On the logical relationship between natural selection and self-organization:
optimizing processes of adaptation

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Premise

- Most contemporary evolutionary biologists recognize only one process that can guide evolutionary change in an adaptive direction; natural selection (NS)
- Self-organization (SO) in complex adaptive systems (CAS) represents an alternative and compelling perspective on adaptive evolution, but it is largely dismissed by evolutionary biologists.

Natural Selection

- Definition: a process that adaptively biases the evolution of a population so as to optimize the functional abilities of its components, given heritability of fitness differences.
- NS maximizes the rate of fitness increase
  - Maximization is a tendency to increase that generates optimizing processes
    - e.g. NS on organisms optimizes genomic architecture to maximize fitness
- NS requires processes of birth and death in a population of entities (e.g., individuals).
- If NS is to persistently drive evolution, it also requires a process of (creative) mutation.

NS and Natural Teleology

- Organismal processes are designed by NS *for the sake of organismal fitness*
  - NS causes adaptation
- NS without adaptation is not a viable (self-sustaining) process
  - e.g., if the environment changed so rapidly that previously adaptive phenotypes would be maladaptive in subsequent generations
- Therefore NS is inherently teleological
  - the process and the purpose cannot be separated

Self-Organization

- Definition: "pattern formation…through interactions internal to the system, without intervention by external directing influences." (Camazine et al. 2001)
- A THERMODYNAMIC PERSPECTIVE: SO systems maximize the rate of entropy gain in the universe at large
  - Primary credit for this perspective goes to Prigogine, although he never stated this position conclusively

Physical Potentials

- Potential for emergence of SO systems exists wherever there are sufficiently concentrated spatial gradients in free energy.
  - Called *voltage* when dealing with electrical energy
- The function of SO systems is to channel the flow of energy across the gradient, thus reducing the steepness of the gradient and increasing entropy at a scale larger than the system itself.
  - Lightning reveals the structure of channels that emerge for the flow of electrical energy in the atmosphere

Self-Organization and Optimization

- Like NS, SO can be an optimizing process (Helbing and Vicsek. 1999. Optimal self-organization. arXiv:cond-mat)
  - Tornado in a bottle demo
  - Weather systems (vortexes and convection)
- SO leads to "autonomous adaptation to a changing environment." (Heylighen. 1999. EOLSS online encyclopedia)

Adaptation of Physical Systems

- Clausius (1850) articulated the 2nd Law of Thermodynamics at about the same time as Darwin and Wallace articulated NS.
  - Entropy (disorder - absence of pattern, homogeneity) must always increase in closed systems, including the universe as a whole
- The 2nd Law as a maximizing process
  - Tendency to increase
  - Basis for optimizing processes that promote global entropy increase
  - Systems that originate in response to this optimizing imperative are called dissipative structures (Prigogine) or Complex Adaptive Systems (CAS)

The Similarity Between NS And SO Is Striking - Relationship?

- Both yield adaptation and functional optimization
- Perhaps some (most?) biological adaptation is better understood as a consequence of SO than NS
- This point has been a central theme of several notable authors (e.g., Kauffman), yet the field of evolutionary biology has not acknowledged this possibility.

Why The Reticence?

- Emphasis has been placed on showing what SO can do, and arm-waiving about its relationship (threat) to NS.
  - Despite compelling scientific work on SO systems, it still appears to many that it relies on magic (reductionist tradition).
- A consensus has not emerged among those focused on SO regarding its relationship to NS.
- Evolutionary biologists are wary of the potential for false refutation of deeply embedded Darwinian principles of biological evolution.

Some Views On This Relationship

- “Evolution … is emergent order honored and honed by natural selection”
  - - Kauffman ‘93
- “Natural selection does not have a lot to do except act as a coarse filter that rejects the utter failures.”
  - - Goodwin ‘94

- “We have documented that ecological processes are driven and governed by thermodynamic imperatives... We believe that these same principles extend to Darwinian selection.”

  - Schneider and Kay ‘94

- “it is obvious that thermodynamic considerations must be one of the priorities of natural selection.”

  “Living systems must … submit to the ultimate ‘censorship’ of natural selection.”

  “a fully adequate theory of evolution must encompass both self-organization and selection.”

  - Corning ‘95

- “natural selection … is not free to evolve any organism, but it is constrained by the self-organizing properties of the materiality of the organisms it acts upon”
  - - Rocha ‘98
- The work of Carlson and Doyle suggests that natural selection (and other sources of engineering) results in structural design that constrains or guides the process of self-organization.
  - - *my words*

- “In biological systems, self-organization reveals itself as a powerful mechanism used by natural selection for the creation of diverse regulatory and morphogenetic processes.”

  - Camazine website

- “I like to compare evolution to weaving of a great tapestry. The strong unyielding warp of this tapestry is formed by the essential nature of elementary non-living matter, and the way in which this matter has been brought together in the evolution of our planet. In building this warp the second law of thermodynamics has played a predominant role. The multicolored woof which forms the detail of the tapestry I like to think of as having been woven onto the warp principally by mutation and natural selection.

- While the warp establishes the dimensions and supports the whole, it is the woof that most intrigues the aesthetic sense of the student of organic evolution, showing as it does the beauty and variety of fitness of organisms to their environment. But why should we pay so little attention to the warp, which is after all a basic part of the whole structure? Perhaps the analogy would be more complete if something were introduced that is occasionally seen in textiles – the active participation of the warp in the pattern itself. Only then, I think, does one grasp the full significance of the analogy."

  - Blum (1968) quoted in Scheider and Kay '94

Where is the gradient channeled by life?

- Vertical temperature gradients in the atmosphere would not be so steep if the earth did not spin relative to the sun.
- If the earth did not spin, weather would only occur at the interface of the light and dark sides, and it would be very different.
- Earth's weather systems promote the transfer of solar energy captured on the sunny side into space in the earth's shadow.
- Weather partly reduces the massive energy gradient caused by the earth's shadow.

Life increases the transparency of the earth to solar radiation.

- Life, too, captures solar radiation and releases it into the earth's shadow.
  - roughly 10^{10} more efficient than weather on a per photon basis.
- If we accept that the purpose (or function) of weather is to diminish the energy gradient caused by the earth's shadow, then this could also be the purpose of life.
- A smaller potential also exists due to thermal radiation from the earth itself.
  - Hydrothermal vent species rely on thermally induced chemical energy sources
  - Might have been the gradient on which original life fed, but recent evidence suggests that current vent species are all recently derived from species that rely on solar energy sources ('sink gradients' that cannot sustain life for long?)

Do NS and SO really optimize different criteria?

- The definitions of the terms suggest that a primary distinction between the concepts, if not the actual processes, is that different criteria are optimized.
  - NS optimizes fitness
  - SO optimizes energy flow across a gradient
- How much do these criteria overlap?
  - Substantially; both require consumption of energy and a reduction of free energy to create structure and function.
- Can they conflict?

Coarse Grains

- As with all emergent structures, organisms can be "atoms" of interaction, thus making thermodynamic processes more coarse grained in space.
  - Entities smaller than organisms (RNA, DNA, proteins) characterized the maximum sizes of particles interacting in the prebiotic 'soup'.
  - Coarseness of the grains can be tuned through evolution of body size
- Recall that NS requires a birth/death process, while SO does not. This creates temporal quanta.
  - Coarseness of these grains can be tuned through evolution of generation time.

Coarse Grains and Stochastic Creativity

- Coarser grains mean smaller interacting sets and increased stochasticity.
- "While large noise generally destroys self-organized solutions, *small noise can further self-organization*" (Helbing and Vicsek, 1999)
  - Note that NS does not lead to adaptation if the mutation rate is too high or too low.
- There are thermodynamic advantages to be had if the noise level can be tuned, so the origin of the birth/death process could be a consequence of thermodynamic imperatives.

Adaptation Of A Population vs. Acclimation Of An Entity

- Biologists traditionally make a gross distinction between these two processes.
- Adaptive phenotypic plasticity has been considered a product of NS.
- However, ecologists have often recognized that ecosystems evolve in a coordinated (adaptive) fashion (e.g., niche theory, food webs, GAIA) due to NS-driven co-evolution.
- Perhaps NS at one level of organization is a mechanism of SO at a higher level of organization.

Synthesis: NS as an Emergent Process

- The concept of emergent structure (e.g. a vortex) is inherent to the notion of SO systems.
- But the physics of dissipative *structures* is impossible to separate from the *process* of energy processing that continually generates the structure.
- The concept of emergent processes is less familiar, but must go hand-in-hand with emergent structures.
- I suggest that NS is an emergent process founded on thermodynamic imperatives.

An Analogy and Some Implications

- NS is to SO as language is to communication
- This implies that NS
  - is a mechanism of SO
  - facilitates the goals of SO
  - is a subset of SO mechanisms
  - is a manifestation of SO when replicators are present
- It is also consistent with the claim that NS takes advantage of the SO tendency of component systems (e.g. the complexity of development)
- It is NOT consistent with claims of conflict, competition, subordination between SO and NS.

An empirical research program?

- New theories, or theoretical paradigms, must be amenable to empirical testing if they are to have real scientific value.
- Because the viewpoint I have expressed is so well grounded in physics, it should be able to generate many empirically testable hypotheses.

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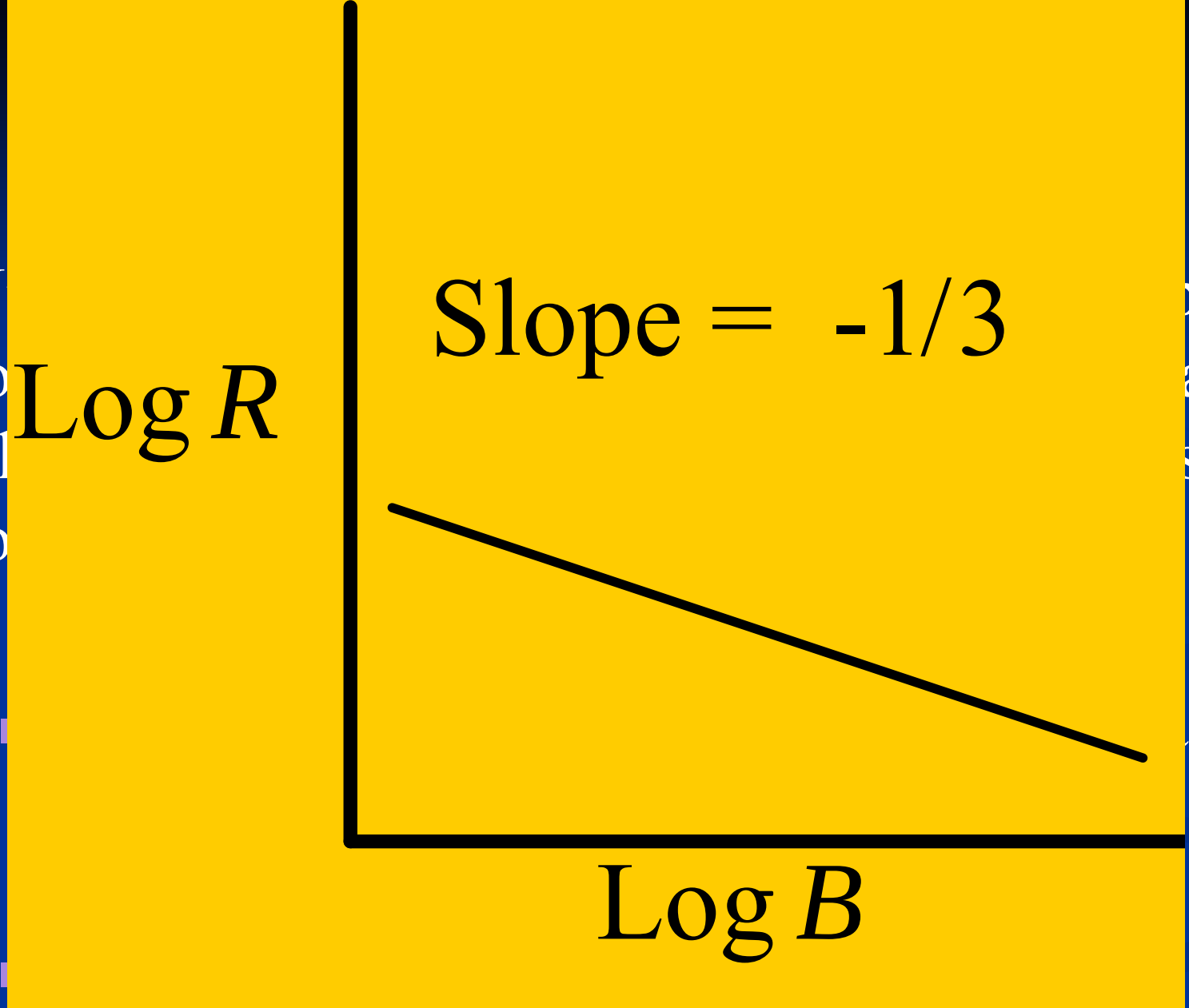


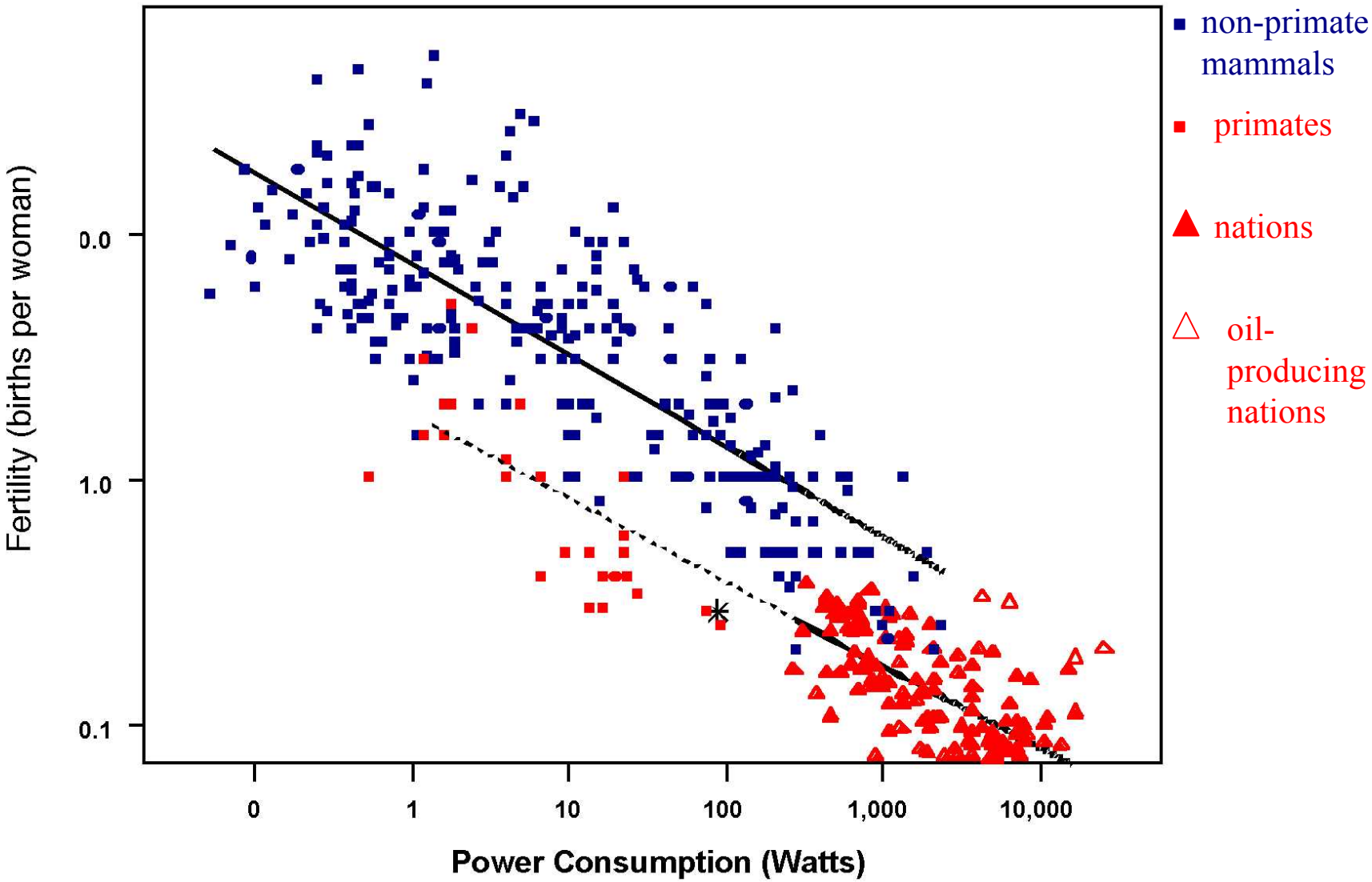
- Therefore

$$R \propto B^{-\frac{1}{3}}$$

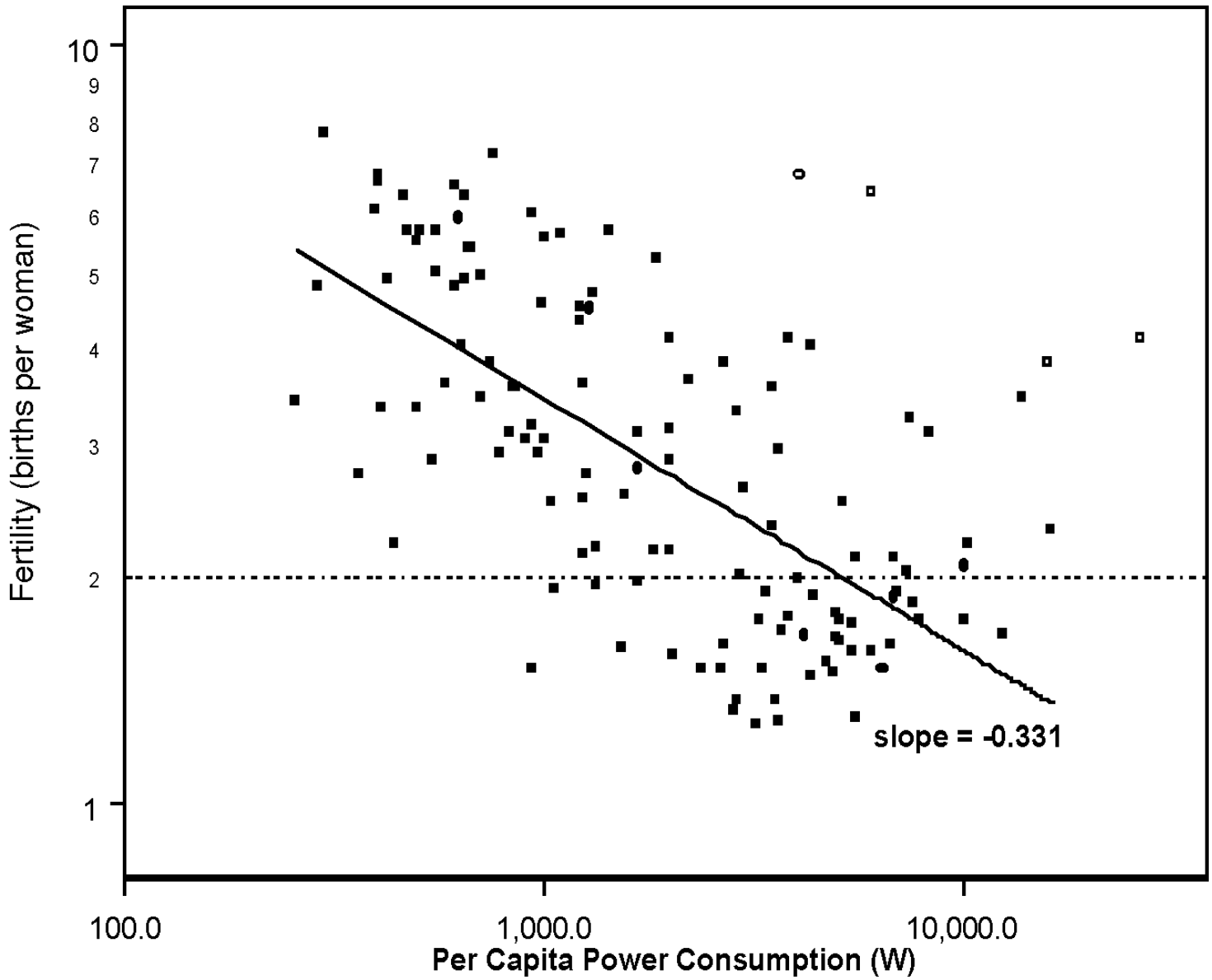
Moses and Brown MS

- Jim Brown and his student Melanie Moses thought it would be interesting to test this relationship with the 'ordinary' biological rate of reproduction.
- They specifically tested the hypothesis that lifetime reproductive success (≈ fitness) should scale like

$$W \propto B^{-\frac{1}{3}}$$



From Moses and Brown MS


Fertility (births per woman)
10
9
8
7
6
5
4
3
2
1
slope = -0.331
100.0
1,000.0
10,000.0
Per Capita Power Consumption (W)

Tentative Conclusions (hypotheses, really)

- NS is an emergent process driven by the thermodynamic imperative.
- NS can cause elaborate co-evolutionary dynamics that optimize fitnesses, but the consequence of NS among lineages within a co-evolutionary system is to optimize the flow of energy through the system as a whole.
- It does not invalidate any of the science relating to NS done over the past 150 years.
- Ultimately, the theory of SO systems provides a more general context in which to understand NS.

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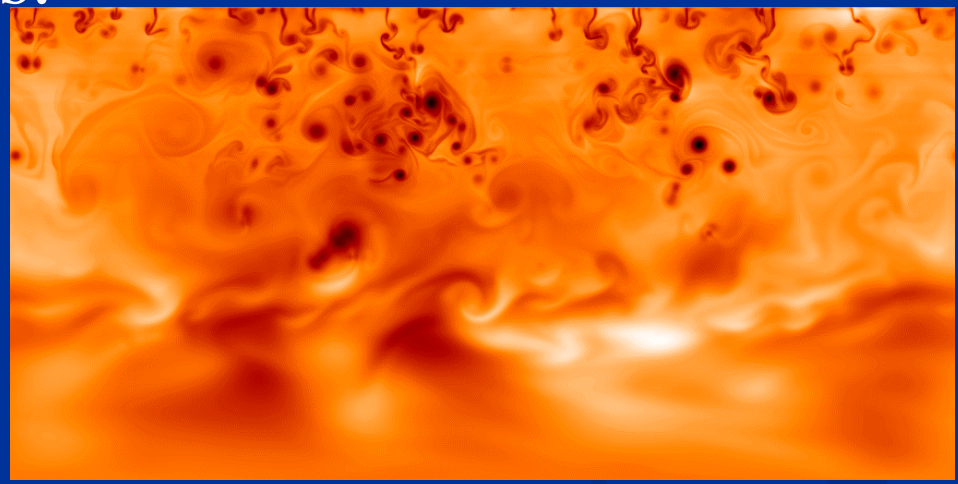
Where Is The Population In A Self-Organizing System?

- SO systems are composed of interacting components (i.e. populations), even though they constitute single entities.
- Consider the model SO system of a convection cell.



- Many convective cells are initiated (~ mutation?), but few proliferate and become stable, functional attributes of the system.