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Short communication

Howard T. Odum's contribution to the laws of energy

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1. Introduction

H.T. Odum's life-long search for the energy basis of general systems principles culminated in proposals for three new energy laws, which if accepted, would double the number currently recognized by engineers and scientists. I review the evolution of his thinking on proposals for a 4th (self-organization for maximum empower), 5th (energy transformation hierarchy) and 6th (coupling of biogeochemical cycles to energy transformation hierarchies) law of energy.

During his lifetime investigation of ecological systems, H.T. Odum sought to generalize his and other's observations about how ecosystems selected their network designs to match their structure and level of activity to the availabilities of energy and resource materials, with the hope that the general principles discovered would accelerate understanding of how these and systems of all kind work. During his quest, H.T. refined Alfred J. Lotka's (1922a) maximum power principle to present it as the 4th Law of Energy and proposed two of his own as the 5th and 6th Laws of Energy. H.T. also clarified the meaning, ubiquity, and implications of the first and second energy laws to many of his students and associates, often stating, "The first law of energy states that the quantity of energy is conserved, while the second law states that the quality of energy, its ability to do work, is not."

2. 4th Law: self-organization for maximum empower

It is evident from H.T.'s Ph.D. dissertation (Odum, 1950, pp. 6–8), that his earliest thinking on what became his proposal for a fourth law was influenced by Lotka's (1922a,b) writings on system energetics and stability, and Charles Darwin's theory of natural selection. Later H.T. pointed out that Darwin's evolutionary law (i.e., natural selection) was developed into a general energy law by Lotka when he said "that maximization of power for useful purposes was the criterion for natural selection" (Odum, 1971). H.T. reformulated Lotka's principle as the "maximum power principle," stating it as "systems prevail that develop designs that maximize the flow of useful energy ... theories derived from the maximum power principle explain much about the structure and processes of systems" (Odum, 1994, p. 6). After H.T. and his associates had sufficiently elaborated their emergy-based comprehension of system dynamics and hierarchical organization, he finalized his restatement of the 4th Law as the Maximum Empower (emergy per time) Principle (Odum, 1996): "In the competition among self-organizing processes, network designs that maximize empower will prevail." This principle forms the foundation underlying H.T.'s ideas about the application of "emergy synthesis" to making better decisions about the fit between man and nature (Odum, 1988). He saw the Maximum Empower Principle as a guide for humanity in its struggle to self-organize to create new social customs, cultural norms and ecological ethics that matched its wondrous, new found, fossil-fuel-based technological

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power for a more mutually powerful fit with nature. In his book "A Prosperous Way Down," Odum wondered how society would self-organize, given a future downturn in energy availability (Odum and Odum, 2001).

3. 5th Law: energy transformation hierarchy

H.T. proposed the 5th Law as, "Energy flows of the universe are organized in an energy transformation hierarchy. The position in the energy hierarchy is measured with transformities" (Odum, 1996, p. 16). According to Odum, there are three factors that contribute to the formation of energy hierarchies: (1) no process is 100% efficient in its energy transformation (2nd Law) so products from the process have less available energy than the sum of their factor 'reactants'; (2) system processes maximize power by the interaction of abundant energy forms with ones of small quantity but large amplification ability; and (3) products from processes in self-sustaining systems must possess some potential ability to amplify the input flow of other energy forms of greater quantity (otherwise, why make the product?). One of H.T.'s favorite ecological examples of the energy hierarchy was a tree in the forest (Odum, 2002). There are many leaves and small roots responsible for collecting dilute sunlight and dispersed resources. The leaves and small roots are connected to larger branches and roots, which perform work through chemical transformation. The branches and large roots converge at the tree trunk, where higher quality wood is manufactured and supports the entire aboveground energy collection structure. Since transformity is defined as the ratio of total energy required of one form to the energy available of another form, it naturally increases along the energy hierarchy. In the case of the tree, the sunlight is the most abundant energy and, by convention, is given a transformity of one, whereas the tree's intermediate chemicals and wood have progressively higher transformity, but represent much less available energy when expressed as heat. But that small amount of structural energy has just as much utility as the sunlight because a unit of tree trunk greatly increases the ability of the system to capture and process the power of the sunlight. H.T. believed that the tree would not have "wasted" its photosynthate on wood construction if that investment did not at least pay for itself in its ability to capture energy and hence contribute to the maximization of the power of the system. He would also utilize this line of reasoning to explain the organization of ecological food webs; predators "paid" for the energy they captured from prey by providing services to the ecosystem, otherwise, he believed, predators would be a net drain on the ecosystem and never selected. This expansion of Darwinian selection explains why, for example, top carnivores are necessary for balanced ecosystems and why insectivorous birds regulate the insect populations of forests. It also implies that all systems will support a hierarchical level as long as it provides a net ability to process more empower. In other words, a higher hierarchical level is always needed to control the excesses of its immediate lower level.

4. 6th Law: coupling of biogeochemical cycles to energy transformation hierarchies

In the first international meeting dedicated to emergy (Brown et al., 2001), H.T. presented his final contribution to the laws of energy, "Material cycles are hierarchically organized in a spectrum measured by emergy per mass that determines mass flows, concentrations, production processes, and frequency of pulsed recycle ... Perhaps it is useful to add it as #6 [Energy Law] ... Or perhaps it should be regarded as a corollary to the energy hierarchy principle (proposed 5th Law)" (Odum, 2000b, p. 246). Described in another manner, H.T. stated,

> The coupling of the biogeochemical cycles to the energy transformation hierarchy explains the skewed distribution [*to the right*] of material [*flux*] with concentration. When self organization converges and concentrates high quality energy in centers, materials are also concentrated by the production functions. Because available energy has to be degraded to concentrate materials, the quantity of material flow also has to decrease in each successive step in a series of energy transformations. (words in [*italics*] added; Odum, 2000b, p. 235)

During my relatively short interaction with H.T. (1994–2002), I believe I witnessed the complete evolution of his thinking related to the emergy of material cycles. There was a harassing question among emergy analysts about assigning emergy to recycled materials. Solving this was critical if emergy evaluation was to consistently account for the emergy content of recycled materials like aluminum cans going from consumers to industry or water going from the wastewater treatment plant to a wetland. Based on the definition of emergy, it was difficult to reconcile the fact that items could "lose" emergy as they were recycled. The thinking at this point was that the emergy of something could only increase during its life cycle.

There were countless 'Systems Seminars' (a weekly meeting to promote intellectual symbiosis that H.T. had organized since arriving in Florida in 1971) in which all participants debated the latest topics, including the emergy of materials. Like most graduate students, this was my first experience participating in the development of theory. I had entered graduate school with the layman's impression that theory was developed over decades by toiling and tweaking the ideas and arguments of fellow scientists. I was amazed to witness the rapidity with which H.T.'s thinking evolved on this issue and how truly independent his thinking appeared. It was fascinating to interact with H.T. and other colleagues during this time laying the foundation for evaluating the emergy of material cycles. Although I cannot remember the date, I can still picture H.T. coming into systems seminar with his graph of emergy per mass (sej/g) versus the concentration of lead (Pb) in various states (Fig. 1). It was a euphoric moment for me, and I am sure for H.T. and others. We had been arguing and debating, literally for years, the issue of emergy and material cycles, but had made little progress other than defining the questions we needed to answer. H.T. had dabbled with us on the subject, but I suppose had never devoted the time required to concentrate his thinking on the matter. In my mind, the idea he presented on this particular day was an extension and formulation of "common sense," as were so many of H.T.'s thoughts. Basically, he pointed out that for a material to become more concentrated in its carrier (e.g., ores of lead) or on the landscape, more emergy was required per gram of material. For example, highly concentrated, refined lead ($10\,g\,cm^{-3}$) required a large flow of emergy through a complex network of natural and human-organized systems for its production, whereas lead dissolved in the ocean ($5 \times 10^{-10}\,g\,cm^{-3}$) represented the planet's background concentration and by definition had only the emergy content of its carrier (i.e., seawater). Thus, when a material is recycled and its concentration diminished, its emergy per gram is reduced. H.T. suggested that the graph could be used to estimate the emergy per gram of a material by knowing its concentration in its carrier.

The question I posed during this seminar was whether his graph of emergy per gram versus material

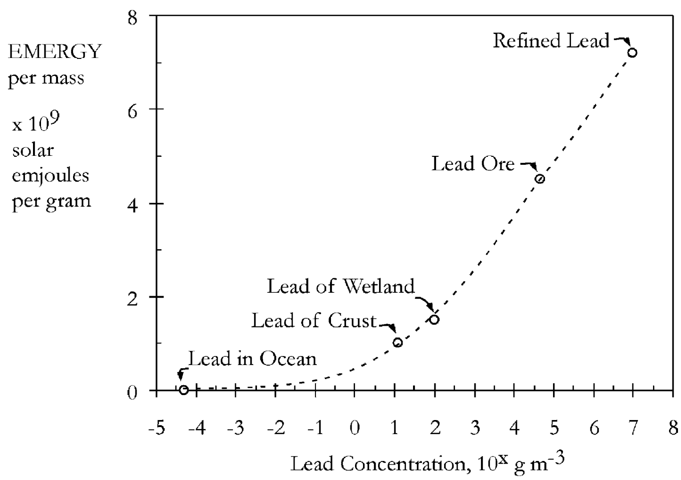

Fig. 1. As the concentration of a material, such as lead (Pb), increases from background levels, often defined by ocean chemistry, through earthly processing in the crust towards a highly refined state, the solar emergy per mass increases (redrawn from Odum, 2000a,b by D. Tilley).

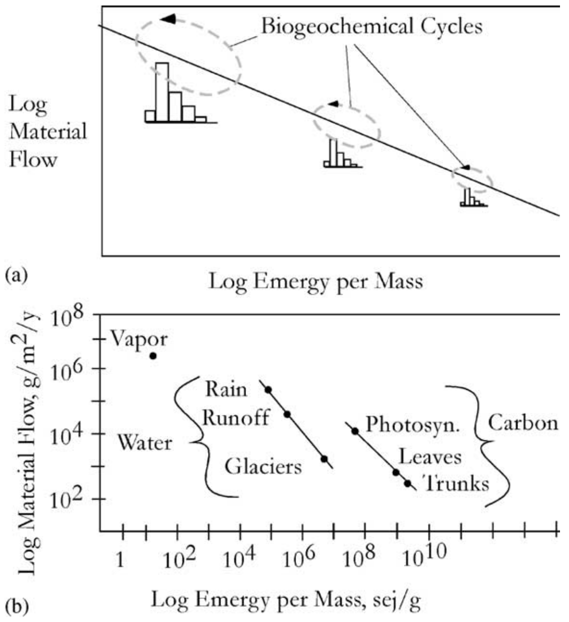

Fig. 2. A schematic (a) summarizing H.T. Odum's proposed 6th Law of Energy with skewed distributions of materials orgained into zones according to the energy hierarchy principles laid out in his idea for a 5th Law of Energy and examples (b) of the water and carbon cycles in the environment (redrawn from Odum, 2000b by D. Tilley).

concentration would appear similar for other elements or would there be a shift according to the inherent transformity of the element (e.g., its abundance in the cosmos or Earth's crust). Proudly, I discovered we were thinking similarly, because later H.T. (Odum, 2000b) presented a plot of emergy per mass versus material flow for water and carbon as an example of how different materials cycled in different segments of the energy hierarchy (Fig. 2).

5. Summary

As with his many other ideas, H.T.'s suggestions regarding the 4th, 5th, and 6th Laws of Energy are controversial, to say the least. According to his perspective on open system energetics, the new Energy Laws are logical extensions of the 1st, 2nd, and 3rd. Each of his new laws accounts for system dynamics absent from classical thermodynamics, forcing all of us to consider the following questions. Is self-organization for maximum empower a general operational principle of all systems? If systems commonly organize energy production units hierarchically, what insight is gained about the workings of less well-understood systems like the Cosmos? Or the human genome? Does an emergy spectrum of materials explain the mass flows, concentrations, production processes and frequency of pulsing material cycles? Most importantly, do his proposals add to humanity's understanding of its role in manipulating the biogeochemical cycles and emergy throughput of the Earth? As H.T. once said during lunch to me, Sergio Ulgiati, Dan Campbell, Mark Brown and Wayne Swank, "I've noticed it takes about 20 years for my ideas to be accepted." The proposals for three new Energy Laws demonstrate H.T.'s boldness in attempting to answer questions that others fail to even recognize. How long will it take for his suggested Energy Laws to be accepted? Or at least thoughtfully considered? There will be detractors, but hopefully H.T.'s groundwork will open a meaningful discussion on such important issues for humanity, nature, and their future.

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