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The continuing importance of maximum power

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Abstract

Of the many extremely ingenious, powerful and, yes, frustrating concepts and approaches that Howard Odum left us, the one with the most power to change how we understand the Earth, was that of maximum power. This theoretical framework, has subverted how most of his students and colleagues think about systems in general, transformed the way we think about ecosystems, natural selection, and even our environmental and general politics. The concept has not always been a comfortable one, but it is an exceedingly exciting and commanding one ... and therein lies its interest. For most of us who have been exposed to it in some detail, there is no doubt as to its veracity [Maximum Power: The Ideas and Applications of H.T. Odum, University Press of Colorado, Niwot]. What remains to be answered, however, is just how wide is its net?

Keywords: Maximum power; Biogeochemical cycle; Ingenious

1. Background

In developing a homeostatic model for the earth's closed biogeochemical cycles in 1949 for his dissertation (Odum, 1950, 1951) at Yale under G. Evelyn Hutchinson, Odum was greatly influenced by Alfred Lotka (1925), who as Odum said ...

> showed that storages develop in front of rate-limiting processes (bottlenecks) and with a quantity inversely proportional to those limiting rates. The closed-cycle mechanism of accumulating storages is a self-organizing mechanism that eliminates any one pathway from being more limiting than others, thus contributing to the maximum processing of the available energy. (Odum, 1995)

In other words, any build up of organic materials tends to lead to their own dissipation, due to a process not dissimilar to the familiar principle of le Chetelier ($A + B \leftrightarrow C + D$, with the equation going in the direction of whichever components are in least concentration). Beginning with his dissertation and extending throughout his life, the concept of "Maximum Power" was ever present in Odum's work. HT always gave credit for the principle to Lotka, stating that ...

> Alfred Lotka (1922, 1925) with an acknowledgement to Boltzmann (1905), suggested that the maximum power principle was a fourth law of thermodynamics that constrained and guided the self organization of open systems. (Odum, 1995)

The concept of maximum power, which Odum referred to as the maximum power principle and later refined to the maximum empower principle, can be summarized in it's broadest terms as follows:

> Over time, through the process of trial and error, complex patterns of structure and processes have evolved ... the successful ones surviving because they use materials and energies well in their own

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maintenance, and compete well with other patterns that chance interposes. (Odum, 1983a)

But in his early field work on trophic processes Odum was apparently rather puzzled by the very low efficiencies he measured at each transformation in an ecosystem. Some existing theory on the importance of efficiency in biology (e.g. Prigonine and Wiaume, 1946; Prigonine, 1978) seemed to be belied by the low efficiencies Odum observed.

2. Early work on maximum power

At the University of Florida in the early 1950s, Odum linked with Richard Pinkerton, a physicist, and together they worked on maximum power, developing a theoretical and conceptual base that they eventually published in 1955 under the title *Time's Speed Regulator: the optimum efficiency for maximum output in physical and biological systems.*

While we do not know what brought Odum together with Richard Pinkerton, we do know that Odum lamented the untimely death of his early colleague, and that it seemed to us that here was one person that Odum clearly viewed as an intellectually important colleague. The maximum power paper (Odum and Pinkerton, 1995) remains an extremely interesting read. It begins by developing the concept of maximum power with a very simple mechanistic example, called Atwood's machine. The machine is simply two baskets connected by a rope over a pulley with the objective to do work, defined in this case as moving some material from a lower elevation to a higher elevation (or applying torque to the axle) using a weight in the upper basket as an energy source. The machine can be run at various rates: if the upper basket has a large weight relative to the lower basket it will operate very rapidly, but will do only a small amount of useful work, defined in this case as the material delivered to the upper level. Most of the input energy will be dissipated as heat when the heavier basket hits the floor with great force. Alternatively, the upper basket can be loaded with barely more weight than the lower one. In this case the machine will be very efficient (it will loose little heat when the basket hits the floor) but it will move very slowly, so the power, the work done per unit time, will be low. Maximum power results when the weight of the energy source is approximately twice the load or back force (the weight to be moved).

Odum and Pinkerton give many other physical examples, including extremely clever renditions of biochemical, metabolic and economic work. These diagrams capture in the energy systems language many basic concepts that we have thought about commonly, although not usually in terms of energy. It would have been great to have their summary diagram of glycolysis when, as sophomores in college, we were first confronted with the intricacy of the biochemistry of metabolism. It would have given us a conceptual roadmap for all the details that overwhelmed us and which as one might expect, were soon forgotten after the test. And just seeing the little diagram of energy running the economy captures the essence of economics in a way I never saw in Econ 201. What wonderful and intuitive summaries these are!

Once I understood what the maximum power concept was really about I found profuse examples in my daily life, including the need to keep my automobile in the middle of each gear range if I wished to accelerate rapidly (maximum power graphs are found in all fast car evaluation magazines). Although high efficiency can be obtained at the low end of each gear range the power transfer there is low, as it is at the high end where the very rapid spinning of the engine is transferred entirely into heat. I have heated my house with wood for all of my adult life, and have spent a great deal of time with a chain saw. I think of work gates and maximum power constantly as I undertake this physical work, as I do when I do other yard work. The forest in my 2 ha back yard captures considerable solar energy. I redirect that energy flow to my own purposes by using a relatively small amount of petroleum in my chain saw to move energy into my woodpile and then furnace, and the petroleum in turn is guided by another work gate, which is my even smaller amount of muscular energy that guides the chain saw. I learned early of the need of a chain sawyer to balance the trade off between having the saw run rapidly under a light load or stall if you press down to hard. I found that I cut the wood fastest (i.e. do the maximum useful work) by pressing down with the saw to just about half the load the saw can bear without stalling! Coal burning electricity power plants too are subject to maximum power constrains, and must operate at about half their maximum possible Carnot efficiency to generate maximum power (and hence revenues for the utility) (e.g. Curzen and Alborn, 1955). I think about maximum power many times a day!

3. Testing the importance of energetics and of maximum power in biology

An early problem with the maximum power hypothesis was that it seemed to be in competition with the standard view of evolution, based on fitness, put forth by population ecologists (e.g. Mayr, 1982). In this view, fitness is defined as those morphological, behavioral and physiological patterns that most lead to reproductive success, essentially the survival of grandchildren. A problem with this conventional view is the circularity of the argument that follows. Question: what is fit? Answer: that which survives and reproduces. What, then, will survive and reproduce? The answer: those organisms that are most fit. This is, of course, a tautology but it has been repeated many times in biology. Maximum power, or energetics in general, offers a resolution to this tautology: that which will be selected for is that which generates the most power, because the surplus energy that is thus generated can be diverted to whatever contingency requires it, and that energy that is left over can be diverted into reproduction. People enamored of the maximum power concept had little trouble making the connection to fitness, but since explicit tests or assessments were lacking the maximum power arguments seemed to make little impact on the rest of biology (but see Hall et al., 1986, Chapter 1; Hall et al., 1992 for syntheses of basic biological thought in energy terms). Odum too felt that the maximum power principle was passed over much too readily by both the physical and biological sciences, but understood, that "... Alone, words ... are not very good for defining network concepts clearly, which may be why many, if not most, people who read the maximum power principle don't understand it, much less see the compelling strength of the argument."

But we note that while Darwin thought that we would never be able to observe natural selection because it was too slow, we now have direct observations and even experimental tests of natural selection in the field (e.g. Grant, 1986; Schluter, 1994), something almost unimaginable even 25 years ago. Although we are not at that point with maximum power, there are certainly many observations that seem completely consistent with maximum power that lend it credibility. Some of these observations are reviewed in Hall (1995) and we give briefly a few here. The rate at which a tree captures solar energy is a function of leaf area index (LAI), the number of leaves that a vertical sunbeam would go through before it hit the ground. The higher the LAI the more photons are captured and the greater the *rate* of energy capture. But each leaf is expensive energetically to maintain. Thus the highest *efficiency* is found with a leaf area index of one, for the large amount of energy captured by that single leaf (which has not been shaded by other leaves above it) is much greater than the expensive maintenance metabolism of the leaf itself. Well, has there been selection for greatest *efficiency*, which would be a LAI of one? Alternatively there might be selection for the greatest *rates* of energy capture, which would be in deciduous trees a LAI of 12 or more. In fact according to the maximum power hypothesis there should be a selection for an *intermediate* rate and *intermediate* efficiency, which would give the maximum *useful* power, i.e. not including the energy that goes to heat in excessive leaf respiration, analogous to the heat loss when the Atwood basket heats the ground at excessive speed. In fact in deciduous forests typical LAIs are about 6, where the maximum power hypothesis says they should be.

More recently there have been a number of extremely well done field assessments of the relation of energy and fitness, and it will come as no surprise to the followers of Howard Odum that they are extremely tightly linked. To my mind the best of these studies is that by Thomas et al. (2001). In this study the authors found that European tits (chickadees) time their arrival on the breeding grounds just before the emergence of their favored food, a large caterpillar, which is in turn dependant upon the phenology (seasonality) of the oak leaves they feed upon. The caterpillars can feed on their main food source, oak leaves, only when the leaves have just emerged from the buds. They can feed on the tender and nitrogen-rich young leaves of oaks, but not the older leaves, which are heavily defended with tannins. Those tits that time their arrival properly with the emergence of the short-lived caterpillars, and their offspring, do very well, with relatively high rates of fledged young. Both parents and young are more likely to return and breed the following year than are others who miss the caterpillar peak. Very clever analyses with double-labeled isotopes that can measure energy costs and gains showed that the tits that miss the caterpillar peak work themselves into a frazzle attempting to feed their young with smaller insects, and parents and young do poorly and both appear much less likely to produce young the next year. The authors also found that climate change is making more tits miss the outbreak of the young caterpillars. All in all this is an excellent study that shows the explicit relation between energy budgets and fitness. To my eye there are more and more such studies being undertaken that show that defense against pathogens and predators, life history choices and fundamentally all selective pressures can be assessed in terms of energy costs and gains that in turn can be translated into fitness in a way that is not circular.

Although the maximum power concept helps with understanding the relation of energy and fitness an important criticism that has been put forth remains. The criticism revolves around the fact that although the theory sounds good, Odum never really tested it, and in fact he said on occasion that, like natural selection, it was extremely difficult if not impossible to do so directly. Yet, I think it is testable if we think hard enough about it, as have those working on the fitness of individuals. Obviously, what needs to be done is to undertake somewhat similar tests to examine the ways that the maximum power principle is, or is not, supported by observations and experiments in nature. Odum felt that ...

> Maximizing ... production ... at each level of hierarchy at the same time is required to maximize the combined economy of humanity and nature. This means simultaneously maximizing ... production and [energy] use at each level's scale of time and space. (Odum, 1995)

I think, in his mind, this gave a reason for the very low efficiency found in ecosystems. Unfortunately, to my knowledge, this hierarchical power transformation has never really been fully tested in a real ecosystem such that one might derive whether the observed low efficiencies were indeed the consequence of serial operations of maximum power relations. This too might be tested in the field with clever experiments. At the same time the mathematics and logic of maximum power (using a quality correction) has been developed in a marvelous publication by Giannantoni (2002). This too needs to be examined and thought about carefully and in time integrated with field tests.

4. Maximum power as more than just intermediate efficiency

Over time it become obvious to H.T. that the Odum and Pinkerton intermediate rate concept was but one of the mechanisms that could be operating to generate maximum power, and he summarized these other factors as a table in Hall (1995) which is given here in Table 1. Fundamentally the idea is that the maximum power principle explains much of the selective pressures that result in "self design" and generates the behavior of organisms and ecosystems that we observe. One of his clearer explanations for how this would work can be found in Odum (1995), where he begins with the abiotic Bernard cell, a small flat glass jar of molten salts, that when subjected to an exterior source of energy would develop a sort of cellular structure that functioned to capture and retain more of the source energy within the structure. It is clear that Odum felt

Table 1
Designs and mechanisms that contribute to maximum power (from Hall, 1985)

Depreciation pathways are always required according to the second law of thermodynamics.
Systems are selected to operate at an optimum efficiency that generates maximum power.
The optimum efficiency will be less during growth phases than at maturity.
There is selection for autocatalytic processes that reinforce production.
These reinforcements may operate at scales above, at or below the processes.
Energy transformation webs are hierarchical.
Storages increase with scale.
Transformities increase with scale.
Different kinds of sources interact rather than add.
Items of different transformity interact multiplicativey.
Energy transformations converge spatially.
Production pathways generate their own storages.
No consumption occurs without reinforcement of production.
Small scale pulses are filtered at larger scales.
Territory of input and influence increases with scale.
All systems pulse: thus sustainability must incorporate pulses.

the Bernard cell operated in the same way as many, or perhaps all systems do. Odum believed that all systems, from ecosystems to stars, under pressure from natural selection, organic or otherwise, would operate to build structure that would feedback to reinforce capture of more energy in a self reinforcing way that he and others have called "self design" (see Odum, 1983a,b, 1995).

Beginning in the 1970s H.T. increasingly focused on aspects of the *quality* of energy, which he originally called simply "energy quality" and later "Emergy." Maximum power was ever present in the development of the concepts of energy quality, and in fact was the impetus for its development. Maximum power concepts lead to energy quality as Odum worked to explain why any system would dissipate energy already captured to create another form of energy. He reasoned that such behavior made no sense unless the higher quality energy (fossil fuels or electricity) was more useful than the lower quality energy from which it was made. Thus the higher quality energy had more amplifier feed back effect and was capable of increasing total power of the system commensurate with the costs of making it.

For Howard Odum maximum power was not some abstract concept that applied only to special laboratory or field situations but rather it was a living, breathing reality that operated in all relevant systems. This led to some extremely uncomfortable confrontations with his graduate students, who, at least in my day, often tended to be hippies, extreme environmentalists and anti-war activists. (Why he attracted so many of these types is a matter for some other discussion!) For example, those of us who were his students during the Vietnam War found that he frequently viewed the world as a power struggle between the Soviet block and the West, to the extent that he felt that the U.S. should not decrease its own birth rate if the Soviet Union did not also do so. This was rather hard for those of us influenced by Paul Ehrlich's book "*The Population Bomb*" to accept. His stance on energy use was often equally disturbing. HT believed that when future energy resources became less available it would be necessary to have policies designed to reduce our use of them, but until that time, as long as they were available in the world, the Unites States should use them first. The harsh realities of this world-view are still with us. If the United States chooses to be environmentally virtuous and not consume the oil reserves of the Middle East are we simply opening up the possibility for China or India to do so, meanwhile, in Odum's terms "taking ourselves out of the race"? In HT's eyes the end of this "frenzy of consumption" we are in now would come only with the exhaustion of the high quality fuels, and until then it was maximum power at a relatively high rate! Late in life he felt ever more strongly that exhaustion of the highest quality fossil fuels was soon upon us and that we should redirect our efforts away from luxury consumption and blind competition toward investments into low energy consuming infrastructure, education, and even birth control. These ideas led to his last book *The Prosperous Way Down* which is reviewed in this volume. With publication of *The Prosperous Way Down*, his graying students from the 60s and 70s breathed a collective sigh of relief!

I believe that these ideas have enormous relevance today in economics, because neoclassical economics (the dominant form of economics increasingly used in this country and all over the world) is normally "sold" because it supposedly leads to "efficiency." However, as beautifully developed by Bromley (1990), efficiency has been used in so many different ways in economics as to essentially have no rigorous meaning at all. In addition in all disciplines people often use the word "efficiency" (output over input) where they should be using "efficacy" (effectiveness), the relation of which is greatly assisted by an understanding of maximum power.

H.T. Odum always emphasized that an ecosystem and its components had to maximize the use of all the energies available to it in its selection for maximum power. This important conceptual framework is illustrated by focusing on the work of sunlight in ecosystems. Many ecologists focus on photosynthesis, or the fixation of carbon, as being the principle use of sunlight by ecosystems. Under this assumption, the efficiency of a green plant is indeed very low, in the vicinity of one percent under moderately favorable circumstances. But as emphasized by Odum, David Gates and others, the work of the sun in a forest, a river or a cornfield is much more than just driving photosynthesis. Most of the sun's energy is used in evaporating water through evaporation and transpiration from leaf surfaces. The sun's energy also drives wind, which moves air, replenishing CO_2, removing waste oxygen, and evaporating volatile organic chemical compounds that are often used as signals for other organisms. While transpiration was once taught as an inadvertent by-product of the need for plants to open their stomates to get CO_2, in fact transpiration appears to be a critical determinant of the rate of photosynthesis, and hence of power generation by ecosystems. In an important, but largely ignored paper, Mike Rosensweig (1968) found that photosynthesis of many different ecosystem types was correlated closely with the level of actual transpiration of each site. It is a remarkable finding. The principal mechanism responsible for this appears to be that with higher transpiration more nutrients can be moved from the roots to new tissues being generated near the top of the plant. Increased transpiration also does other work, including cooling the leaf when subject to highest sunlight.

5. Conclusion

In conclusion, Howard Odum's intellectual development may appear to some as jumping from one concept to another, but in fact there were very strong recurrent themes that, once developed, he applied to the various ecosystems that the contingencies of the world sent his way. The systems view, importance of energy and the role of maximum power are perhaps the most consistent concepts and theories that he studied and thought about again and again. The maximum power principle, from its formulation in the early 1950s, was perhaps the most consistent concept that Odum thought about and developed, and it permeates most of his writings. I too have been enormously influenced and sometimes obsessed by this idea, and find it routinely operating around me in ecosystems and in everyday machinery. I believe that the concept should occupy a much more central position in how we think about natural selection and ecology, and it may be enormously important as we come to grips with an energy-limited future. Odum, too, felt that it had been passed over by the sciences and provided some insights why this might be so. When writing about the lack of interest by most scientists in, or understanding of, maximum power he said:

> Many physical scientists are not trained in natural selection and think of natural selection as tautological because it involves a closed loop. Partly it was a question of fear. Many did not want their fields to have such a constraining law that would simplify and reduce the mystery and value of their careers of measurement. Those with heavy statistical views believed nature to be basically indeterminate. Application to human-scale systems and economies was counter to the roots of these fields in the dogma of humanism, where the indeterminate and free will judge of value is the central belief. Energy determinism in the fifties and sixties implied limits to growth imposed in a world where growth was identified with progress. It was easy for emotional fears of opposite kinds to form majority coalitions to ridicule and blacklist the maximum power approach and discredit the search for general laws that might make some studies unnecessary. (Odum, 1983b)

In my own mind, the search for causality within systems, and the rejection of some existing principles, would be enhanced if researchers would begin with the maximum power principle. It remains surprising to me that this idea has not entered mainstream science, for I believe it to be extremely interesting and enormously more important than most things with which we fill our student's heads.

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