Evolution Selects For *and* Against Complexity

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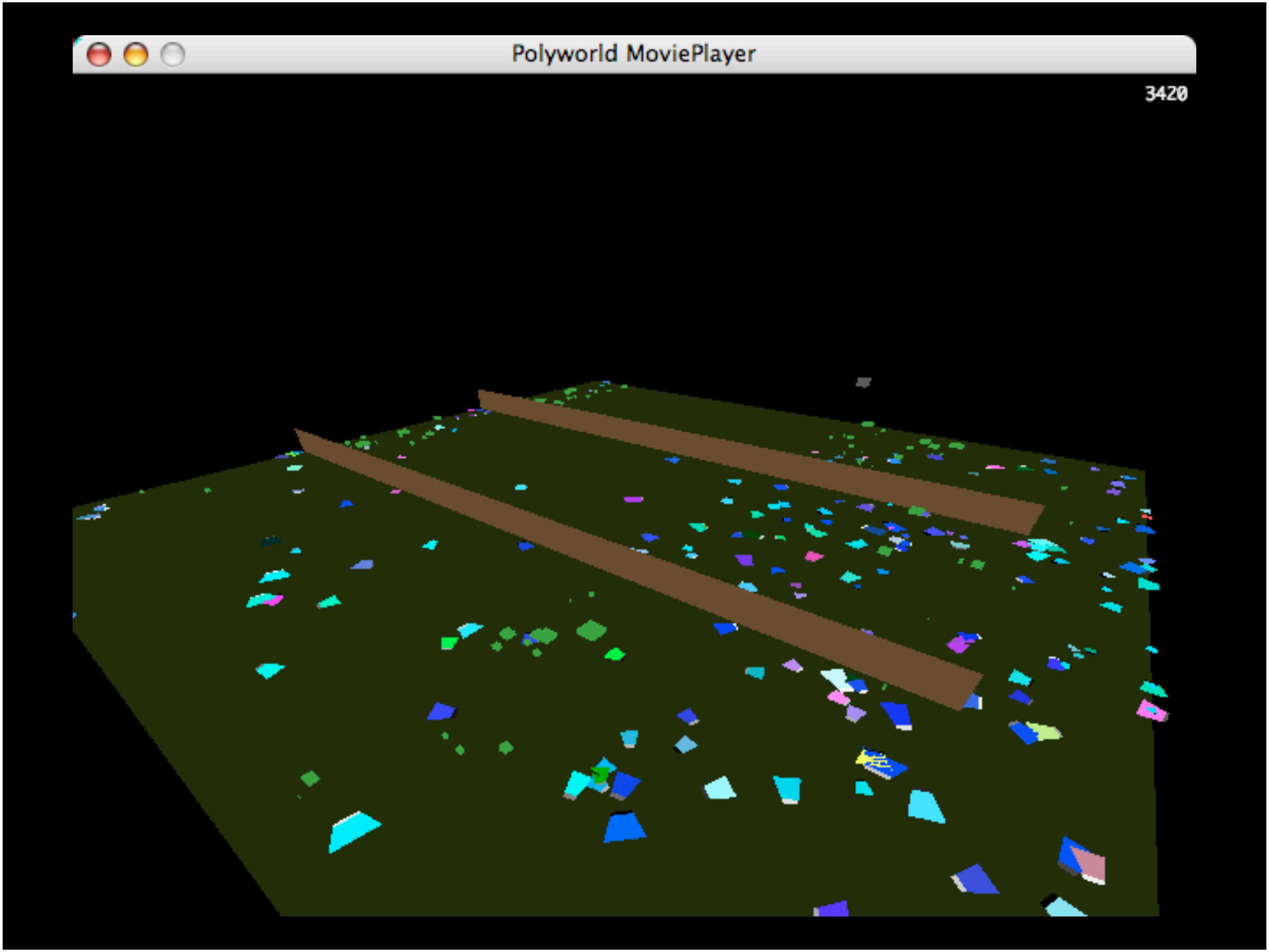
Evolution of Machine Intelligence

- Follow the path leading to natural intelligence
- *Evolution* of *nervous systems* in an *ecology*
  - *Evolution*, because it is an incredibly powerful innovator and problem solver
  - *Nervous systems*—collections of neurons and their internal, sensory, and motor connections—because that's how biological evolution has produced all known examples of natural intelligence
  - *Ecology*, because intelligence only makes sense in context
- Allows us to evolve simple intelligences (adaptive behaviors) first, along a spectrum of intelligences


Polyworld MoviePlayer
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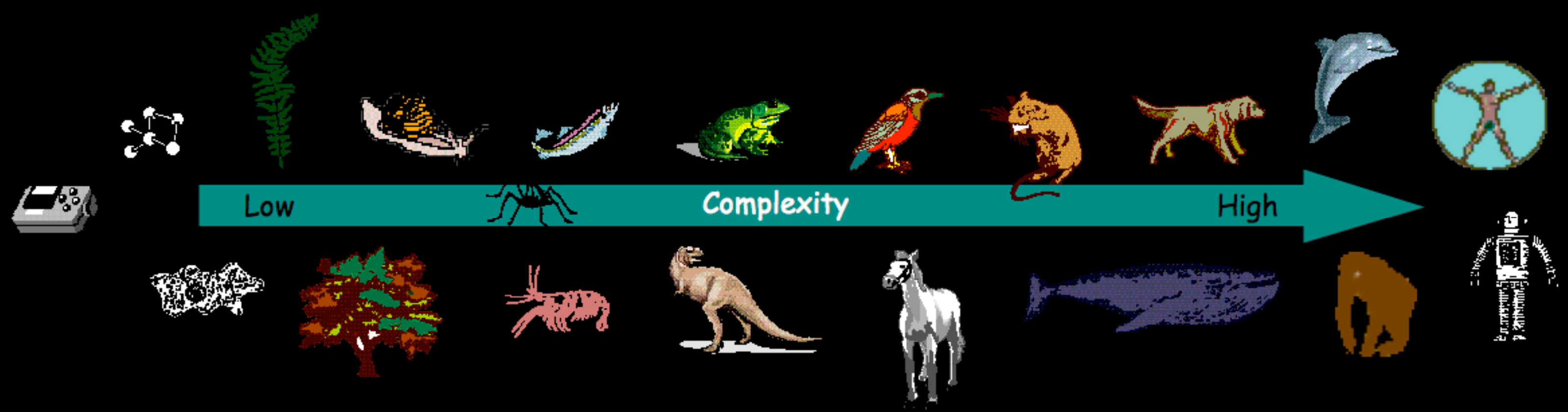
Measuring Progress



Spectrum of Life and Intelligence

Graduated Intelligence

- Darwin wrote (*The Descent of Man, and Selection in Relation to Sex* 1871, 1927, 1936)

  "If no organic being excepting man had possessed any mental power, or if his powers had been of a wholly different nature from those of the lower animals, then we should never have been able to convince ourselves that our high faculties had been gradually developed. But it can be shewn that there is no fundamental difference of this kind. We must also admit that there is a much wider interval in mental power between one of the lowest fishes, as a lamprey or lancelet, and one of the higher apes, than between an ape and a man; yet this interval is filled up by numberless gradations."

Measuring Intelligence

- Seth, Izhikevich, Reeke, Edelman in *Theories and measures of consciousness: An extended framework* (PNAS 2006)

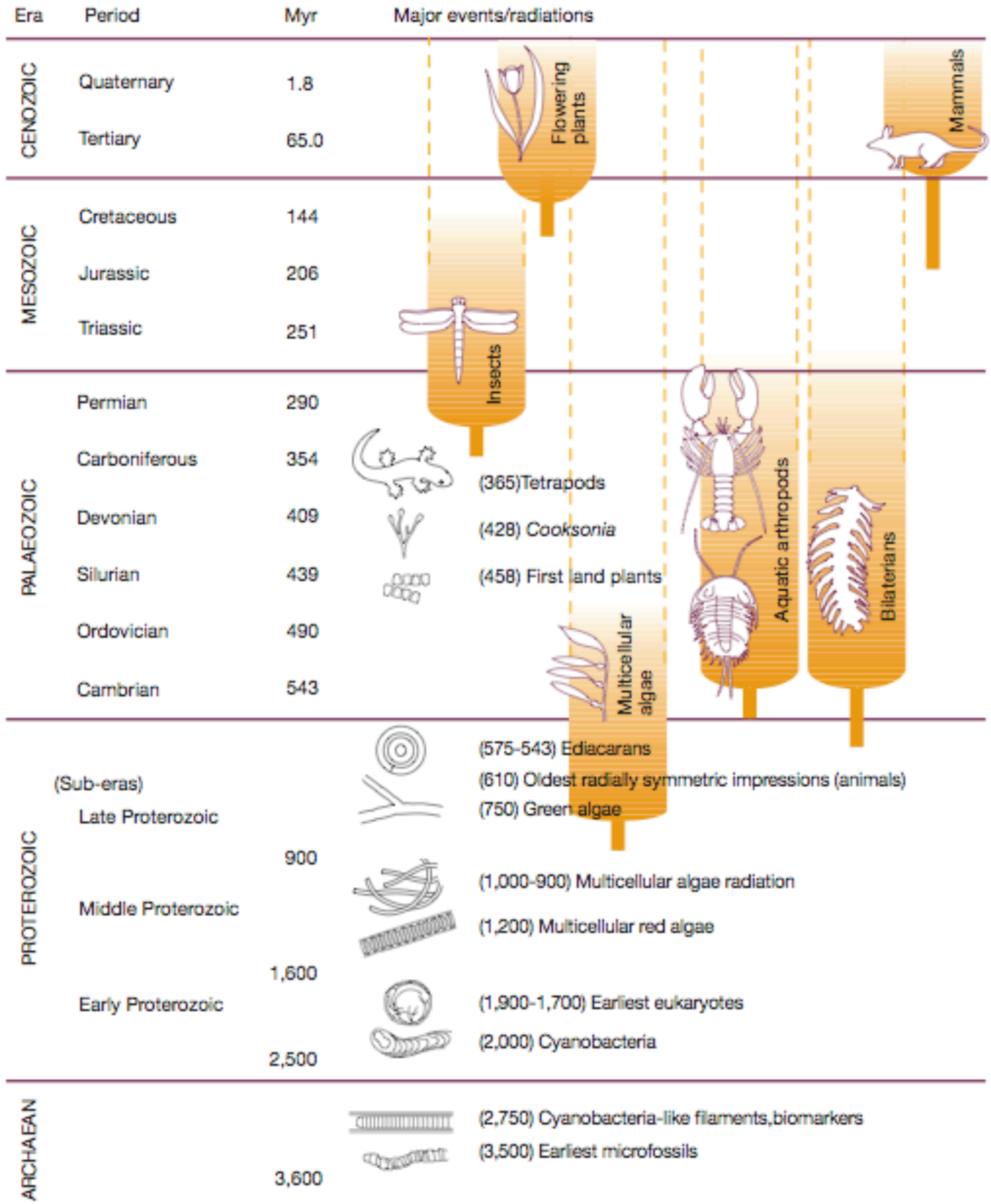
  "The existence of quantitative measures of relevant complexity, however preliminary they may be, raises the important issue of identifying the ranges of values that would be consistent with consciousness. … it may then become possible to define a measurement scale for a proposed measure of relevant complexity by establishing a value for a known conscious system (for example, an awake human) and a value for a known nonconscious system (for example, the same human during dreamless sleep)."

Spectrum of Intelligence

- Laboratory evidence exists for self-awareness in humans, chimpanzees, and orangutans, based on the classic red-dot and mirror test
- Koko the gorilla, Washoe the chimp, and Kanzi the bonobo ape all demonstrate language skills comprehensible to humans
- Dolphins demonstrate intelligent behavior and learning in the field and in the "lab"
- Alex the parrot demonstrates language skills, and Betty the crow demonstrates tool creation (as well as use)
- Honeybees (1M neurons) exhibit associative recall and learn the abstract concepts ***same*** and ***different***
- Fruit flies (250K neurons) learn by association and exhibit a ***salience*** mechanism akin to human attention
- *Aplysia* (20K neurons) demonstrate sensitization, habituation, classical and operant conditioning

History of Major Evolutionary Events from the Fossil Record

Carroll (2001)



The Great Chain of Being

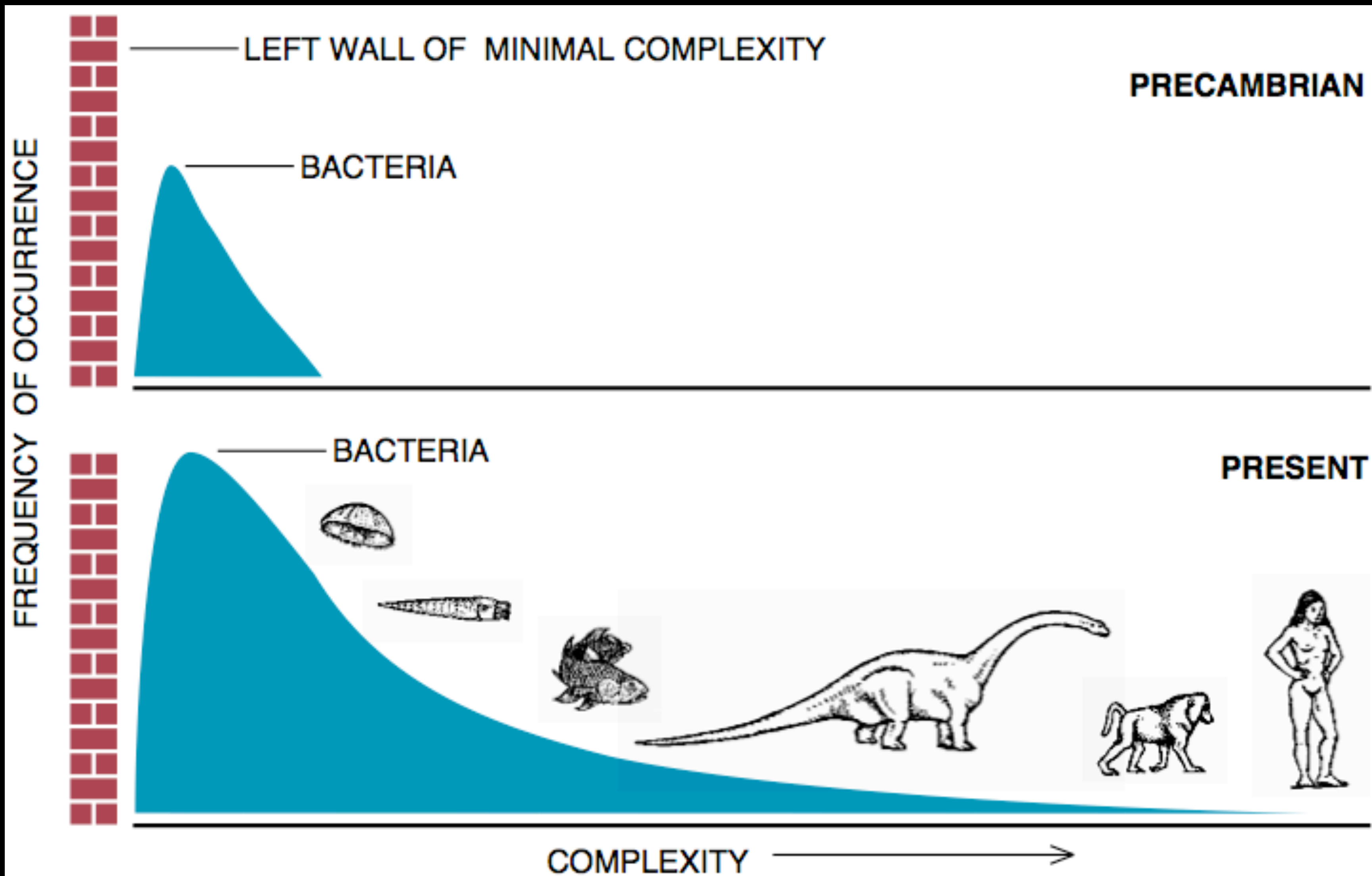
- Concerns exist about whether all such explanations might merely encode an anthropocentric bias, where "human-like" is the real measure of some loosely-defined complexity

Didacus Valades,
Rhetorica Christiana
1579

Evolutionary Trends in Complexity?

- In a 1994 Scientific American article, Steven J. Gould famously argued against an evolutionary "ladder" of increasing complexity
- However, he actually acknowledges the appearance of greater complexity over evolutionary time scales

Evolutionary Trends in Complexity?



Evolutionary Trends in Complexity?

- In a 1994 Scientific American article, Steven J. Gould famously argued against an evolutionary trend towards increasing complexity
- However, he actually acknowledges the appearance of greater complexity over evolutionary time scales
- The focus and conclusion of his argument is that evolution is better viewed as a branching tree or bush, rather than a purely gradualist ladder, with punctualist winnowing and accident being as important as growth in the natural record

What Kind of Complexity?

- McShea (1996) observes that loose and shifting definitions of complexity allow sloppy reasoning and highly suspect conclusions about evolutionary trends
- Defines two (or three) distinctions that produce four (or eight) types of complexity
  - Hierarchical vs. non-hierarchical
  - Morphological (objects) vs. developmental (processes)
  - (Differentiation vs. Configuration)
- Suggests there may be upper limits to complexity
- Discusses (limited) evidence for increases in number of cell types, arthropod limb types, and vertebrae sizes
- Acknowledges complexity of human brain, but otherwise ignores nervous systems
- Distinguishes *driven* vs. *passive* trends, using changes in minimum values and ancestor-descendent differences

Sources of Complexity Growth

- Rensch (1960a,b; Bonner 1988) argued that more parts will allow a greater division of labor among parts
- Waddington (1969; Arthur 1994) suggested that due to increasing diversity niches become more complex, and are then filled with more complex organisms
- Saunders and Ho (1976; Katz 1987) claim component additions are more likely than deletions, because additions are less likely to disrupt normal function
- Kimura (1983; Huynen 1995; Newman and Englehardt 1998) demonstrated value of neutral mutations in bridging gulfs in fitness landscape, through selection for function in previously neutral changes

Evolutionary Trends in Complexity?

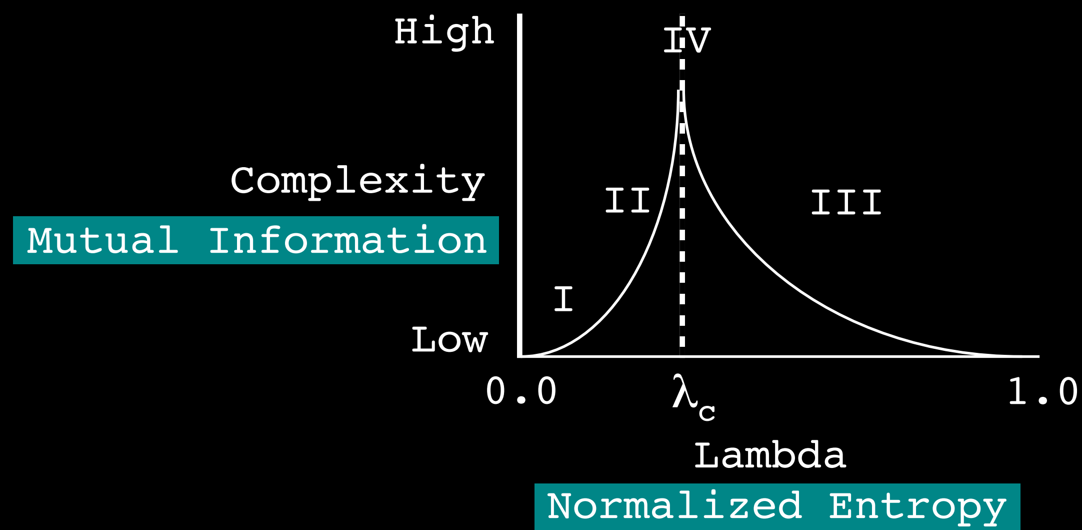
- Adami (2000, 2002) defines complexity as the information that an organism's *genome* encodes about its environment and demonstrates that asexual agents in a fixed, single niche always evolve towards greater complexity
- Turney (1999) uses a simple evolutionary model to suggest that *evolvability* is central to progress in evolution, and predicts an accelerating increase in biological systems
- Bedau (et al. 1997, Rechsteiner and Bedau 1999) provides evidence of an increasing and accelerating "evolutionary activity" in biological systems not yet demonstrated in artificial life models

Information Is What Matters

- "Life is a pattern in spacetime, rather than a specific material object." - Farmer & Belin (ALife II, 1990)
- Schrödinger speaks of life being characterized by and feeding on "negative entropy" (*What Is Life?* 1944)
- Von Neumann describes brain activity in terms of information flow (*The Computer and the Brain*, Silliman Lectures, 1958)
- Physicist Edwin T. Jaynes identified a direct connection between Shannon entropy and physical entropy in 1957
  - James Avery's *Information Theory and Evolution* (2003) discusses some of the consequences
- *Informational functionalism*
  - It's the process, not the substrate
  - What can information theory tell us about living, intelligent processes…

Information and Complexity

- Chris Langton's "lambda" parameter (ALife II)
  - Complexity = length of transients
  - λ = # rules leading to nonquiescent state / # rules



Wolfram's CA classes:

I = Fixed
II = Periodic
III = Chaotic
IV = Complex

- Crutchfield: Similar results measuring complexity of finite state machines needed to recognize binary strings
- Olaf Sporns: Similar results measuring complexity of dynamics in artificial neural networks

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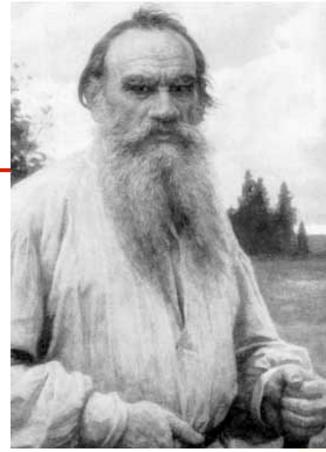


“All work and no play makes Jack a dull boy.
All work and no play makes Jack a dull boy.
All work and no play makes Jack a dull boy.”

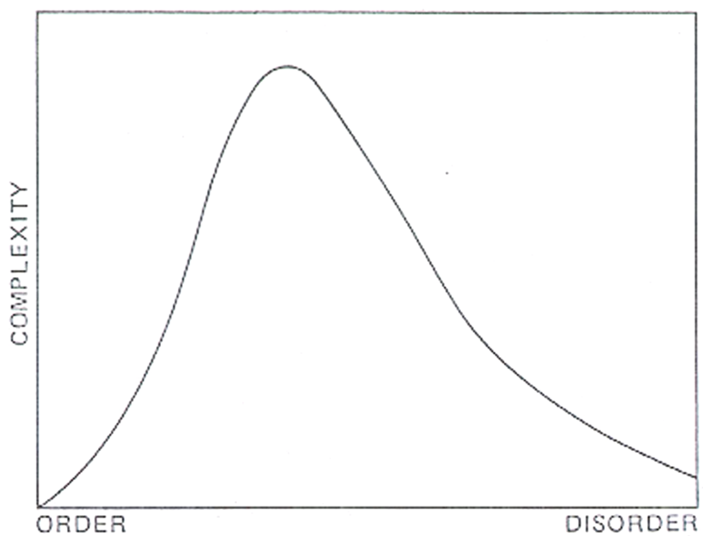
“What clashes here of wills gen wonts, oystrygods gaggin fishygods! Brékkek Kékkek Kékkek Kékkek! Kóax Kóax Kóax! Ualu Ualu Ualu! Quáouauh!”

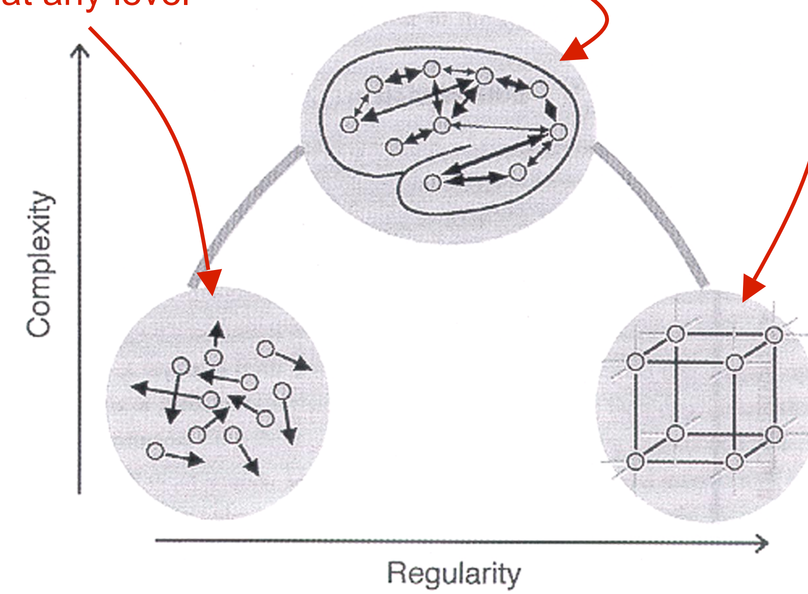
“Happy families are all alike; every unhappy family is unhappy in its own way.”

identical structure at all levels

non-repeating structure at multiple levels

randomness, no structure at any level





Reference:
B.A. Huberman and T.Hogg (1986) Physica 22D, 376.

Reference:
G. Tononi, G.M. Edelman, O. Sporns (1998) TICS 2, 474.

Integration

Integration measures the statistical dependence among all elements $\{x_i\}$ of a system X.

$$I(X) = \sum_{i=1}^{n} H\{x_i\} - H(X) \qquad MI(x_1,x_2) = H(x_1) + H(x_2) - H(x_1x_2)$$

$H\{x_i\}$ is the entropy of the i^{th} individual element x_i
$H(X)$ is the joint entropy of the entire system X

Note, $I(X) \geq 0$.
Note, $I(X) = 0$ if all elements are statistically independent

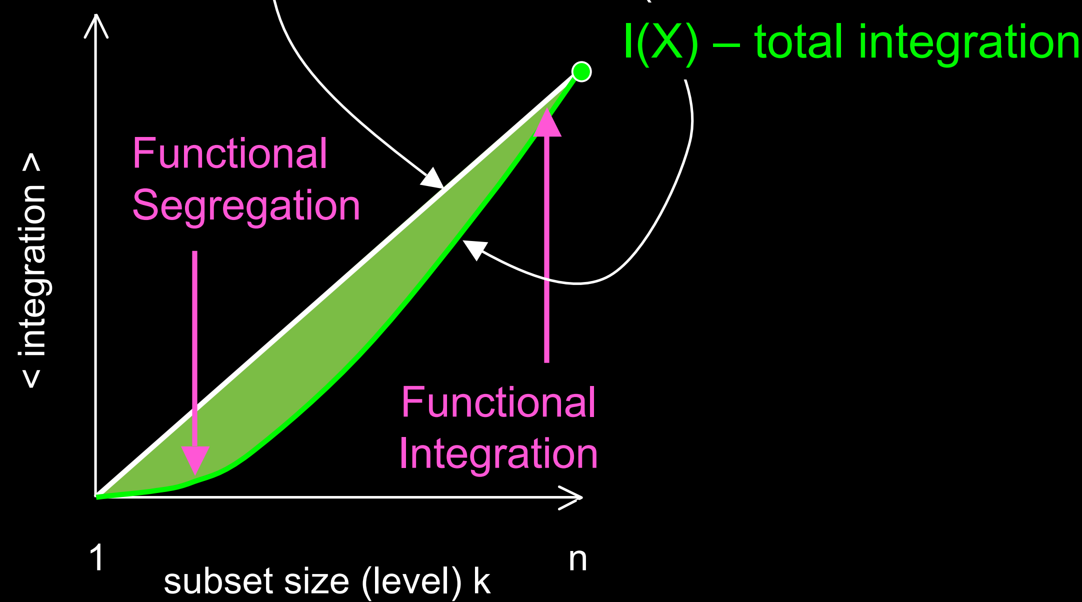
Any amount of structure (i.e. connections) within the system will reduce the joint entropy H(X) and thus yield positive integration.

Tononi, Sporns, Edelman, PNAS (1994)

Information and Complexity

- **Complexity**, as expressed in terms of the ensemble average of integration (structure) at all levels:

$$C_N(X) = \sum_{k=1}^{n} [(k/n)\, I(X) - \langle I(X_k) \rangle] \;=\; \sum_{k=1}^{n/2} \langle MI(X_k; X-X_k) \rangle$$

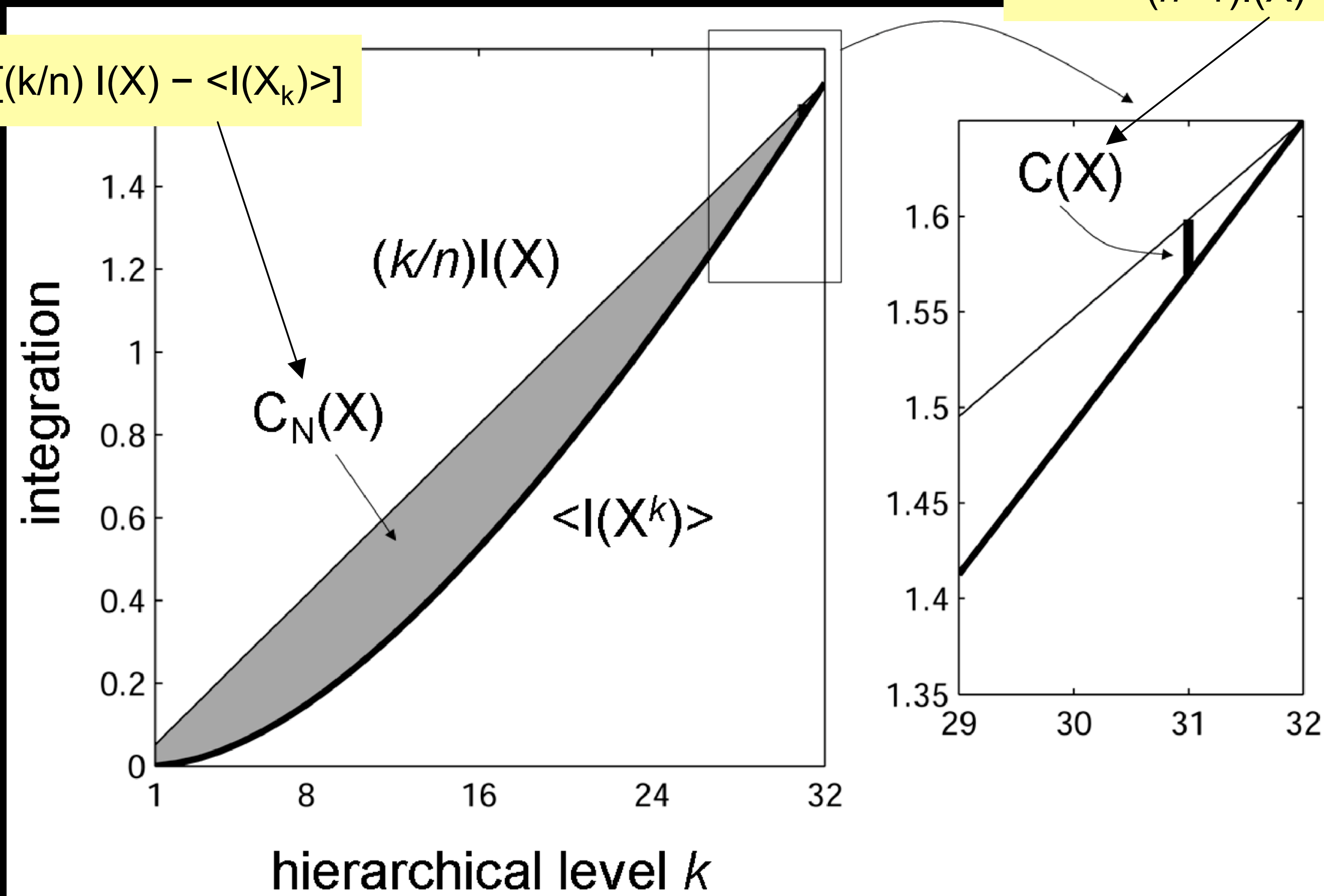


Tononi, Sporns, Edelman, PNAS (1994)

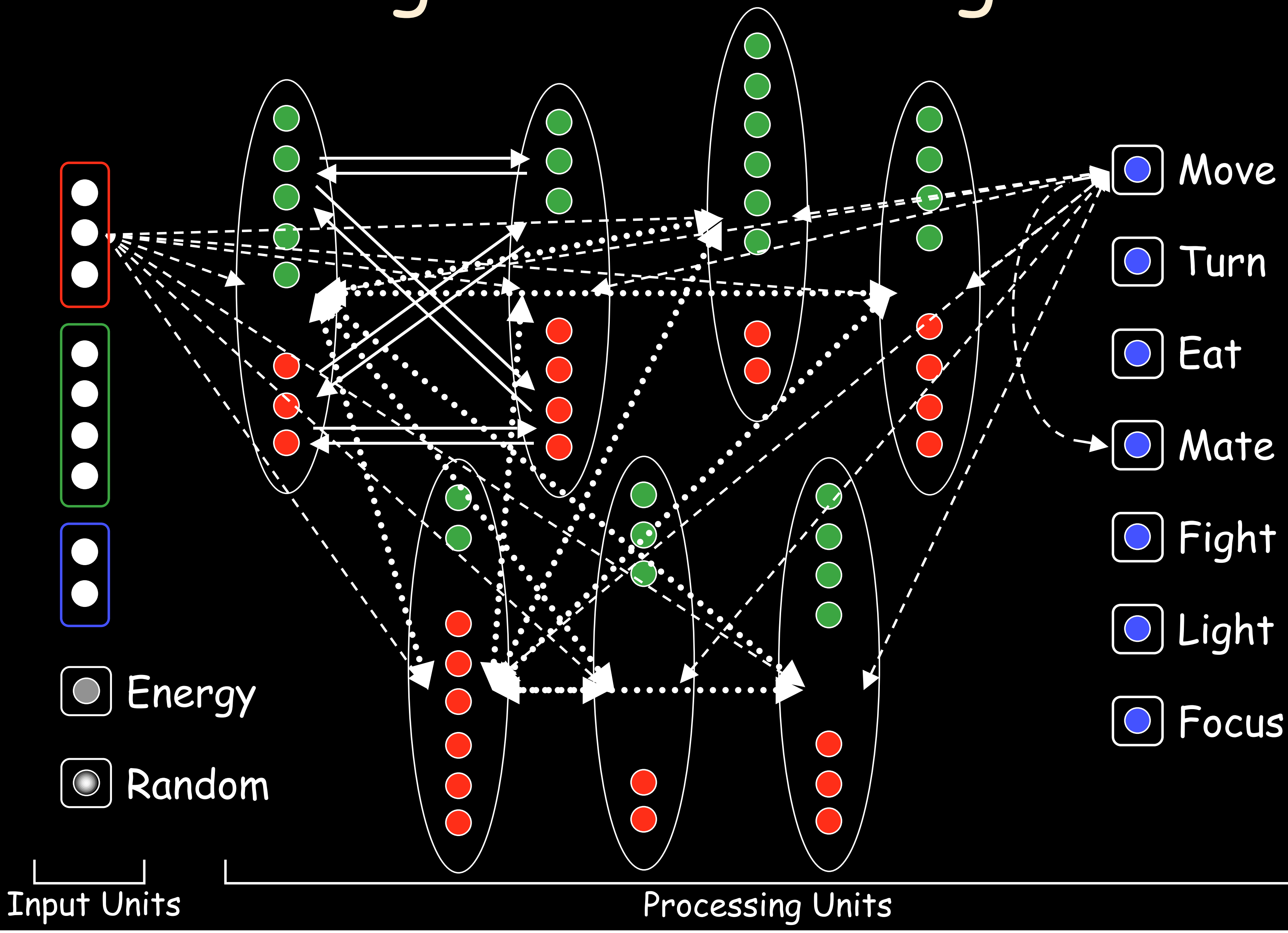
Simpler Complexity

$$C_N(X) = \sum_{k=1}^{n} [(k/n)\, I(X) - \langle I(X_k) \rangle]$$

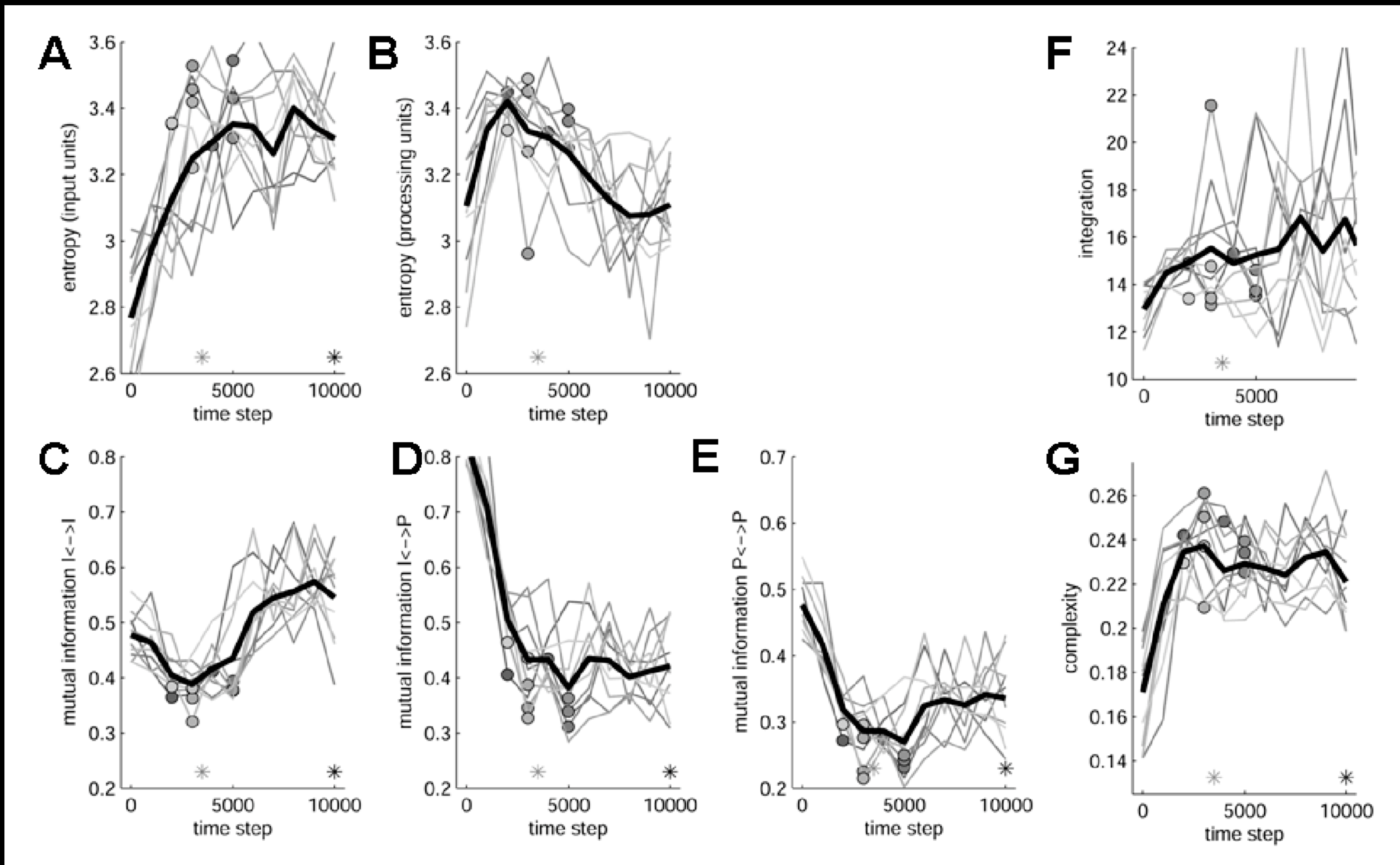
$$\begin{aligned} C(X) &= H(X) - \Sigma_i H(x_i \mid X - x_i) \\ &= \Sigma_i MI(x_i, X - x_i) - I(X) \\ &= (n-1) I(X) - n \langle I(X - x_i) \rangle \end{aligned}$$



Neural Architectures for Controlling Behavior using Vision



Evolutionary Trends in Complexity



Driven or Passive?

- Original experiments did not address the distinction between *driven* and *passive* sources of complexity
  - Established ability to compute neural complexity of Polyworld agents
  - Demonstrated increase in complexity as evolution proceeds
- Current experiments directly assess driven vs. passive contributions to complexity resulting from natural selection

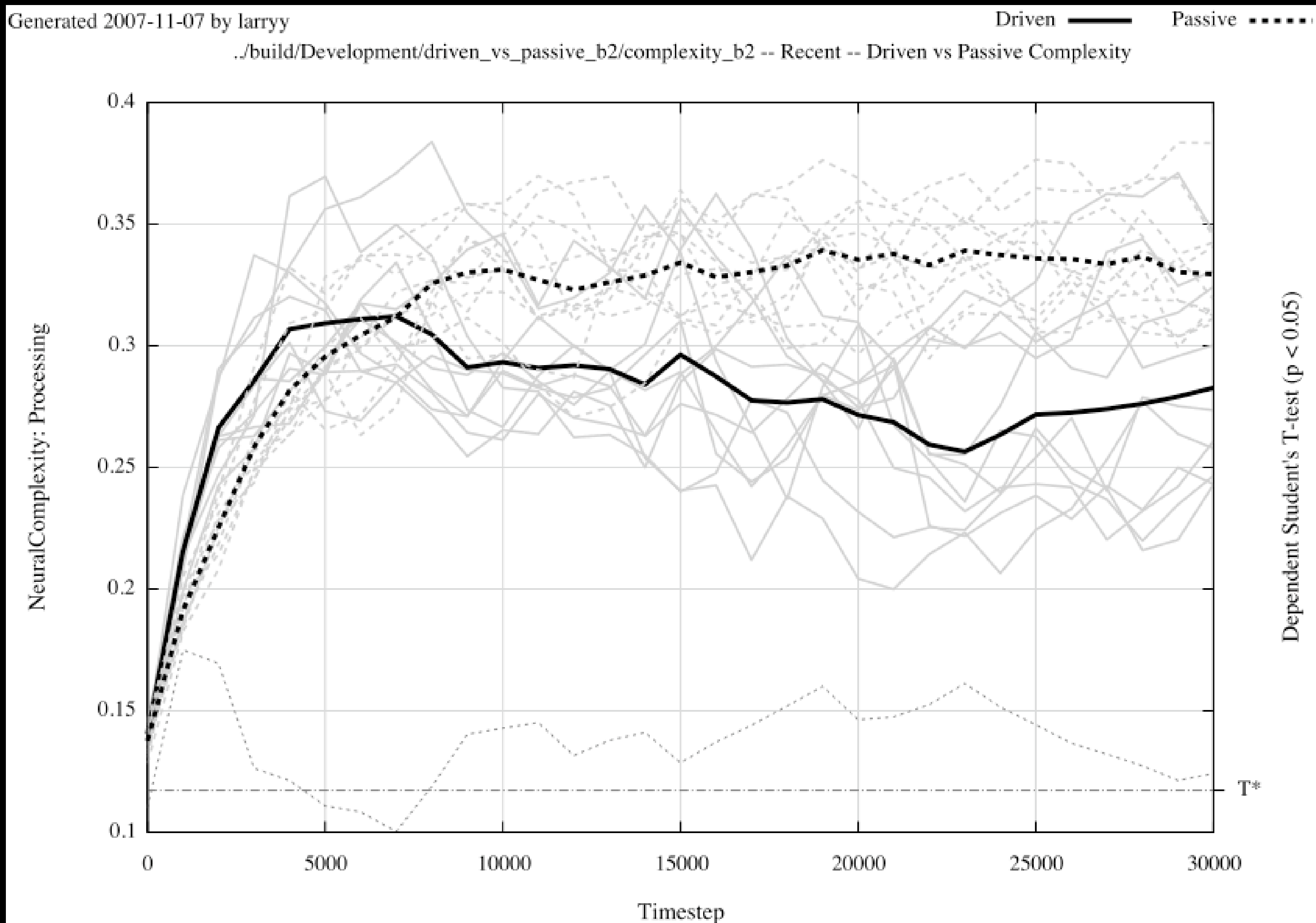
Natural Selection vs. Random Drift

- By default Polyworld agents are subject to natural selection
  - Genes are passed on as a direct result of success at survival and reproduction
- Goal: Produce a random drift of agent genes in Polyworld in a simulation that is directly comparable to a standard, natural selection run
  - Same initial conditions
  - Same population statistics
    - Same statistics for genetic mutations and crossover operations

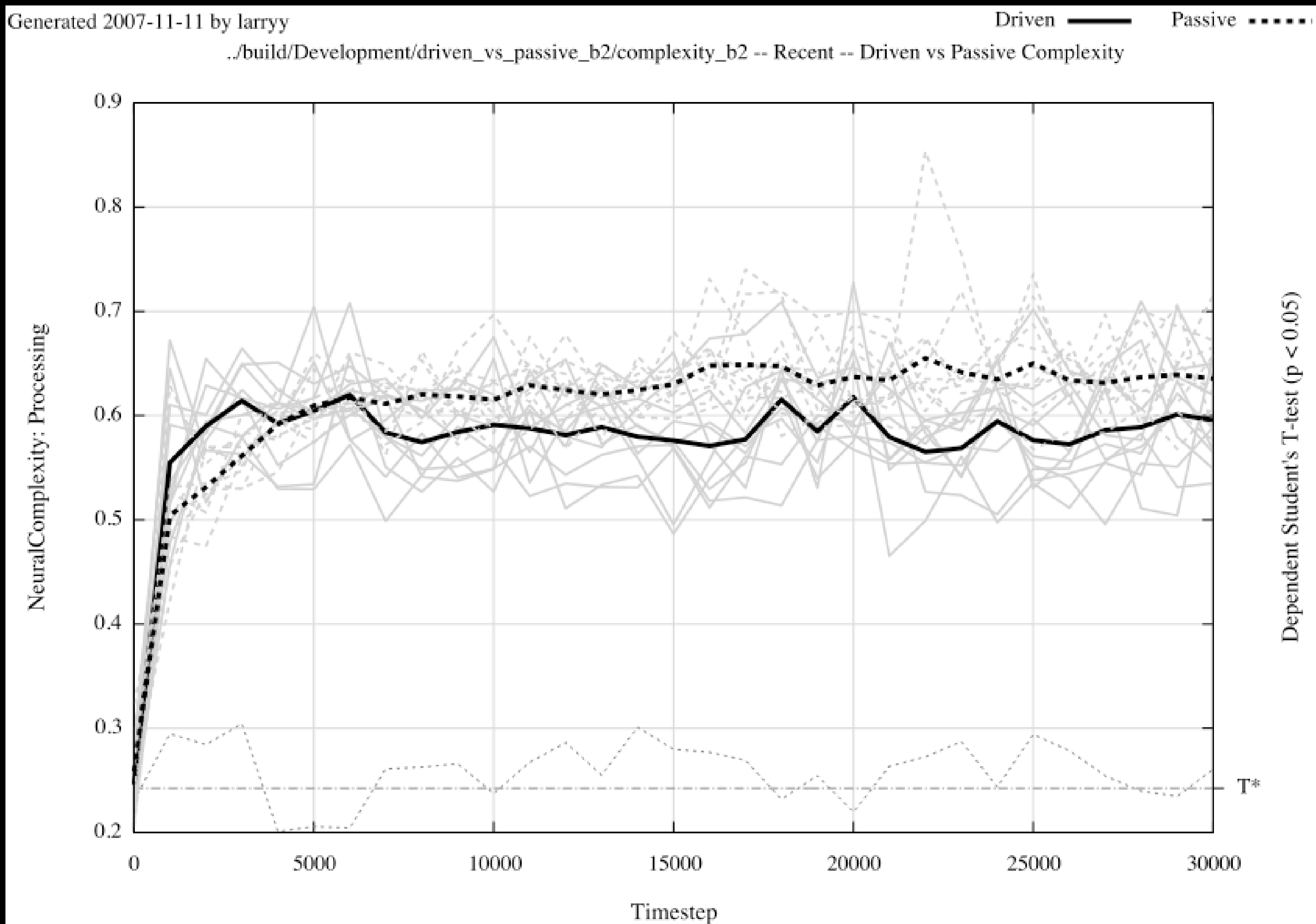
Eliminating Natural Selection

- Run standard simulation, logging all births and deaths
- Run random-drift simulation, with following conditions:
  - Use identical initial conditions
  - Eliminate behaviorally generated births and deaths
  - At each time step, for every birth in the standard run, select two parents at random and produce their offspring
    - Deposit the offspring at a random location
  - At each time step, for every death in the standard run, select one agent at random and kill it
- Produces identical statistics for population genetics and comparable visual inputs ("life experiences") to agents in the two simulations
- Natural selection no longer affects gene histories

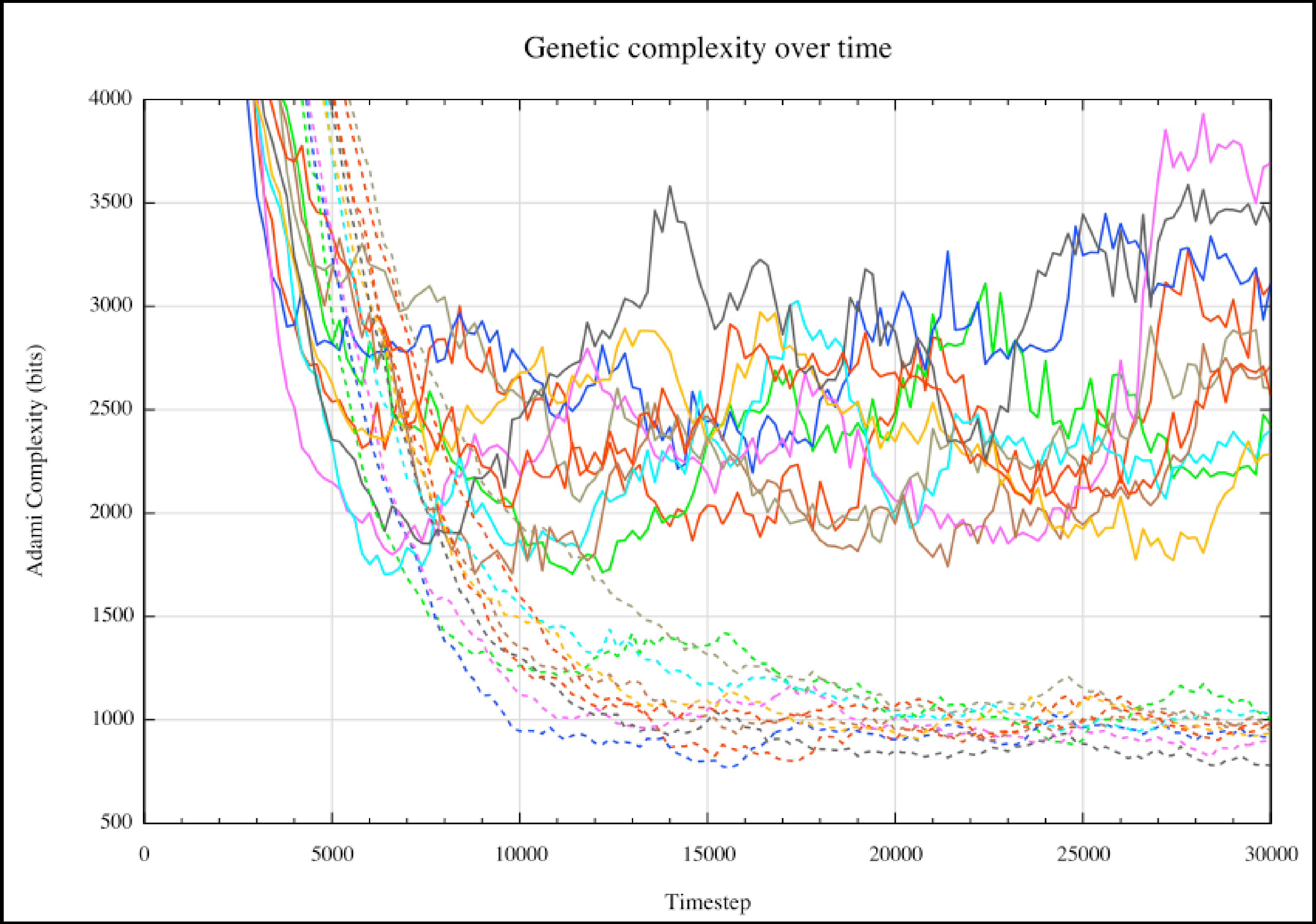
Driven vs. Passive Mean Complexity

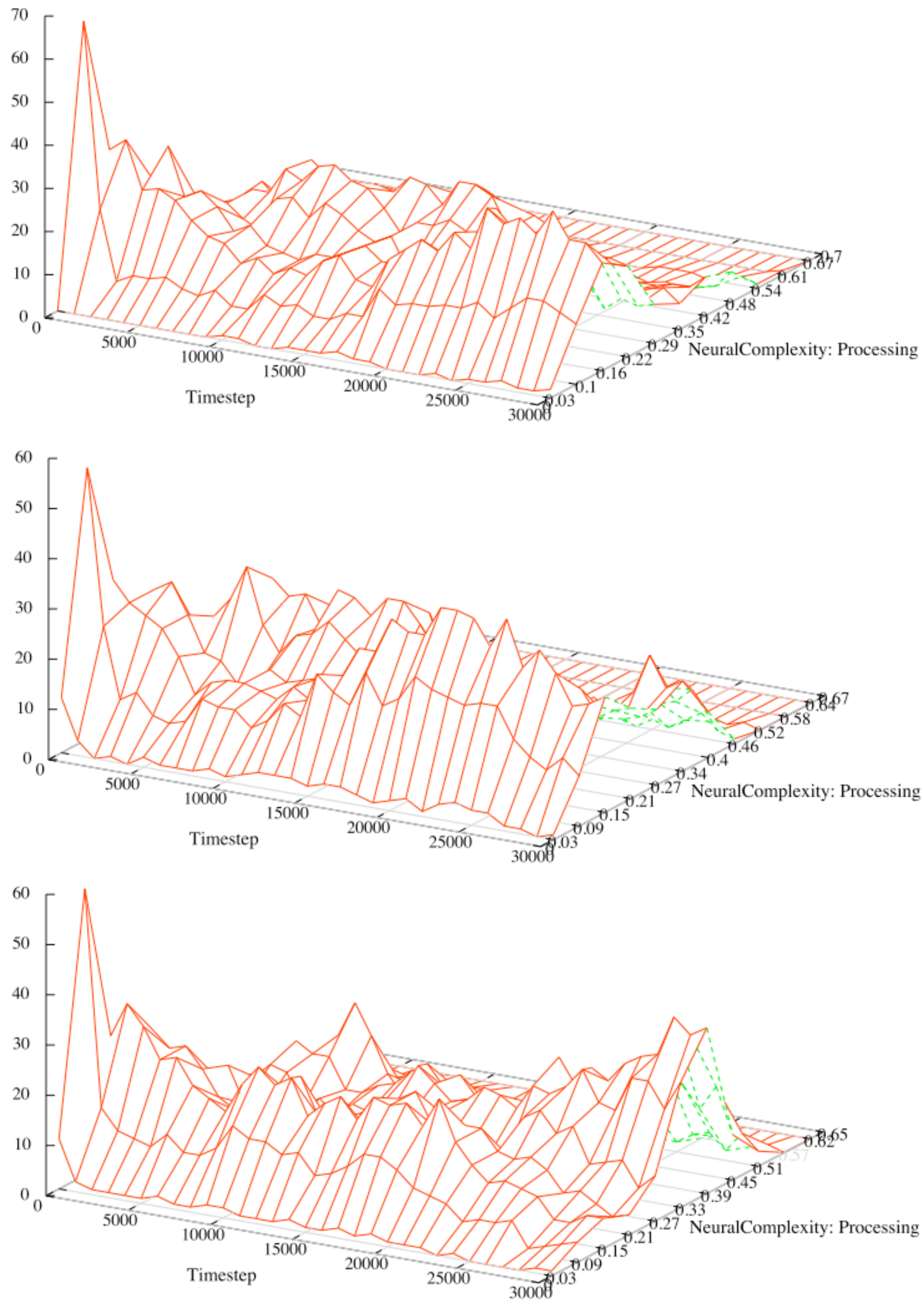


Driven vs. Passive Max Complexity



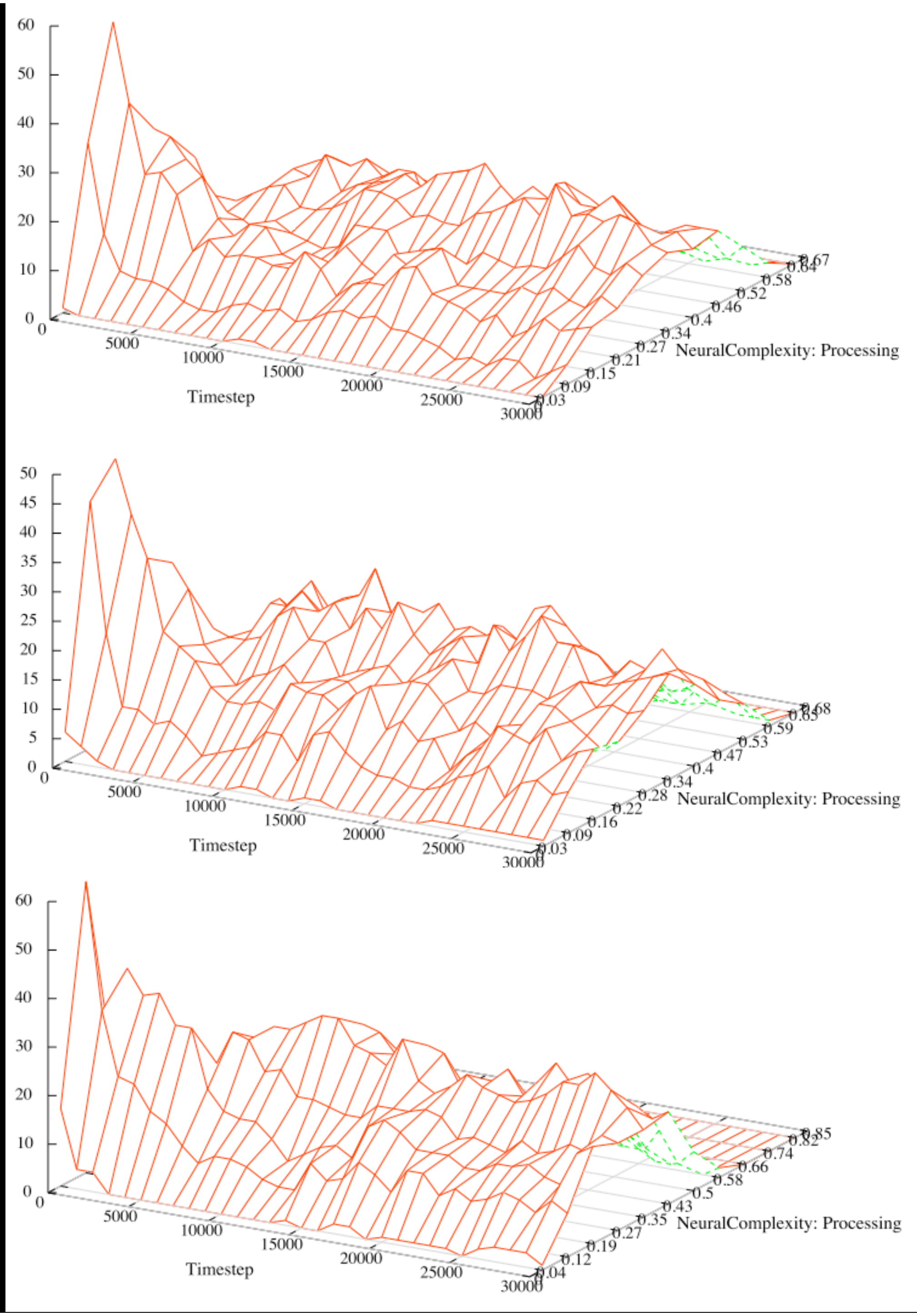
Genetic Similarity





Complexity Histogram Over Time - Driven

Complexity Histogram Over Time - Passive



Conclusions

- Evolution selects FOR a complexity increase when it enhances the ability to survive and reproduce
- Evolution selects AGAINST a complexity increase when existing characteristics are "good enough"
- Framing the question of an evolutionary progression of complexity in terms of driven vs. passive is helpful, but the two forces are not mutually exclusive
  - Nor does evolution "drive" in just one direction
- Conflicting evidence for complexity growth in the biological record is to be expected
- Seemingly conflicting intuitions about a clear evolution of complexity in the paleontological record vs., for example, the longevity of the cockroach and its extreme suitability to its ecological niche are not actually in conflict

Speculation

- Though current experiments effectively explore complexity dynamics only in a single niche, for hardly more than a single species…
  - Multiple niches, niche creation, and potential arms races associated with competition within a niche are all likely to confer an evolutionary advantage on at least some complexity increases
  - Inherently more complex niches will require *greater* biological complexity
    - All niches are *not* created equal
  - Increasing the complexity of Polyworld's ecology—the range of organism-environment interactions and available niches—will allow a measurable selection towards *greater* neural complexity

Evolution of Neural Complexity

Polyworld source code for Mac/Windows/Linux (on Qt):
http://sourceforge.net/projects/polyworld/

Polyworld technical papers:
http://www.beanblossom.in.us/larryy/Polyworld.html

Complexity paper and MATLAB toolbox:
http://www.indiana.edu/~cortex/intinf_toolbox.html

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