Evolutionary origins of modularity

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Presented by

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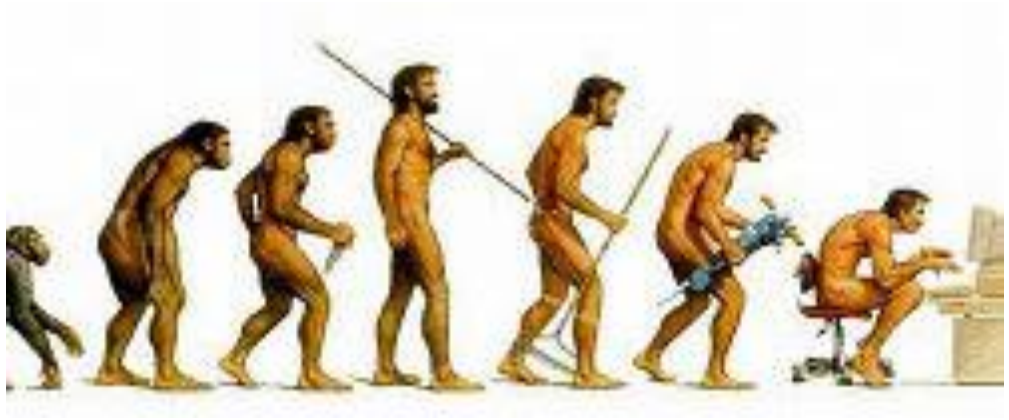
Evolvability

- Evolvability – capacity to rapidly adapt to novel environments
- Two organisms with the same phenotype and fitness in a current environment may differ in their evolvability

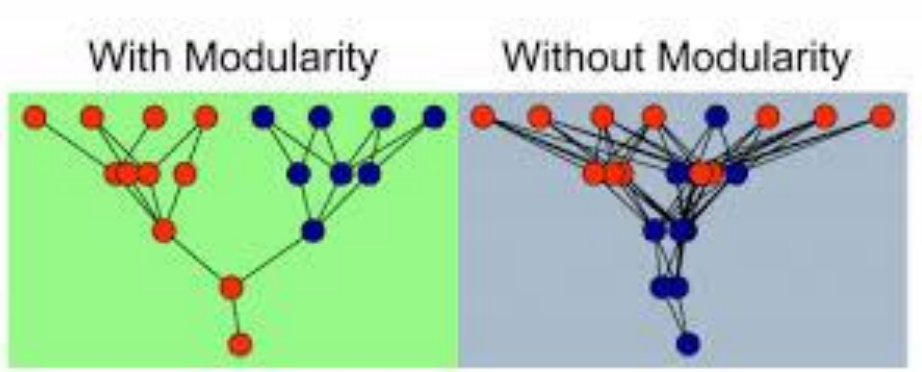


How does evolvability arise?

Modularity contributes to evolvability

- Engineering – easier to design/rewire modules

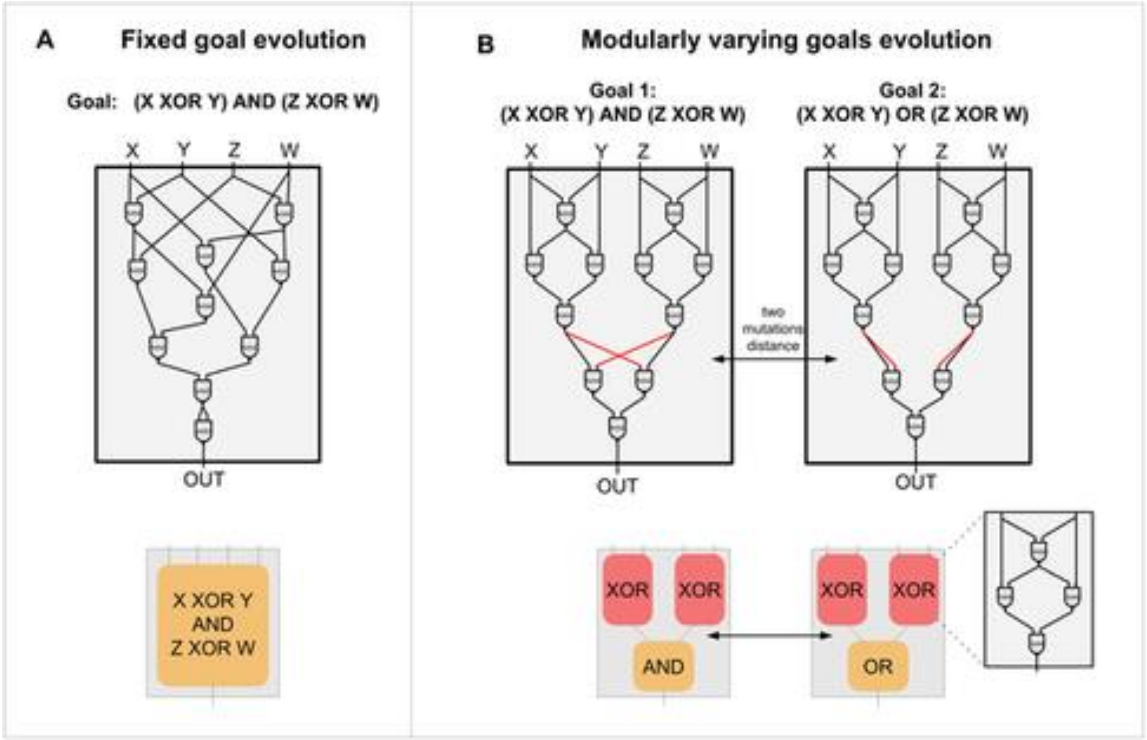
- Biological entities are modular
  - Brain
  - Metabolic Pathways
  - Protein interactions



Why does modularity evolve?

Why does modularity evolve?

- (Indirect) selection for evolvability (modularity)
- Leading Hypotheses
  - Rapidly changing environments with common subproblems



Why does modularity evolve?

- (Indirect) selection for evolvability (modularity)
- Leading Hypotheses
  - Rapidly changing environments with common subproblems
  - Bacteria occupying diverse environments have more modular metabolic networks

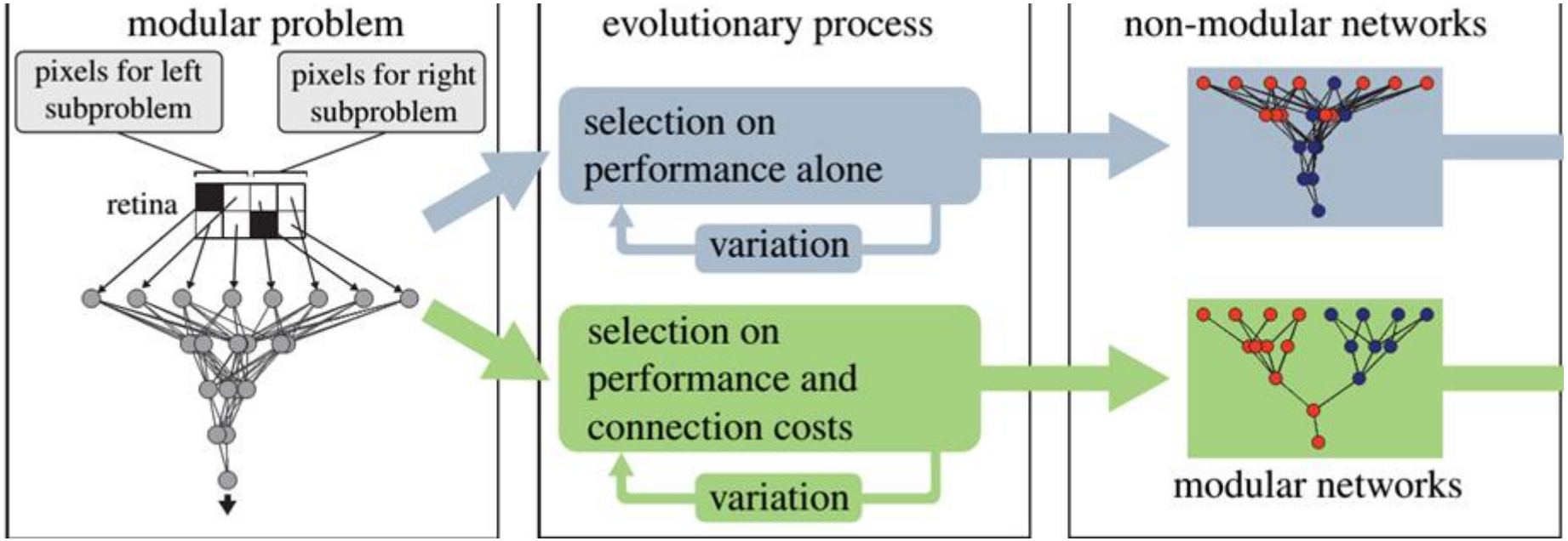
Is there a simpler/testable hypothesis?

Selection to reduce connection costs leads to modularity?

- Connection costs in networks
  - Neural networks – metabolic / energy
  - Signaling pathways – delay in output of a critical response
  - Gene regulation – Limit on DNA binding sites

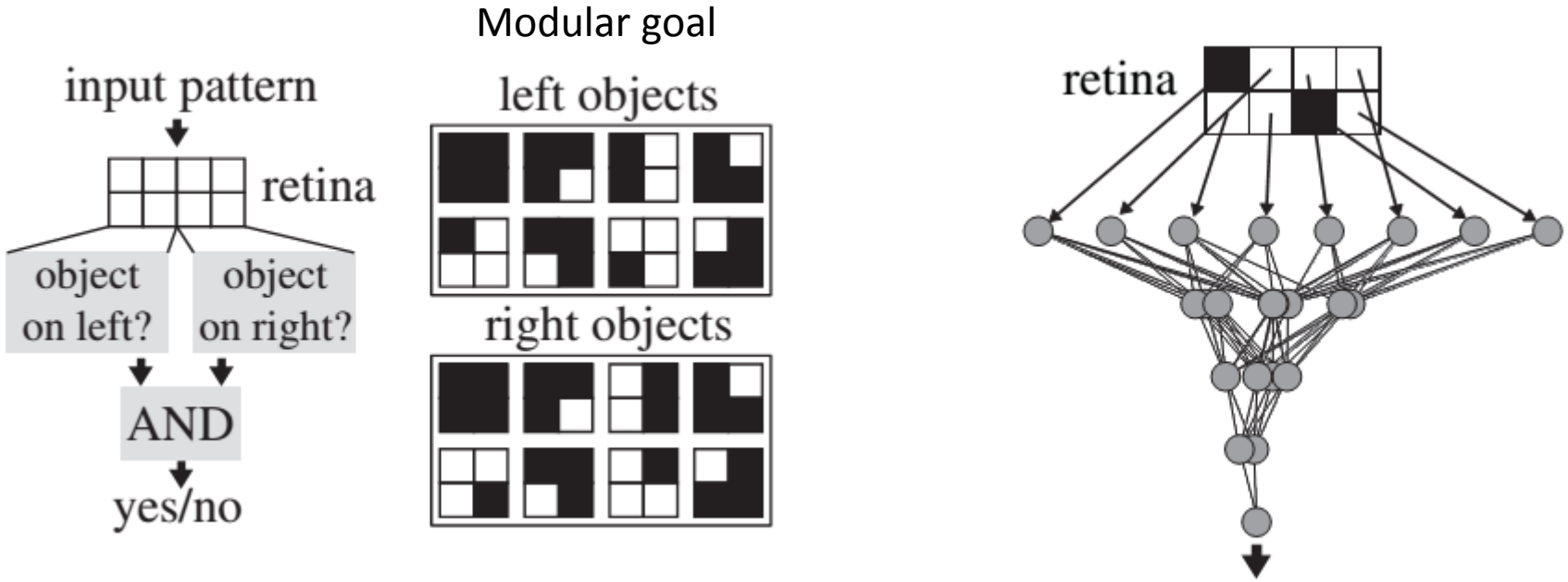
- Evidence for cost selection
  - Summed length of wiring diagram minimized in animal brains

Computational evolution of modularity



Computational Evolution of Modularity

- Each individual is a network that takes stimuli and returns an output



Fitness of a network = Fraction of input stimuli the network gets correct

Modularity:

$$q(G,C) := \sum_{u,v \in V} (A_{uv} - k_u k_v/(2m))(1 - x_{uv})$$

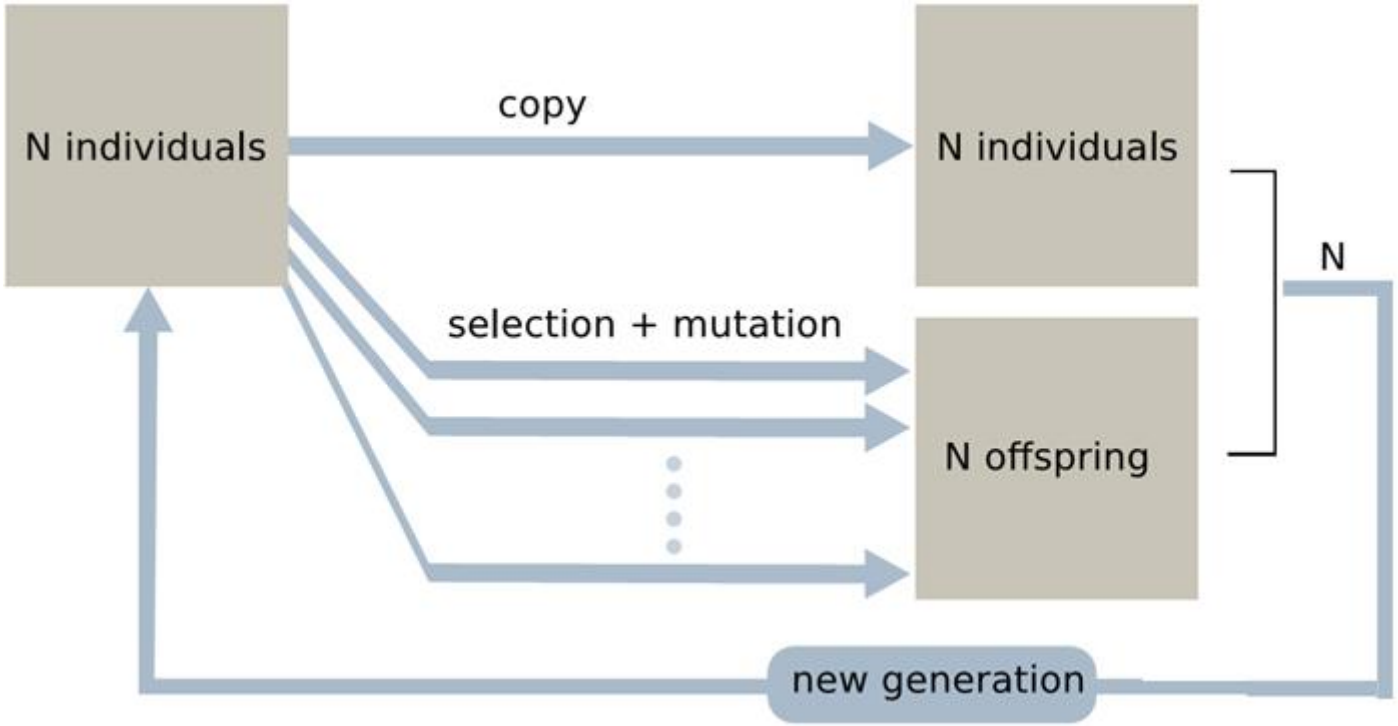
Two simulation experiments

PA
Maximizing Performance
alone

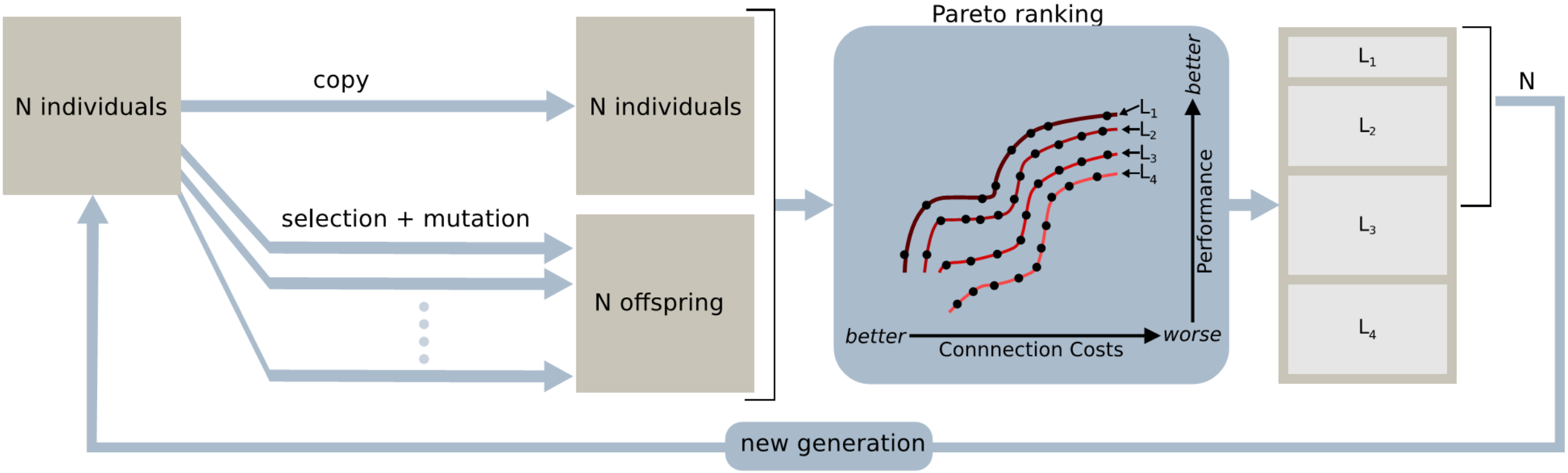
P&CC
Maximizing Performance
and
Minimizing Connection Costs

- Connection Costs: Distance between the nodes
- Compare the modularity of optimal networks evolved in the two simulations

PA evolution



P- CC: Non-dominated Sorting Genetic Algorithm



- Stochastic Pareto Dominance – use CC only 25% of the time
  1. To select parent for mutation, leading to offspring
  2. To select N fittest individuals for the next generation

Results

- 25,000 iterations/generations of evolution with fitness calculated using the two different conditions

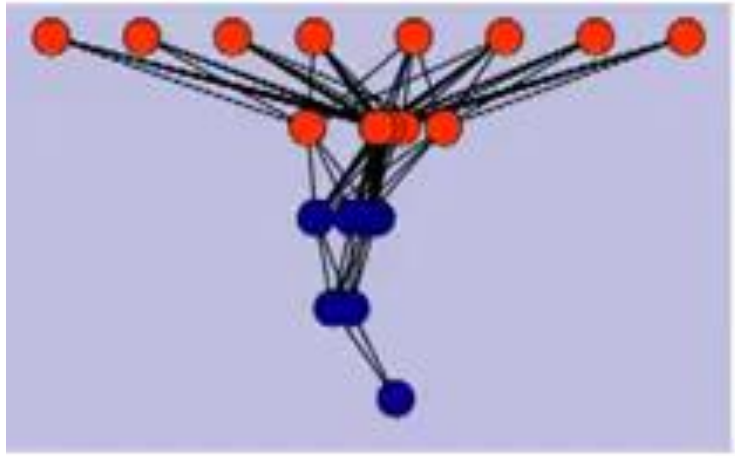
PA	**P&CC**
Maximizing Performance alone	Maximizing Performance and Minimizing Connection Costs

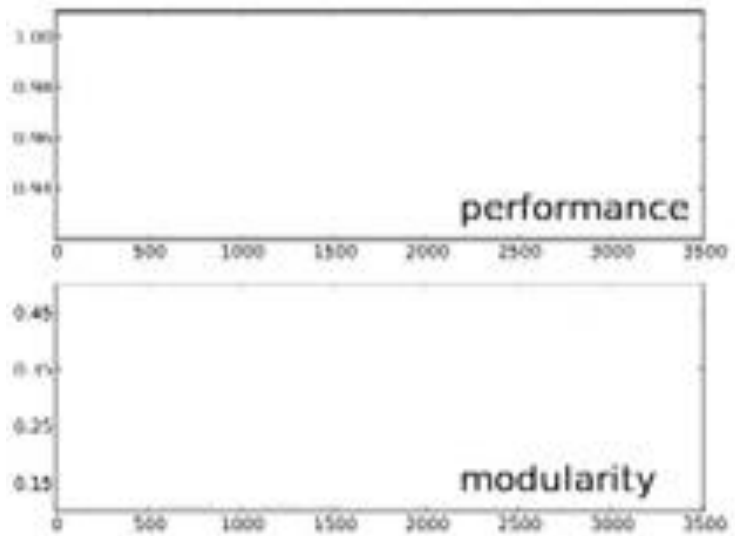
50 trials each

- Mutations – randomly adding or removing edges from the network; modifying weights on edges, bias on the nodes of neural network

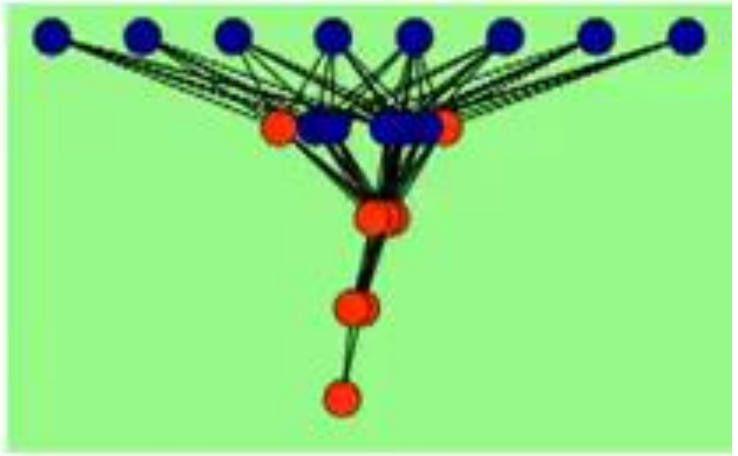
generation 0

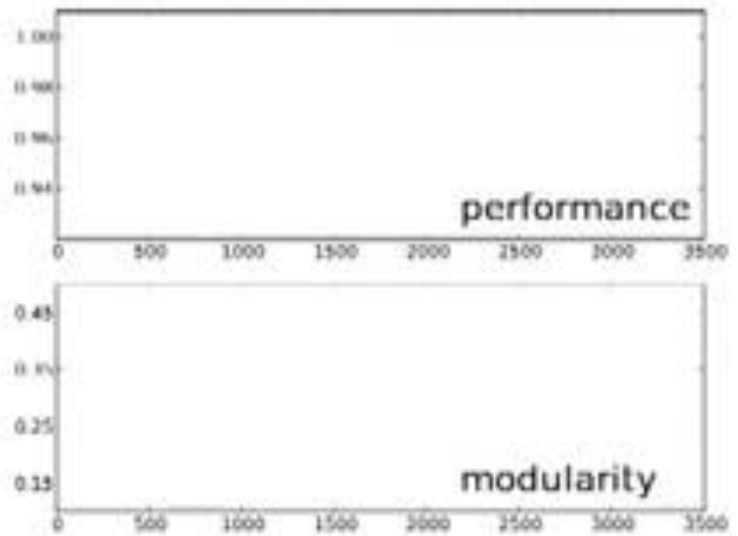
Performance Alone(PA)



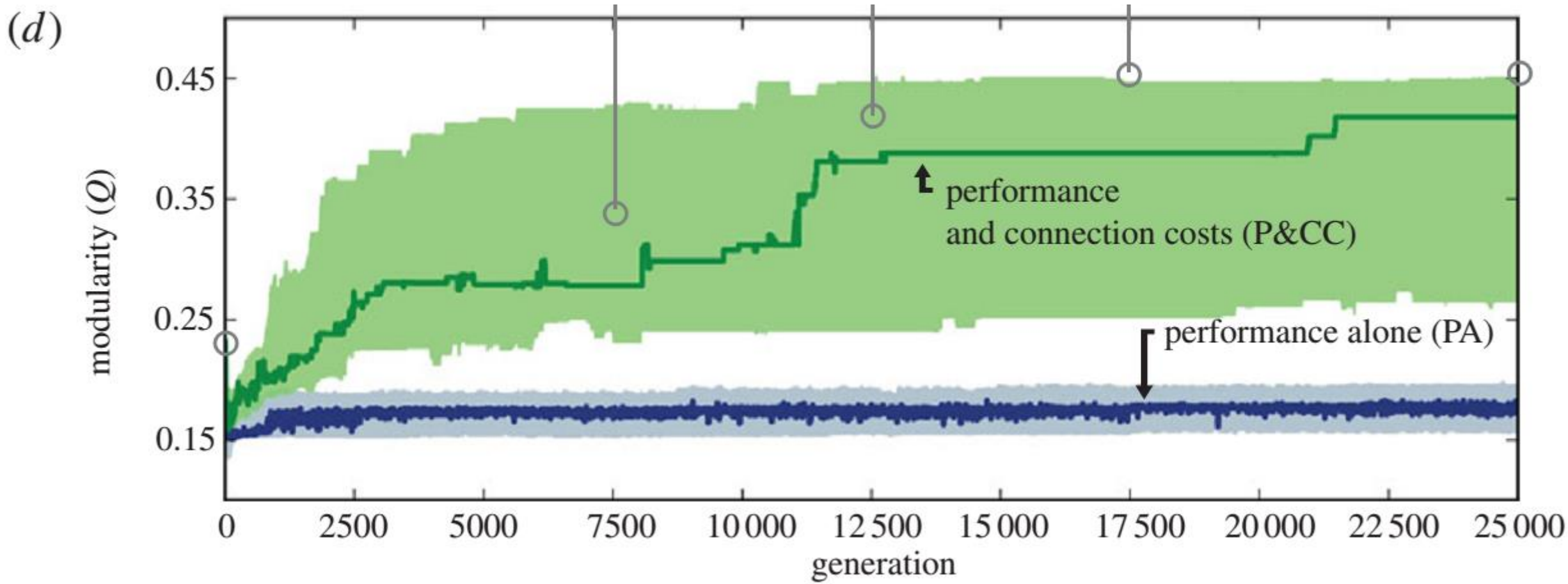


Performance and Connection Cost (P&CC)





P-CC evolution produces more modular networks



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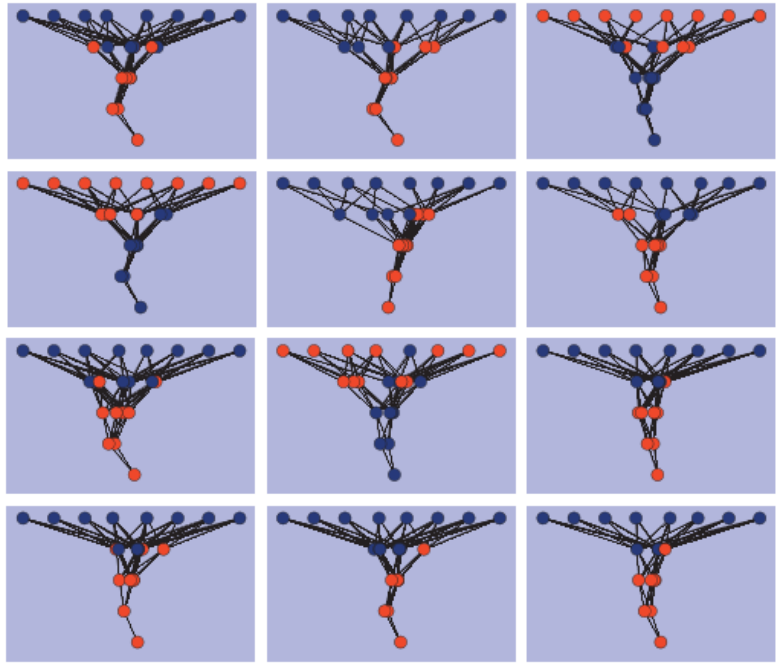
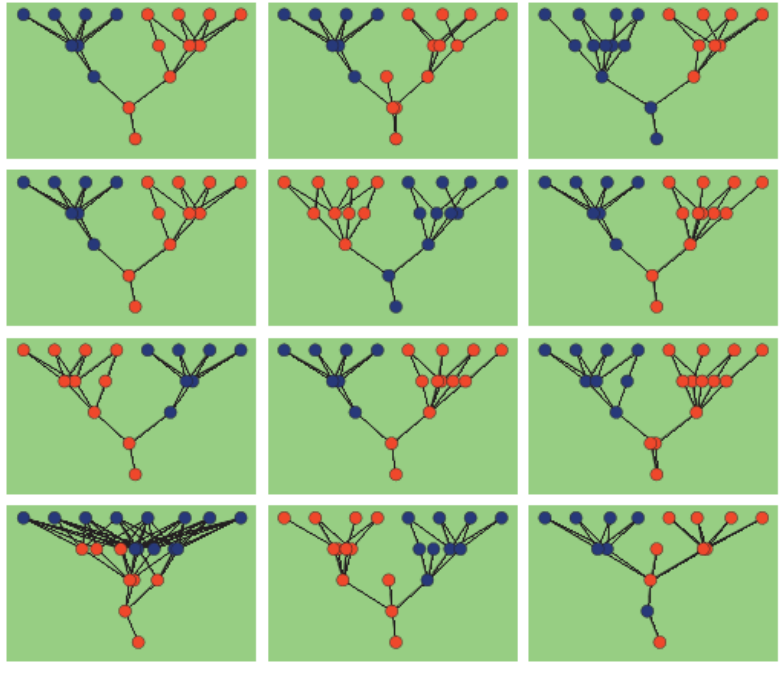
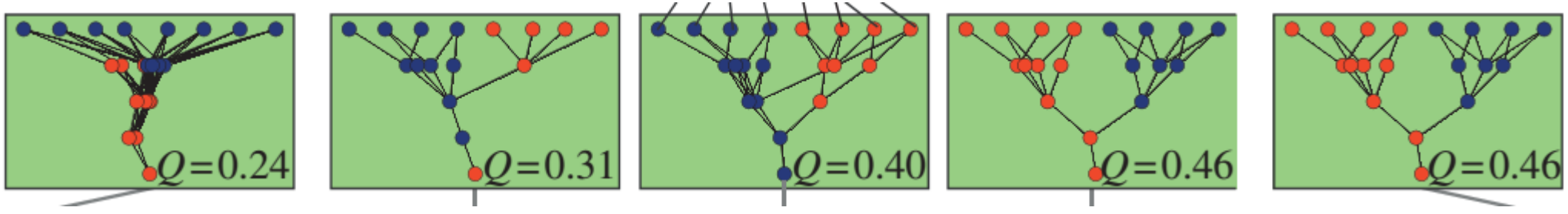


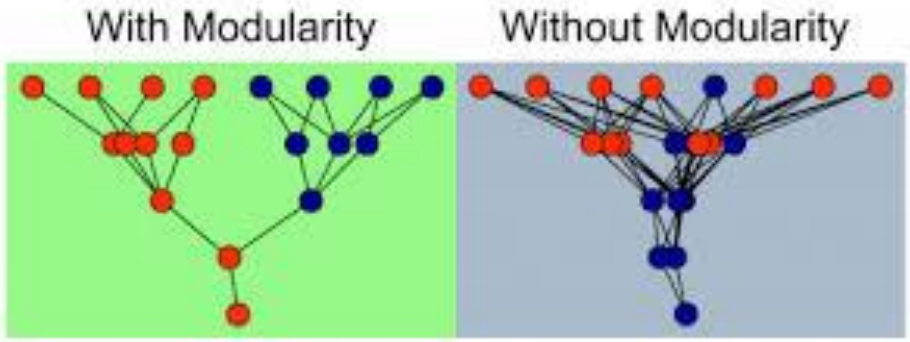


- Best performing network becomes more and more Modular

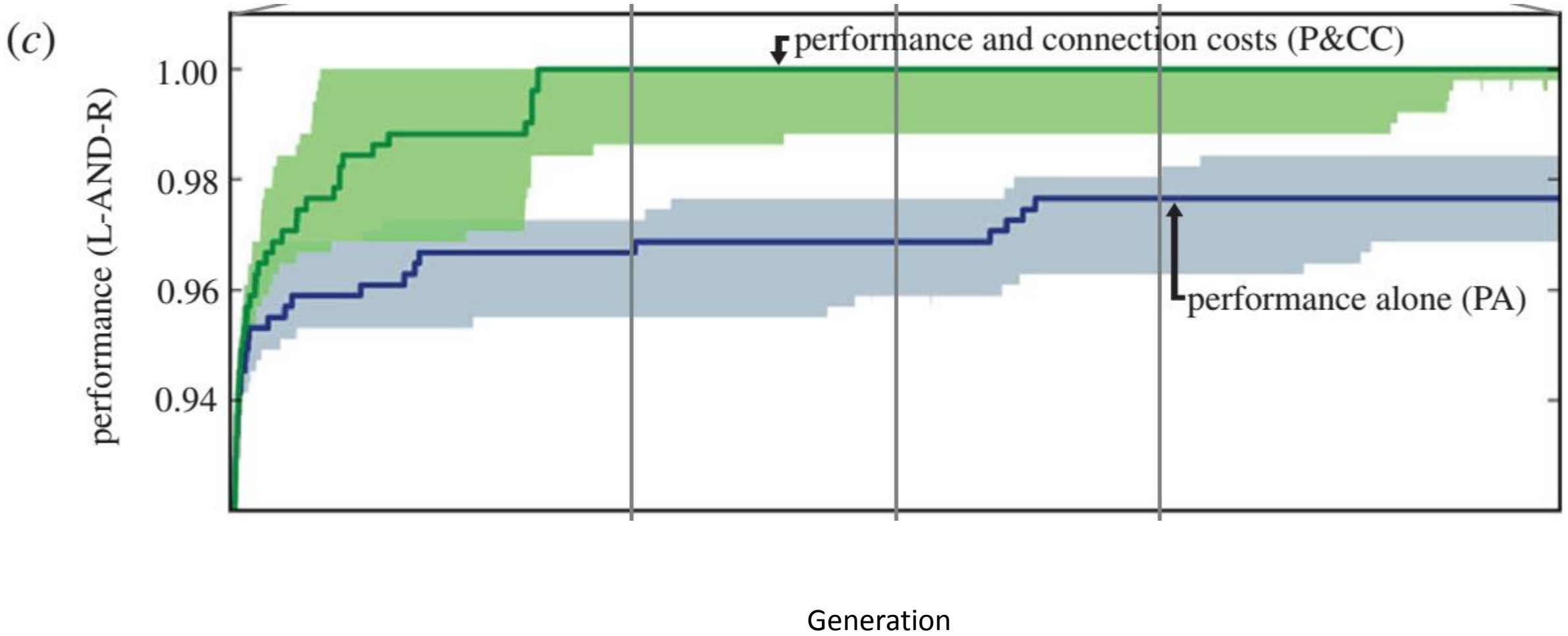


Is the modularity functional?

- Are the Left and Right subnetwork inputs in separate modules?
  - 56% of networks evolved under P&CC
  - 0 networks evolved under PA



P-CC produces better networks

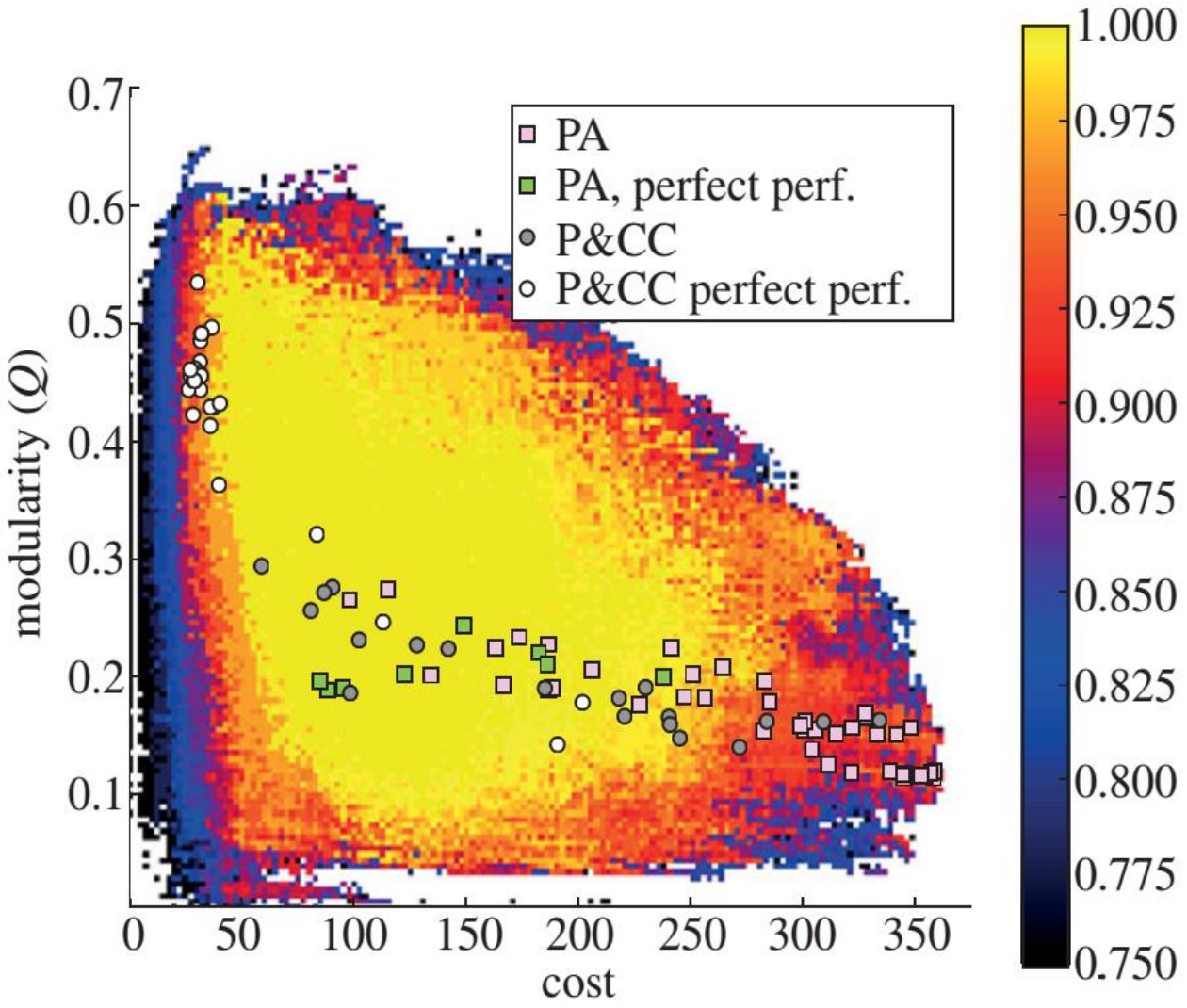


Why do P-CC networks achieve higher performance than PA networks?

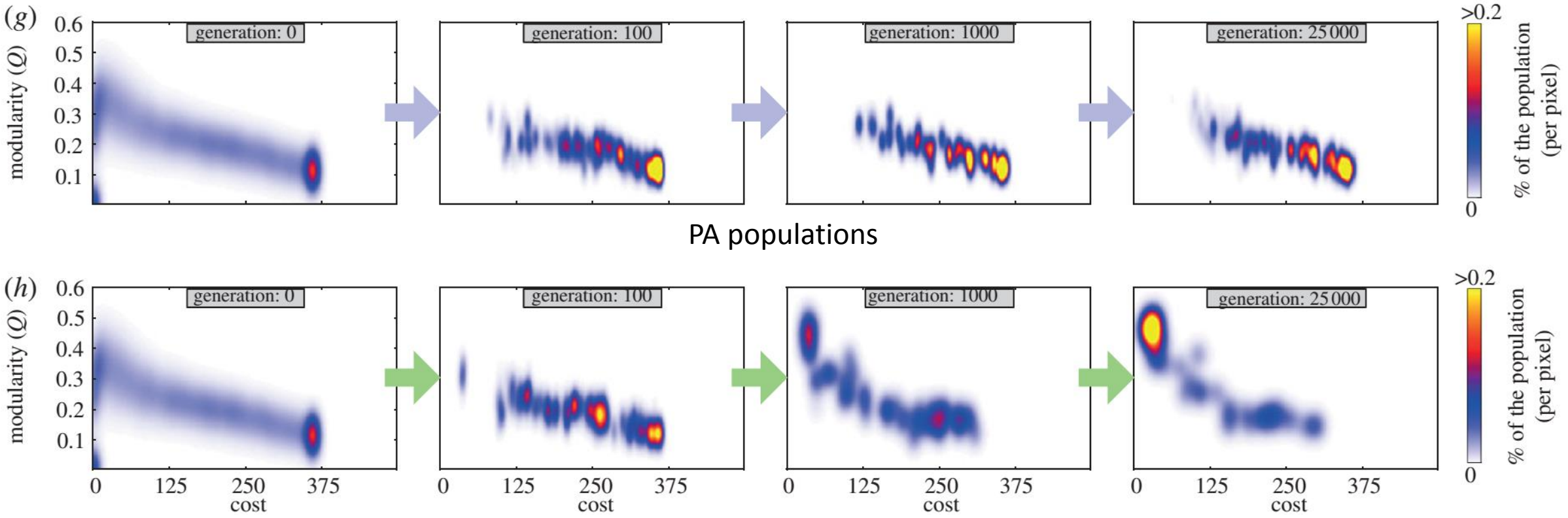
- P&CC has additional constraint (minimizing costs) but still does better in terms of performance than PA
- Mutational effects are smaller, restricted to subcomponents
- Fewer connections – fewer parameters being optimized
  - Faster optimization

Why do P-CC networks are more modular and high-performing?

- Inverse correlation between Cost and Modularity for high performing networks
- Existence of high performing networks with low modularity



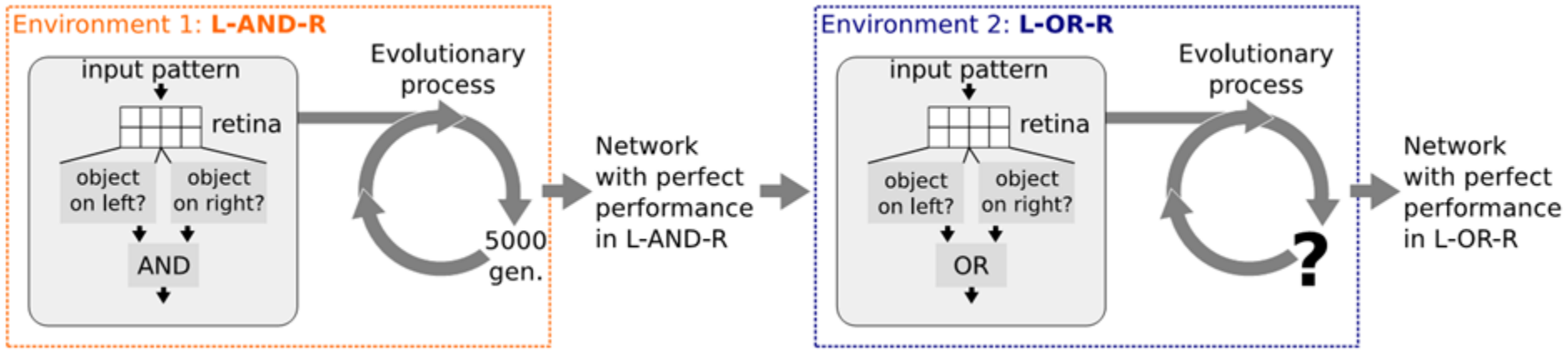
P-CC moves populations towards low cost high modularity solutions

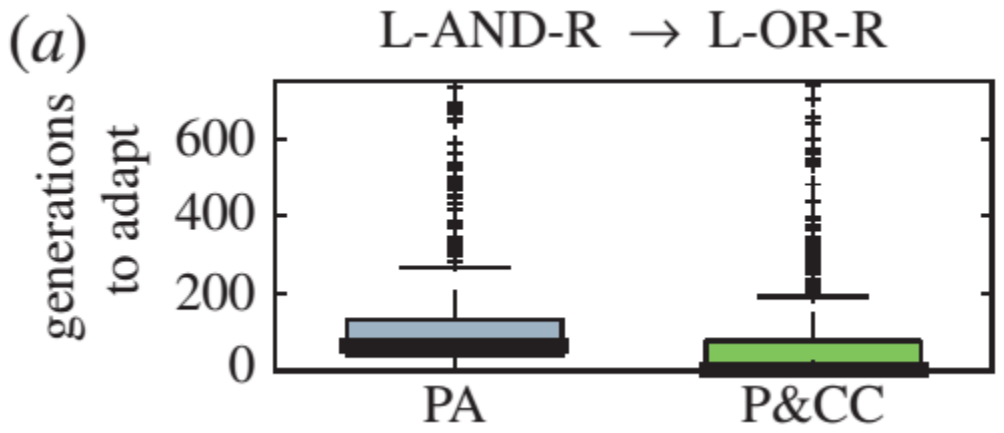


Evolvability

- How evolvable are the networks that were obtained from the previous two simulation experiments?
- Which is suited better to adapt to a slightly different environment?
- L-OR-R vs L-AND-R

Modular networks are more evolvable





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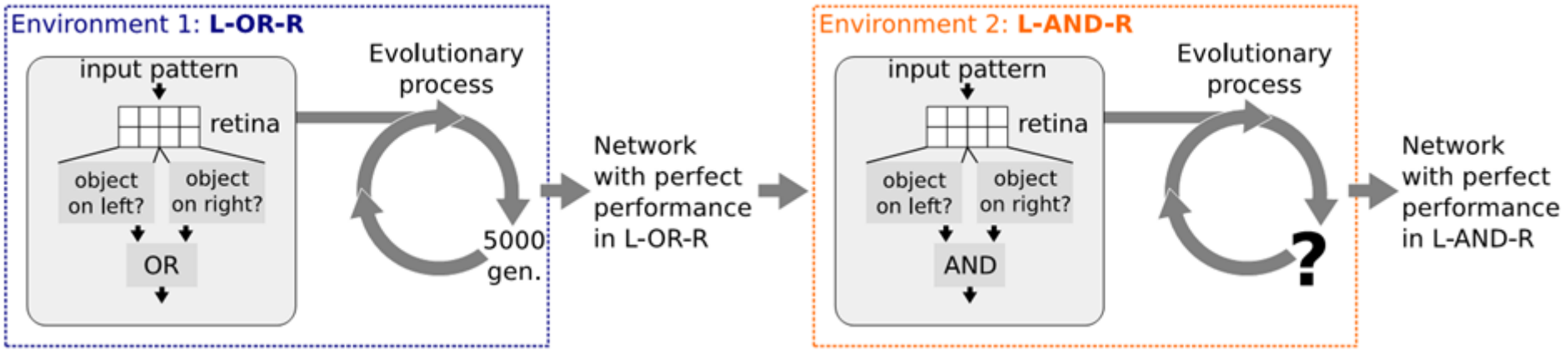
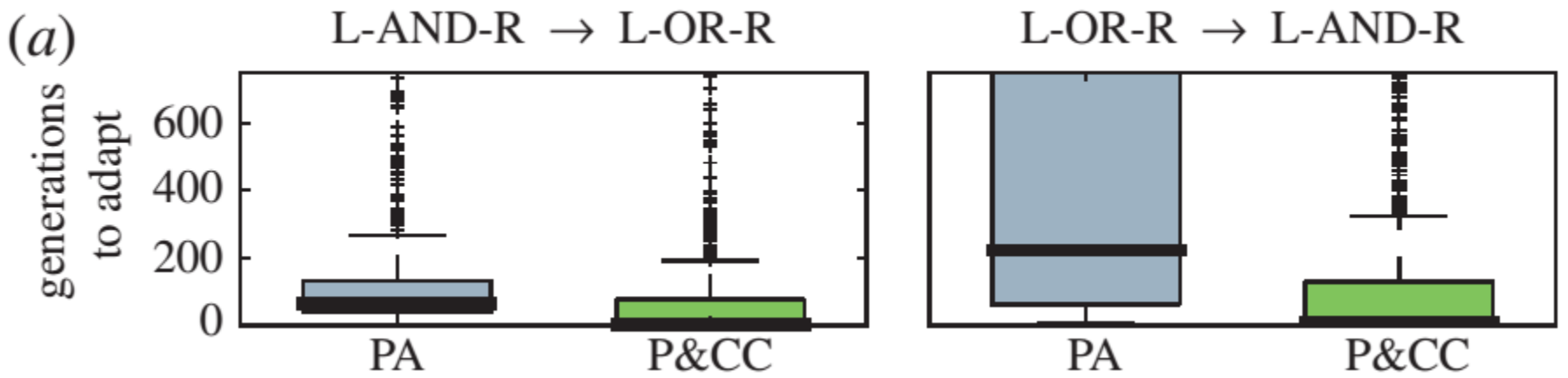
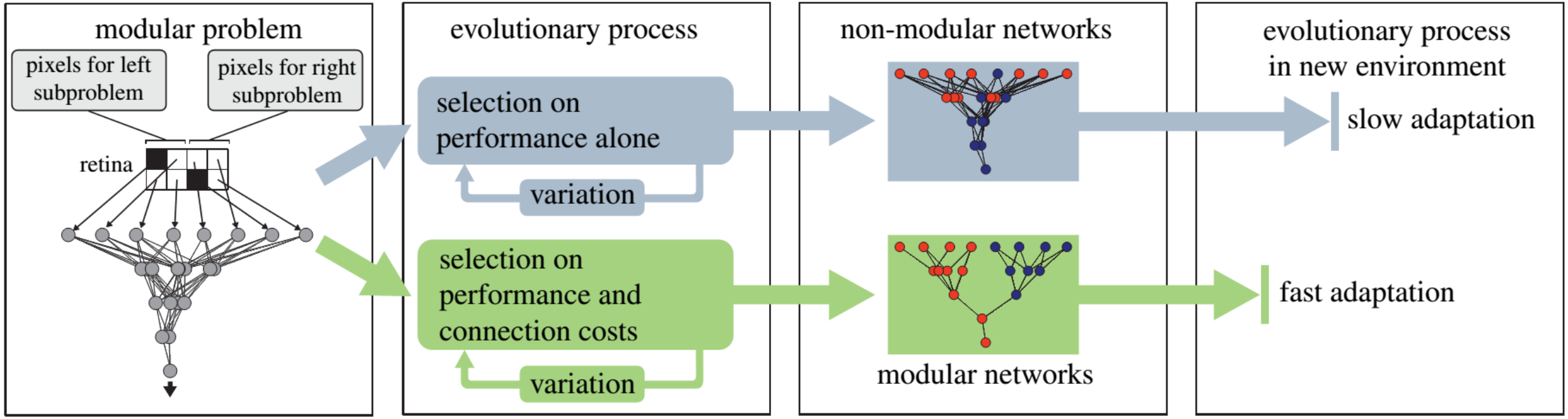
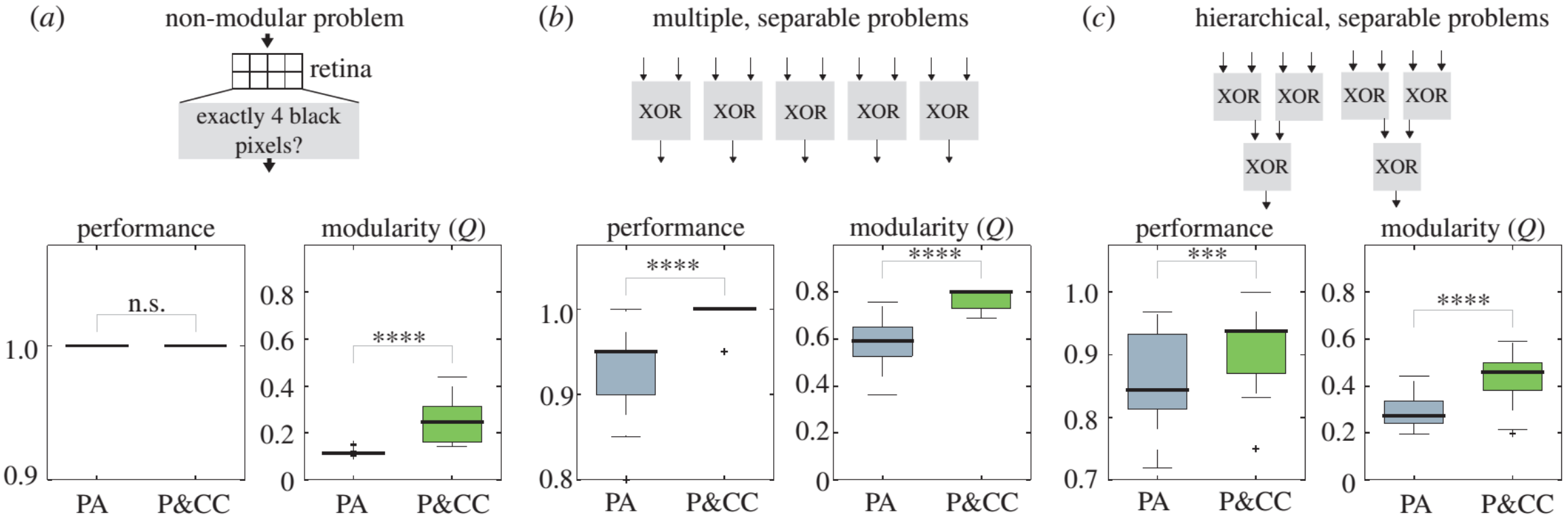




Computational Evolution of Modularity



Selection on connection costs leads to modularity



Summary

- Selection to reduce connection costs causes modularity, even in *unchanging* environments
- Got a lot of media attention for discovering ‘holy grail’ of evolving modular networks
- Significant advance in evolving modular design
  - Faster adaptation/evolvability