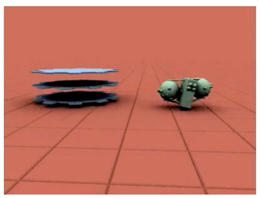
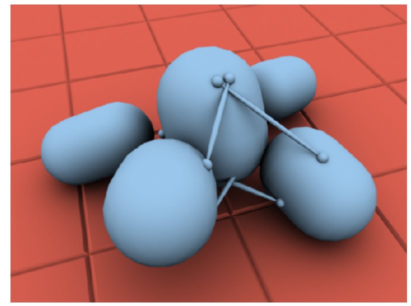
Neuroevolution Under Constraints

- 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.

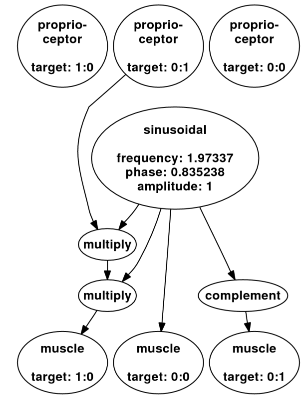


Emergence of Intelligence

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



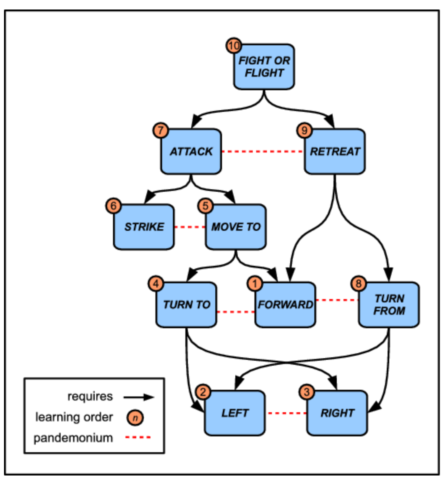
Body



Brain

Syllabus

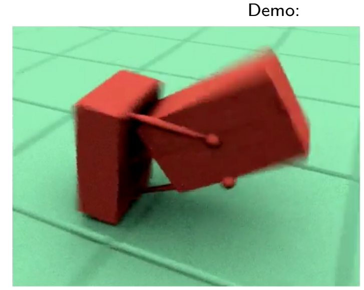
- Step-by-step construction of complex behavior
- Primitives and three levels of complexity
- Constructed by hand; body and brain evolved together

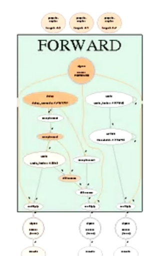


Encapsulation

- Once evolved, a trigger node is added

Demo:

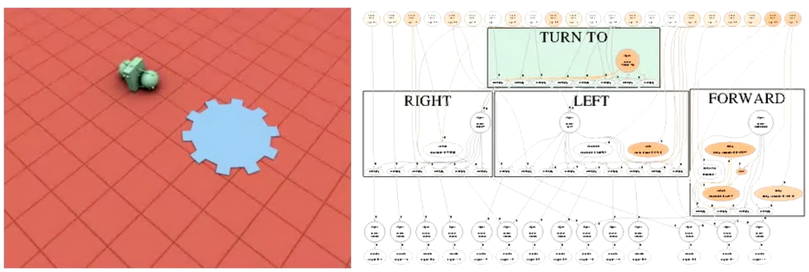




Turn to Light

- First level of complexity
- Selecting between alternative primitives

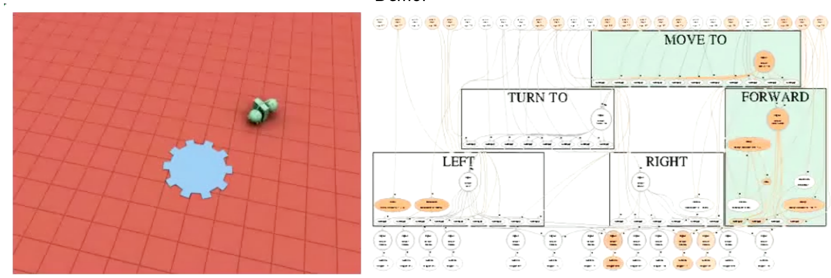
Demo:



Move to light

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

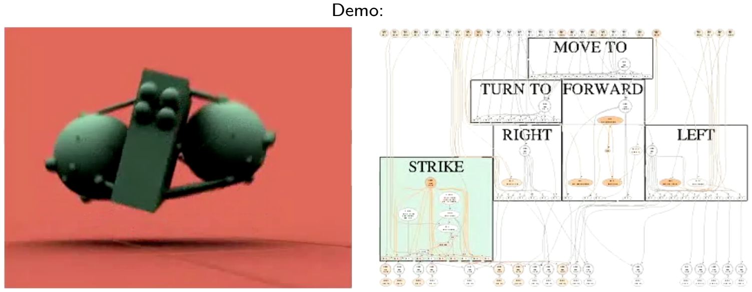
Demo:



Strike

- Alternative behavior primitive

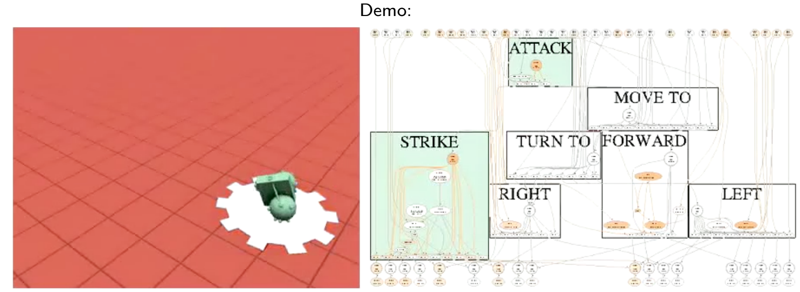
Demo:



Attack

- Second level of complexity (beyond Sims and others)

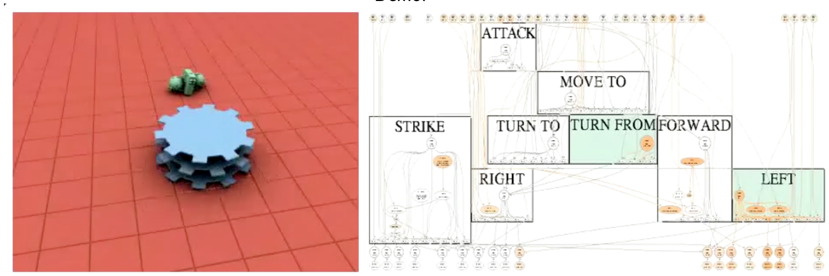
Demo:



Turn from Light

- Alternative first-level behavior

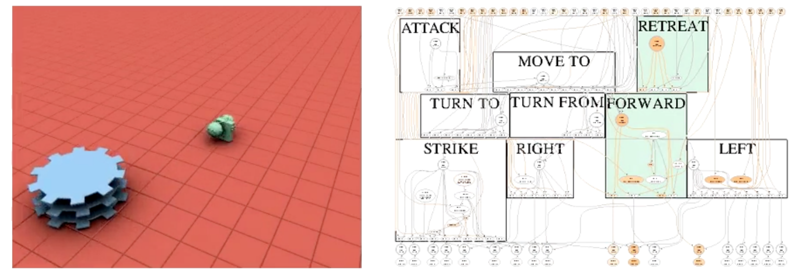
Demo:



Retreat

- Alternative second-level behavior

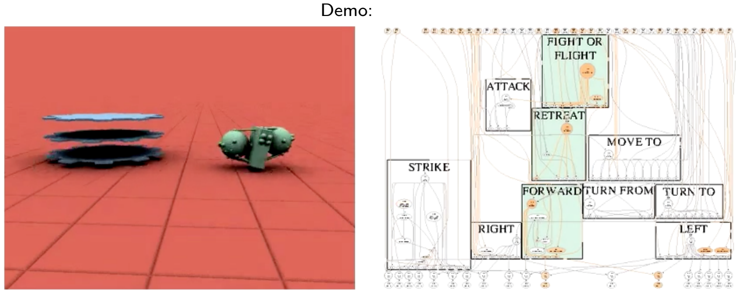
Demo:



Fight or Flight

- Third level of complexity

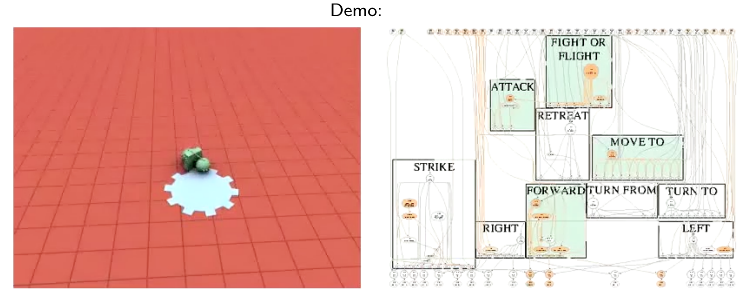
Demo:



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

Demo:



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.

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.

Early Challenges and Findings

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

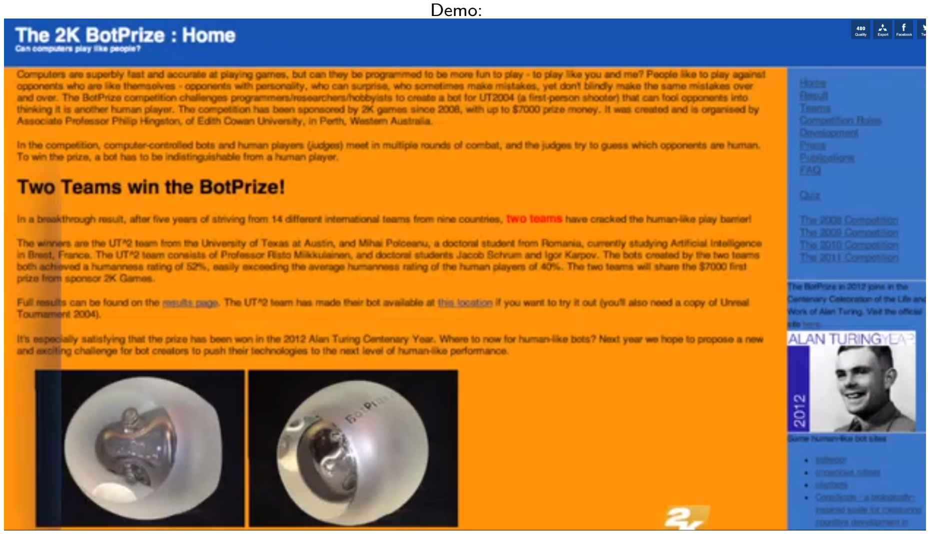
Imposing Constraints on Bots

- 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.

After Five Years, Success!!!

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

Demo:



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.

Emergence of Intelligence

Evolved Virtual Creatures

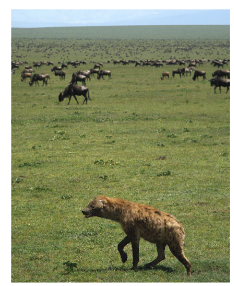
- Neuroevolution of intelligent behavior
- Useful e.g. for video games

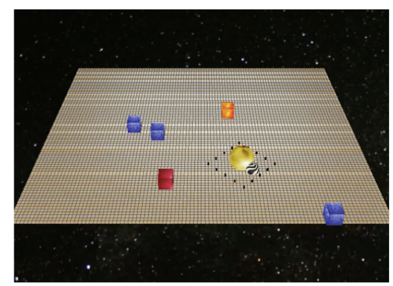
Can such experiments lead to insights in biology?

Collaboration with Kay Holekamp's lab (MSU)

- Studying hyenas in Masai Mara since 1982

Biological Insights from Simulations





In simulation[69,70,71,72]

- 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

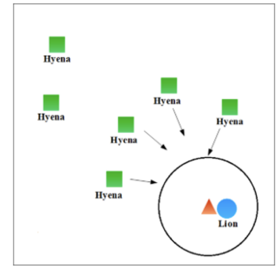
Demo:

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



Lion at a kill, with an interaction circle around it[69]
Ten hyenas chosen and placed randomly in the field
If 4 or more hyenas enter the circle simultaneously, they get the kill

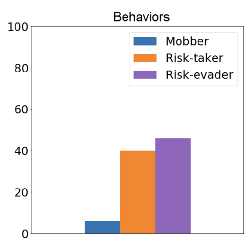
- Otherwise they die

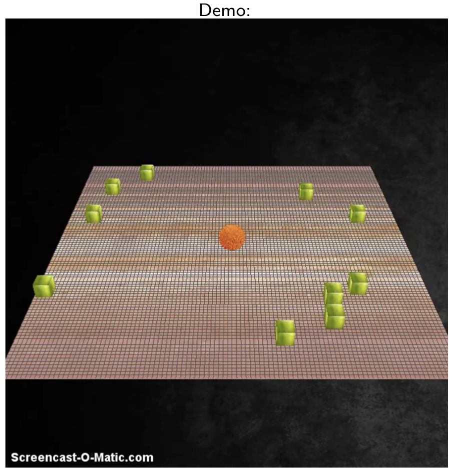
Does mobbing behavior evolve?

- What are the stepping stones for it?

Initial Behaviors

Demo:





Risk evasion is common

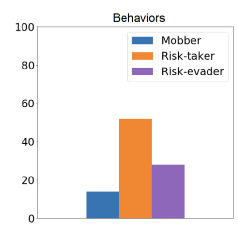
- Never reach the circle; Medium fitness

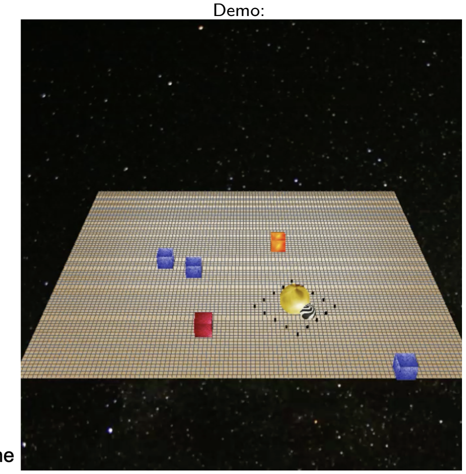
Risk taking is common

- Charge the circle; Frequent low fitness
- Occasional high fitness by accident

Early Behaviors

Demo:



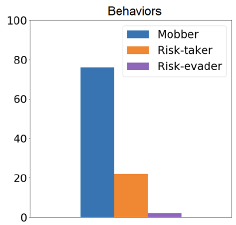


Risk taking grows

- 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

Later Behaviors



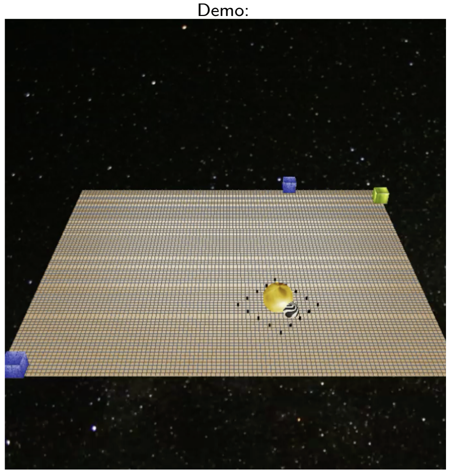
Mobbing emerges

- Not just coincidence of risk takers
- Hyenas wait until there's enough of them

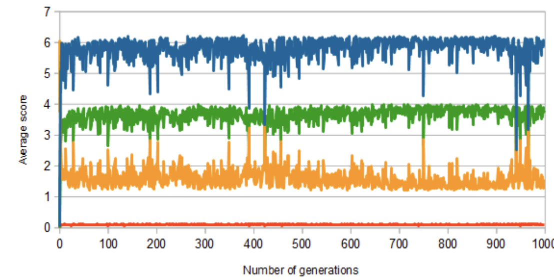
Risk-evaders evolve into latecomers

Simple risk-taking and risk-evasion still exist

Demo:



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

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.

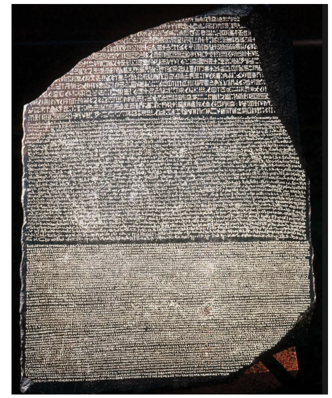
Parallels in Human Behavior

- 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.

S

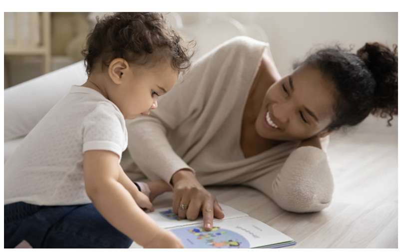
Evolution of Language

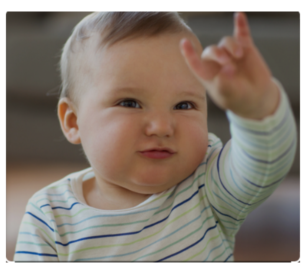
- Language: a major evolutionary transition enabling complex societies.
- Unique to humans: the ability to create infinite meanings from finite symbols.
- Evolution and learning play interconnected roles in the emergence of language.



Biological Basis of Language

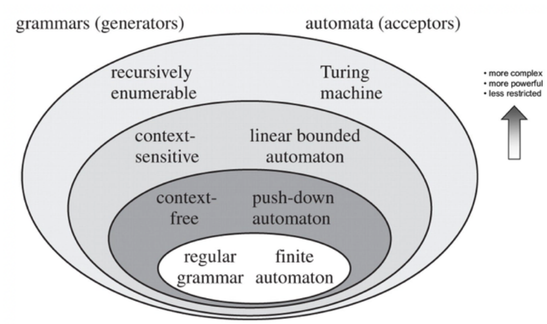
- Genetic predisposition: Language is biologically programmed but learned through interaction.
- Critical period for development: Ages 1-5 are crucial for linguistic input.
- Language emergence in deaf children and pidgin-to-creole transitions illustrate innate capabilities.





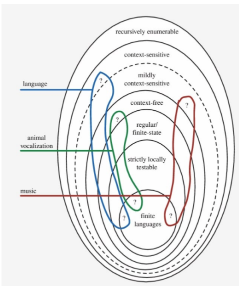
Debate on Language Structure

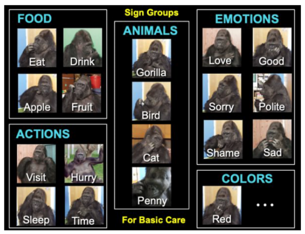
- Chomsky's Universal Grammar: Language structure is genetically coded.
- Modern evidence: Large language models learn language patterns from data without explicit grammar.
- Humans learn language efficiently with far fewer examples than AI, suggesting evolved biases.



Clues from Biology and Other Species

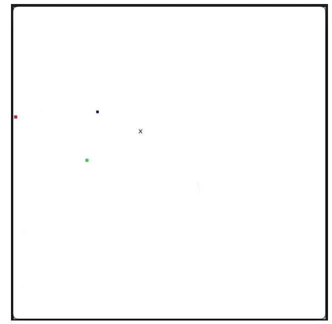
- Early hominids like *Homo erectus* may have had protolanguage abilities.
- Current species (e.g., dolphins, apes) show advanced communication that can be extended with training.
- These behaviors may serve as models for intermediate stages in language evolution.

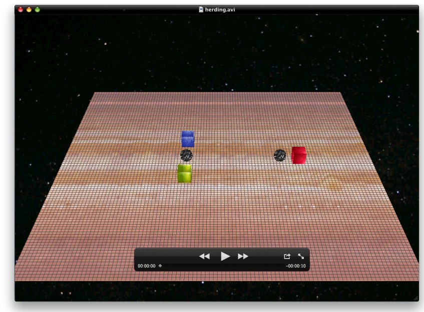




Evolving Communication Codes

- 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.





Origin of Communication: Mating or Hunting?

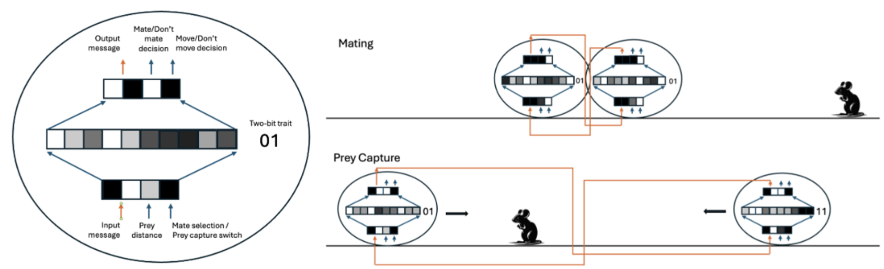
Mate selection important for high-quality offspring
- Often based on visual displays, gestures, vocalizations

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?

Simulating Mating vs. Hunting

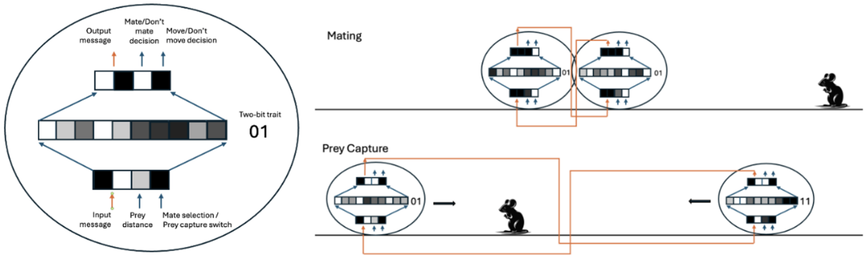


Two tasks (w/switch): mate selection, prey capture
- 2-bit inheritable trait; 2-bit output/input message; sense distance to prey
- Mating successful if compatible traits, both agree to mate
- Hunting success if move on the prey at the same time

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

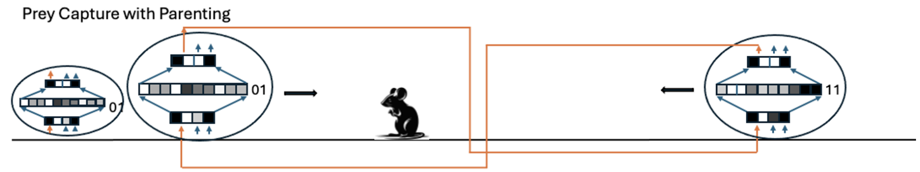
- Evolves faster
- Communication code is simpler: fewer symbols

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!

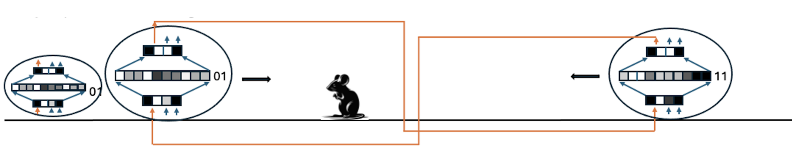
- Paired up to hunt and mate
- Parenting phase: offspring learns through RL
- Adult phase: performance evaluation
- Best adults reproduce

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

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

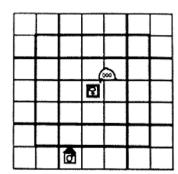


Figure 5.a. Default: "move forward"

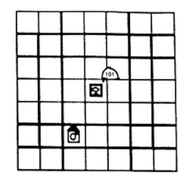


Figure 5.b Female signals "move forward"

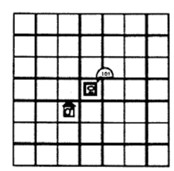


Figure 5.c. Female signals "forward".

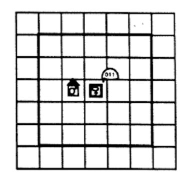


Figure 5.d. Female signals "turn right"

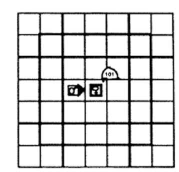
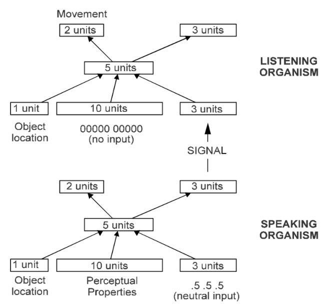


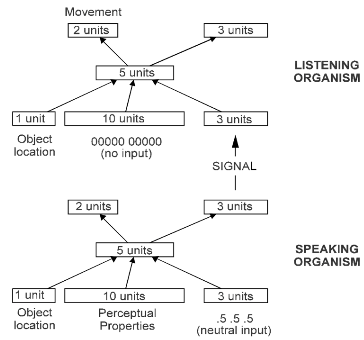
Figure 5.e. Female signals "move forward."

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?

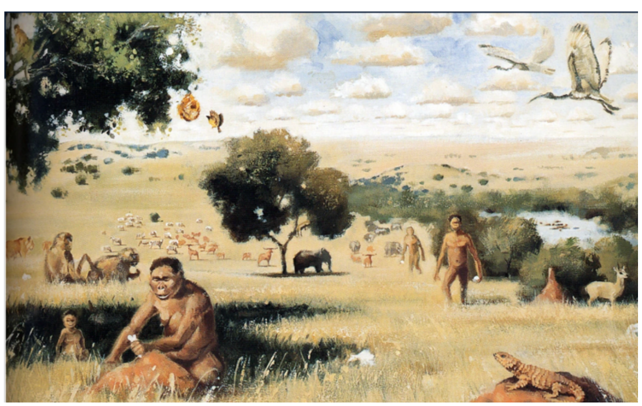
E.g. world with edible and poisonous mushrooms

- 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.

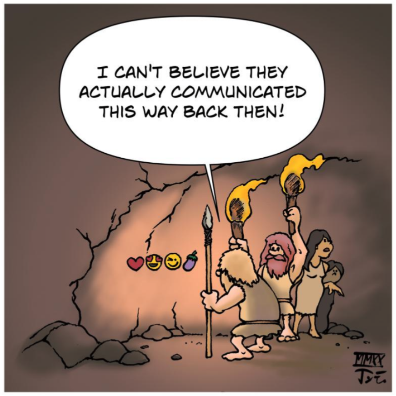


The Role of Social Complexity

- 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).

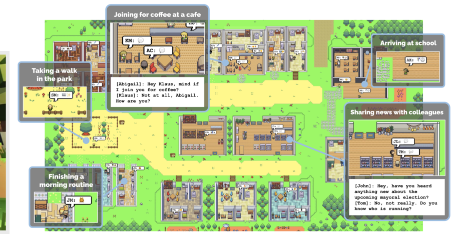
Symbolic Culture and Language

- Language may have co-evolved with symbolic culture.
- Evidence from early art and symbolic artifacts suggests abstract thinking and communication.
- Then again, we don't really know.



Computational Simulations of Language Evolution

- Modern computing power enables complex simulations of language evolution.
- Neuroevolution can simulate environments with cognitive and social constraints.
- Incremental simulations can shed light on how linguistic structures emerge.



Concluding Insights on Neuroevolution and Biology

- **Neuroevolution as a Tool for Insight:**
  - Demonstrates how neural structures and behaviors evolve under constraints.
  - Helps understand the interplay of evolution, learning, and the environment.
- **Key Successes:**
  - Simulated evolution of cooperation, role differentiation, and team dynamics.
  - Insights into circuitry, synergetic development, optimization under constraints.
  - Insights into the emergence of intelligence and the origins of communication.
- **Future Opportunities:**
  - Identifying constraints that lead to observed circuitry and behaviors.
  - The emergence of structured language and cognitive constraints.
  - Simulating major evolutionary transitions, including symbolic culture and social complexity.