
- If mobbing starts to get lost, it can be reintroduced



Insight into Real-life Behaviors



(Howes 2024)

These behaviors are observed in real-life hyenas as well ³⁸

A computational explanation of why they are there:

- Stepping stones in discovery
- Safeguards in maintaining



Potential for Future Evolution

- ▶ Could mobbing behavior in hyenas evolve into more complex strategies?
- ▶ Simulations can help predict potential developments like advanced communication or learning.
- ▶ Deceptive fitness challenges must be overcome for more significant evolutionary shifts.



(<https://nn.cs.utexas.edu/?mobbingfactors>)



Parallels in Human Behavior

- ▶ Similar patterns of risk-taking and innovation are seen in human explorers and pioneers.
- ▶ Bold individuals drive exploration, discovery, and progress.
- ▶ Historical and contemporary examples include migration, exploration, and space colonization.



(Ho'okuleana 2024)

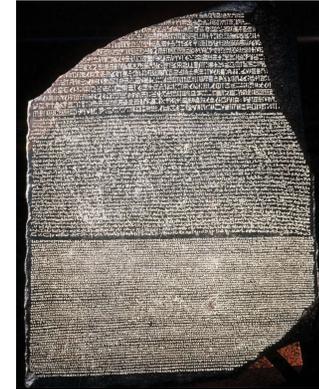


(Brumfield & Landau 2013)



Evolution of Language

- ▶ Language: a major evolutionary transition enabling complex societies.
- ▶ Unique to humans: the ability to create infinite meanings from finite symbols.
- ▶ Evolution and learning play interconnected roles in the emergence of language.



(Britannica 2024)



Biological Basis of Language

- ▶ Genetic predisposition: Language is biologically programmed but learned through interaction.
- ▶ Critical period for development: Ages 1-5 are crucial for linguistic input.
- ▶ Language emergence in deaf children and pidgin-to-creole transitions illustrate innate capabilities.



(ChildrensHealth 2024)

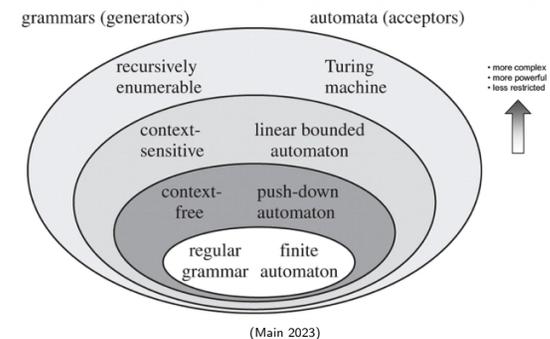


(Shutterstock 2017)



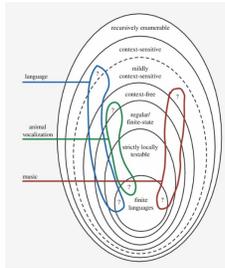
Debate on Language Structure

- ▶ Chomsky's Universal Grammar: Language structure is genetically coded.
- ▶ Modern evidence: Large language models learn language patterns from data without explicit grammar.
- ▶ Humans learn language efficiently with far fewer examples than AI, suggesting evolved biases.



Clues from Biology and Other Species

- ▶ Early hominids like *Homo erectus* may have had protolanguage abilities.
- ▶ Current species (e.g., dolphins, apes) show advanced communication that can be extended with training.
- ▶ These behaviors may serve as models for intermediate stages in language evolution.



(Main 2023)



(<https://www.koko.org/communication/>)

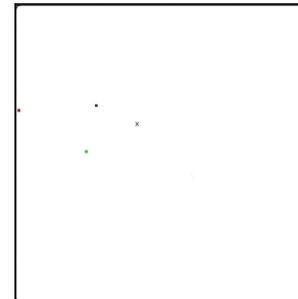


(DALLE-E 2024)

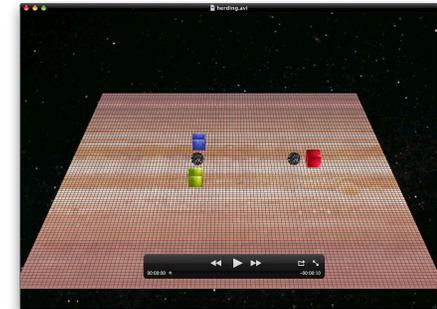


Evolving Communication Codes

- ▶ Simple communication codes emerge in simulations of mating, hunting, and cooperative tasks.
- ▶ Codes often consist of context-based symbols, not full grammar.
- ▶ Asymmetry in roles and group selection enhance code convergence.



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



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



Origin of Communication: Mating or Hunting?

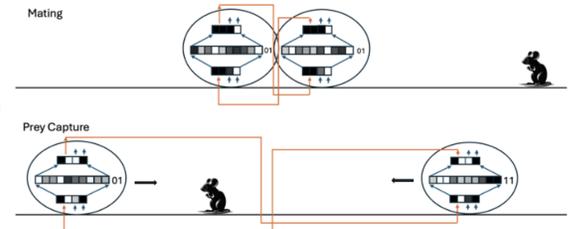
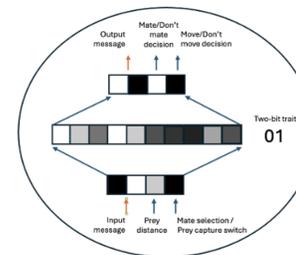


(Couanon 2022)



(Radke 2024)

Simulating Mating vs. Hunting



(Miikkulainen 2024)

Mate selection important for high-quality offspring

- Often based on visual displays, gestures, vocalizations
- Hunting groups can be more successful and scale up to larger prey
- Requires coordination through movements, gestures, vocalizations
- Once discovered, can serve as a foundation for other communication
- Which one is the likely origin?

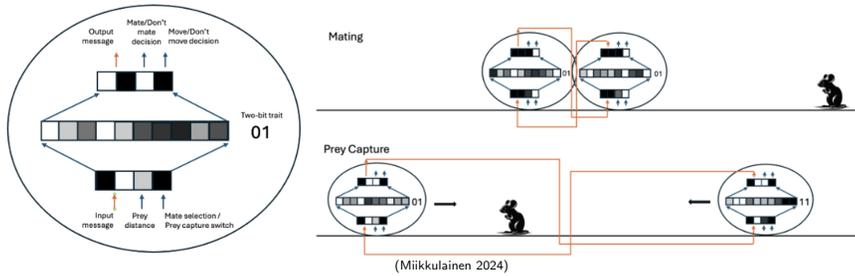


Two tasks (w/switch): mate selection, prey capture

- 2-bit inheritable trait; 2-bit output/input message; sense distance to prey
 - Mating successful if compatible traits, both agree to mate
 - Hunting success if move on the prey at the same time
- Evolve one first, then the other, or both at once
- Which is faster? Are the evolved codes different?



Mating is a Better Foundation



When mating first, then hunting

- Evolves faster
- Communication code is simpler: fewer symbols

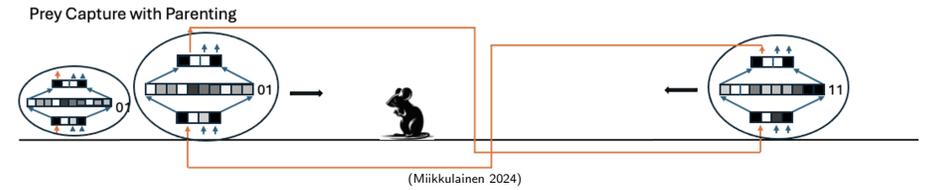
Mating code reused and complexified to provide for hunting

- E.g. same code for readiness

Mating communication is a better foundation for general communication



Evolving Language Learning



Agents need to hunt, mate--and do parenting!

- Paired up to hunt and mate
- Parenting phase: offspring learns through RL
- Adult phase: performance evaluation
- Best adults reproduce

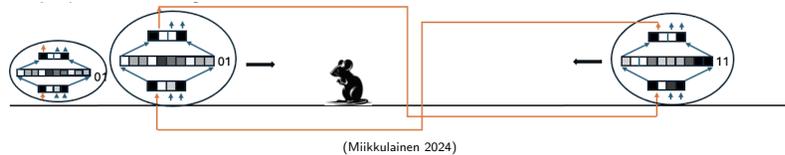
Evolution improves learning ability rather than encode policy

Discovers a teachable code



Evolutionary Pressure for Communication

- ▶ Communication evolved only when direct sensing was insufficient.
- ▶ If communication was necessary for success, evolution favored its emergence.
- ▶ Once evolved, communication was adapted for other tasks, demonstrating evolution's flexibility.



Discovering Multi-Symbol Systems

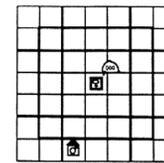


Figure 5.a. Default: "move forward"

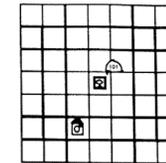


Figure 5.b. Female signals "move forward"

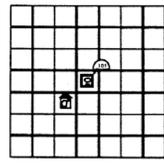


Figure 5.c. Female signals "forward".

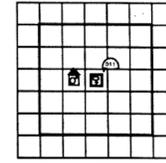


Figure 5.d. Female signals "turn right"

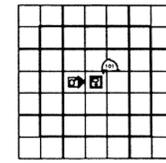


Figure 5.e. Female signals "move forward."

(Werner & Dyer 1992)

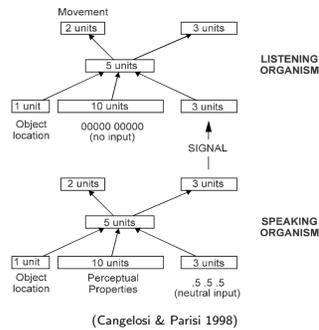
Discovering more complex codes: navigation instructions

- Males move and listen, females see and speak (3 bits)
- Evolve a code to find each other and mate
- Initially just the last step, gradually from further away

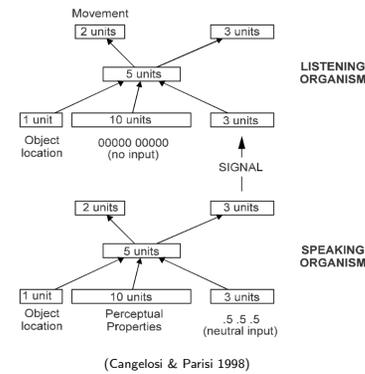


Steps to Structured Language

- ▶ Signaling evolved first, followed by context-based codes.
- ▶ Linguistic structure may emerge from the reuse and complexification of signaling systems.
- ▶ Example: action-object signaling in simulations involving edible and poisonous mushrooms.



Discovering Structured Communication



Signaling consist of single symbols:
Can compositional structure be evolved?

E.g. world with edible and poisonous mushrooms

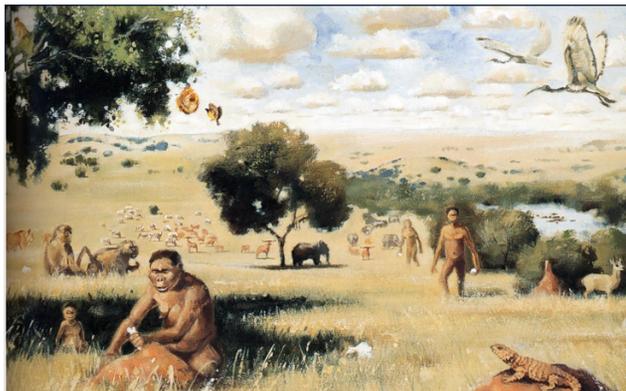
- Agents evolve to guide others
- Action-object structures evolved

Similar to what can be taught to e.g. chimpanzees
Hard to go beyond that: What is still missing?



Evolution of Human Language

- ▶ Language might have originated from cognitive functions, not just communication.
- ▶ Grammatical structures may stem from the need for flexible role coordination in group activities.
- ▶ Once cognitive structures were in place, they were exapted for structured language.



(Voigt 2006)



The Role of Social Complexity

- ▶ But other animals live in societies as well; what's different?
- ▶ Complex predators: need to communicate location and type of kill?
- ▶ Displacement in space and time?
- ▶ Alliances and cliques? Gossip?
- ▶ Possible origins include symbolic culture and abstract representations (e.g., early art and symbols).



(Borjomi88 2024)



