Non-Adaptive Evolvability

Jeff Clune
Assistant Professor
Computer Science

Evolving Artificial Intelligence Laboratory
Evolution Fails to Optimize Mutation Rates
(though it would improve evolvability)

Evolution Fails to Produce Modularity For Adaptive Reasons
(though it would improve evolvability)
Part I: Mutation Rates

- natural selection is short-sighted
- a non-low mutation rate
  - good in the long-term
  - bad in the short term
Mutation Rates

- Key driver of evolvability

- Optimized?
  - (for long-term adaptation)
Experimental Design

- Identify the optimum
  - evolve organisms with different, fixed (non-evolving) mutation rates in new environment
Experimental Design

- Identify the optimum
  - evolve organisms with different, fixed (non-evolving) mutation rates in new environment

- Does evolution produce the optimum?
  - allow mutation rates to evolve
  - start well below and well above the optimum

![Fitness vs Mutation Rate Graph](image.png)
System

- computational evolution
- Avida
  - well-studied
    - Lenski et al. Nature 1999
    - Adami et al. PNAS 2000
    - Wilke et al. Nature 2001
    - Chow et al. Science 2004
    - etc.
  - population of self-replicating digital organisms
Avida Organisms

- genome: list of computer instructions
- phenotype: execution of instructions with virtual hardware

Lenski et al. Nature 2003
Fitness

- limited space (overwrite neighbors)
- faster replication = more offspring
- extra energy = faster replication
  - traditional: 9 logic tasks (Lenski et al. 2003)
Experiments

• sweep range of fixed mutation rates
• allow mutation rates to evolve
Evolved Mutation Rates Less Fit

- natural selection fails to optimize for long-term
- ...in a complex fitness landscape (Avida default)
Hypothesis

Ruggedness of fitness landscape?

X (low mutation rate): higher avg. fitness

Y (high mutation rate): lower avg. fitness
Simplified Avida Environment

Season 0

Season 1
Simplified Avida Environment

Season 0

Season 1

fitness

number of ones

number of ones
- Optimized on smooth landscapes
- Not optimized when ruggedness above threshold
- Valley is crossed many times, but any delay = self-reinforcement
Same Results with Different...

- implementations of mutation rate evolution
  - size of changes
  - frequency of changes
  - increases more likely
  - self-reflexive

- environments
  - complexity
  - static vs. changing
  - rate of change

- ancestors
Part I: Evolvability
Conclusions

• natural selection fails to optimize mutation rates for long-term adaptation on rugged fitness landscapes
• i.e. natural selection is short-sighted
  • sounds obvious, but many disagree!
Part II

Evolutionary Origins of Modularity

Jeff Clune
University of Wyoming

Jean-Baptiste Mouret
Marie Curie University
Paris, France

Hod Lipson
Cornell University

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Modularity

- Localization of function in an encapsulated unit (Lipson 2007)
  - Car (spark plug, muffler, wheel), bodies (organs), software, etc.
- Enables increased
  - Complexity
  - Adaptability
Modularity: Major driver of Evolvability

- For the same reasons as in engineering
  - reuse building blocks in new combinations
  - tinker with one module without affecting everything
Modularity

- Rare in current neuroevolution
  - Suggests selection on performance alone does not produce modularity

*Kashtan and Alon 2005*
Why did modularity evolve?

- Leading Hypothesis: Selection for evolvability
- We provide evidence for a new force:
  - Selection to minimize connection costs
Minimizing Connection Costs

- Hypothesis from founding neuroscientist (Ramón y Cajal 1899)
  - There are costs in biological networks
  - Evidence that selection acts to minimize costs
- Test by evolving neural networks
- Why?
  - answer longstanding, fundamental biological question
  - harness for artificial intelligence
Retina Problem

object on left side? (L)

object on right side? (R)

object on both sides? (L&R:)

Kashtan and Alon. PNAS. 2005
Summary

- Performance Alone (PA)
- Performance & Connection Costs (P&CC)

Clune, Mouret, & Lipson. 2013. Proceedings of the Royal Society
• P&CC significantly more modular, higher-performing \((p < 0.0001)\)
• Perfect decomposition in 56\% of P&CC, never for PA \((p < 0.0001)\)

Clune, Mouret, & Lipson. 2013. Proceedings of the Royal Society
Why?

- **New technique: MOLE map**
  - Multi-Objective Landscape Exploration


Performance Alone (PA)

Performance & Connection Costs (P&CC)
More evolvable?

• Evolved in one environment, transfer to another
  • L-AND-R $\rightarrow$ L-OR-R
  • L-OR-R $\rightarrow$ L-AND-R
• Ran extra trials until 50 had perfect networks

P&CC significantly more evolvable

P&CC < PA (p < 0.0001)

Evolve modularity to reduce connection costs, which happens to help because of problem-modularity

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• Modularity forces can combine
• P&CC less sensitive to rate of environmental change
  • P&CC >= MVG at its strongest
A Non-Modular Problem

Exactly 4 black pixels?

Performance

Modularity ($Q$)

B Multiple, Separable Problems

XOR XOR XOR XOR XOR

Performance

Modularity ($Q$)

C Hierarchical, Separable Problems

XOR XOR XOR XOR

Performance

Modularity ($Q$)
Modularity Improves Learning

Performance and Connection Cost (P&CC)

CC minimizes “catastrophic forgetting”

Ellefsen & Clune, In prep.
Biological Implications

- May be a major explanatory force behind evolved modularity
- May bootstrap evolvability explanations
  - initial modularity due to connection costs
  - indirect selection for evolvability takes over

Neuroevolution Implications

- Adding a cost increased
  - performance
  - modularity
  - evolvability

- Could be powerful technique for evolutionary algorithms
Non-Adaptive Evolvability

• Evolution fails to evolve optimal mutation rates
  • any evolvability likely due to cost of fidelity

• Evolution fails to evolve modularity
  • any evolvability likely due to connection costs

• How many other cases of evolvability are non-adaptive?
  • converse: how many examples of evolvability do we know are adaptive?
Non-Adaptive Evolvability

Thanks!

- Evolution fails to evolve optimal mutation rates
  - any evolvability likely due to cost of fidelity
- Evolution fails to evolve modularity
  - any evolvability likely due to connection costs
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Avida Organisms

- self replicate
Minimizing Connection Costs

- Many studies suggest overall wire length in brains and nervous systems are minimized
  - Most connections in brains are short
  - Most nodes are not connected
  - Neuron placement optimized to reduce wire length

- Primary reason may be *connection costs*
  - clear in networks with physical connections (neural)
    - building, maintenance, energy to use, signal delays, weight, etc.
  - may also exist in other networks (e.g. genetic regulatory)
    - slow replication, slow regulation, added constraints