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Short communication

Maximum (em)power: a foundational principle linking man and nature

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Abstract

Hypothesized as a universal principle of system self-organization, selection for maximum power provided the basis for H.T. Odum's systems-based understanding of energy transformation dynamics, which ultimately resulted in his emergy-based methods of ecosystem and environmental policy analysis. Odum's formulation of the principle emphasized the selective advantage potentially available to systems that acquire useful energy at the maximum rate possible within their environments, with energy deemed useful if it reinforces production through increased available energy acquisition. Based on this principle, Odum postulated a correspondence of the maintenance requirements of energy fluxes with their contributions to system power acquisition. A quantitative correlate with usefulness is thus provided by emergy, i.e., by the available energy of one kind used directly or indirectly to maintain storages and flows. A more explicit and precise understanding of the energetics of self-organization was thus suggested, and Odum accordingly reformulated the principle as selection for maximum rate of emergy acquisition (i.e., empower), which provides the standard for assessment of system adaptedness in current methods of emergy analysis. The many corollary hypotheses derived from the principle include the selective prevalence of intermediate efficiencies and process rates and of pulsing dynamics, emergy hierarchies, and territoriality under appropriate energy-influx regimes. Assessments of socioeconomic and environmental alternatives might be further improved by integrating this principle with modern theories of multilevel selection.

Keywords: Maximum power principle; Empower; Self-organizing systems; Multilevel selection

The fruitfulness of H.T. Odum's commitment to a systems-based understanding of our biosphere, its dynamics, and the potential role of humans within it is indicated by his extensive and seminal contributions to the many branches of environmental science and socioeconomic policy studies. A unifying theme supporting all these branches of his work is the capacity for self-organization possessed by all systems—socioeconomic, environmental, and ecological—subject to processes of selection operating on alternative system designs and thus on alternative self-reinforcing patterns of energy flow. Such alternative designs correspond to the differing configurations of the energy flow networks possessed by any given system or systems. Network configurations differ with respect to their component structures and pathways of energy flow; the parameters that govern the dynamics of storage, transformation, and flow within the network; and composite traits such as network power acquisition and energy dissipation rate (Odum, 1975, 1983). Along with related principles

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of energy network dynamics, selection for maximum power provides a fundamental thermodynamic determinant for the properties of all self-organizing systems that extends the principles of classical thermodynamics to systems and processes maintained far from thermodynamic equilibrium (Lotka, 1922a; Odum, 1975, 1995a). Odum (1991, 1994, 1995a) summarized the foundational role of this maximum power principle (MPP) in the development of his hypotheses about self-organization in all systems and consequently of his emergy-based method of environmental accounting. In this paper we provide a brief synthesis of Odum's half century of published explanations and refinements of the principle and indicate major hypotheses and methods of systems analysis that have been (or might be) derived from it.

The MPP was originally formulated by Lotka (1922a,b, 1925) to characterize the effect of selection among individual organisms, species, or groups (of two or more species) on the entire system of energy transformations in which they participate. Because these system elements can be reinforced selectively by an increased flux of available energy, he postulated that a general tendency toward increased available energy flux through the system will characterize its evolution, toward the maximum power compatible with thermodynamic, environmental, and biotic constraints. Odum (1983, 1988, 1994) applied this principle of system evolution to the development of systems during self-organization as well as to the evolutionary prevalence and selective persistence of systems with power-maximizing network configurations.

Odum also emphasized selection among alternative integrated designs, rather than only among the individual elements within alternative designs, as a fundamental determinant of system development, prevalence, and persistence. In brief, Odum (1982, 1995a, 1996) suggested that the designs that prevail in self-organizing systems are those that maximize useful power (i.e., the rate of acquisition of available energy that is subsequently used to reinforce production through increased energy acquisition and gains in efficiency), as such reinforcement increases the capacity for adaptation to prevailing and fluctuating environmental conditions, thus providing a selective advantage over alternative designs. In ecosystems, such integrated designs occur whenever mutually reinforcing relations persist among populations, features of their habitats, or other functional units within these systems. The potential for coevolution provided by such relations is discussed further by evolutionary ecologists such as Thompson (1994), Dieckmann and Law (1996), and Bronstein (2001).

1. Power maximization as a determinant of process efficiencies and rates

Based on fundamental principles of nonequilibrium thermodynamics, Odum and Pinkerton (1955) proposed relations between power, efficiency, and process rates that might be expected in systems selected for maximum power. They also suggested that tradeoffs between power and efficiency requirements could be fundamental to the development of alternative resource-capturing strategies and thus to the organization of the energy flow within systems. For systems ranging from photosynthesis and glucose metabolism to ecological communities and civilizations, they hypothesized that power maximization would result in intermediate efficiencies and rates of energy conversion. Illustrations of the achievement of maximum power at intermediate efficiencies and/or rates have been provided for power generation by heat engines (Sanchez Salas and Calvo Hernandez, 2002), muscle contraction (Santillan and Angulo-Brown, 1997), fluid flow (Bejan, 1996), and biological production (Hall et al., 1986). Further discussion of the relations between power and efficiency during energy conversion can be found in Gordon and Huleihil (1992), Chen (1994), Santillan (1999), Chen et al. (2001), and Sanchez Salas et al. (2002).

2. Which energy fluxes are maximized?

According to the MPP as postulated by Odum, it is the total *useful* energy flux of surviving systems that is maximized, and thus the flux associated with any given energy transformation within such systems is expected to be that which contributes most to this total useful flux. This flux is, more specifically, the rate of acquisition of useful energy by the system (Odum, 1983), rather than either a total available energy influx or a summation of the fluxes through the system's components. Power is acquired by a system through its initial transformation (or direct storage) of an available energy influx, and this power is considered useful if the subsequent transformations through which the available energy is dissipated contribute a feedback that amplifies other pathways (Odum, 1988, 1991). In systems receiving inflow of available energy to multiple processes, rather than to a single production process, the total power acquisition from all inflows is the quantity maximized by selection for maximum power. Such quantities could be difficult to measure in practice due to the difficulty in distinguishing the contributions of inflows to the system from those of feedback flows to production processes within the system and to their associated dissipation rates. Odum (1994), however, in a discussion of ecosystems with substantial organic matter inputs, suggested that maximization of total power acquisition requires maximization of consumer respiration, which is driven by both internally produced and imported energy sources.

3. Maximum empower versus maximum power

Odum (1975, 1988, 1994) refined the MPP further, along with the concept of energy quality, by suggesting a correspondence between the potential contribution of an energy flux to a system and the quantity of available energy directly or indirectly required to sustain this energy flux. Energy quality factors (later termed "transformities") provide a weighting of energy fluxes that accounts for this hypothesized correspondence between their maintenance (i.e., steady-state generation) requirement and contribution, which is expected to be particularly close in systems that prevail following selection. The MPP as modified by the use of these weighting factors becomes selection for maximum empower (i.e., the flux of available energy of one kind used directly or indirectly to maintain storages and flows), which Odum (1988, 2002) offered as a more precise understanding of the self-organization of systems. Odum (1995a,b) also hypothesized, however, that the attainment of maximum empower by fully organized systems will coincide with maximum power, as higher-quality sources and reinforcing cycles ultimately increase the influx and efficiency of conversion of lower-quality sources.

4. The MPP and multilevel selection

The question of which energy fluxes are maximized is also quite relevant to the recent and recurring units/vehicles-of-selection debate among evolutionary biologists. The MPP has generated some confusion among those accustomed to thinking in terms of a discrete unit of selection identifiable with a single level of organization, whether population, organism, or gene. This is understandable given that the MPP proposes the maximization of a property or trait borne at the system level based on selective persistence and reinforcement of alternative designs (existing within and among systems) that occurs through competition among design elements for available energy (Odum, 1983, 1994, 1995a). The emerging consensus among evolutionary biologists with respect to the multilevel nature of the selection process (Williams, 1992; Sober and Wilson, 1998; Reeve and Keller, 1999; Gould and Lloyd, 1999) suggests a potential for collaboration. Such collaboration could improve our understanding of specific system properties that result from or enhance selection for maximum power by elucidating the more specific mechanisms (Wilson, 1997) through which the MPP operates within the relevant environments in which these systems develop.

The specific examples and mechanisms of selection offered by such biologists as Lewontin (1970), Wilson (1980, 1997), Gould (1998), and Thompson (2001) have broadened our understanding of selection and of its operation at multiple levels. The MPP could help to consolidate these achievements by providing a general principle of selection as it operates on the generic units that make selection possible in whatever system and at any level that it occurs and by further providing an explicit measure of inclusive fitness at the system level. An integrated formulation of the principle applicable to its operation within particular selective environments has not yet been achieved. Such a formulation, however, together with its accompanying symbolic expression through mathematical equations and the energy circuit language developed by Odum (1975, 1994), could provide a basis for both theoretical understanding and empirical investigation of more specific principles or processes of selection and self-organization (Odum, 1983, 1994).

5. Other properties of designs and flow paths of (em)power-maximizing systems

Many other hypotheses and predicted properties of (em)power-maximizing systems have been derived from the MPP. While more extensive lists are provided by Odum (1975, 1991, 1996; Hall, 1995), the following is a brief summary:

(1) Greater power acquisition provides a capacity for higher diversity as well as for overcoming stress and disturbance (Odum, 1975, 1994; Lugo and McCormick, 1981);
(2) Linear paths are selected at low energy influx; autocatalytic paths above one energy threshold; quadratic paths above another, higher threshold; upgrading and storage are required by the nonlinear paths to amplify influx and increase its effective use (Odum, 1975, 1991);
(3) Consumption reinforces production; pulsing maximizes power at autocatalytic levels of available energy influx given the presence of producers and consumers (Odum, 1982; Hall, 1995);
(4) Selection for growth occurs while untapped or net energy remains accessible, then selection for relatively higher efficiency (i.e., a minimization of entropy tax) occurs (Odum, 1975, 1991); and
(5) Hierarchy with territoriality is produced based on replacement time along with (multiplicative) interactions based on transformity matching within an energy network (Odum, 1991).

6. Conclusion

The maximum (em)power principle provides a thermodynamic explanation for the ubiquitous process of hierarchical self-organization observed in all environmental and socioeconomic systems, including cities, farms, watersheds, and other ecosystems. It is the key concept upon which H.T. Odum's insights, understandings, and predictions about the world were based. Further development of emergy accounting as an application of this principle could provide an explicit method for the assessment of socioeconomic and environmental alternatives in terms of the most fundamental energetic determinants of the survival and prevalence of all self-organizing systems. As a universal principle, it could also serve as the basis for new approaches within the existing scientific disciplines. A large-scale, collaborative effort based on a consistent, rigorous, and empirically informed application of systems diagrams and accompanying mathematical models might be useful in establishing whether the maximum empower principle is indeed, as Odum suggested, a universal principle and 4th law of thermodynamics.

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