Non-Adaptive Evolvability

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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

2008 PLoS COMPUTATIONAL BIOLOGY

Natural Selection Fails to Optimize Mutation Rates for Long-Term Adaptation on Rugged Fitness Landscapes

Jeff Clune[1,2*], Dusan Misevic[3], Charles Ofria[1], Richard E. Lenski[4], Santiago F. Elena[2,5], Rafael Sanjuán[2,6]

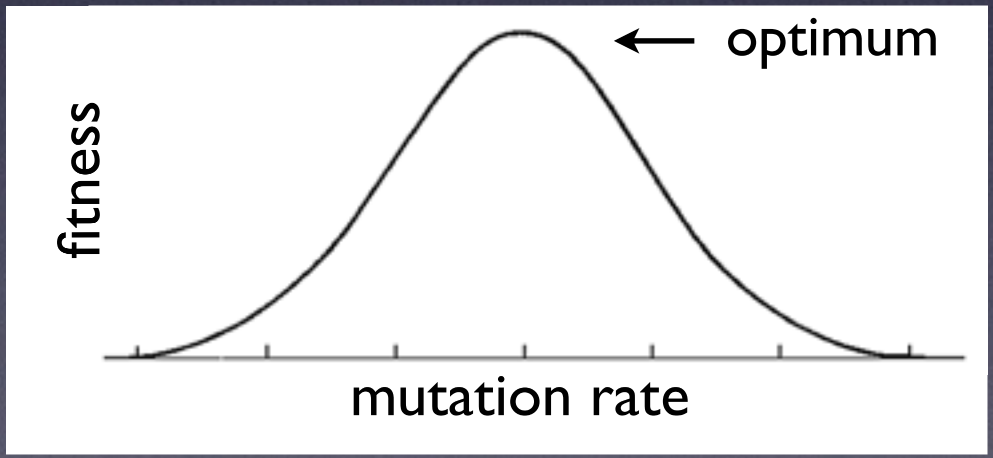
- natural selection is short-sighted
- a non-low mutation rate
  - good in the long-term
  - bad in the short term

Mutation Rates

- Key driver of evolvability
- Optimized?
  - (for long-term adaptation)

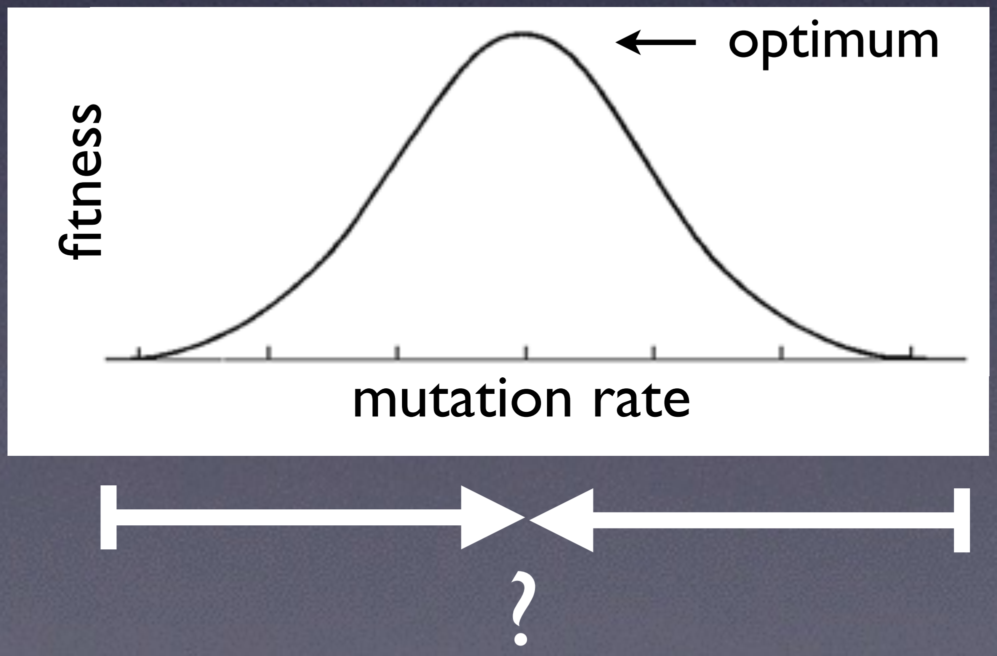
Experimental Design

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



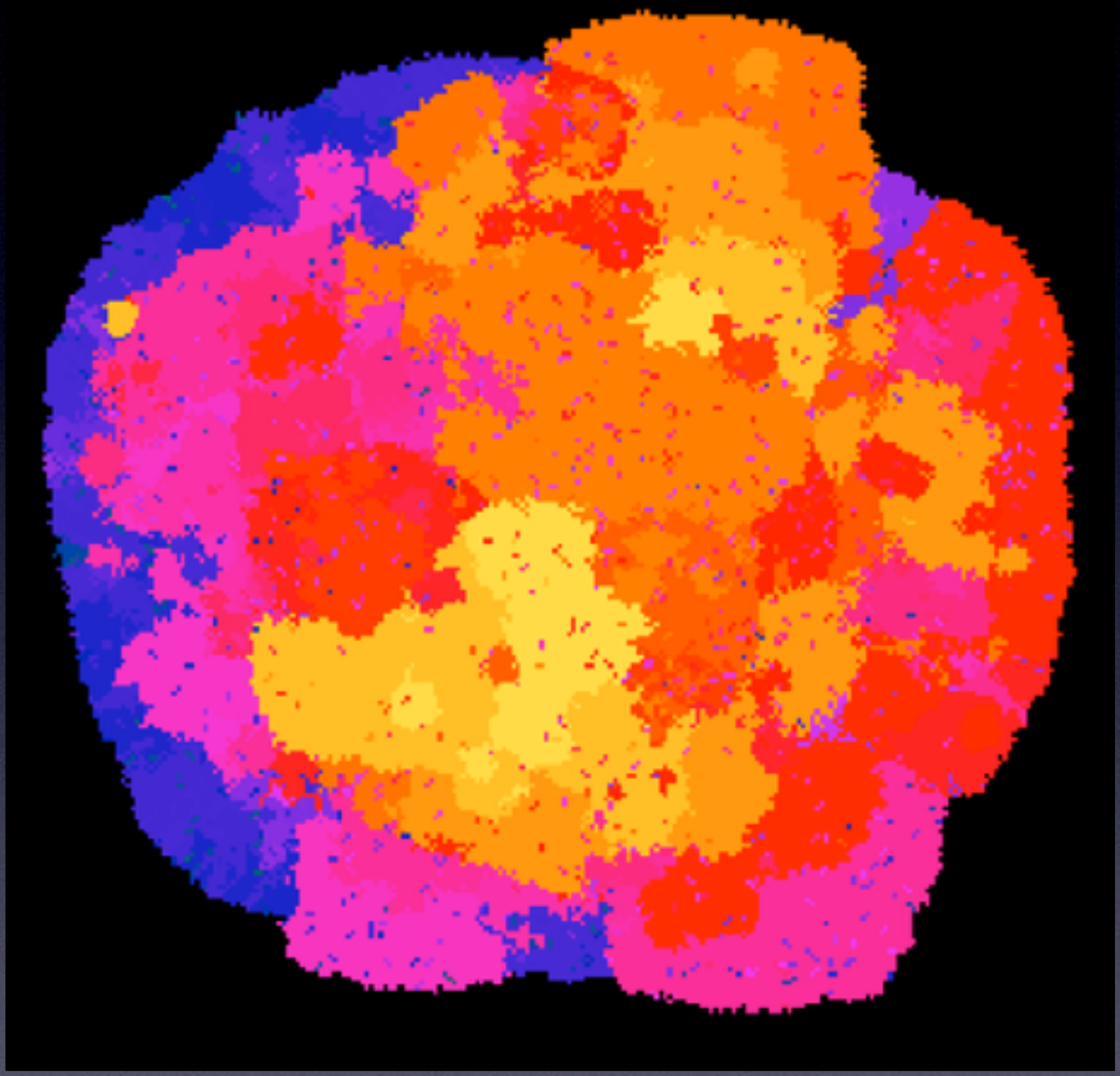
Experimental Design

- 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



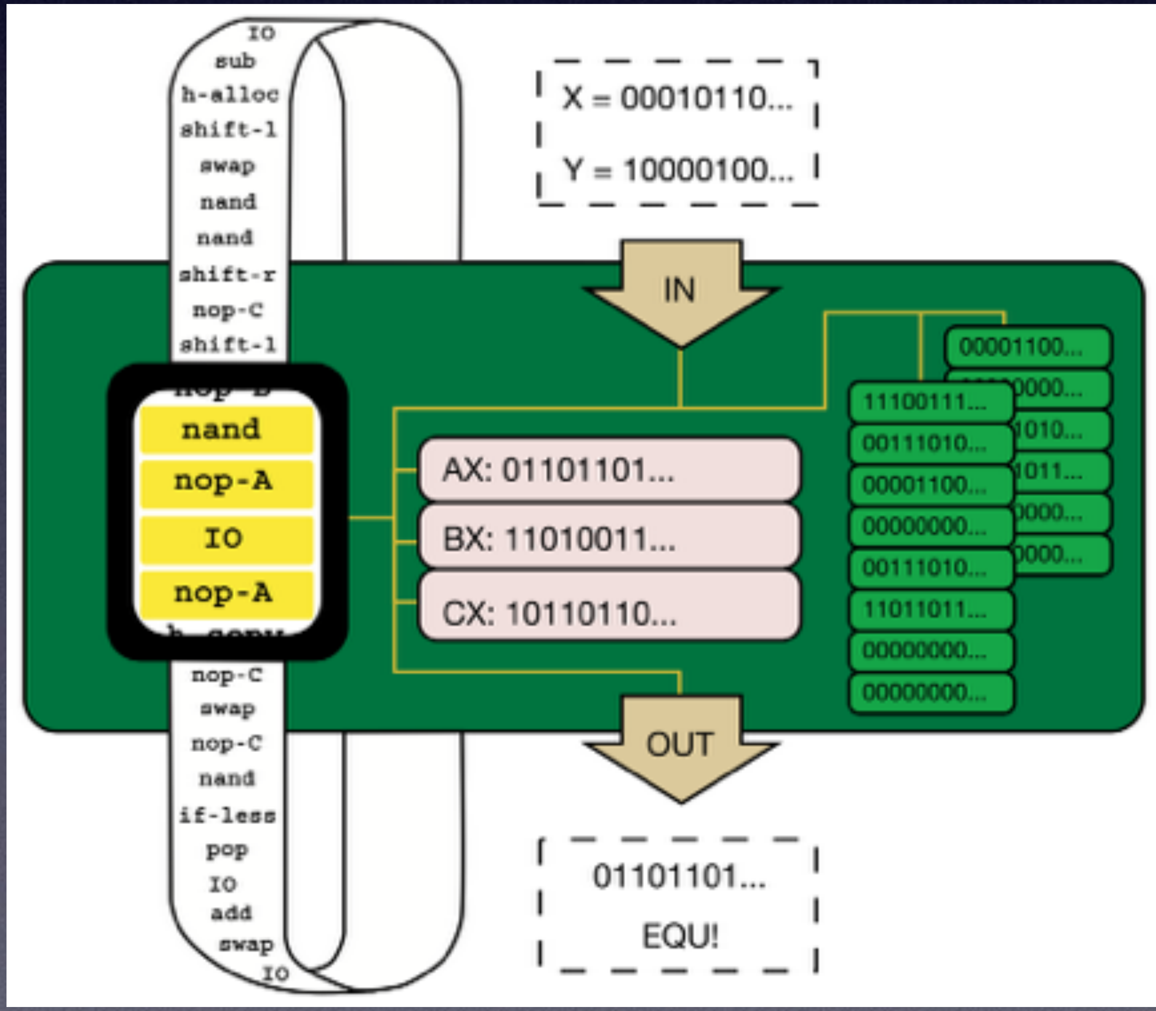
System

- computational evolution
- Avida
  - well-studied
    - Lenski et al. Nature 2003
    - 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

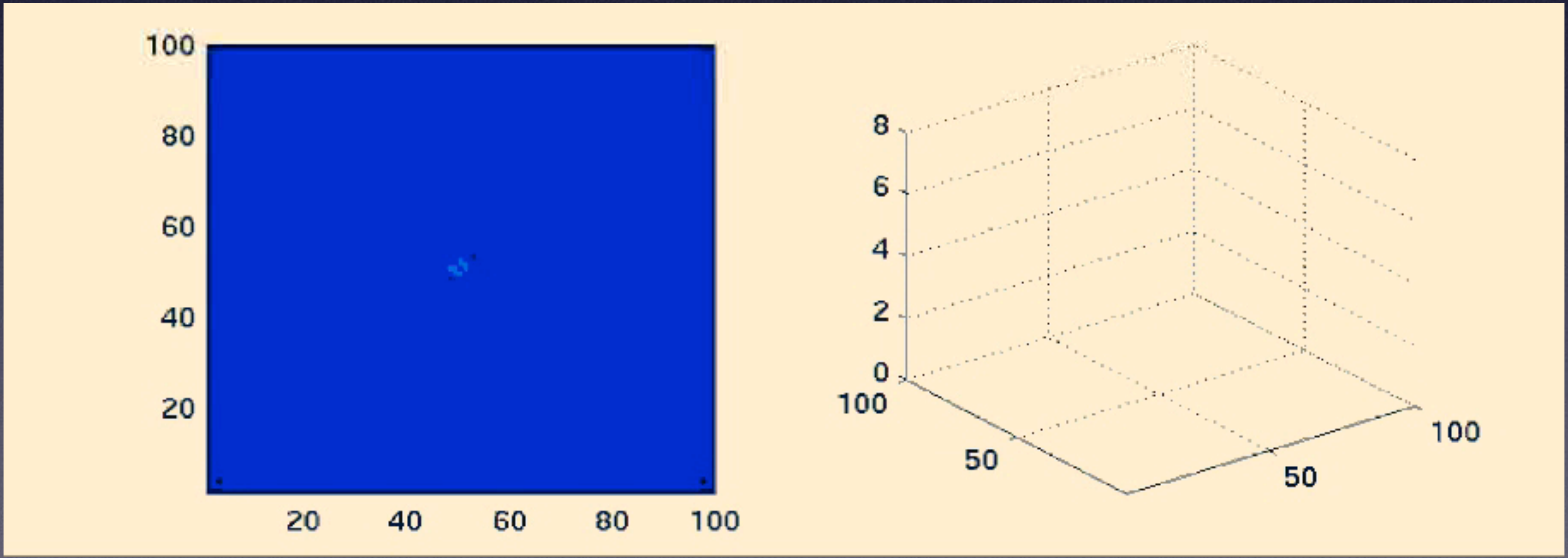
- genome: list of computer instructions
- phenotype: execution of instructions with virtual hardware



Lenski et al. Nature 2003

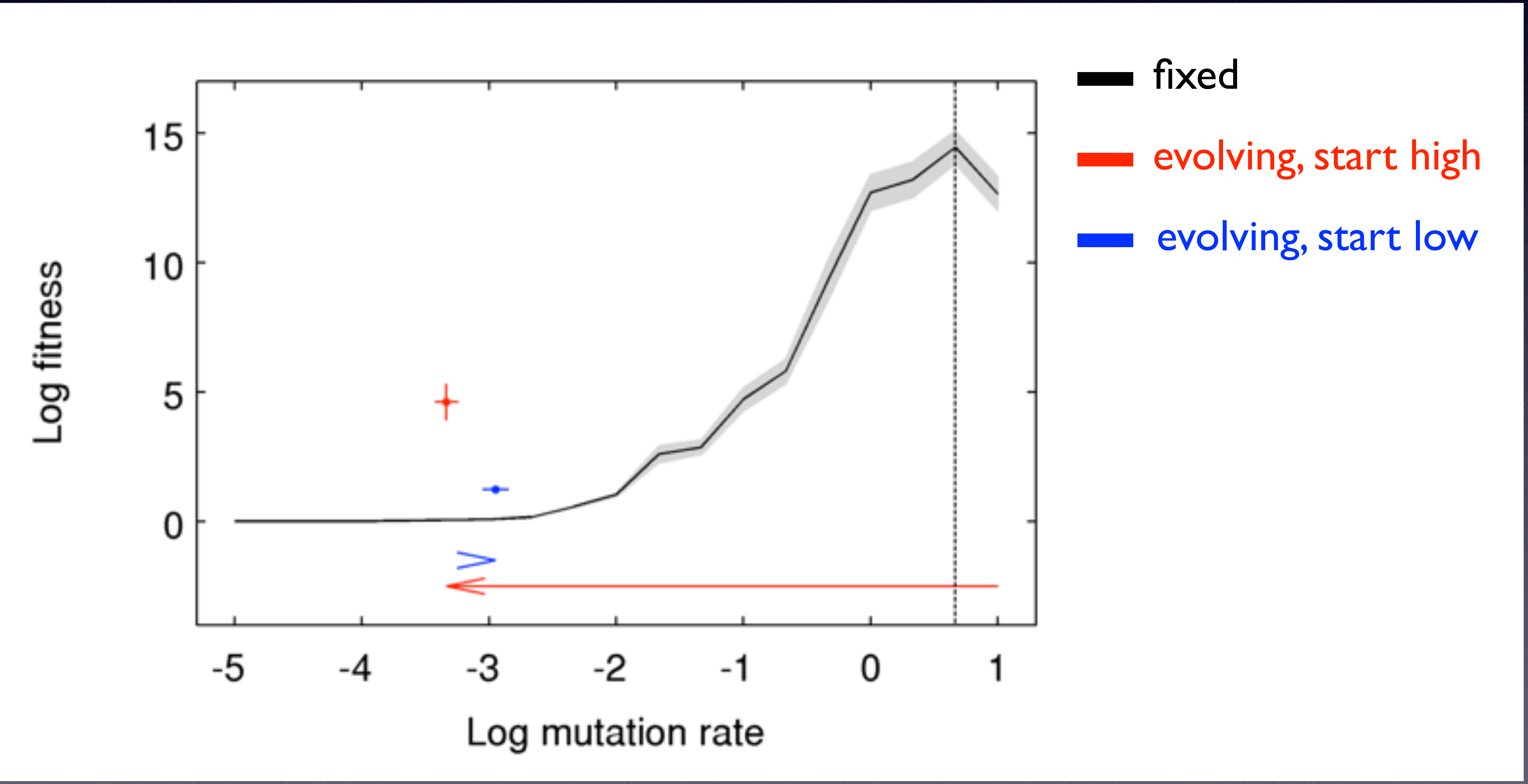
Fitness

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

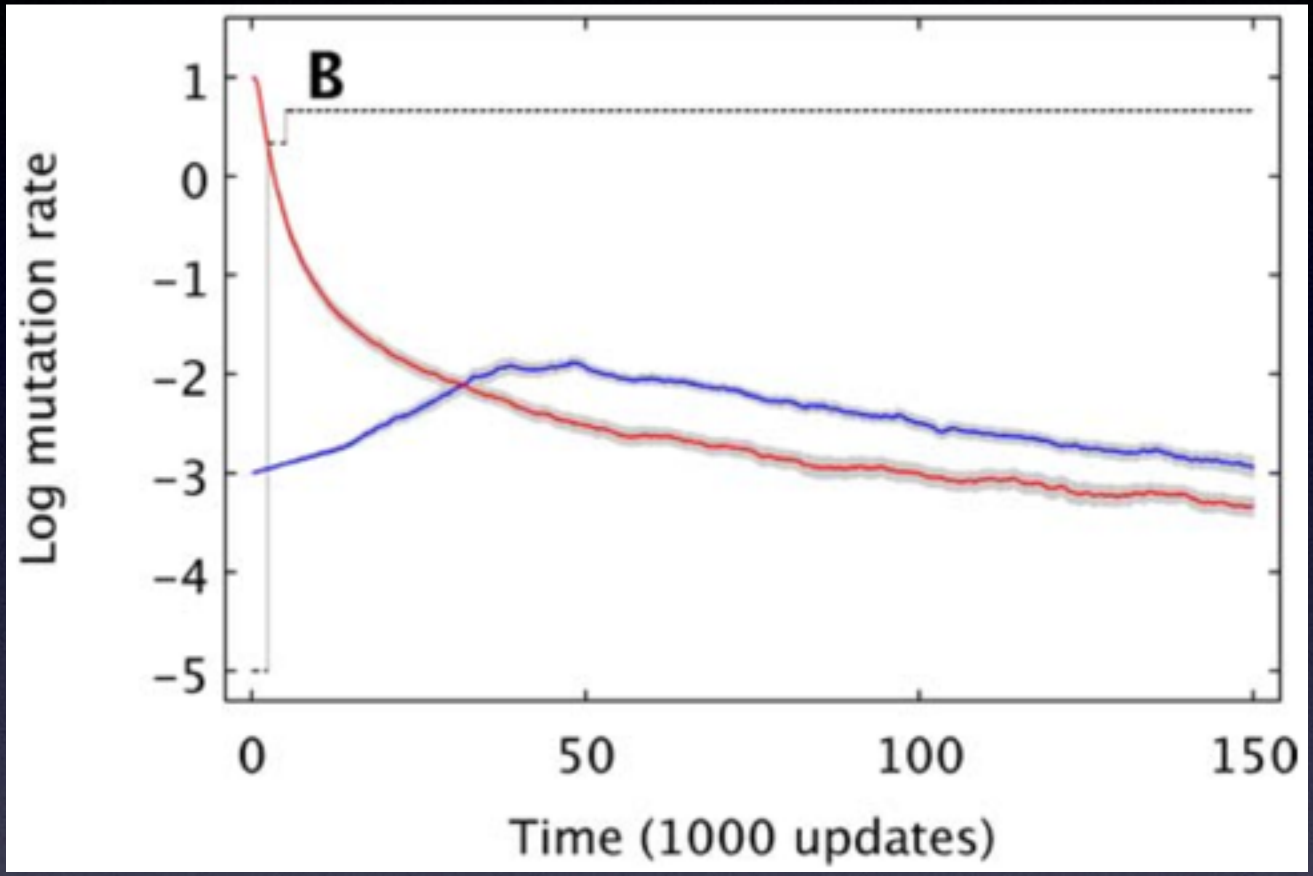


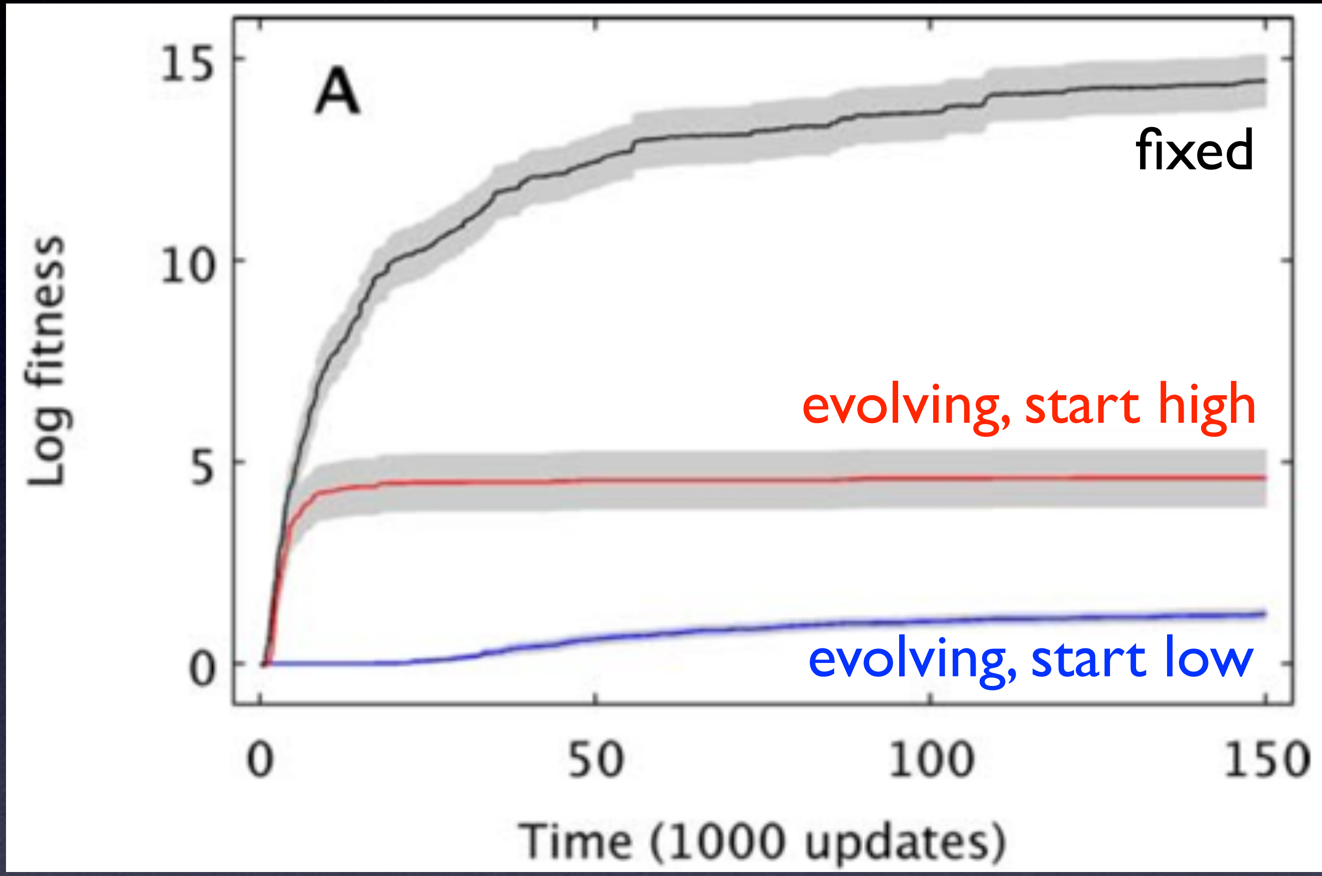
Experiments

- sweep range of fixed mutation rates
- allow mutation rates to evolve



Evolved Mutation Rates Less Fit

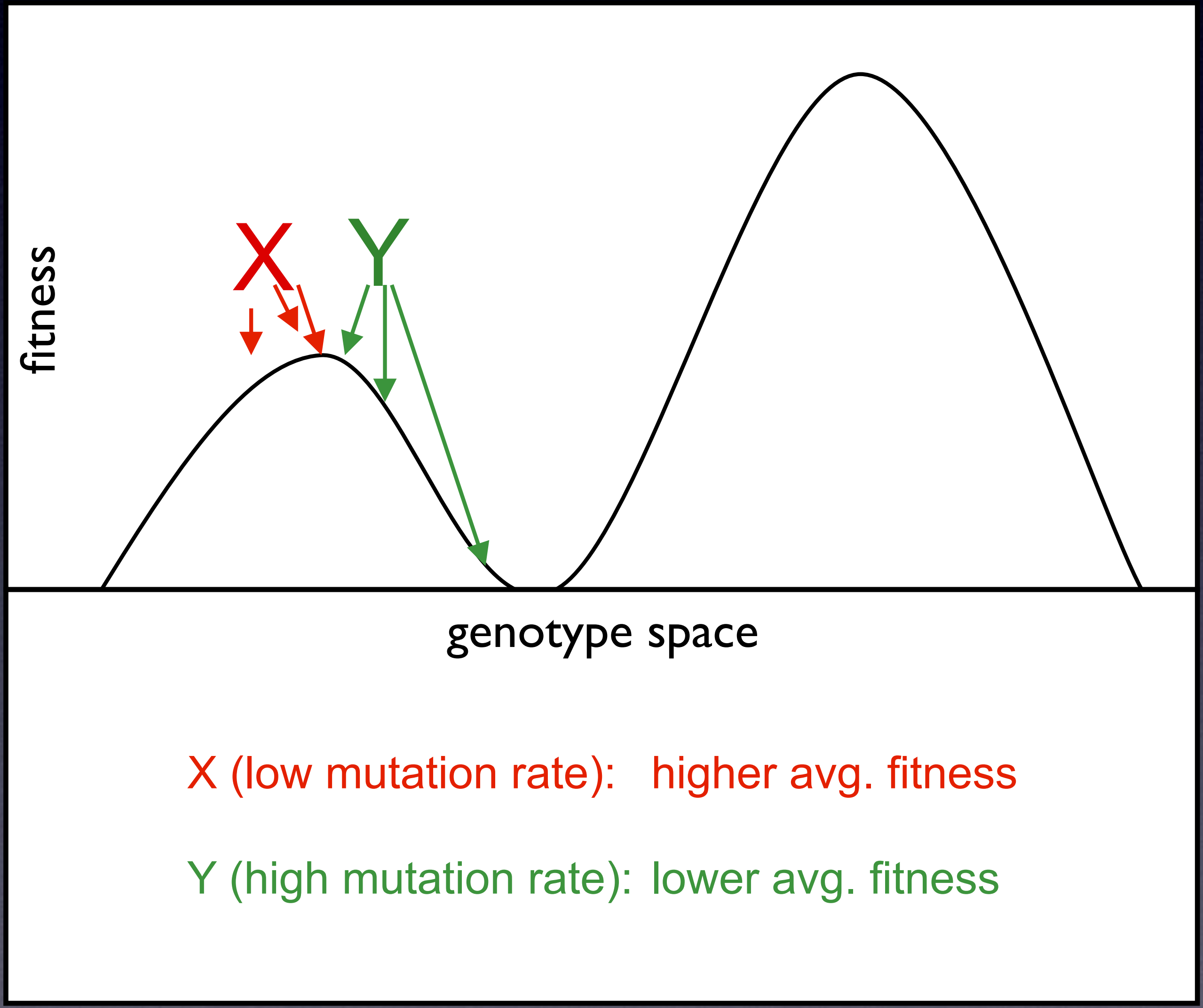




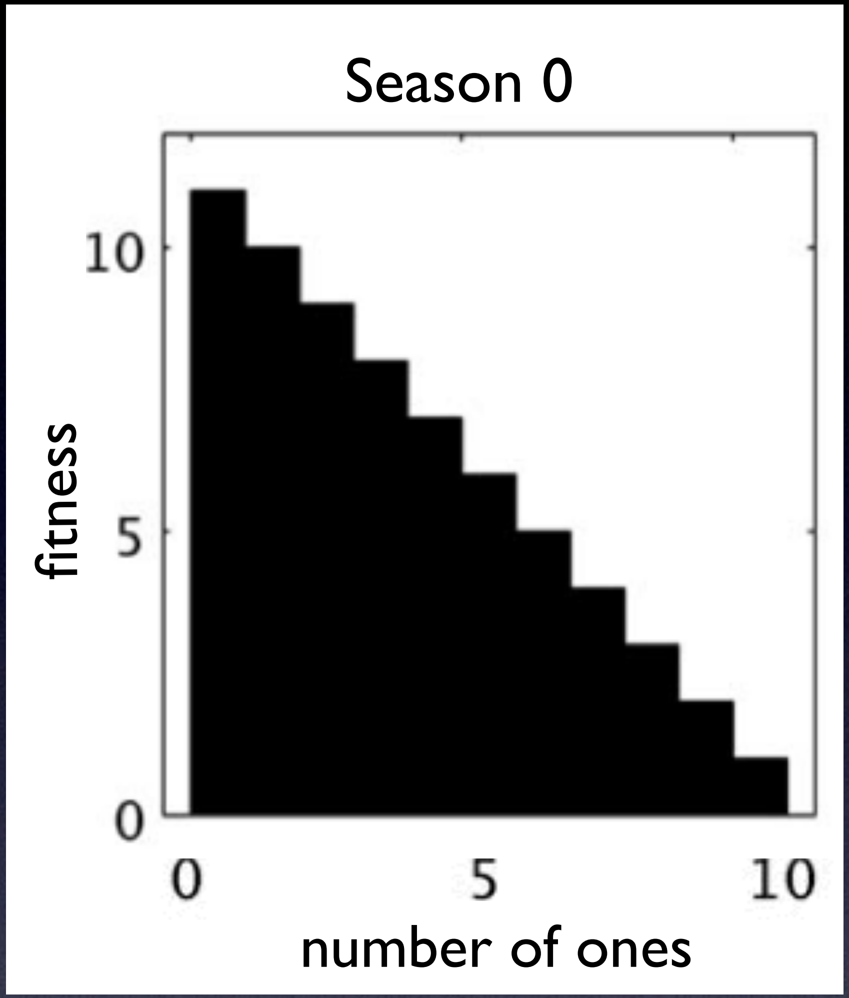
- natural selection fails to optimize for long-term
- ...in a complex fitness landscape (Avida default)

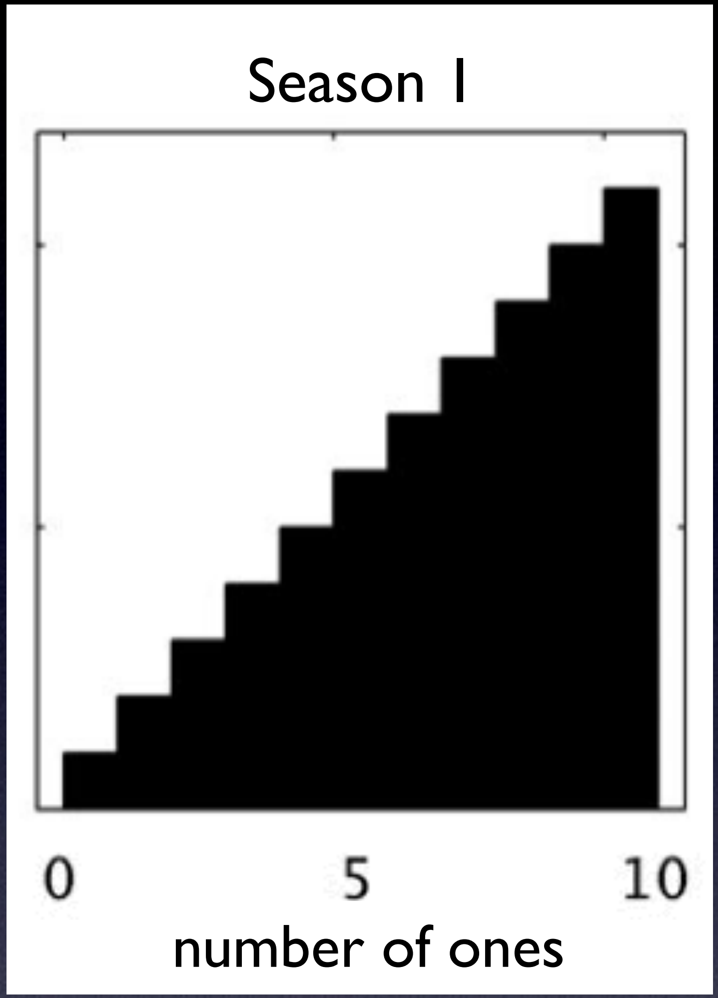
Hypothesis

Ruggedness of fitness landscape?



Simplified Avida Environment





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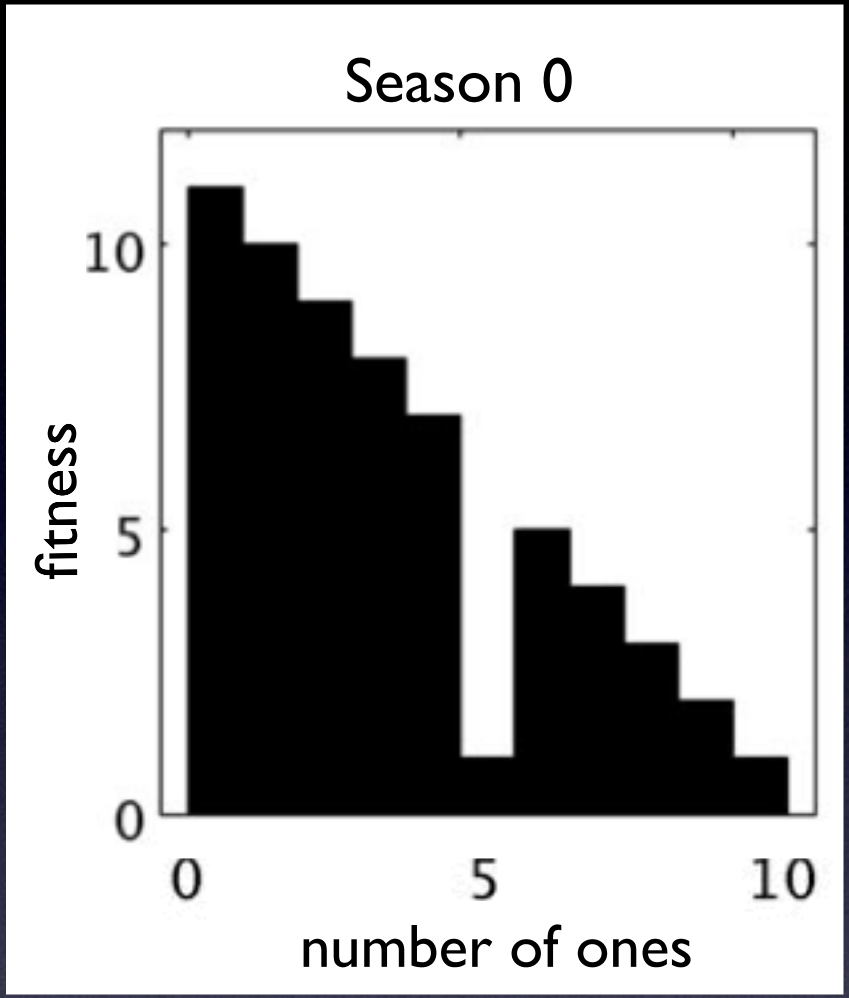

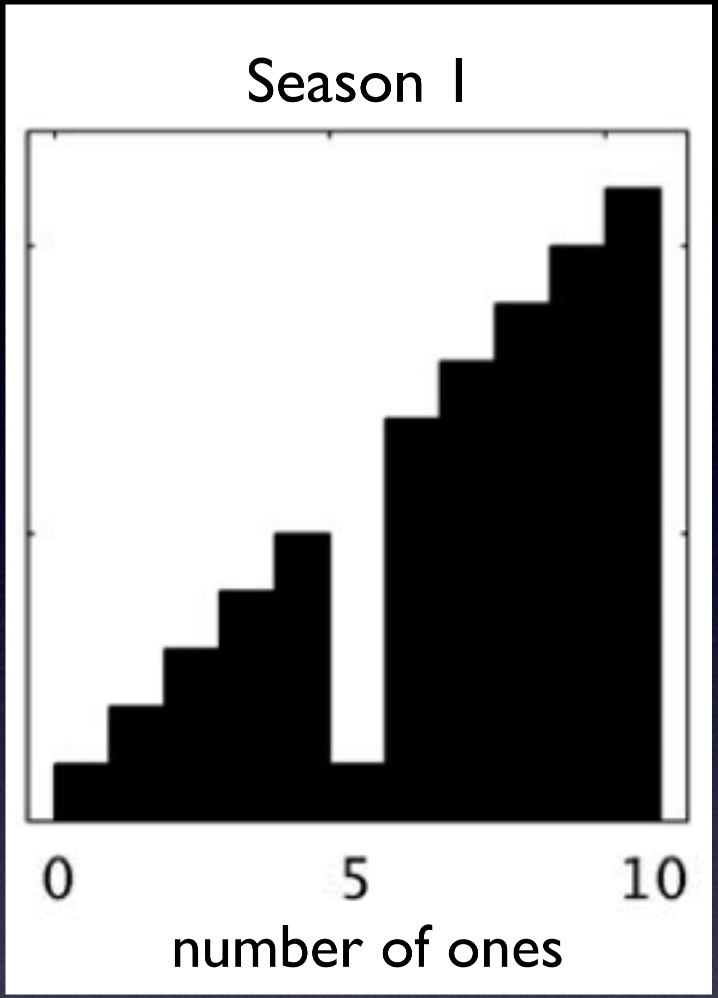

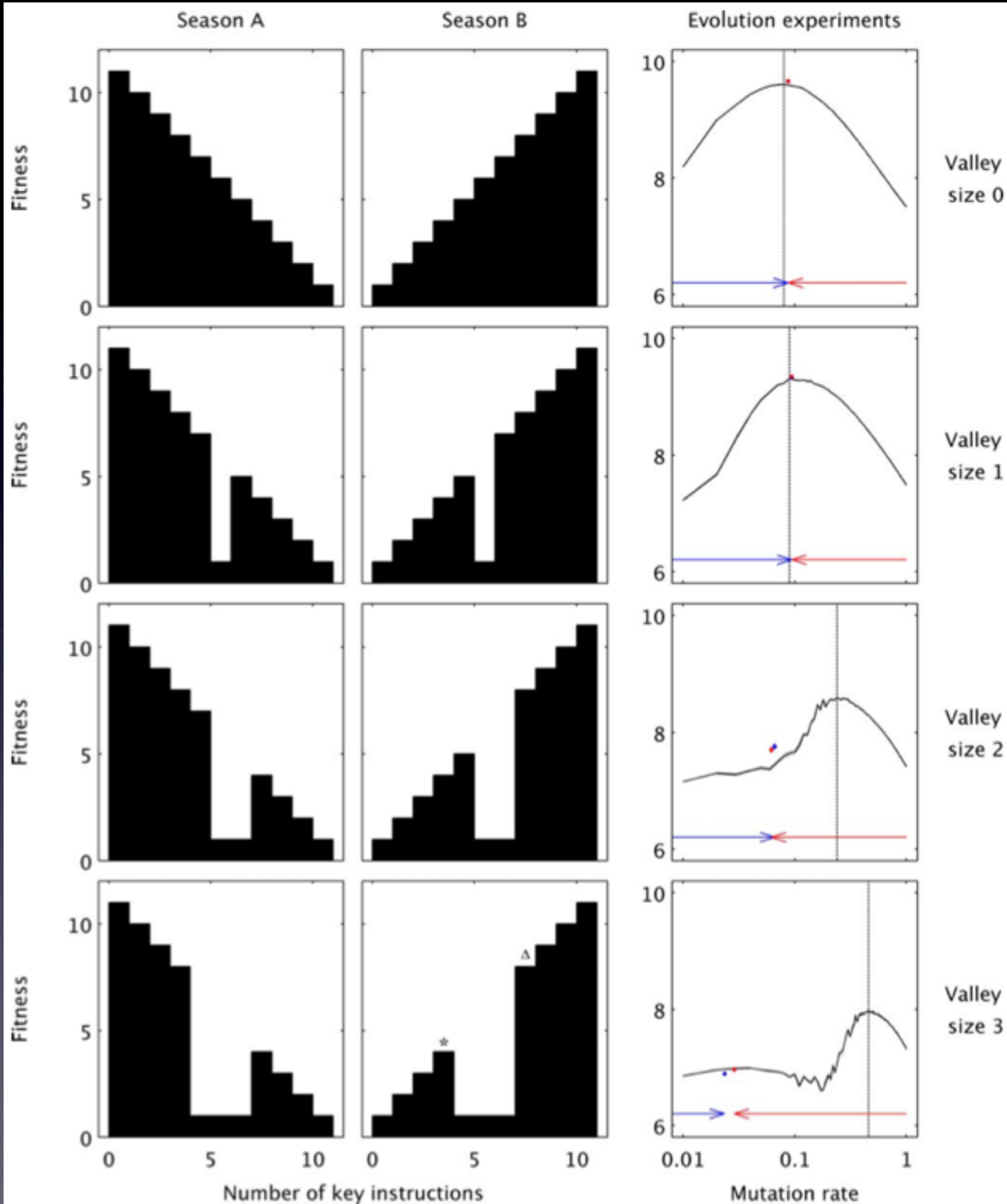

- Optimized on smooth landscapes
- Not optimized when ruggedness above threshold
- Valley is crossed many times, but any delay = self-reinforcement

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

PROCEEDINGS OF THE ROYAL SOCIETY

2013

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Jean-Baptiste Mouret

Marie Curie University
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Cornell University

Funding: NSF Postdoctoral Research Fellowship in Biology

Modularity

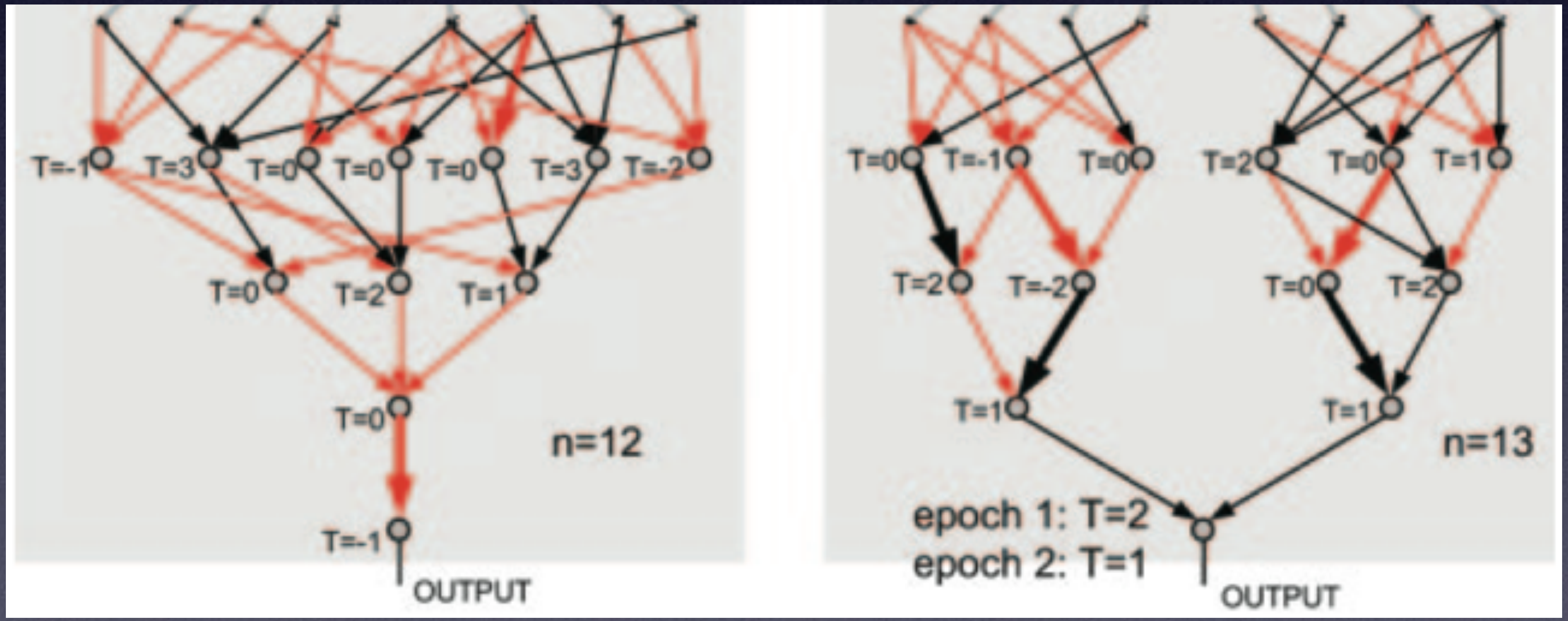
- Localization of function in an encapsulated unit (Lipson 2007)
  - Car (spark plug, muffler, wheel), bodies (organs), software, etc.
- Enables increased
  - Complexity
  - Adaptability

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

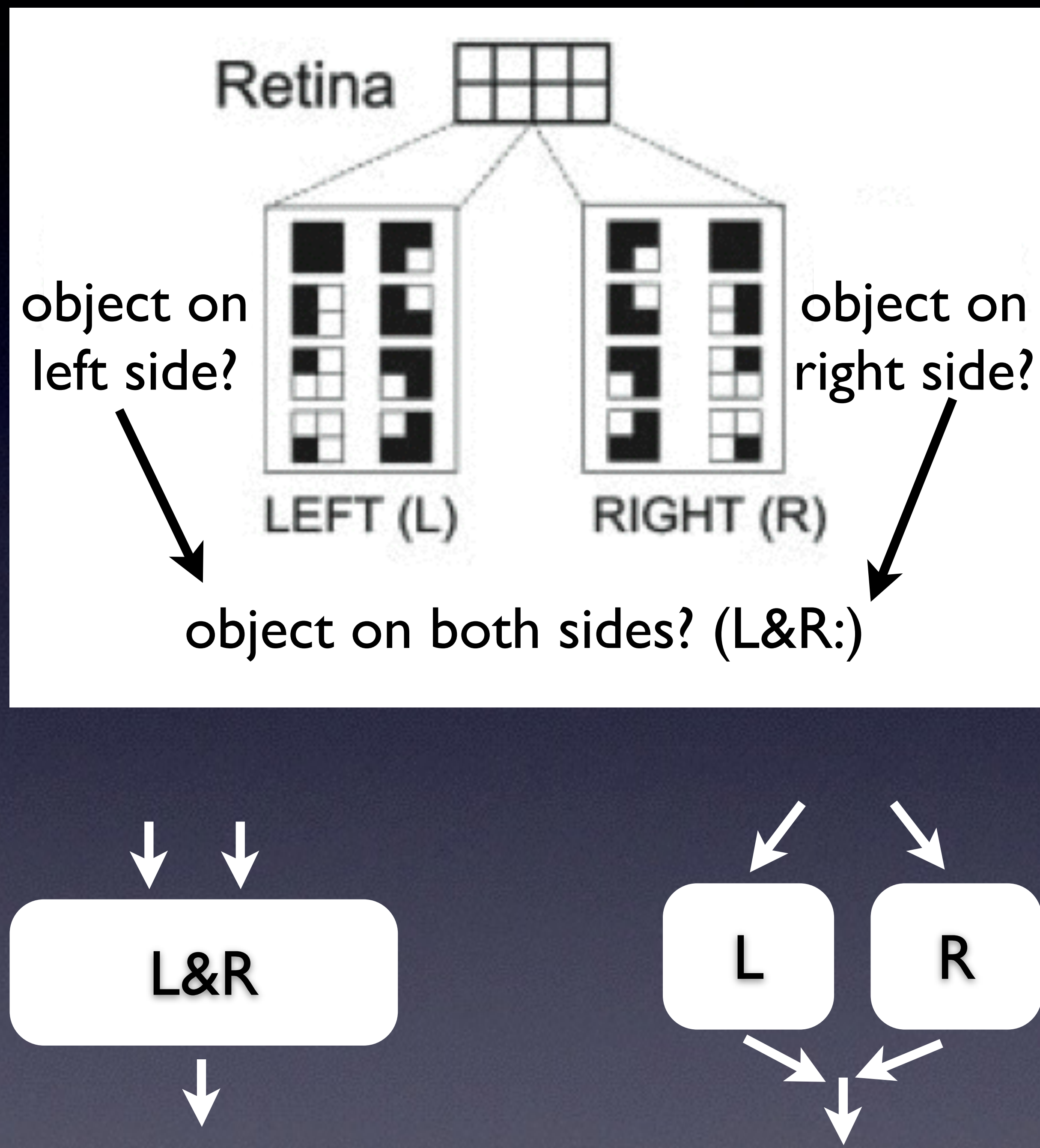
Why did modularity evolve?

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

Minimizing Connection Costs

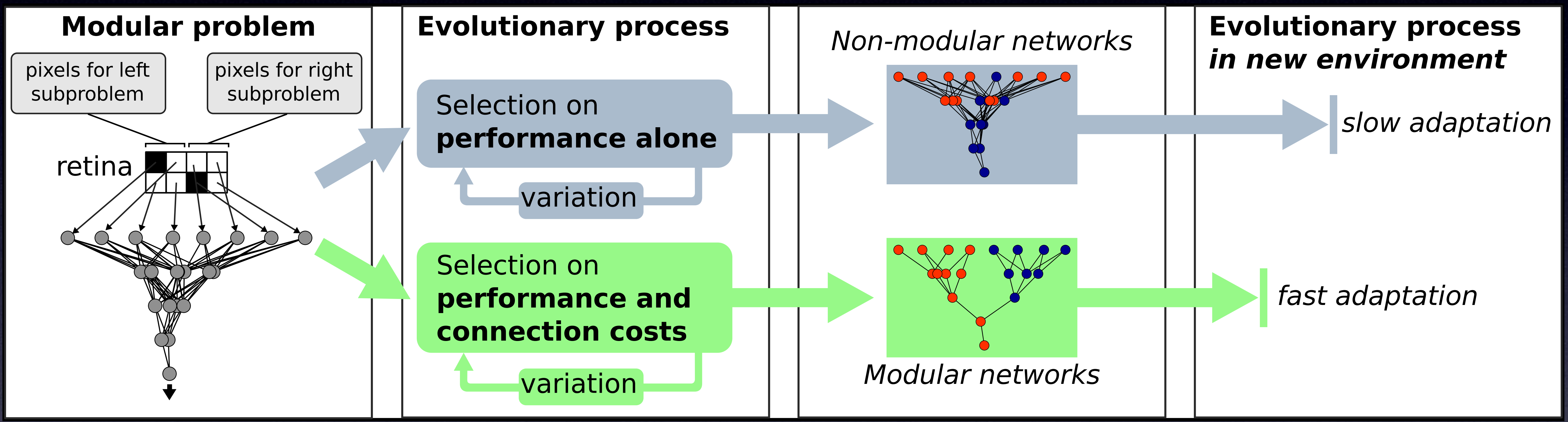
- Hypothesis from founding neuroscientist (Ramón y Cajal 1899)
  - There are costs in biological networks
  - Evidence that selection acts to minimize costs
- Test by evolving neural networks
- Why?
  - answer longstanding, fundamental biological question
  - harness for artificial intelligence

Retina Problem



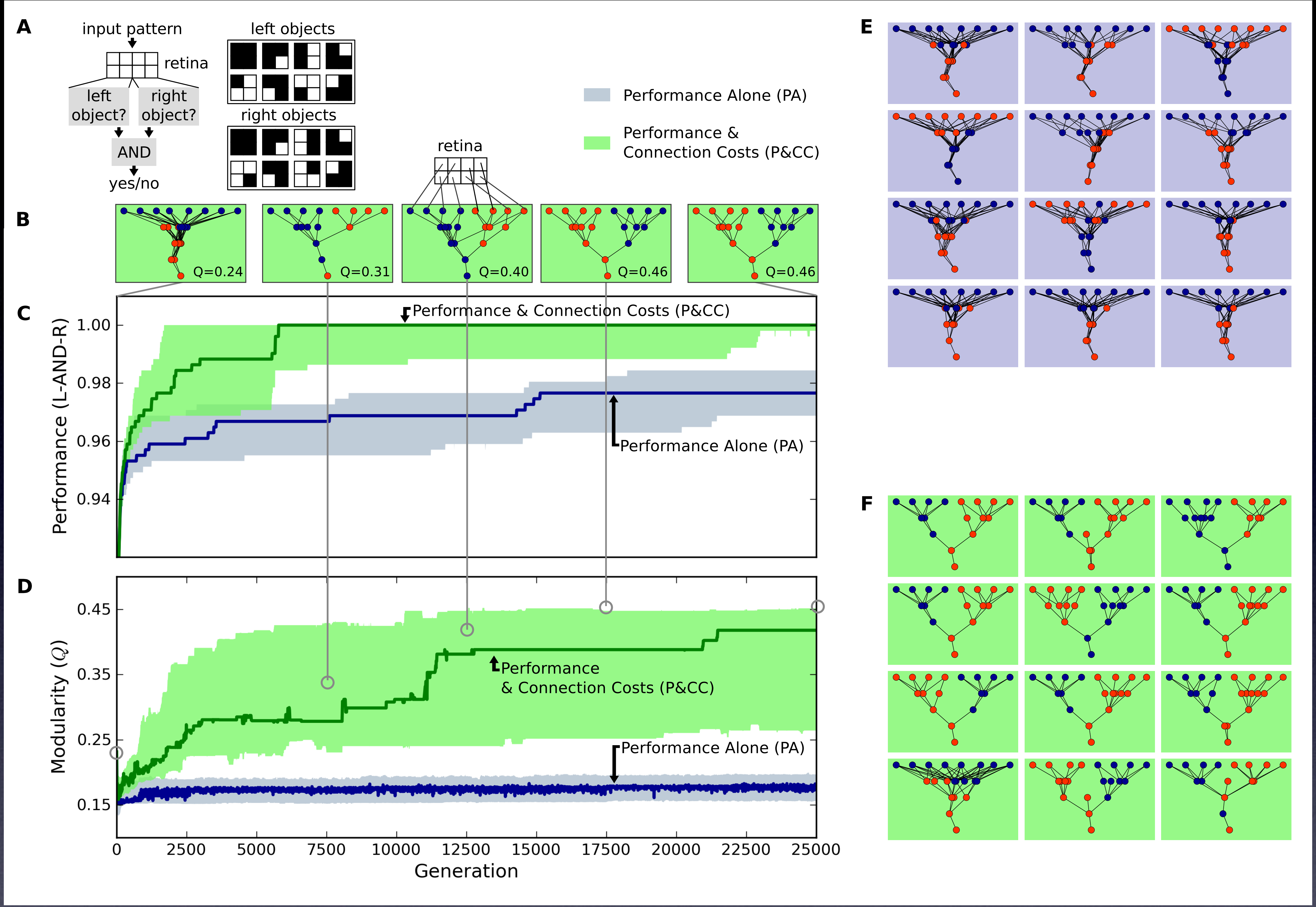
Kashtan and Alon. PNAS. 2005

Summary



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

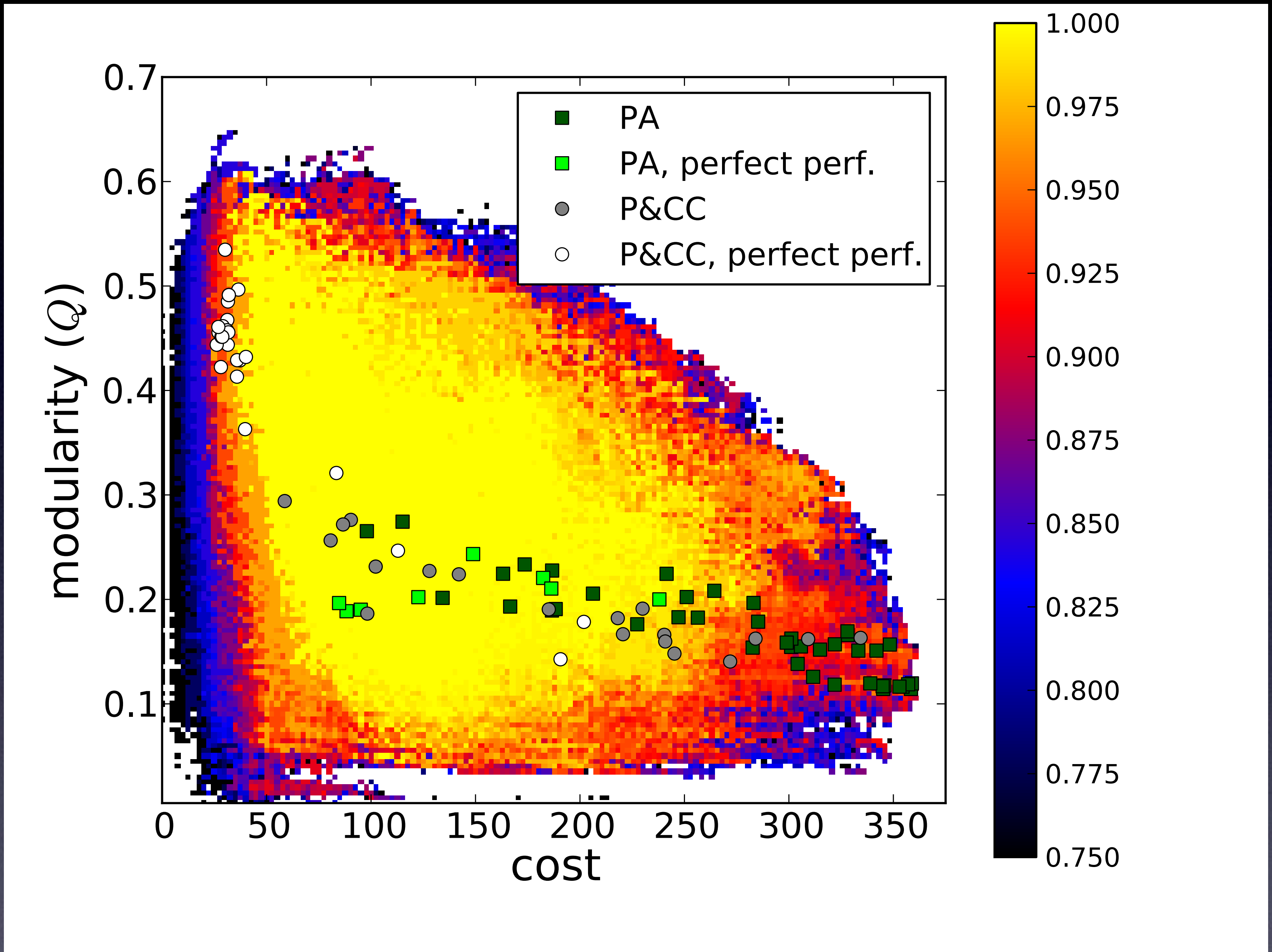
Clune, Mouret, & Lipson. 2013. Proceedings of the Royal Society



- P&CC significantly more modular, higher-performing ($p < 0.0001$)
- Perfect decomposition in 56% of P&CC, never for PA ($p < 0.0001$)

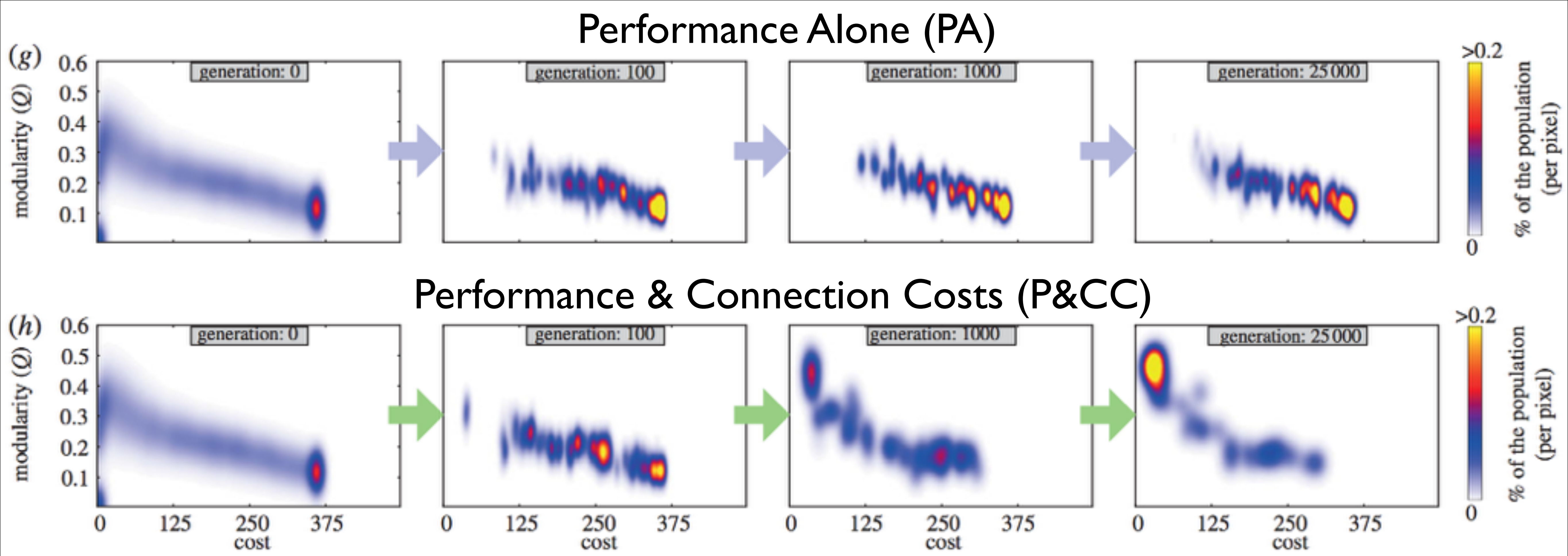
Clune, Mouret, & Lipson. 2013. Proceedings of the Royal Society

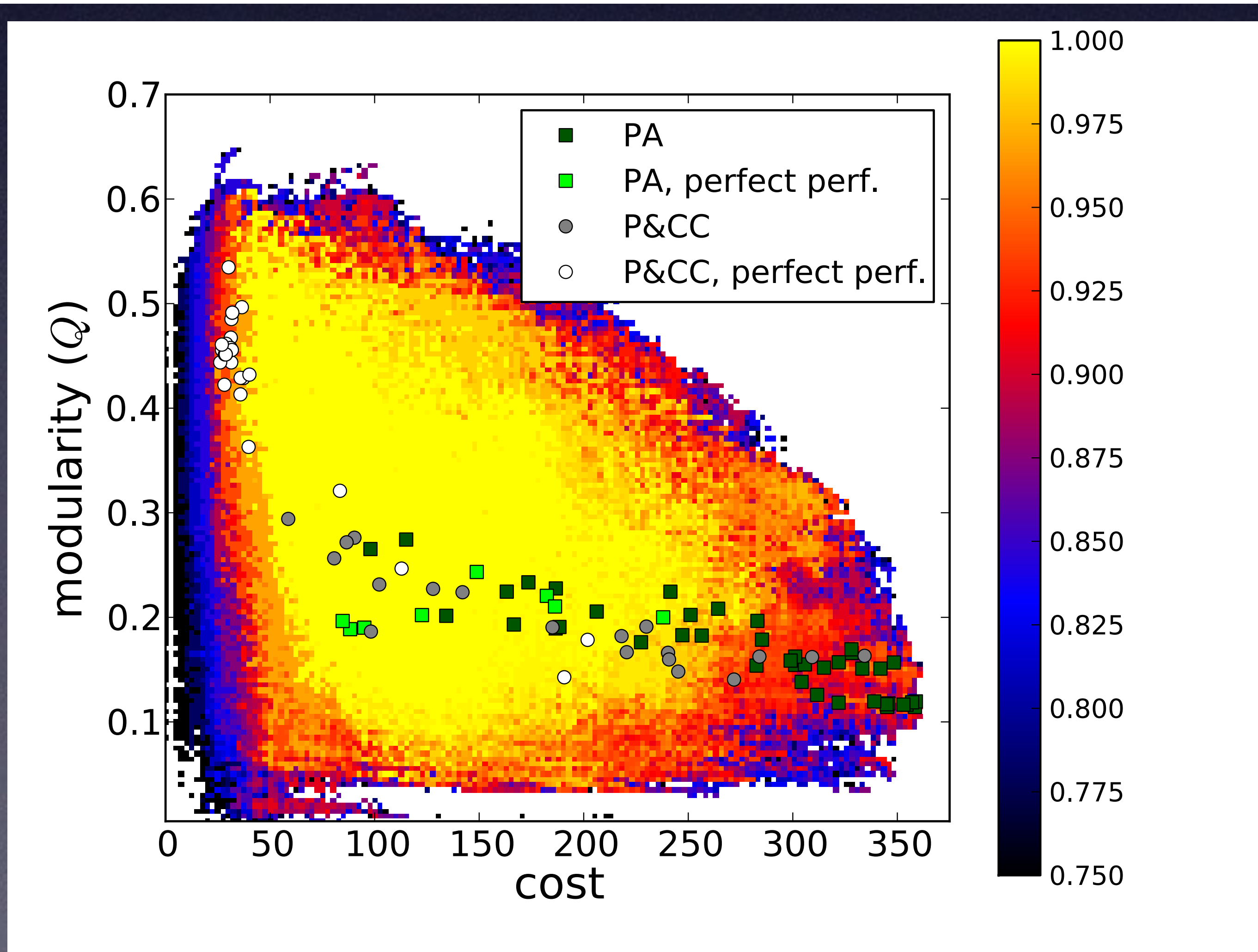
Why?



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

Clune, Mouret, & Lipson. Proc. Royal Society. 2013





Clune et al. Proc. Royal Society. 2013

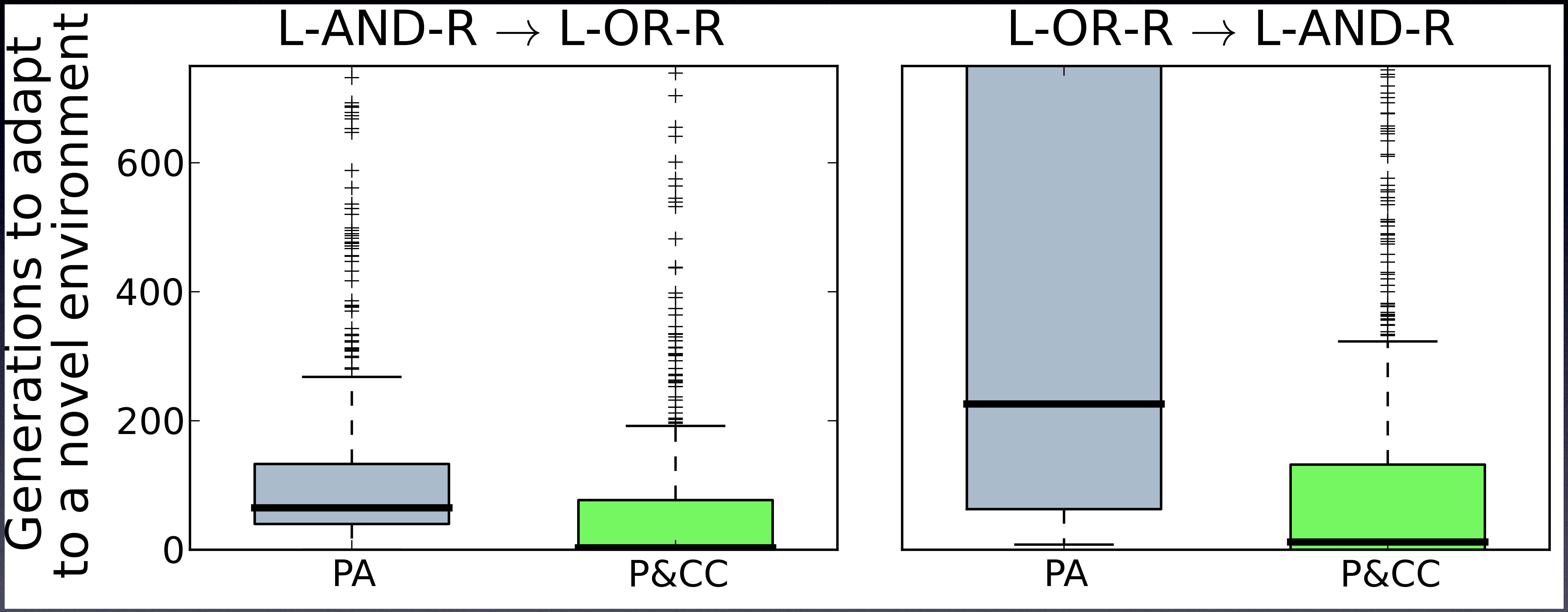
More evolvable?

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

Clune, Mouret, & Lipson. Proc. Royal Society. 2013

P&CC significantly more evolvable

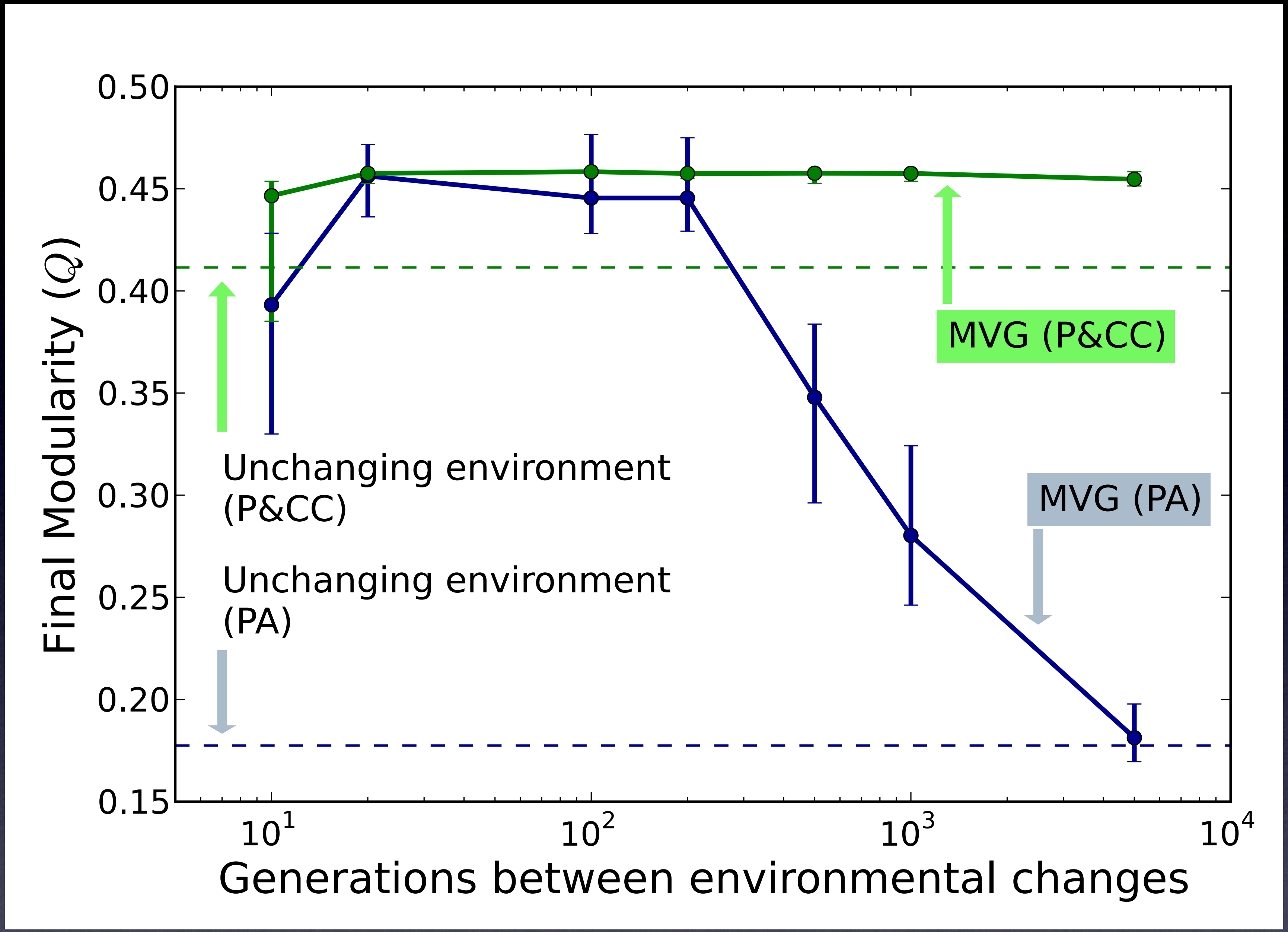
P&CC < PA ($p < 0.0001$)



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

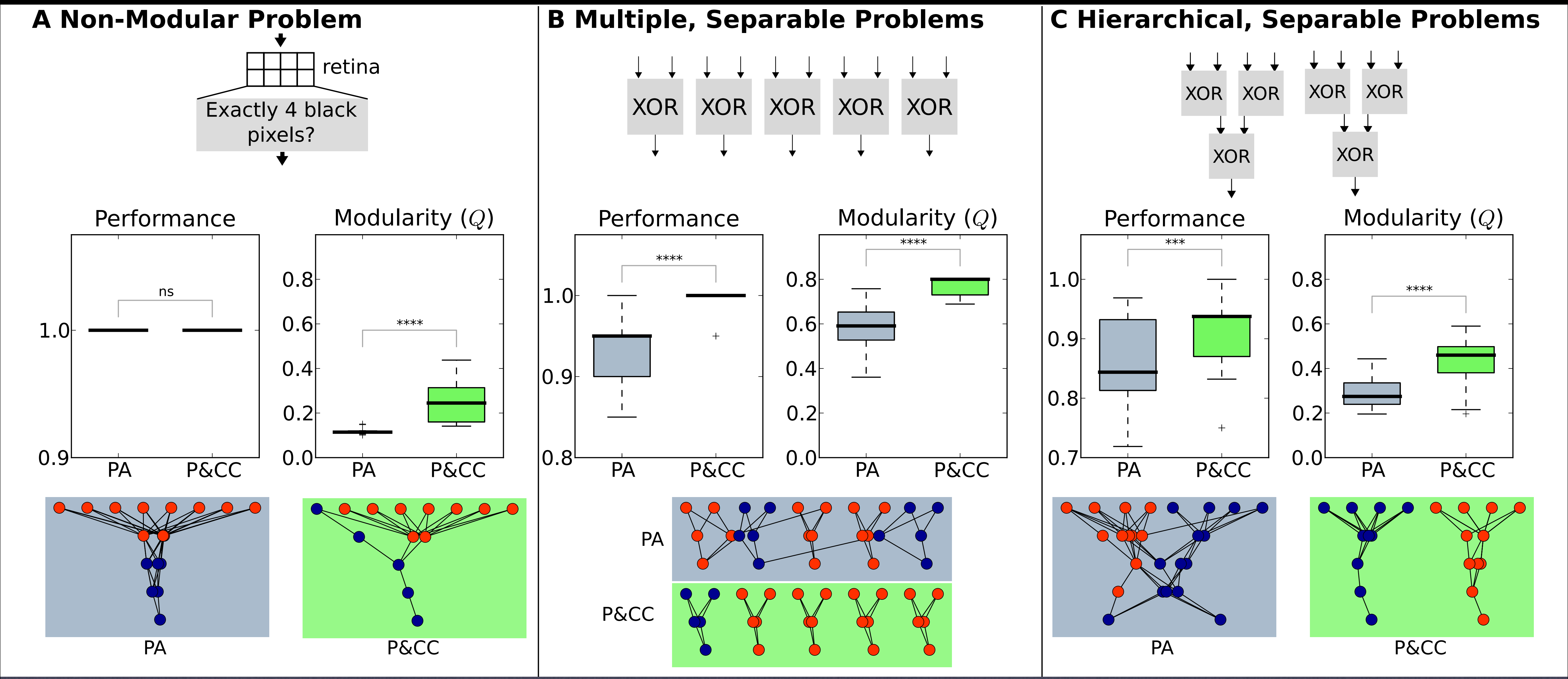
Clune, Mouret, & Lipson. Proc. Royal Society. 2013

Generality



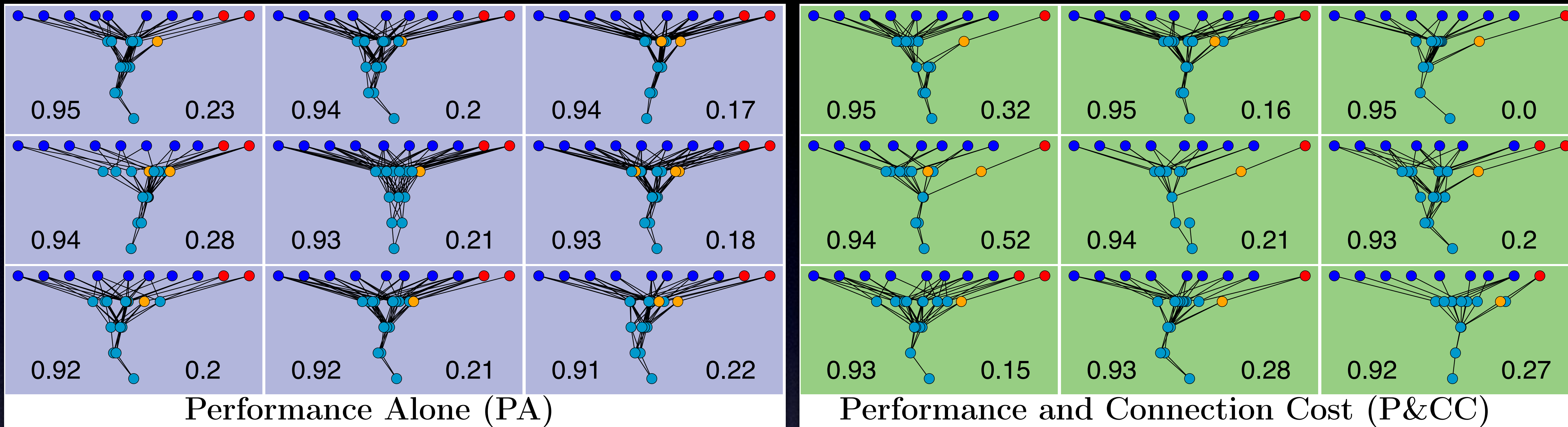
- Modularity forces can combine
- P&CC less sensitive to rate of environmental change
    - P&CC >= MVG at its strongest

Clune, Mouret, & Lipson. Proc. Royal Society. 2013

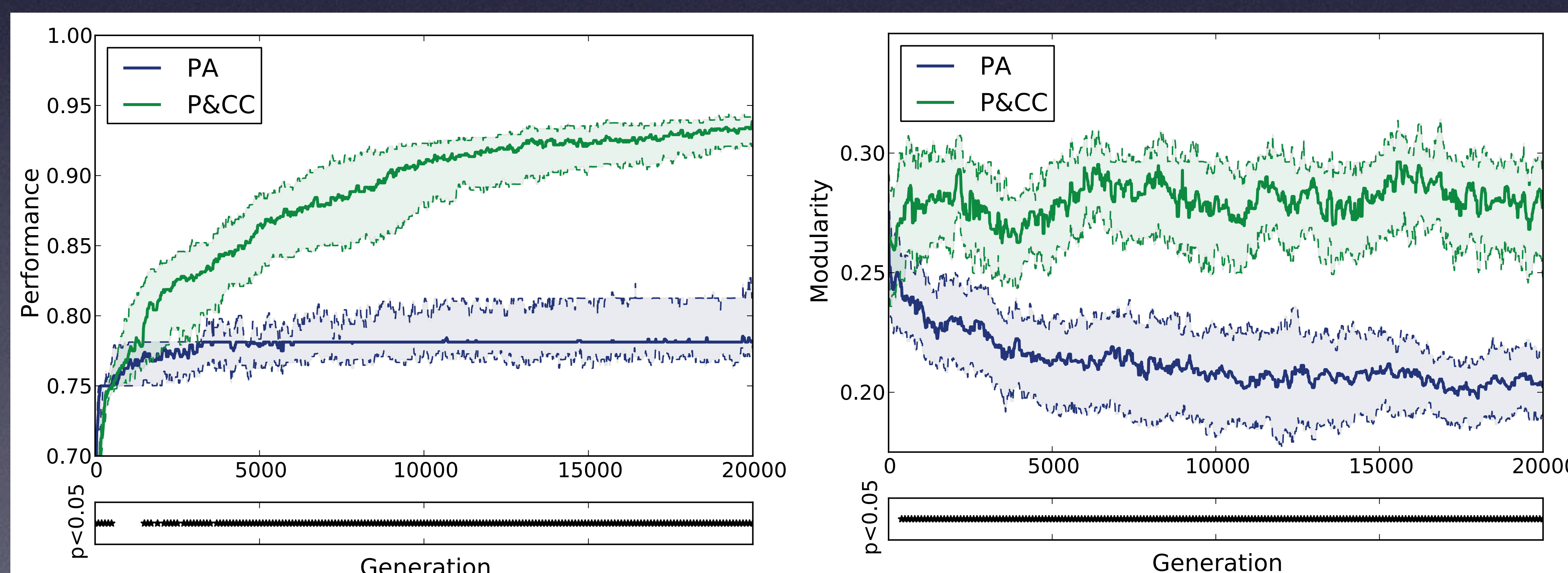


Clune, Mouret, & Lipson. Proc. Royal Society. 2013

Modularity Improves Learning



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

Clune, Mouret, & Lipson. Proc. Royal Society. 2013

Neuroevolution Implications

- Adding a cost increased
  - performance
  - modularity
  - evolvability
- Could be powerful technique for evolutionary algorithms

Clune, Mouret, & Lipson. Proc. Royal Society. 2013

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
- How many other cases of evolvability are non-adaptive?
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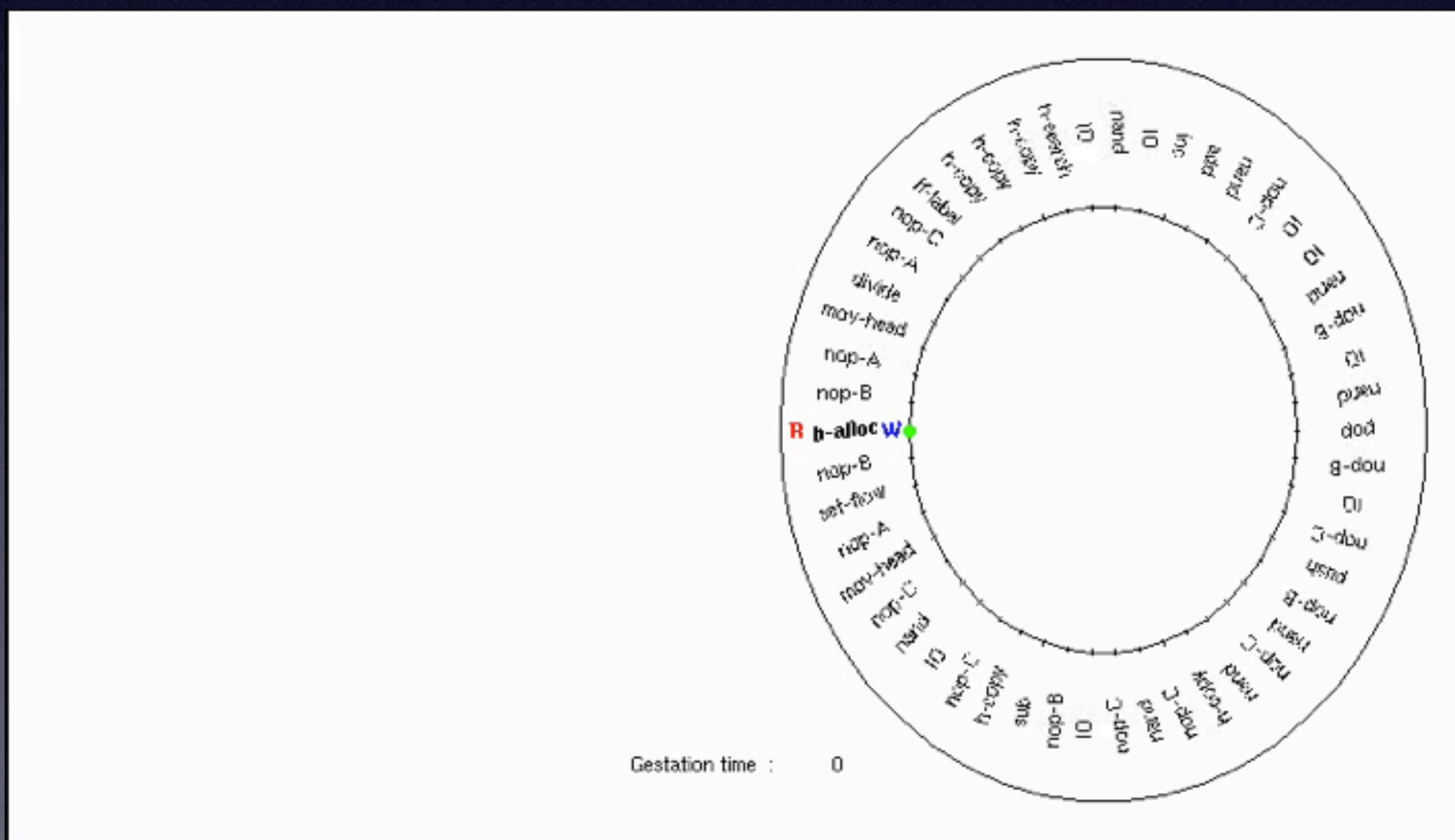
Avida Organisms

- 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