
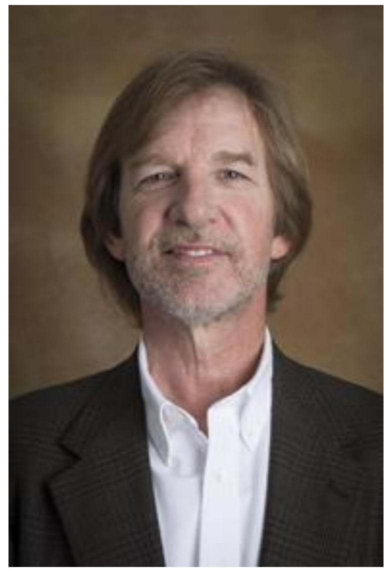

Energy and Evolution: The Systems Approach

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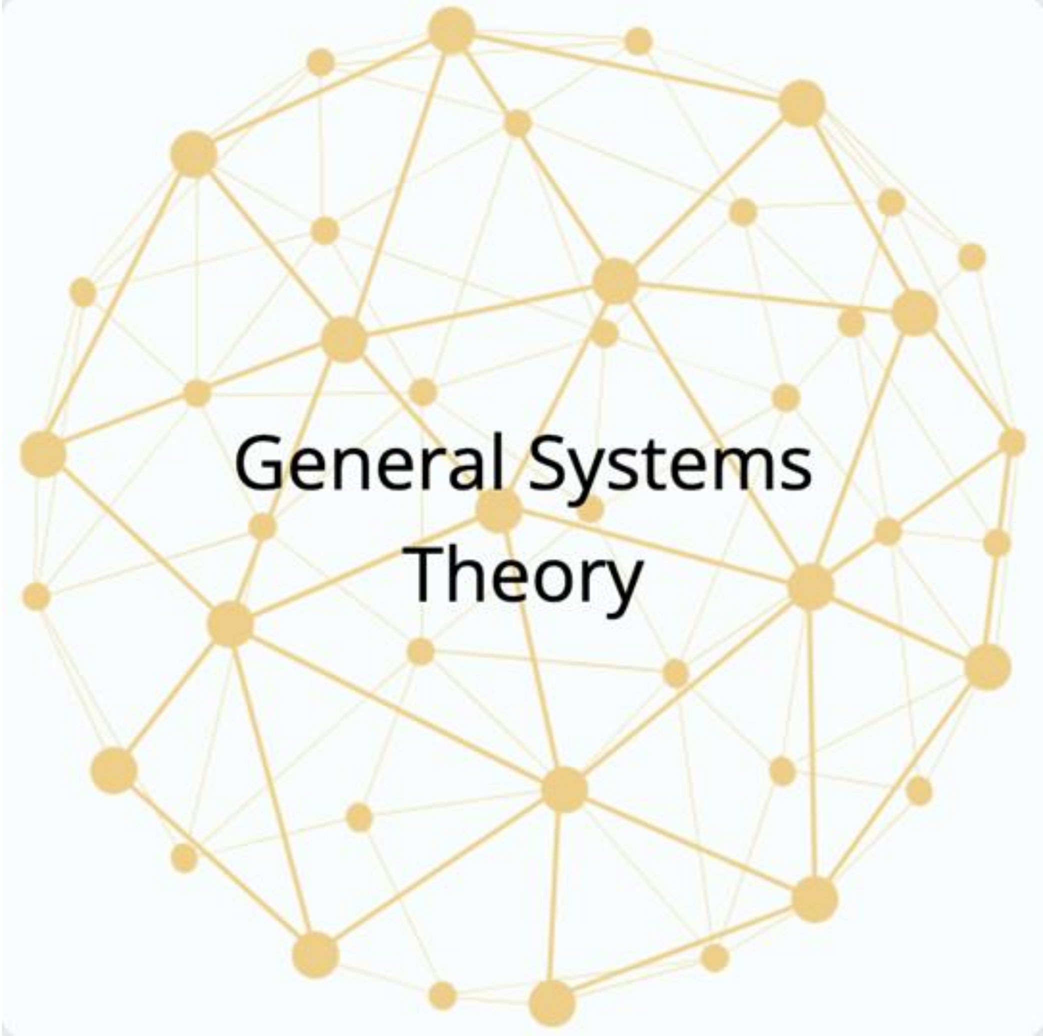
Our Presentation

- The network approach to thermodynamic evolution developed by Sven Jørgensen et al.
- The systems approach latent in H. T. Odum's work.
- Alfred Lotka's Principle of Maximum Energy Flux (PMEF).
- Odum's Maximum Power Principle (MPP).
    - Its relation to the principle of natural selection.
- An advantage of Odum's systems approach.
- A brief summary of our book project.



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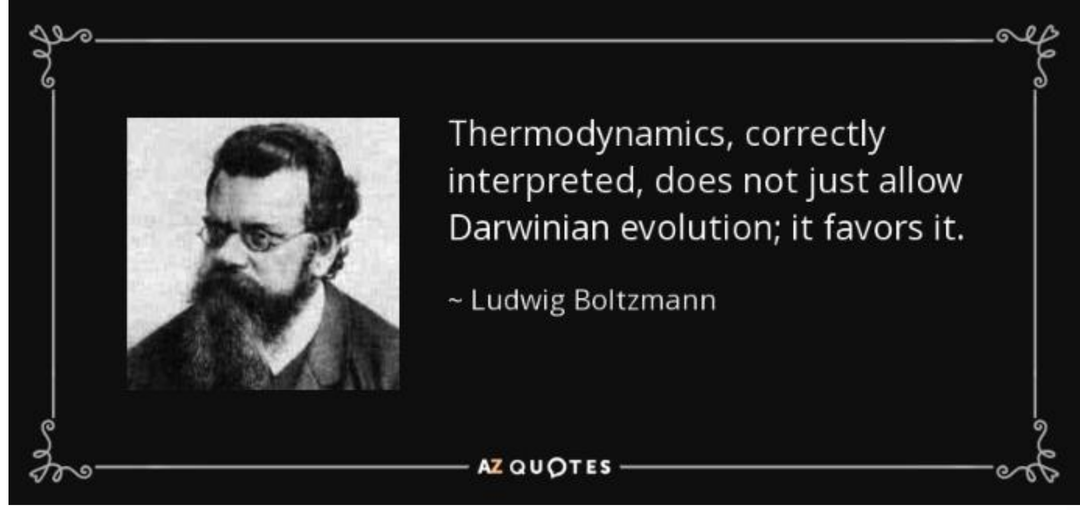
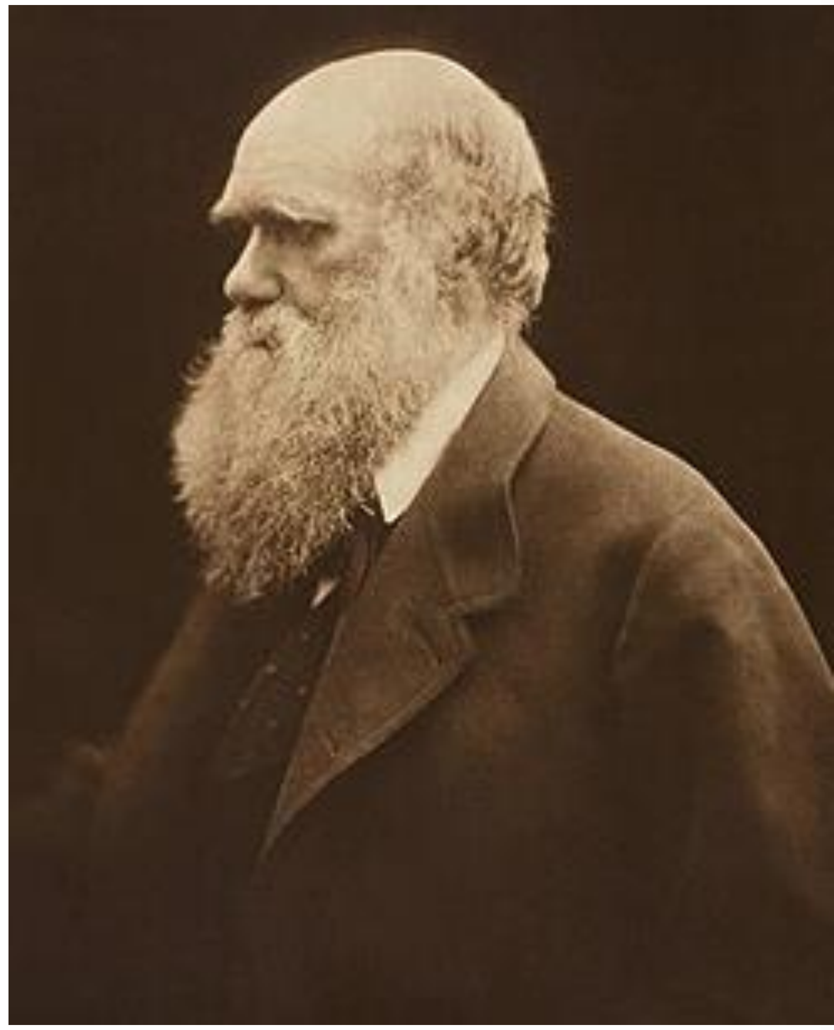
What guides thermodynamic evolution?

Optimality Principles *or* ***Goal Functions***



The Principle of Maximum Energy Flux (Lotka 1922a)
The Minimum Entropy Production Principle (Prigogine & Wiame 1946)
The Maximum Power Principle (Odum & Pinkerton 1955)
The Maximum Entropy Production Principle (Paltridge 1975)
Energy Return on Investment (Hall et al. 1986)
The Constructal Law (Bejan & Zane 1996)
The Equal Fitness Paradigm (Brown et al. 2018)
The Maximum Efficiency Principle (Glazier 2024)
Maximum dissipation
Maximum reproduction
Maximum complexity (Lotka 1945)

maximum diversity
maximum profit
minimum heat
maximum stability
maximal energy dispersal
maximum ascendancy
maximum storage
maximum cycling
Maximum biomass



- *Collectively these principles have been described as being "**contradictory**," referring to "**apples and oranges,**" and "**local, and disunited**"* (Bejan & Lorente 2010, 2011).

The Discussion of These Optimality Principles

- Many scientists have ***championed their principle of choice*** and argued that it is more "accurate" or more "general" than the other principles (Glazier 2024; Salthe 2010; Bejan & Lorente 2010; Brown & Burger 2024).

- In many cases, they have used ***strawman arguments***, which undermine our ability to accurately understand the relation between these principles. There are two reasons for this problem:

  1. ***Complexity*** -- Many of these principles are deceptively complex (e.g., Sciubba 2011).

  2. ***Fragmentation*** -- The exponential growth of scientific research described by these optimality principles has made it increasingly difficult for scientists to keep up with relevant developments.

     - Chapman et al. write we "found evidence of a ***highly fragmented*** and disjointed historical development of the maximum entropy production principle (MEPP) and therefore of its impact on MEPP studies in ecosystem ecology and ecology in general" (2016).

     - Martyushev, L.M., Seleznev, V.D. wrote publications on the MEPP "were ***fragmented*** and different research teams … were unaware of studies performed by other scientists" (2006).

     - In 2023, A Paleoecologist named Vermeij wrote a book entitled *The Evolution of Power: A New Understanding of the History of Life* and does not mention Odum's maximum power principle or Lotka's principle of maximum energy flux. The ***Vermeij discipline*** of the ***maximum power principle department*** of the ***natural selection division*** of the ***thermodynamic school*** of evolution.

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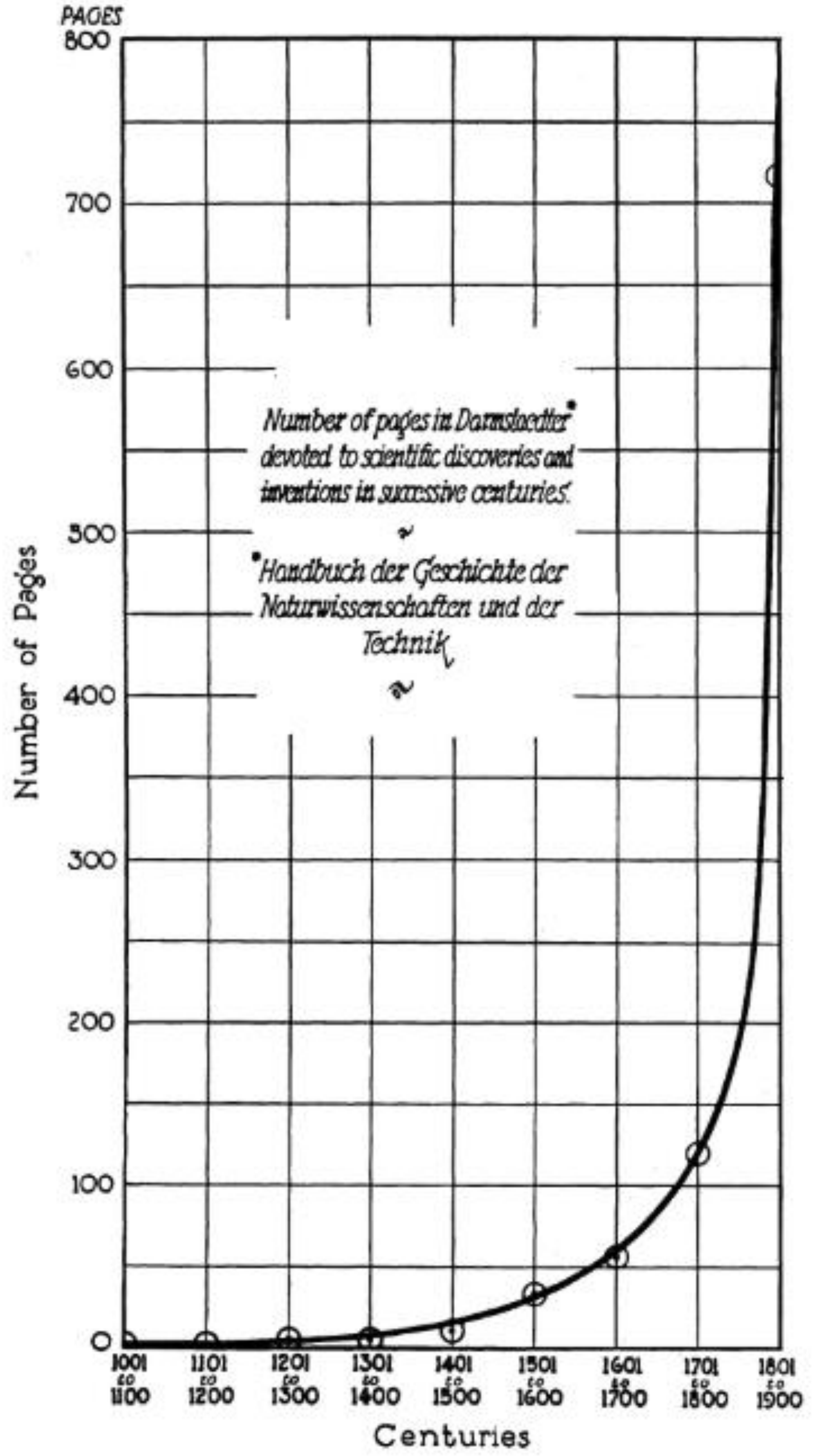
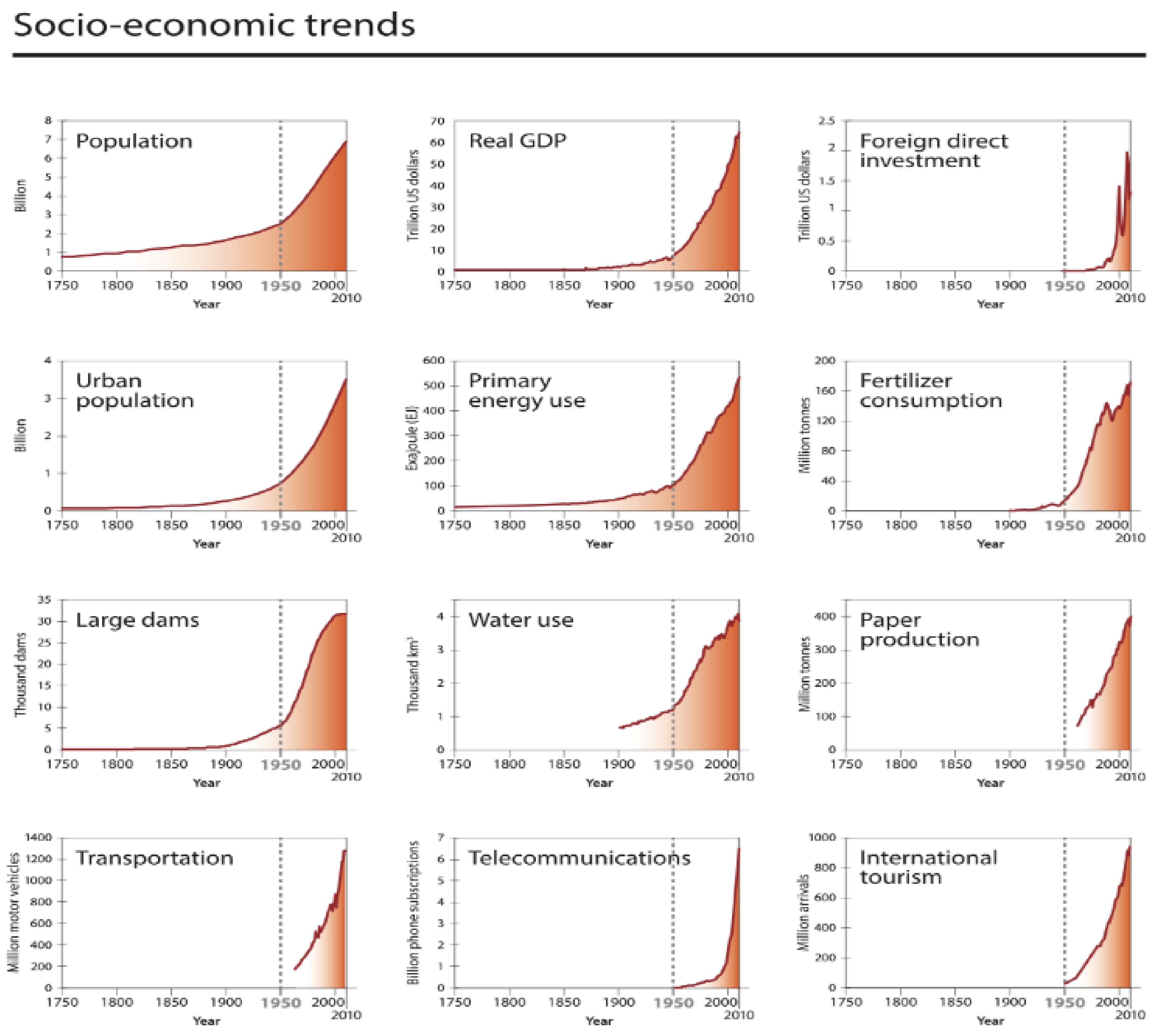


Fig. 4. Growth curve of human knowledge.



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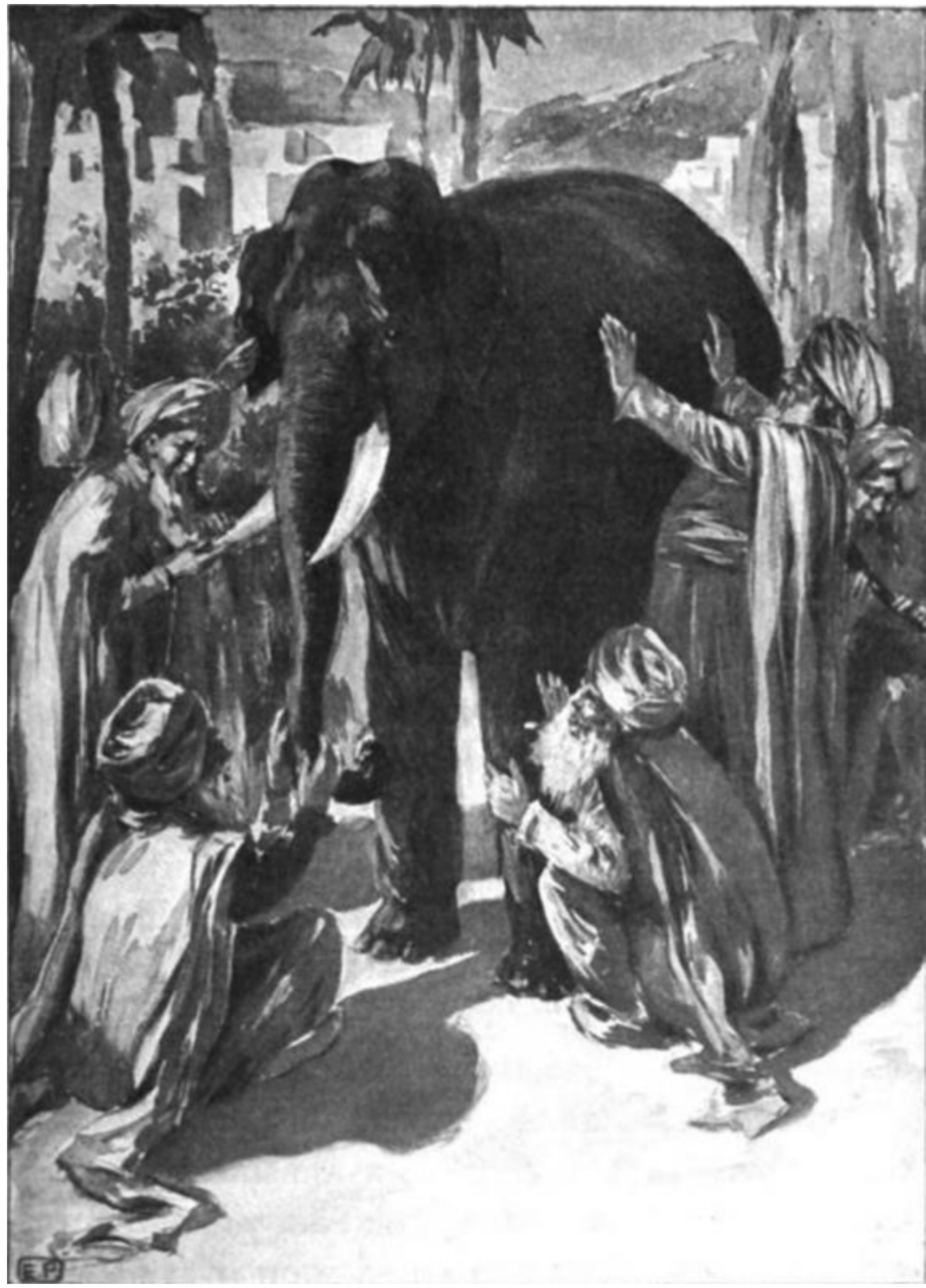
The Optimality Principles

- Focus on ***different parts*** of the process of evolutionary development:
  - The maximization of power, the production of entropy, the persistence of biodiversity, the evolution of design…
- These principles provide an ability to predict, and in some cases, explain the phenomena in these parts of the process. But each principle only provides a partial picture of the evolutionary process.



The parable of the blind men and the elephant

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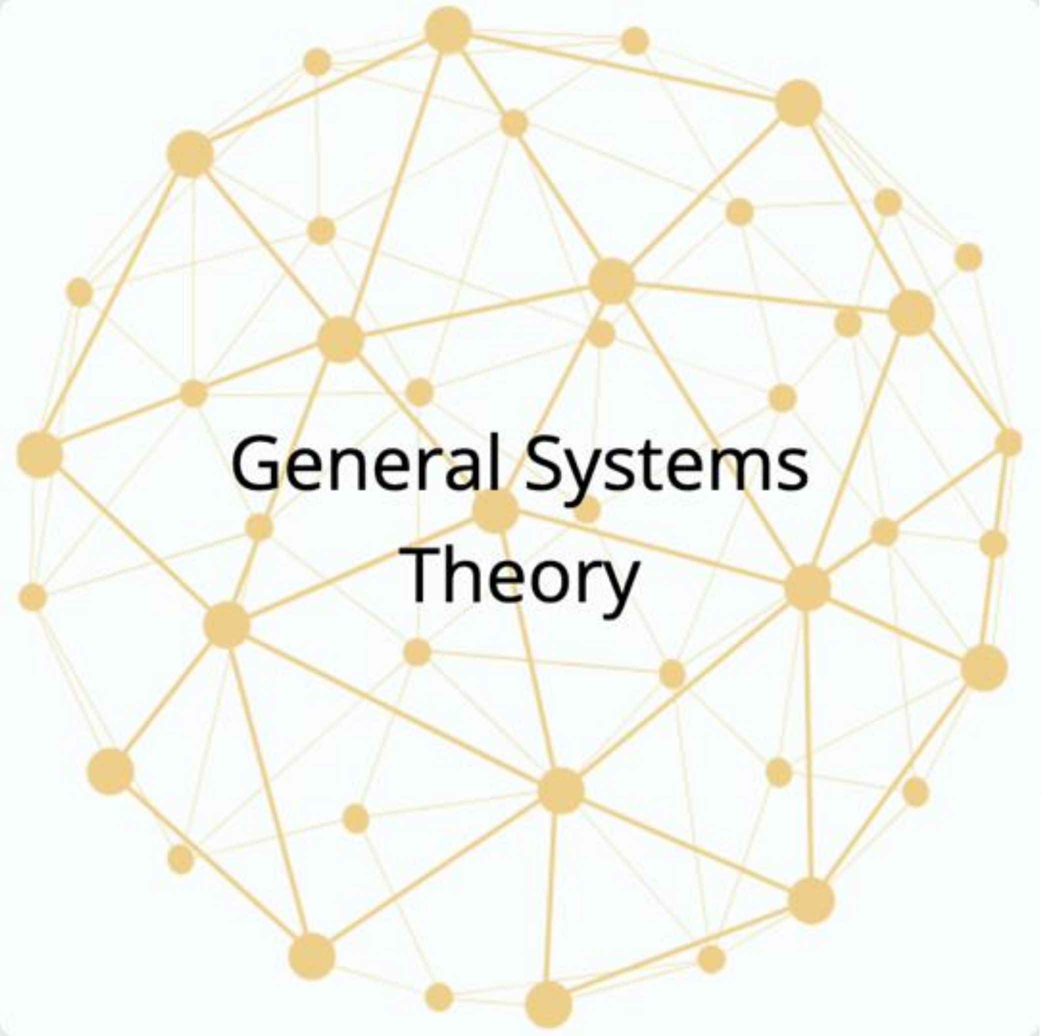
The Network Approach

- A group of scientists has focused on illustrating how these optimality principles work together as a network. (Jorgensen 1992, 1994, 2001; Jorgensen et al. 1998, 2007,2011, 2014, 2016, 2020; Patten 1995; Fath et al. 2001).
  - They view the evolutionary process as a complex system with many different parts that are ***connected by a web of relationships*** (Banathy 1997).
  - Jorgensen (1997) describes how the optimality principles work together in a way that forms a pattern, which he describes with his proposed 4th law of thermodynamics.
    - "If a system is moved away from thermodynamic equilibrium by the application of a flow of exergy, it will utilize all avenues available … to reduce the effects of the applied gradient."
      (1997, 339; cp. Schneider & Kay 1994, 29)

Sven Jørgensen (1934-2016)



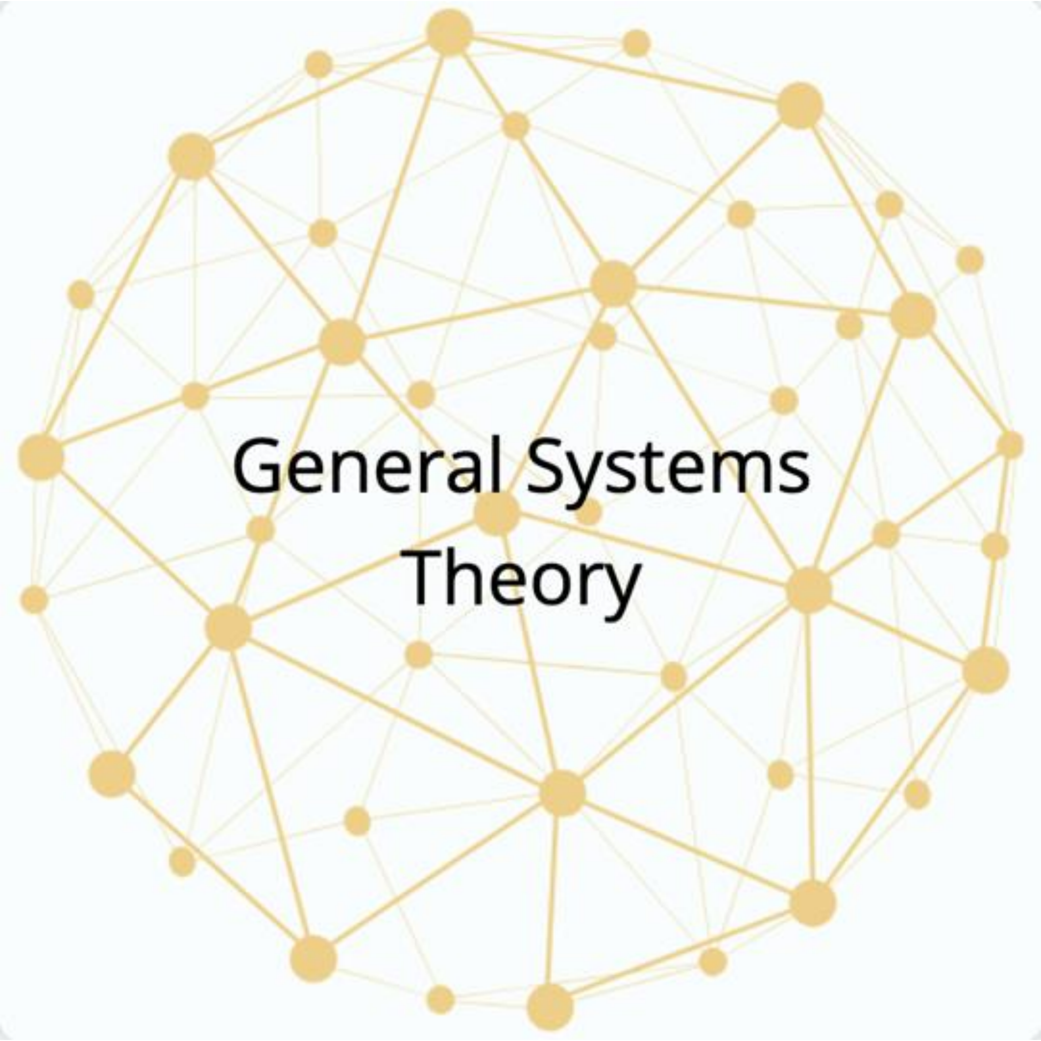
The Systems Approach

- Jorgensen describes H. T. Odum as a source for an optimality principle, but not as a source of a systems theory of optimality principles.

- However, Odum suggested a long list of optimality principles were "***special cases***" of the maximum power principle (1983a; 1983b): They align with the principle under certain conditions. In other words, they work together in a way that forms a pattern, which he describes using the maximum power principle.

  - He provides information throughout his work that supports this suggestion, which can be used to construct a systems theory of optimality principles.

H. T. Odum (1924-2002)



The Principle of Maximum Energy Flux (PMEF)

- Definition: “natural selection tends to make the energy flux through the system a maximum so far as compatible with the constraints to which the system is subject” (1922a).

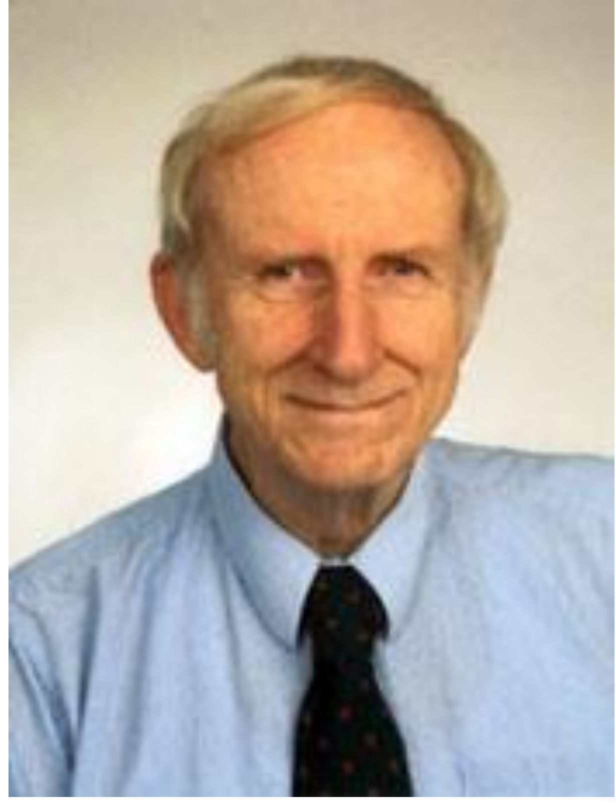
- He noted that the phrase “so far as compatible with the constraints to which the system is subject” “modifies” the meaning of the PMEF in an important way.
  - Organisms that are more efficient have a selective advantage when the available energy is limited.

Alfred Lotka (1880-1949)

- PMEF applies to ***all natural systems far from equilibrium***, both biotic and abiotic (1922b, cp. 1945).

- Lotka believed that the ***principle of natural selection functions as fourth law of thermodynamics*** (1922b).

The Maximum Power Principle (MPP)



H. T. Odum (1924-2002)

- Developed by H. T. Odum (and Richard Pinkerton) (1955), who attributed the principle to Alfred Lotka (1922). But Odum altered the MPP in substantive ways.

- ***Definition***

    - "Lotka (1922) proposed a "law of maximum energy" for biological systems. He reasoned that what was most important to the survival of an organism was a large energetic output in the form of growth, reproduction, and maintenance … Let us make the following postulate: Under the appropriate conditions, maximum power output is the criterion for the survival of many kinds of systems, both living and non-living" (1955).

- Odum and Pinkerton described how maximizing power entails a trade-off between the ***Efficiency*** and ***Speed*** of energy transformations (1955).

- Odum referred to the ***MPP as the fourth law of thermodynamics*** (2007).

Similarities between the PMEF and the MPP

- The MPP also applies to ***all natural systems far from equilibrium***, both biotic and abiotic (Odum 2007; Lotka 1922b, cp. 1945).

- Odum also believed the MPP applied "so far as compatible with the ***constraints to which the system is subject***" (Lotka 1922a).

  - Odum recognized that living systems have "special aspects" that affect the way the MPP applies to them (1983b).

  - He argued that the optimum efficiency for maximizing power output increases as the available energy and resources decreases (1955, 2007).

    - Maximizing power by increasing efficiency does not require more energy; maximizing power by increasing the speed of energy transformation requires more energy.

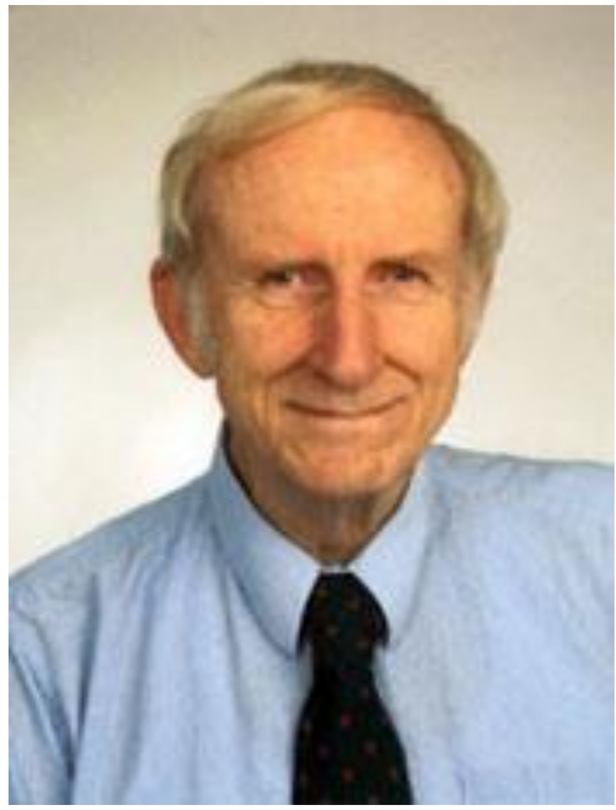
    - This evolving tradeoff between the speed and efficiency of energy transformations helps us understand the relations between the MPP and other optimality principles.

The Maximum Power Principle (MPP)

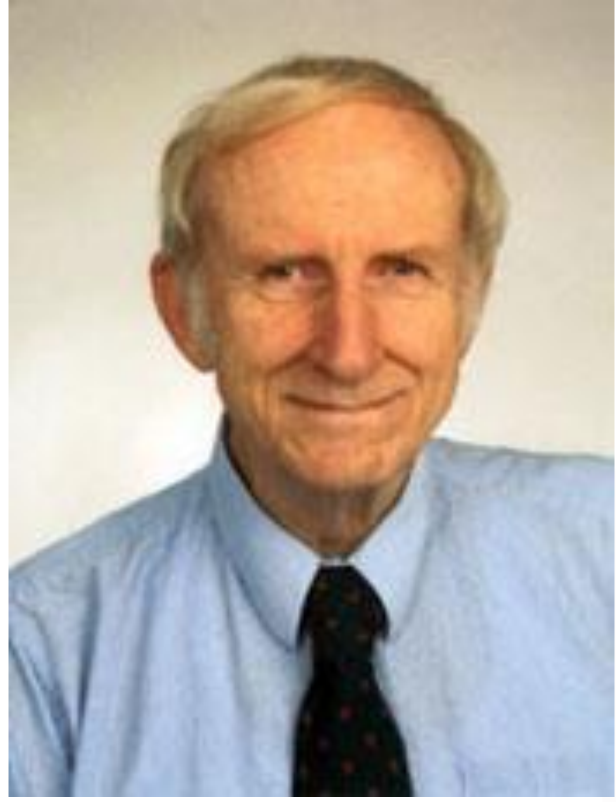
- "The maximum power principle explains why ***early succession*** minimizes diversity and ***later succession*** maximizes diversity"(2007, p. 56-57).

  - ***Early succession*** –
    - when the available energy tends to be abundant,
    - the "priority of a system is to maximize energy intake, to cover the area with energy receivers quickly, with units adapted for most rapid growth."
    - ***Power is increased by increasing the speed of energy transformations***.

  - ***Later succession*** –
    - when the available energy tends to limited,
    - the "priority is to maximize efficiency in its energy processing. When there are no excess, unused resources to be found, a high diversity of cooperating units develops, with ***better efficiency*** and division of labor."
    - Maximizing diversity becomes more important than maximizing the production of biomass (1983b, 79).
    - ***Power is increased by increasing the efficiency of energy transformations.***



Odum's Systems Theory of Thermodynamic Evolution:
A Brief Summary



- ***Early succession***
  - The MPP will be more closely aligned with:
    - The maximum biomass principle (1983b, p. 79)
    - The maximum reproduction principle (2007, p. 56-57)
    - The maximum storage principle
- ***Later succession***
  - The MPP will be closely aligned with:
    - The maximum efficiency principle (2007, p. 56-57)
    - The maximum diversity principle (2007, p. 56-57)
    - The equal fitness paradigm

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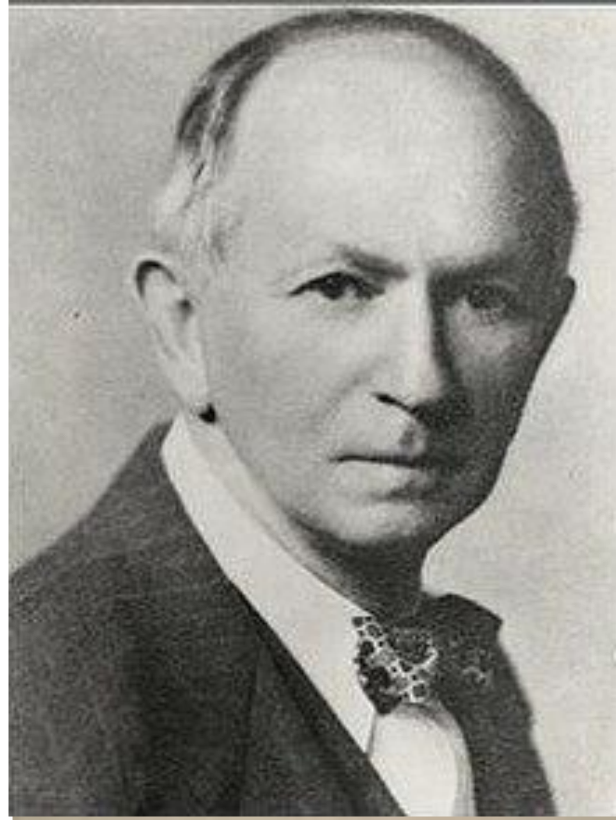
A Difference between the PMEF and the MPP

- The PMEF focuses on the ***flow of energy*** through the system; the MPP focuses on the ***output of useful power.***

  - This difference is ignored by Jørgensen et al. ***They describe the MPP increasing the flow of energy through systems*** (Fath et al. 2001, p. 494; Jorgensen 1997, p. 87; Jorgensen and Fath 2007, p. 190).

  - This mistake is understandable: Odum does not mention this difference.



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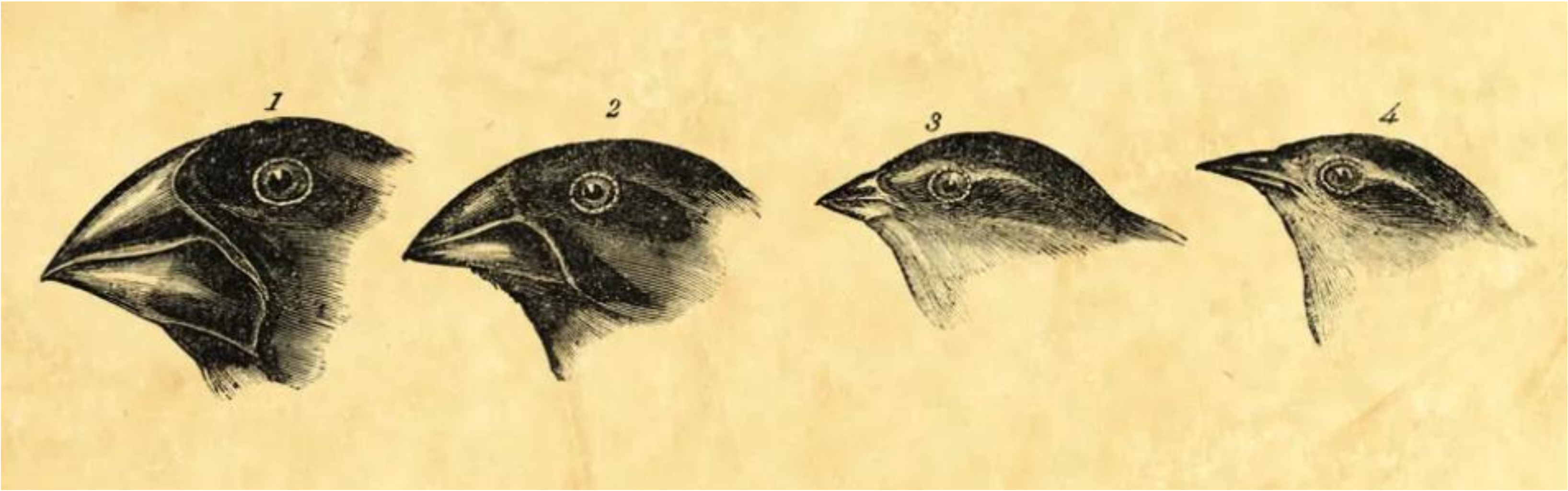
The MPP and the Principle of Natural Selection

- The ***MPP*** is defined in terms of the maximization of the ***output of useful power***.
  - This output is defined as being in the form of "***growth, reproduction, and maintenance,***" processes directly related to the principle of natural selection.
- ***The MPP is therefore selected directly by the principle of natural selection***.
  - The ***MPP*** has ***fundamental role in the causal hierarchy of evolutionary development***.
  - Other optimality principles, like the PMEF and Jørgensen's 4th law, are ***selected indirectly*** to the extent that they are related to the MPP.



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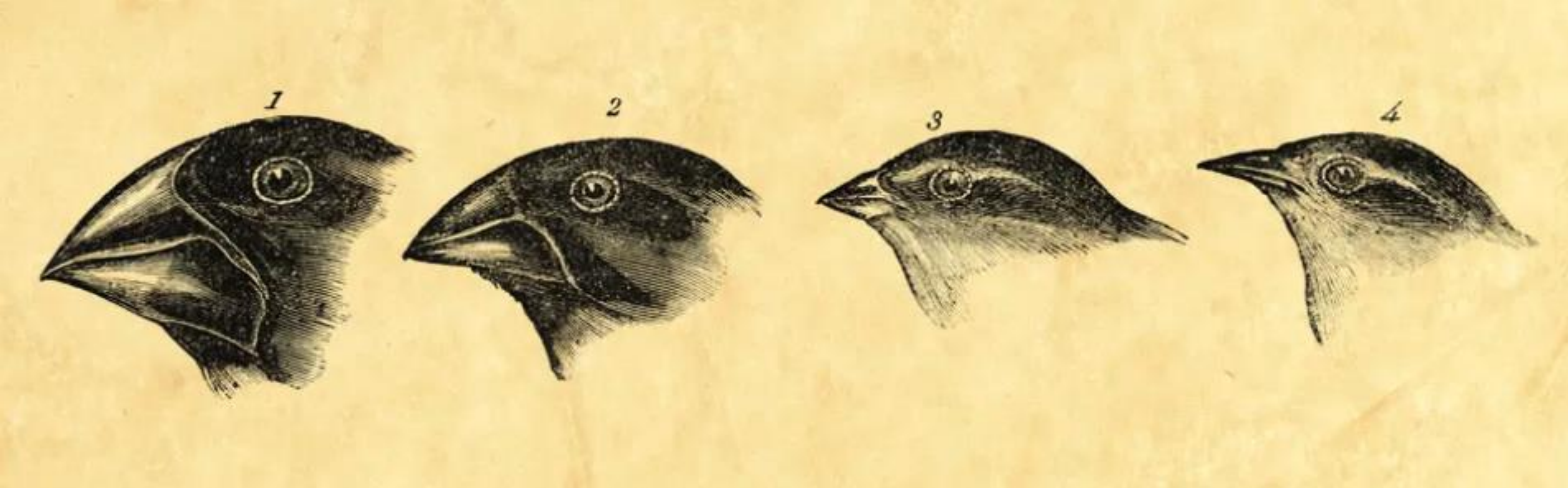
Jørgensen and the Principle of Natural Selection

E. D. Schneider

J. J. Kay

➢ *The Degradation of Gradients*

- Jørgensen 4th law is based on the work of Schneider and Kay. They argue that natural systems develop in ways that “degrade gradients” to reach a “state of equilibrium” (Schneider and Kay 1994).
    - Jørgensen’s 4th law states: ““If a system is moved away from thermodynamic equilibrium … it will … reduce the effects of the applied gradient” (1997, p. 339).
- Their language is based on an analysis of systems near equilibrium (the Bernard cell) rather than systems far from equilibrium, like life.
- They assume systems far from equilibrium develop like systems near equilibrium



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Jørgensen and the Principle of Natural Selection

E. D. Schneider

J. J. Kay

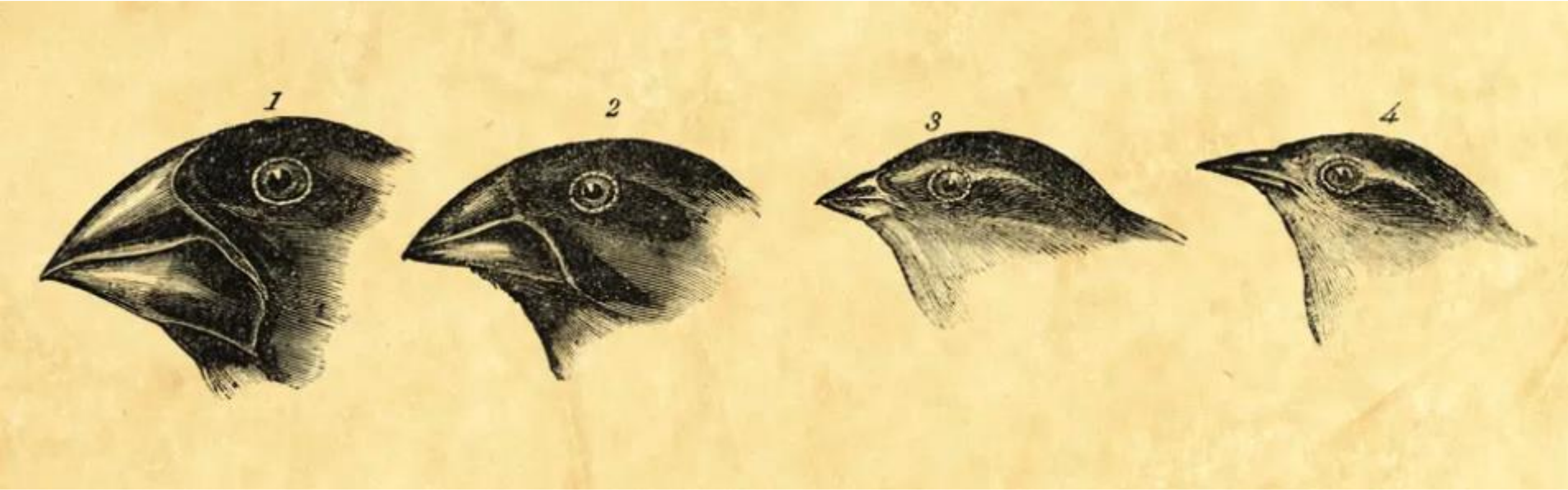
- ***The Degradation of Gradients***

  - ***Their view is not consistent with the the principle of natural selection.***

    - It does not give a selective advantage to organisms and natural systems that more effectively ***seek their own death, i.e., equilibrium***.

    - The MPP, which is based on the principle of natural selection, describes systems evolving in ways that lead them ***further away from equilibrium***.

    - Because Jørgensen et al. ***do not accurately define the MPP***, they do not see that ***it is selected directly***.



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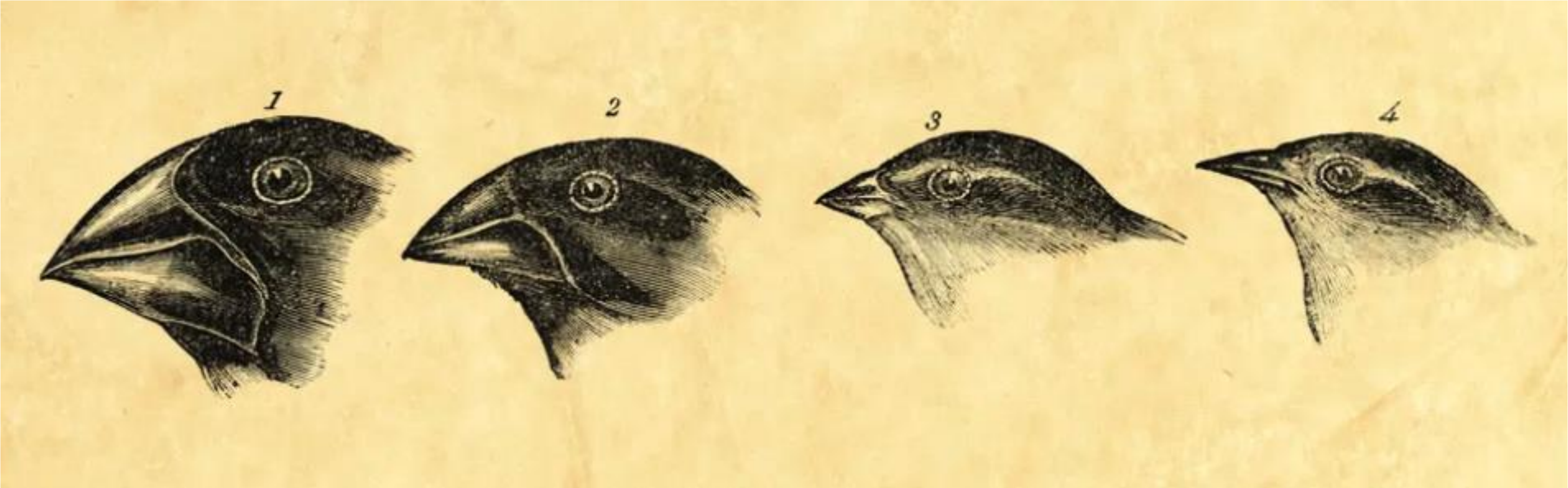
Jørgensen's 4th Law and the Principle of Natural Selection

- Jørgensen describes the relation between his ***4th Law of thermodynamics*** and the principle of natural selection as an "***open question***" (1997, 339).

  - "the open question is, however, whether life by Darwin's theory gives survival…higher priority than reducing imposed gradients" (1997, 339).

  - He is right: Gradients can be reduced in ways that do not enhance maintenance, reproduction, or growth.

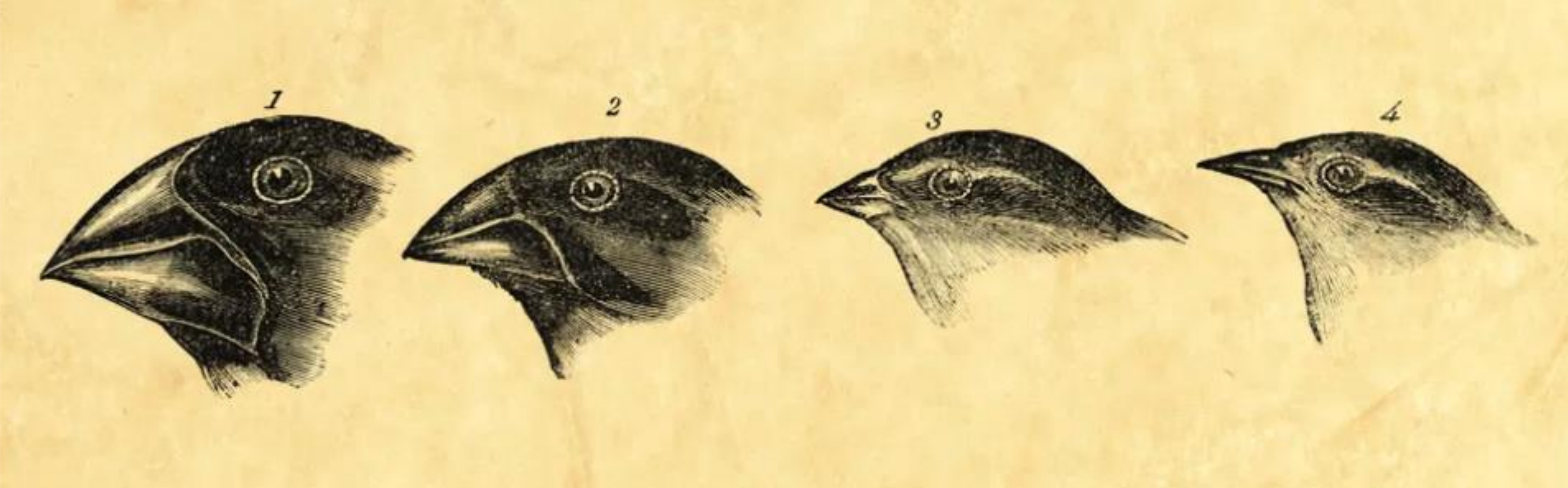


The Odum's Systems Approach v. Jørgensen's Network Approach

- Jørgensen et al. argue that optimality principles interact to form a pattern whose relation to the principle of natural selection remains an "open question."

- Odum argues that optimality principles interact to form a pattern that he describes using the MPP, which is defined in terms of the principle of natural selection.

  - ***Odum's approach is consistent with both the fundamental laws of thermodynamics and the basic principles of evolutionary biology***.



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Descriptions and Causal Explanations

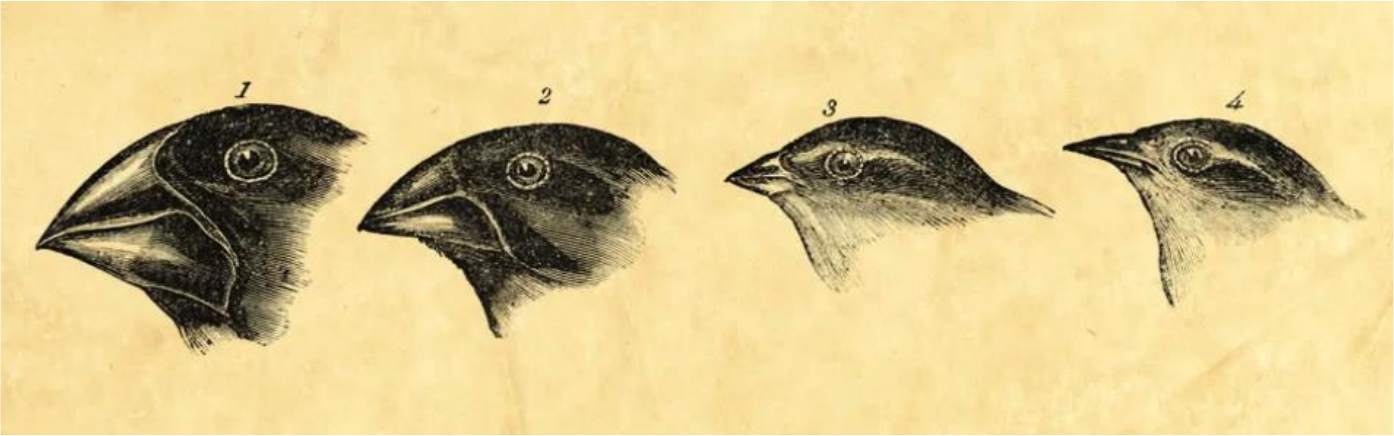
- Without a clear link to ***causal explanation*** for evolutionary development provided in ***evolutionary biology***, Jørgensen and his colleagues must rely on the ***descriptions based on statistical probabilities*** provided in ***thermodynamics***.

  - Julius Mayer suggested that questions regarding how to ***explain*** the physical processes behind energy transformations ***are "useless and typical of poets and philosophers of nature"*** (1978). ***He developed equations that accurately described*** the relation between heat and motion, and electricity and motion.

  - Richard Feynman wrote "it is important to realize that in physics today, we have no knowledge what energy is."

  - Jørgensen and his colleagues attempt to ***describe*** the relation between evolutionary development, the degradation of gradients, and other optimality principles.

  - These descriptions are unable to distinguish between what causes evolutionary development, like the MPP, and what is constantly associated with it, like the production of entropy.



$$\Delta S \geq 0$$

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Descriptions and Causal Explanations

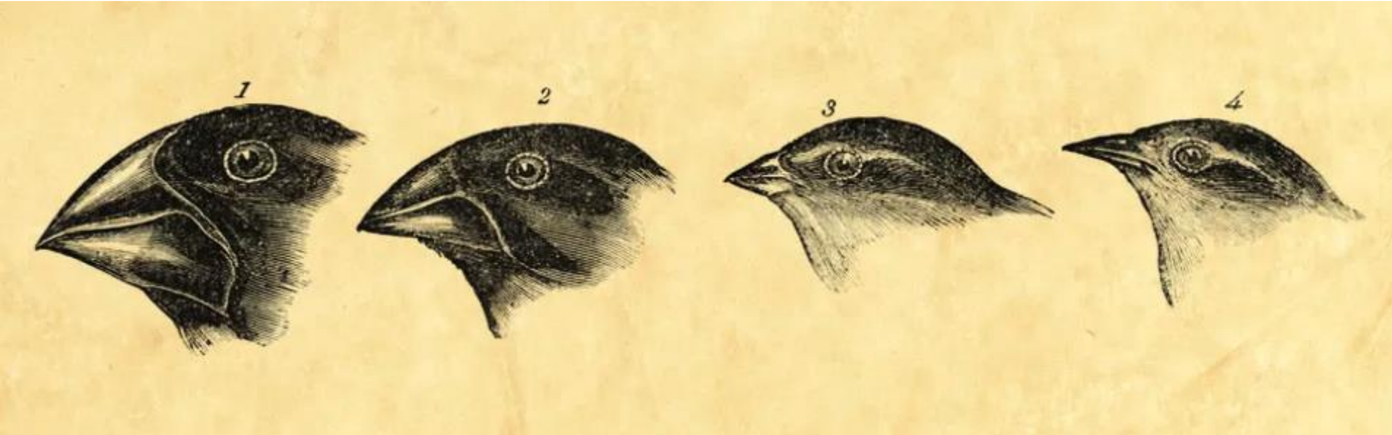
- In evolutionary biology, ***Darwin, and the scientists that followed him, provided an elegant causal explanation for evolutionary development that has been exceedingly well confirmed***.

- Odum's systems theory of optimality principles illustrates how principles that provide causal explanations, like the MPP, relate to principles that provide descriptions based on statistical probabilities, like the maximum entropy production principle or Jørgensen's proposed 4th law.

  - This can enable us to ***refine*** the descriptions and causal explanations provided by optimality principles.

    - For example, evolutionary development does not merely maximize the degradation of gradients; it maximizes the degradation of gradients associated with the output of useful power.

- We argue that using ***both*** the causal explanation for evolutionary development from evolutionary biology and the descriptions based on statistical probabilities from thermodynamics provides a more accurate and comprehensive understanding of evolutionary development.



$$\Delta S \geq 0$$

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Testing the Maximum Power Principle

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cool, cloudy, moist, saturated soils
GPP /
Plant
Respiration
Elevation
hot, dry, sunny

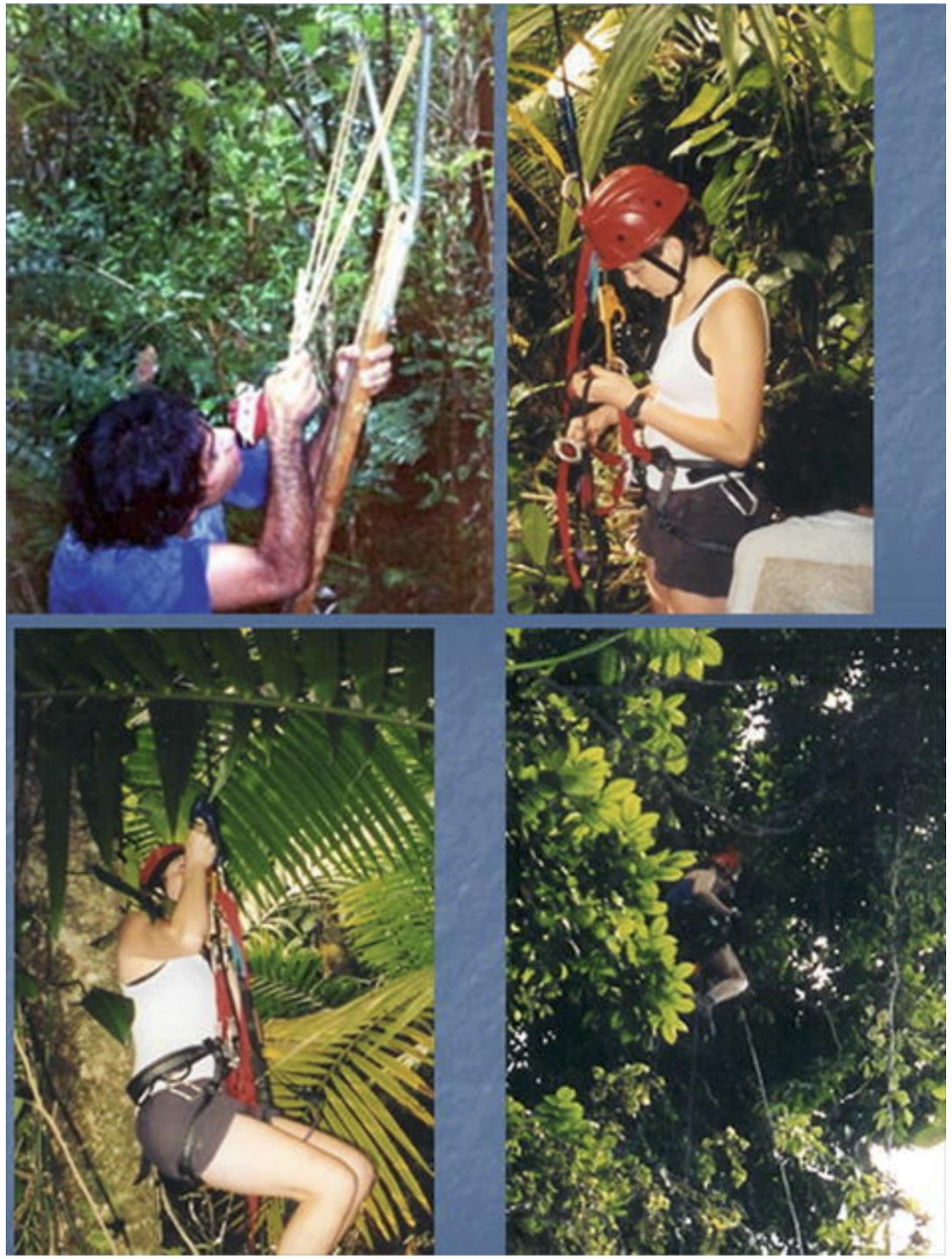

Fig. 7.15 How to access the upper leaves in a large tropical tree

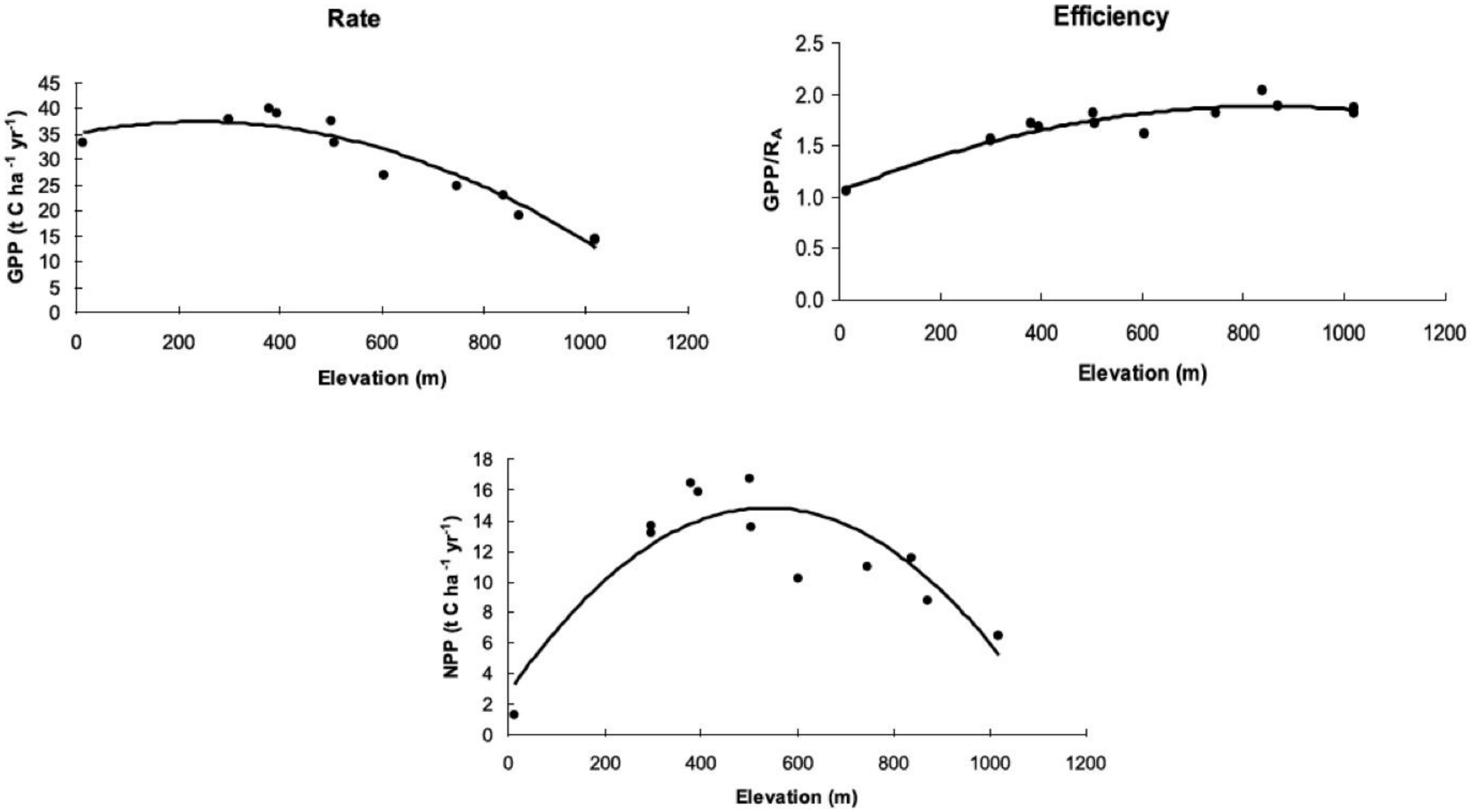

Fig. 5 Results of studies by Harris *et al.* that measured the gross photosynthesis and community respiration of a column of forest along a gradient of elevation in the Luquillo Forest, Puerto Rico. These data show a tradeoff of rate and efficiency of carbon capture, with the difference (net primary production) being maximum at an intermediate elevation, consistent with the maximum power hypothesis of Howard Odum. See Hall and McWhirter (2023).

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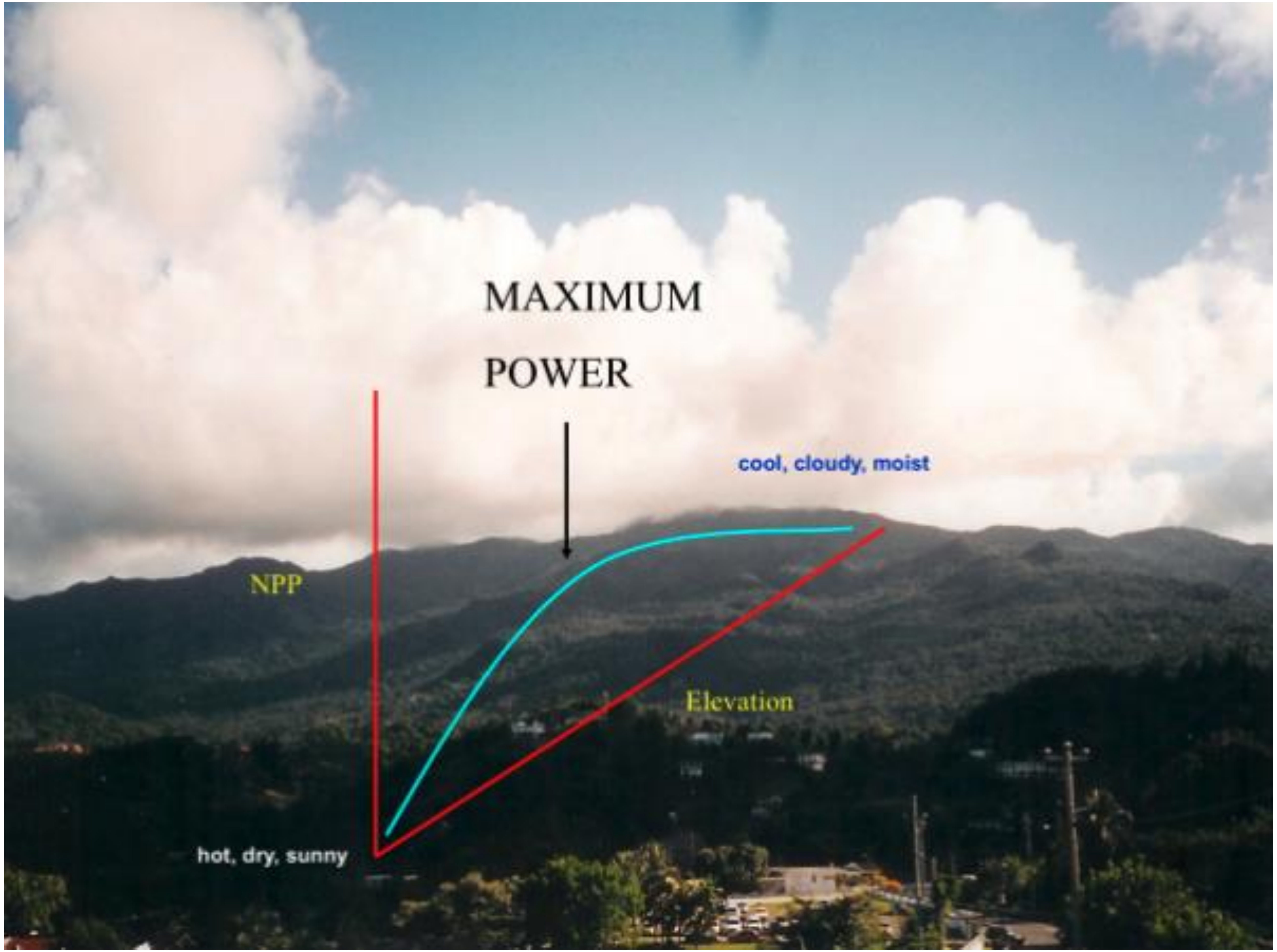

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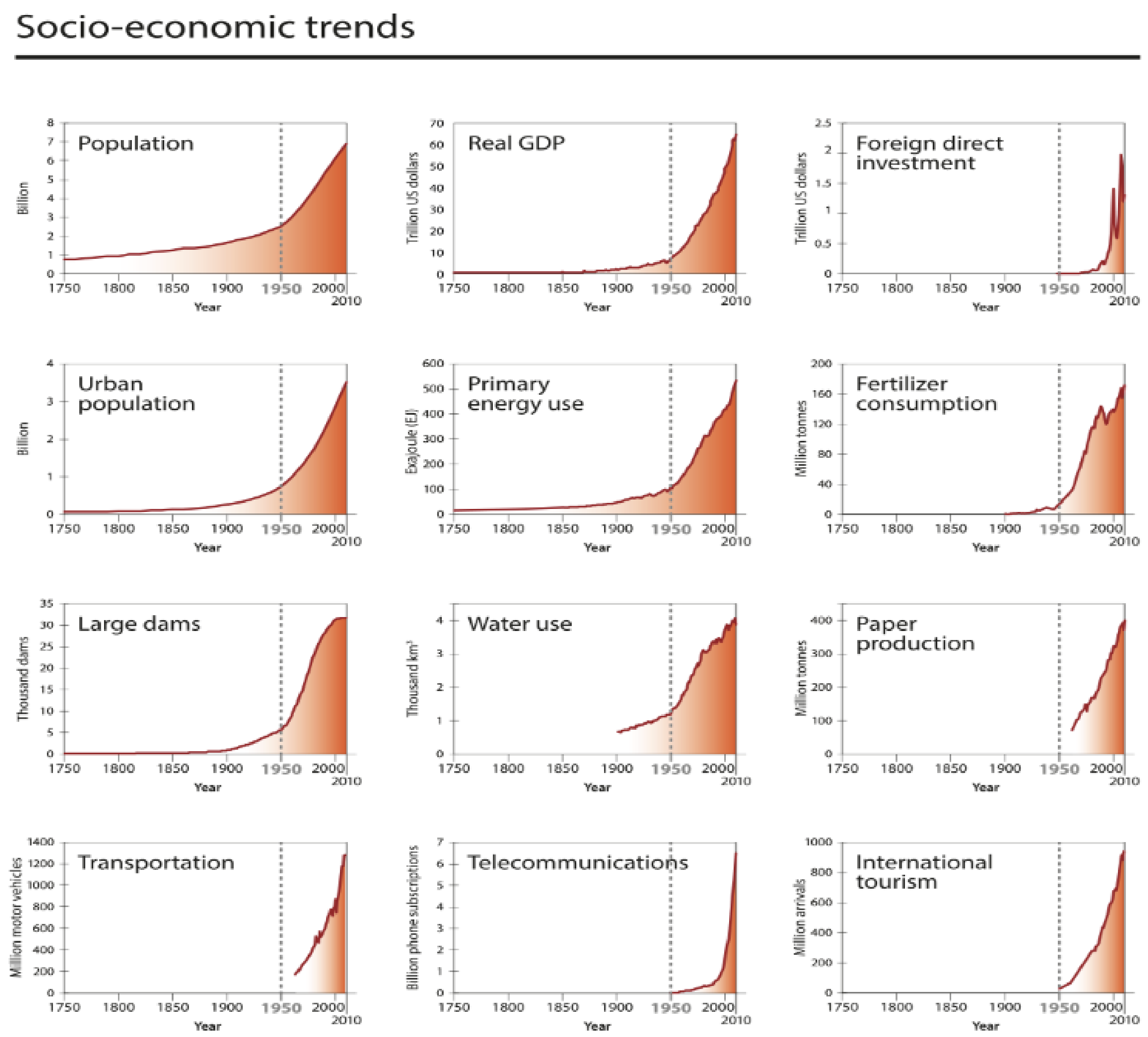
Studies of the MPP at the Ecosystem Scale (Chapman et al. 2016)

1. The MPP has been applied to studies that used models to optimize exergy relative to the effects on planktonic and zooplankton body size in aquatic ecosystems (Ray et al. 2001).
2. Used to constrain hydrological conceptual models (Westhoffand Zehe 2013).
3. Used to model the role of exotic species ecosystem self-organization (Campbell et al. 2009).
4. Applied to studies that simulated the role of the MPP in self-organizing forest plantation ecosystems (Li et al. 2013).
5. The MPP has been used to predict the outcomes of competitive exclusion experiments (DeLong 2008).
6. To indicate benthic ecosystem recovery following a disturbance (Libralato et al. 2006).
7. To examine microcosm ecosystem self-regulation using pH to control photoperiod (Cai et al. 2006).
8. To model the ecosystem organization of energy flows and storage (Fath et al. 2004).
9. It has been used in simulations of ecosystem responses to resource pulses (Lee 2014).
10. It has been used to predict the leaf area index in forests at different elevations (Hall et a. 2013).

Evidence that is consistent with the MPP and the MEPP

- Empirical evidence from other disciplines.
  - The Great Acceleration – Climate Science (Steffen et al. 2015)
  - Energy revolutions in earth and human history – Climate Science (Lenton et al. 2016)
  - The earth and energy – Energy, Environmental & Chemical Engineering (Thimsen 2024)
  - Evolution and the mind and consciousness – Philosophy (Nagel 2012)



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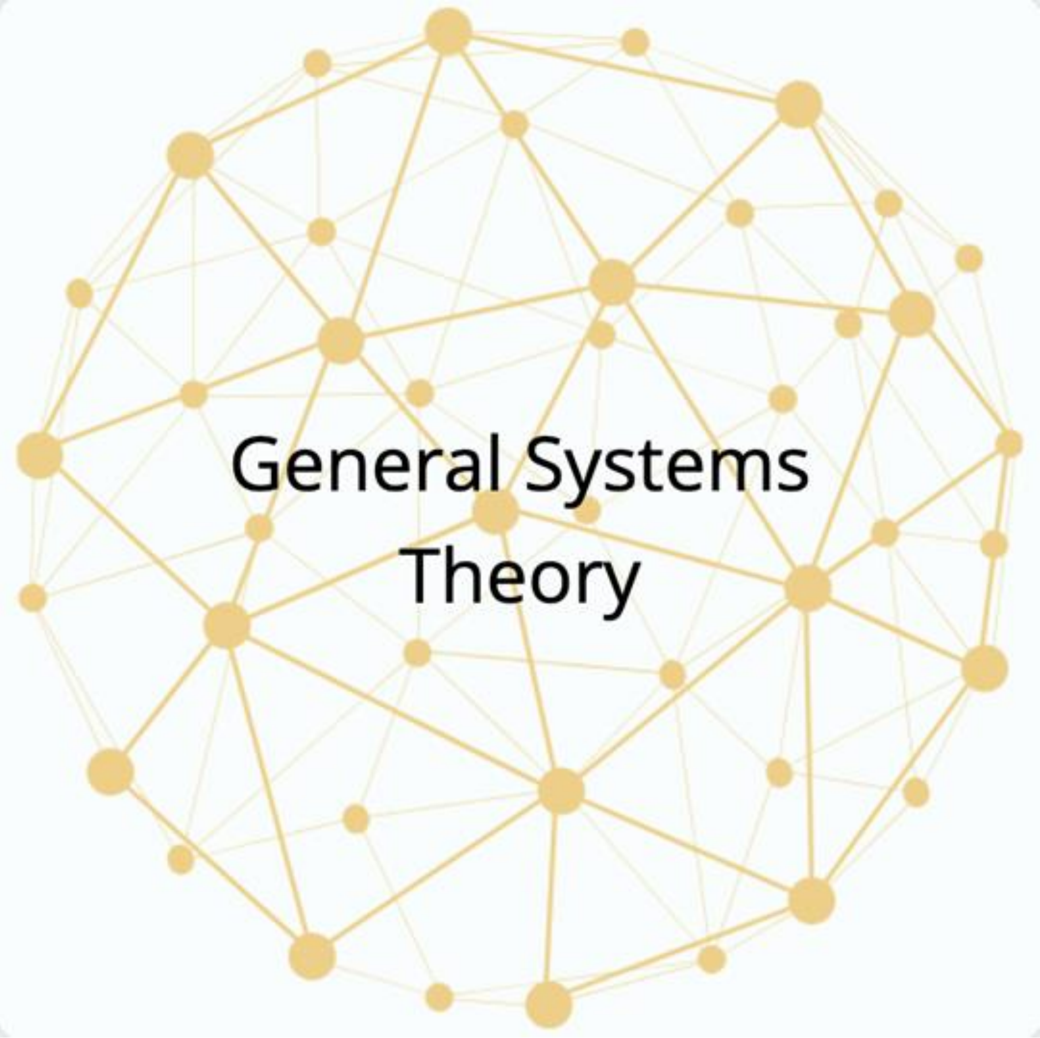
Conclusion

- Odum suggests that different optimality principles are “special cases” of the MPP. We plan to:
  - develop this framework latent in his work into a systems theory of thermodynamic evolution that explains the relations among optimality principles,
  - argue that it is consistent with both thermodynamic laws and the principles of evolutionary biology, unlike Jørgensen’s network approach,
  - and extend it to optimality principles that have not yet been considered.



- Our argument is not that the MPP replaces other optimality principles. Rather, it provides a framework for understanding how they relate to one another. These principles describe different aspects of the evolutionary process operating under different constraints.

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