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MAXIMUM POWER AND MAXIMUM ENTROPY PRODUCTION: FINALITIES IN NATURE

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ABSTRACT: I begin with the definition of power, and find that it is finalistic inasmuch as work directs energy dissipation in the interests of some system. The maximum power principle of Lotka and Odum implies an optimal energy efficiency for any work; optima are also finalities. I advance a statement of the maximum entropy production principle, suggesting that most work of dissipative structures is carried out at rates entailing energy flows faster than those that would associate with maximum power. This is finalistic in the sense that the out-of-equilibrium universe, taken as an isolated system, entrains work in the interest of global thermodynamic equilibration. I posit an evolutionary scenario, with a development on Earth from abiotic times, when promoting convective energy flows could be viewed as the important function of dissipative structures, to biotic times when the preservation of living dissipative structures was added to the teleology. Dissipative structures are required by the equilibrating universe to enhance local energy gradient dissipation.

KEYWORDS: Dissipative Structures; Entropy Production; Evolution; Final Cause; Maximum Power; Teleology

INTRODUCTION

The purpose of this paper is to locate energy gradient dissipation as a fundamental conceptual node for a natural philosophy. Mathematical formulations are avoided, and can be found in the various cited works.

Central to this paper is the concept of final cause. There have been many treatments of this since Aristotle (e.g., recently, Rosen, 1985; Wians, 2007). My own perspective on it was presented in 1993, 2006, and 2008. I view finality as residing in answers to the question of 'why' something occurs rather than 'where' or 'how'. These latter I view as the 'setup' for an occurrence—its formal causes—which organize it. In most scientific analyses and all engineering applications, these have in effect been considered sufficient for understanding an occurrence. Yet, implicitly following Kant (Zuckert, 2007), most biologists take it as self-evident that a biological system acts in order to preserve itself and to reproduce. In this we have a final cause because we have an 'in order to' statement, answering the question 'why?'. That kind of answer provides the 'meaning' of a system. Kant went on to consider the universe from a similar perspective, and this figures in the present paper as well. In order to extend finality to the universe, I generalize it to situations where an action that occurs (whether or not associated with human or biological purposes or functions) is 'end directed' by way of furthering the advancement of some general condition (Robinson and Southgate, 2010), so that it can be seen to have acted in order to promote that condition. Finalities can be parsed as:

{teleomaty {teleonomy {teleology}}}

or:

{propensity {function {purpose}}}

Thus, purpose is a particular kind of function, which in turn is a kind of propensity (Salthe, 2008).

Turning now to Power, I begin with a typical Definition:

> Webster's has: 'The time rate at which work is done, or at which energy is emitted or transmitted.'

'Work' here refers to material adjustments or behaviors made in the interests of some system that continues to persist (at our observational scale). Work is not a typical 'physical' variable, as it associates to finality; it is energy utilization *for a purpose.*

Power transmitted is proportional to forces x flows, thus:

voltage x current

potential difference x mass flow

chemical affinity x reaction rate

PUSH / PULL x FLOW, VELOCITY

(More generally, APPLIED ENERGY x RESULTANT MOTION)

Opposed to any flow or motion in most material systems will be some kind of resistance, which will determine, along with the mass being moved, the rate of motion achieved by the magnitude of the free energy expended in the push / pull. Increasing the flow, or rate of motion, will increase the resistance to it in most natural media, reducing the energy efficiency of the work done. In some cases, however, there will be a switch at a threshold energy flow rate from conductive flows to less frictional convective flows during which a dissipative structure will be formed that uses some of the free energy to maintain itself (Bénard, 1900). Entities for which 'work' is a sensible concept are all dissipative structures, and their work is subject to the energy efficiency constraint as just stated. Figure 1 shows the general relations between work rate and entropy production.

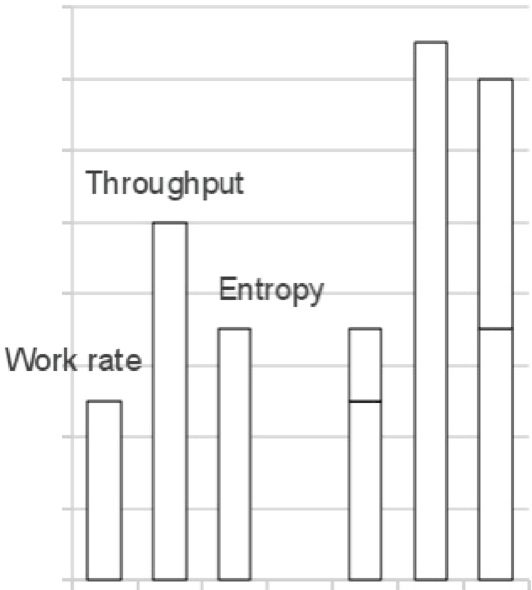

Figure 1: Qualitative relations between entropy production and work rate. The left panel represents the combination at maximum power. 'Throughput' refers to free energy dissipated; 'entropy' refers to heat energy produced during the work.

In electrical circuits, power = rate of energy supply. The need for a separate definition of power in electronic circuits arises because the actual work being done pushing / pulling electrons through resisting media occurs at too small a scale (is too microscopic) to be observed—*as* work—by us at our scale. We can observe only an ensemble entropic phenomenon produced by the work—heat production, as it accumulates at a larger scale, along with the desired macroscopic results of the work done. In this version of power, the finalism disappears because the focus is on the amount of energy gradient being expended prior to its division into exergy and entropy. Of course, as soon as the dissipated energy is expressed in a flow of current, there will be an accompanying heat production reflecting the resistance in the circuit which, again, is not explicitly represented (current ~ voltage/resistance; resistance ~ current squared) in the power expression, voltage x current.

THE MAXIMUM POWER PRINCIPLE

Maximum power (Lotka, 1922; Odum and Pinkerton, 1955) is obtained during work at the most effective combination of work load (resistance) and work rate, which needs to be established empirically for particular systems. For any given work load, maximum power is defined as the work rate after which any increase in rate results in less energy efficiency and more entropy production. Given some work load, working more slowly than in the most effective range may be more energy efficient in some cases, but it would usually be less effective, while working more rapidly than in this range would be less energy efficient, as this decreases the proportion of energy gradient dissipated that gets put into effective work (Carnot, 1824). Such work is energy wasteful.

The effectiveness of work relates to some goal definable with respect to some system. Typically, if the work is done more slowly than at the rate associated with maximum power, the interests of that system would not be maximized, even if that work would be more energy efficient.

Despite two definitions of power, the rate of energy flow through a system ≠ work rate, but does = work rate + entropy produced.

Given sufficient free energy resources, increasing work rate is associated with increased energy throughput (or rate of free energy gradient dissipation). The two are always positively correlated, delivering inconstancy in the product of free energy dissipated and associated work rate.

So, work rate will be a monotonically increasing function of energy throughput. In some systems (heat engines, plants) increasing the energy throughput will by itself, because of the organization, drive faster work. In animals, faster work will entrain greater energy throughput, because the internally stored free energy in ATP is ready to be tapped for use at any time. Here too, if work rate increases from the range of maximum power, it will be less energy efficient overall, because the regeneration of ATP is dissipative (~ 60% efficient, Morowitz, 1968), and because of various macroscopic frictional entailments.

Maximum power tends to associate with optimal energy efficiency. Optima are finalities, as they serve to maximize or minimize some systemic function in the interest of some system. I would argue that all variational principles are finalistic in form. Energy utilization at maximum power will increase as a system grows or develops, as it refers to gross energy flows. Thus, from the present point of view, because they involve increasing energy flows, we could take development and growth to be entrained by the Second Law of thermodynamics in light of the 'maximum entropy production principle'.

THE MAXIMUM ENTROPY PRODUCTION PRINCIPLE

This (MEPP) can be stated as:

> an energy dissipative system that can assume several to many conformations, will tend too take up one, or frequently return to one, that maximizes the entropy production from the energy gradients it is dissipating—to a degree consistent with that system's survival.

The mode by which most dissipative structures carry this out is by increasing the energy throughput affording their activities. Differing perspectives on this can be found among Dewar (2005), Kaila and Annila (2008), Lorenz (2002), Schneider and Kay (1994), Swenson (1989), and Ulanowicz and Hannon (1987).

Since energy gradient dissipation is a necessary stage in the production of entropy (heat energy), and given the generically poor energy efficiency of any work (Odum.

1983), energy gradient dissipation can serve as an approximate or rough stand-in for entropy production, even though any work performed in the process will tend to delay the dissipation of some of the gradient. As well, effective work tends to produce waste products other than heat energy. These are generally closer to being completely dissipated to heat than was the original gradient, and can be considered relatively 'entropic'. The hastier the work, the less complete will be the dissipation, and MEPP tends to favor rapid utilization of the original energy gradient, and so will be less effective in reducing it completely to heat energy.

Consequent upon MEPP, if a system produces work, it should tend to work, not at maximum power, but at a greater rate of work production. Effectiveness of work production should trump energy efficiency in most kinds of systems much of the time. In economic cases where there is abundant energy available, there will be a tendency to use any savings from increased efficiency in ever more applications and at greater rates (Jevons, 1866; Saunders, 1992). Maximum energy efficiency in animals appears to be a default position that would likely be found only under basal metabolic, resting conditions (Andresen et al, 2002).

In abiotic dissipative structures, like tornadoes, the energy gradient will be depleted as fast as possible, allocating a relatively small amount of free energy to the work of maintaining the form of the dissipative structure during the process. The 'function' of the energy flows here may be taken—in the context of the Second Law of thermodynamics in a far-from-equilibrium universe—to be gradient depletion, with the dissipative form being the means to that end. The finalism here is imposed by the current distance of the universe (or our section of it) from thermodynamic equilibrium (Salthe, 2008).

With biotic dissipative structures, the function of the energy flows is rather taken to be the preservation of the dissipative forms themselves (see Alexander, 1999, for the various forms of work engaged in by animals). It seems reasonable to suppose that, if they could, living dissipative structures would, while active, tend to use their free energy stores near the range of maximum power. It has been claimed that plants do tend to operate at near maximum power. As well, there have been studies suggesting that biological evolution has produced increases in energy efficiency (e.g., Young et al. 2009). But in a world characterized by unavoidable capricious events, and occupied as well by other-directed agencies, a living dissipative structure is continually being impacted and deranged, so that it will frequently be in a state of striving. This would entail greater energy flows than those that deliver maximum power. In animals this involves, e.g., fleeing, fighting, mating, competing for resources, shivering, healing wounds and infections, migrating, and taxing brain activity at all times – everything beyond mere basal homeostasis. With plants this would involve outgrowing competing individuals, producing toxins and allelopathic substances, and healing wounds.

A question that can be raised here is whether there is any objective difference in the work done by abiotic and biotic dissipative structures. Tornadoes, although capable of fantastic feats of material (re)arrangements, are not typically viewed as doing work, even though they do maintain themselves for a time. The proper comparison would perhaps be between a tornado and a fully armed modern soldier in a fire fight. It might be supposed that abiotic dissipative structures like tornadoes are not individuals at all, but rather temporary environmental configurations. But each one is in fact just as individuated as are organisms (although with fewer degrees of freedom!). As well, organisms are just as dependent upon particular environmental configurations for their nurture as are abiotic dissipative structures. I leave this question unanswered, merely pointing out that the import of the thermodynamic perspective is not restricted to meteorology or technology, and may be deeply philosophical. (I note in passing that we 'non-animists' do name hurricanes!)

ENERGY FLOW AND EVOLUTION

Given the above discussion, we can imagine a development on Earth from abiotic times, when promoting convective energy flows was the important function of dissipative structures, to biotic times when the preservation of living dissipative structures was added to the teleology. This can be represented using a specification hierarchy (Salthe, 2002, a) thus:

{dissipative energy flow function → {dissipative structure preservation function}}

Notice that the logic here represents energy dissipation as subsuming dissipative structure preservation. One salient meaning that can be discerned in this is that living, as well as abiotic, dissipative structures are being entrained into the universal project of thermodynamic equilibration, in the direction of zero global energy density. It seems likely that this global equilibration could not actually be achieved without the attendance of dissipative structures (from galaxies to bacteria), some of which may, then, be expected to accompany equilibration far out onto the asymptote approaching universal thermodynamic equilibrium (Ulanowicz, in press).

The developmental process of aging in organisms is instructive in showing that when the effectiveness of striving declines, an organism gets set up for recycling – and so we see that utilizing the maximum power regime is not in itself sufficient for survival. The key data here are those showing that, after their inception, the per unit mass energy throughput of organisms steadily declines onto an asymptote (Zotin, 1972; Aoki, 1995) as they spin out their lives. This is an expression of the 'minimum entropy production principle' (Prigogine, 1961) as it works out in dissipative structures (Kay, 1984; Salthe, 1993). The 'development' of Prigogine's experiment mimics the decline in energy density flow rate throughout an organism's life. Consequent upon this, the increase in gross energy throughput entrained by growth and development will gradually slow down as well (Salthe, 2002,b), impacting the ability to recover from injuries Thus, it looks as though when failing to contribute as much as they had been doing to the maximum entropy production project of the universe, organisms begin to fail.

CONCLUSION

Maximum power is a finalistic concept inasmuch as it refers to energy flows utilized to support the existence of dissipative structures. Extending this, we could say that engineering harnesses physical principles to the interests of human dissipative systems. The maximum entropy production principle is a finalism in the more general sense of the entrainment of all activity by the universal project of thermodynamic equilibration. The evolutionary emergence of dissipative structures served / serves to enhance the rate of dissipation of energy gradients that are resistant to dissolution by conduction alone (Salthe, 2007). Furthermore, living dissipative structures can access energy gradients that are not available to abiotic ones. From this we can see that the physical world is harnessing human engineering onto a broader, universal finality.

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