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Full Research Paper

The Natural Philosophy of Work

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Abstract: Work, by dissipative structures (DS), imposes delay on energy gradient degradation. It diverts energy flow into DS maintenance while enhancing energy degradation. DS can be viewed as tradeoffs between enhancing entropy production maximization (the maximum entropy production principle, MEP) by way of convective gradient degradation, and the need to maintain DS form, which is what mediates the convective dissipation. This tradeoff frameworked the origin of living DS. In the Big Bang, the Universe departed increasingly from an ordered state of low entropy. As a result the Second Law (locally, dS> or = 0) became an ever more powerful attractor, insuring that work could have only limited energy efficiency (utilization / throughput). That is, the '>' in 'dS > or = 0' increased on average locally as the universe departed further from thermodynamic equilibrium. Energy efficiency becomes significant in the context of possible energy shortage, which implies embodied agency, implying in turn the possibility of some stability into the future. Energy efficiency is needed in living DS which yet serve MEP by becoming relatively less energy efficient when striving. Biodiversity multiplies modes of energy consumption, also furthering MEP by compensating for the diversion of energy flow into the maintenance of living DS. Modular (hierarchical) structure is very stable to perturbations, and also generates the variety requisite for adaptive flexibility, affording as well evolutionary access to increased adjacent possibilities. Dynamical rate separation between hierarchical levels streamlines energy flows, enhancing orderly energy gradient degradation. I conjecture that new levels are interpolated when that fosters MEP overall. Of the three phases of energy flow -- low level conduction, mid level convection, and high level explosion -- orderly convection associates with DS form, constraining moderated energy flows, and defusing potential explosions.

Keywords: Big Bang, convection, dissipation, energy efficiency, energy gradient degradation, MEP, scale hierarchy, Second Law, work

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Introduction

Entropy is arguably the most pervasively important physical concept in our Western culture [1]. The Second Law of thermodynamics conceives a universal disorder attractor governing our world to the effect that the world tends towards ever more probable configurations of its substance. Formally, this requires the plausible supposition that our universe is an isolated system. The effect on us of this universal tendency is that we cannot ‘have it all’ because our ‘having it’ generates a degree of greater improbability in local energy distributions. This limitation comes about because we go about getting what we want, ***and*** we even experience wanting, only by mobilizing energy gradients, which degrade and partially dissipate as a result. By ‘dissipation’ of an energy gradient I mean its degradation all the way to completely degraded energy -- heat energy, or entropy. Gradient degradation involves some dissipation directly as well promoting further dissipation by exposing waste products to further dissipative forces. Energy gradients are orderly alignments of ‘free’ energy, potentially ‘available’ to be tapped for work. ‘Order’ in this sense, and ‘availability’, means ‘arranged so as to be consumable’, and this necessarily reflects the properties of consumers as much as those of an energy gradient, since these must in some way, and to some degree, match. And so energy gradient order, being improbable, is not only unlikely to be spontaneously achieved, but is also implicitly subjective, as well as semiotic (i.e., meaningful to potential consumers).

This paper concerns the consumption of thermodynamic order, or available (free) energy. Plants consume solar energy, we consume fresh organic matter, engines consume fossil organic matter. Sunlight is in this sense not ‘available’ to us, or to our engines [2]. With entropy being defined as disorder [e.g., 3], energy gradients that cannot be consumed might as well be viewed as entropic with respect to excluded consumers. So, from the point of view of our physiology, sunlight and fossil organic matter are virtually disordered because we cannot mobilize them directly as sources of assimilable energy (even though they do contain measurable free energy). The ultimate form of non-consumable energy for any consumer whatever has been conceived in physics as ‘heat energy’ -- entropy. This is energy that has been so thoroughly disordered that no gradients are sustained within it long enough for any consumer to mobilize them [4]. Energy gradients might form spontaneously within a volume of heat energy by way of fluctuations, but these will be randomly oriented with respect to any intents and purposes , and so unable to be harnessed to action at any scale larger than Planck scale. Such gradients would be ‘randomized’ with respect to the possibility of accomplishing work. As well, they dissipate spontaneously before they can be harnessed to (what we at our scale would reckon to be) work. Work [e.g., 5] is activity mediating a change from one form of energy to others of lesser amount, but more orderly than heat energy, some of which would be ‘useful’ to the working system. Useful work, however, is always accompanied by the production of heat energy / entropy as well. Available (free) energy degrades into exergy (used in work) plus the energy eventually dissipated into entropy.

Wanting and Work

Now, we cannot obtain all the energy we want even when consuming energy gradients appropriate to us. The concept 'being consumed' is not simple. In typing a file we consume organic matter. But not all that we have assimilated can get used in this (or in any) way. Effective energy consumption is not very efficient (only about 50% on average-- [6]), with much of a dissipating gradient that is being consumed typically getting lost as heat energy and other waste products (lesser energy gradients not available to the consumer). Somehow, we cannot get perfectly aligned with respect to our foods so as to transfer all the joules they contain to our own ends. Then, of course, obtaining and eating these foods requires energy expenditures up front; we must work in order to appose our metabolic system to appropriate energy gradients in the first place. And then assimilation and mobilization of the energy require further expenditures (in, e.g., its internal transportation and storage). Mobilization in biological systems involves the production of ATP and other compounds, which are chemical energy gradients that can be used metabolically. This production is dissipative -- that is to say, it too is not very energy efficient. Finally, we can focus down on one of our muscle fibers or mitotic spindle fibers to watch it contract as energy that bonded phosphate atoms onto ATP molecules is transferred without dissipation to the fiber, causing its contraction in support of work [7]. On average approximately as much of that chemical bond energy gets converted by friction to heat as that which actually moves the contractile fiber. Since we use heat produced in this way to warm ourselves, heat is here the product of work! Work is useful (to some agent) energy degradation.

So, in our works we build -- ourselves, others, buildings and cities, farm produce, transportation, dances and artworks, music, riots, bombs and battles -- all of our accomplishments and works. Those products that are embodied more than fleetingly would be energy gradients themselves if there were consumers appropriately formed so as to be able to use them (all matter is a form of energy -- 'mattergy'). Fires could use many of these products of work to support further chemical transformations, and would produce a good deal of heat as well since fires are very poorly energy efficient. Do fires do 'work'? Cooking, burning trash, making fire breaks, smelting metals, disabling our enemies -- the answer seems to depend upon whether we desire the ends or not. So we must further ask: 'do tornadoes, while consuming the energy of large scale temperature / pressure gradients, do work'? Technically, it seems they must. They lift and move objects from one place to another and break them into pieces. Ecologically, along with fires, they recycle ecosystems, restarting the developmental work of ecological succession. But the question of energy efficiency does not seem to us to arise in regard to the works of abiotic dissipative structures like storms and fires. Neither is acknowledged to do work, which amounts to denying them the status of agents having purpose [1]. One thing we know that these abiotic systems do is obey the Second Law of thermodynamics by degrading energy gradients to -- or further in the direction of -- heat energy, and this they do better the less 'efficient' they might be calculated to be. Of course, what we do take to be work in our interest obeys this law as well.

We will see that, in a very general sense, work imposes impediments upon energy gradient dissipation, slowing it down from its fastest possible rate, resulting in delaying its dissipation all the way to heat energy [8].

Dissipative Structures

Abiotic dissipative structures (e.g., tornadoes, eddies, winds) would be as little energy efficient as it is possible to be if we could assign some work to them. Indeed, they are energy profligate, dissipating apposed gradients as fast as possible. As pointed out by Carnot long ago, the faster work is done, the less efficient it will be. As energy gradients build up they become increasingly metastable, and at some point their degradation transits from a slow, gradual conduction of energy by way of frictional processes like diffusion and decay, to rapid convection mediated by spontaneously generated macroscopic forms like winds and fires [9]. The steeper a gradient is before going into crisis, the more powerful the macroscopic energy flows generated -- generating, say, tornadoes instead of just thunderstorms. Such abiotic dissipative structures are the forms generated by an energy gradient itself in its process of dissipating. And they could be said to be nothing more than the shape or mode of a gradient's dissipation, differing according to the kind of gradient -- as winds, rain, waves, vortices, fires, or tree forms like lightning. In our world all of these general forms of energy flow come into being spontaneously. It has been plausibly suggested that in dissipating a gradient they produce entropy at maximal rate for the kind of system they happen to be [9, 10, 11]. Dewar [12] has recently shown that complicated non-equilibrium material systems that are free to assume many different configurations will assume one that maximizes the system's entropy production. This is the 'maximum entropy production principle' -- MEP (see also 13) -- of which more below.

Organisms fit within this pattern as well, even though we are not formed spontaneously during the dissipation of gradients powering us. Energy gradients are the basis of our existence, but, as unusually stable dissipative structures, we can survive short periods away from our supporting gradients, during which time we can search for them, or, as with plants, simply await their return. In connection with organisms, an aspect of the process of dissipation becomes more salient than it is with abiotic dissipative structures (where it nevertheless does exist). This is that some of the energy flow must be used as exergy, supporting the work of building and maintaining the form of a dissipative structure. That is, it cannot all be directly 'wasted' as heat energy, during any but microscopic maximized entropy production. This is as true of tornadoes as it is of organisms, but work has seemed to be a useful concept only in connection with complicated, exceptionally stable, definite forms taken to be agents, like us.

The forms of living systems are delicate and easily disrupted, and so literal entropy production maximization within them or in their close vicinity would tend to tear them apart. Here it becomes clear that entropy production can always be maximized only to a degree allowed by bearing constraints. In gradients less steep than those affording explosions, entropy production could not be furthered toward maximization without a dissipative structure itself being present, and so the degree of direct maximization must be tailored to the continuing presence of that structure. Put another way, natural dissipative structures are those that can degrade external gradients without destroying themselves; other kinds, of course, cannot exist. We can see that even organisms are maximizing because their works often tend to be as rapid as possible, being urgently entrained by competition for energy gradient and mates, by reproduction, and by the need for the rapid healing of injuries and the continual fending off of infections -- by all kinds of striving. Bejan and Marden [14], for example, found that with respect to locomotion, animals of all kinds are organized so as to reduce the friction opposing the energy flowing through them, thereby favoring macroscopic convection over microscopic conduction during gradient dissipation. This reduction of friction is exactly what happens when a tornado organizes heat flow from slow conduction to fast convection. Of course, convective forms also generate friction, but not as much as conduction, for the same amount of gradient degradation or energy flow. Dissipative structures are tradeoffs between maximizing entropy production from energy gradients and the maintenance of their form, which mediates the convective degradation. This need for form was the framework within which life originated.

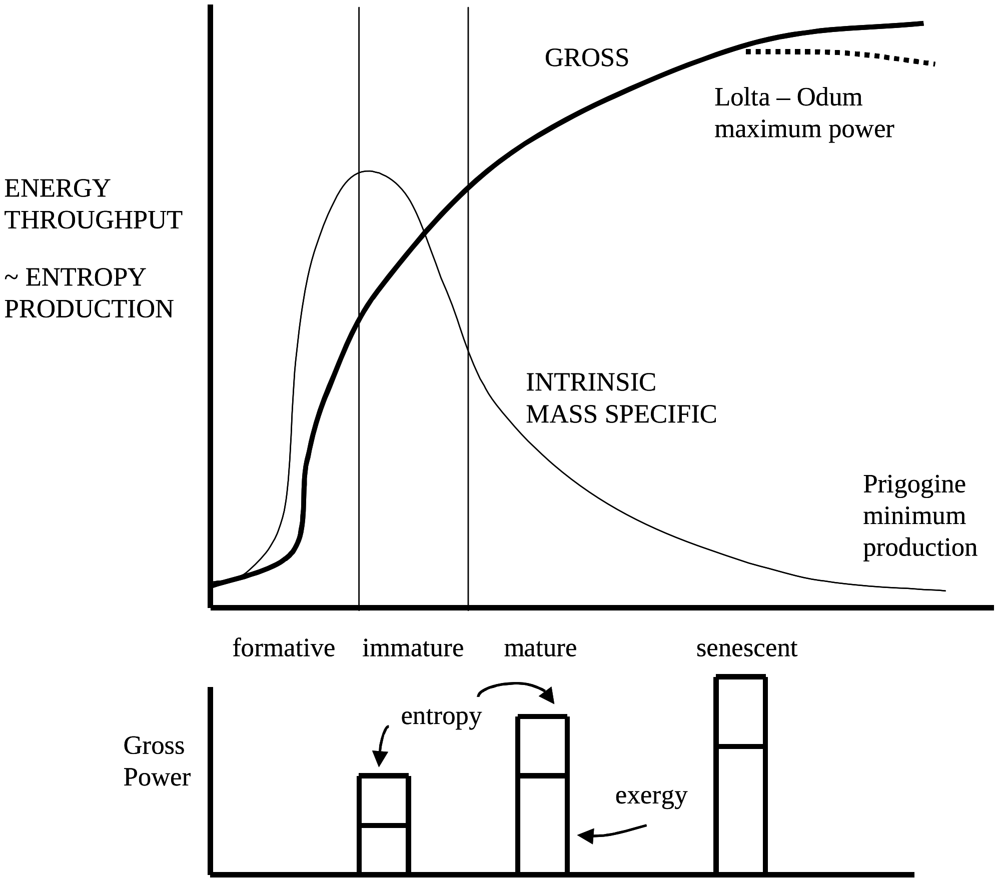

Figure 1. Qualitative curves showing the thermodynamic relations of dissipative structures mapped according to stage of development. The upper portion shows the patterns for power (energy throughput rate, potential work rate) tallied both for the system as a whole (gross), and for energy density throughput (per unit mass, specific, or intrinsic energy flow). The dotted portion of the gross curve applies to systems that stop growing, after they stop. The lower portion of the figure shows the work efficiency (proportion of the energy throughput used as exergy). As the system ages it becomes more energy efficient, and its effectiveness in the work of order maintenance depends upon increased absolute size. No explicit boundary is shown between the mature and senescent stages because these grade into each other more gradually than the transition from immaturity.

It has been noted that the intensity of energy use (energy flow per unit of mass) within organisms tends to decrease during their life span [15, 16], even though they do continue to maximize, to the extent possible given increasing constraints, the rate of degradation of the gradients they consume. This decrease in the intensity of energy throughput is the ‘minimum entropy production’ principle of Prigogine [17]. In more detail, an organism’s energy density (per unit mass) throughput rises rapidly during their formation, peaks, and then gradually trails off from immaturity through maturity into senescence (Figure 1). This pattern of energy flow affords growth of the system in immaturity and subsequent maintenance, with later fluctuations being associated with intense activities, like reproduction and healing. Gross energy throughput, reflecting growth, while also increasing rapidly at first, levels off rather than dropping after peaking, and may continue to increase slowly onto an asymptote during senescence, and so it tends to increase throughout (Figure 1). This is the 'maximum power principle' of Lotka [8] and Odum [18], first enunciated for ecosystems. Organismic energy flow roughly follows this gross flow-through pattern as well, and therefore is increasing during most of the life of the system, dropping slightly in later senescence -- that is to say, power tends to be maximized only within constraints, which increase with development. These constraints are what keep such a complicated system from literally maximizing its entropy production [12]. In early development the rate of developmental work is so great that proportionally more of the available energy throughput dissipates entropically, but after the system has become definitive, its greater mass makes for continued large heat production even though metabolism becomes increasingly more efficient (lower part of Figure 1).

The relationships between energy throughput, work and entropy production need closer scrutiny. Energy throughput is what powers work, and, indeed, 'power' has been defined both as rate of energy throughput and as work rate, the implication being that most throughput is enlisted for work. However, not all of it can be (the Second Law), and, as Carnot found, the further from the most efficient possible work we get, the less energy efficient will the work done be. That is, increased work rate will elicit both greater energy throughput (supposing it to be available) and increased entropy production. The Bénard instability experiment, which dissipates a temperature gradient, is useful in seeing these relations clearly. A fluid is heated from below. Initially heat energy passes through the fluid via microscopic conduction, producing entropy frictionally. As the temperature of the external gradient powering the system is increased, a threshold is reached when the fluid reorganizes into orderly convection cells, which move the heat more rapidly from its source to the sink. Microscopic conduction continues, but macroscopic convection has been added to dissipate the increased temperature gradient because no further increase in conduction rate is possible. Yet, even though macroscopic friction has been added to the microscopic friction, the macroscopic activity obviates some entropy production, and the rate of entropy production is less after emergence of the cells. This is because formation and maintenance of the cells itself demands energy, and so the system is still maximizing entropy production, but within greater constraints. Here the convection cells are dissipative structures, and can be directly compared to the likes of eddies and hurricanes.

If the temperature gradient in the experiment continues to be raised, the system becomes turbulent, as with boiling water. That is, dissipative structures can only exist in an intermediate gradient. Above that we get what I will herein call 'explosions'. In nature explosions are relatively rare because dissipative structures tend to arise spontaneously as gradients increase to a scale that will support them [9], preempting explosivity.

We can interpret animals from this model as well. Basal metabolic rate (as during sleep) is modeled by the system in its conductive state. Animal activity (i.e., work) is powered by increased utilization of internally stored energy, and striving enlists still further energy utilization. The experimental cells represent organismic motion, which adds higher scale friction to the internal entropy production. Some of this activity resupplies the internal energy stores, closing the metaphor. The motion of Bénard cells is a kind of , or is akin to, work. In both animals and Bénard cells the source of energy is external; in the latter it immediately powers the cells, in the former, it gets converted internally after capture and assimilation to other forms of energy before being used to power the system. The activities of both the Bénard cells and organisms hastens the degradation of external energy gradients to heat and, in animals, to forms of gradient (scraps) closer to heat than the original gradient -- that is, the activities of both tend to increase entropy production, furthering MEP. In plants the major entropy production occurs during transpiration, a combination of diffusion, capillary action and evaporation that takes place only in the presence of the gradient, solar energy. The work in this case involves chemical synthesis of osmotically active substances, and the resulting active pumping of water in root hairs and stomates.

The Big Bang

We need to understand in a general way why entropy production everywhere tends to be maximized [19]. An answer can be derived from the Big Bang theory of the generation of the Universe (Figure 2 -- see, e.g., 20, 21, 22 for recent details). Universal expansion, classically accelerated, occurred so fast that global energy equilibrium could not be maintained, generating a cooling whereby matter precipitated from radiation energy [19, 23]. This led, with the initiation of gravitation, to secluding large amounts of energy as gradients in varied clumps of mass very far from thermodynamic equilibrium. This process of energy embodiment interrupted a global microscopic process of energy equilibration also engendered by the expansion, giving rise to the entraining pull of the Second Law of thermodynamics -- the tendency for matter to scatter as widely as possible in its smallest bits, and for energy itself to become uniformly distributed. Locally, this law manifests as the nonequilibrium requirement for entropy production to accompany any occurrence whatever [24], including during the buildup of new energy gradients, which therefore serves, as already noted, to further energy equilibration because effective work is so energy inefficient. So the continued production of order entrains as much, or more, of an available dissipating energy gradient in the direction of disordered ‘heat energy’ than gets used as exergy, and does so to the extent that the work is accomplished quickly. In this way the universe entrains macroscopic activities to the service of global microscopic equilibration: black holes consume galaxies; asteroids smash planets; glaciers, via mass wasting, erode mountains; carnivores and detrivores consume other organisms; plants disperse water; economic activity dissipates oil deposits; warfare destroys artifacts. These processes are not energy efficient, producing many new gradients of lesser amount and scale. The resulting smaller pieces and particles are generally closer to thermodynamic equilibrium than were the prior larger clumps, volumes and forms [25].

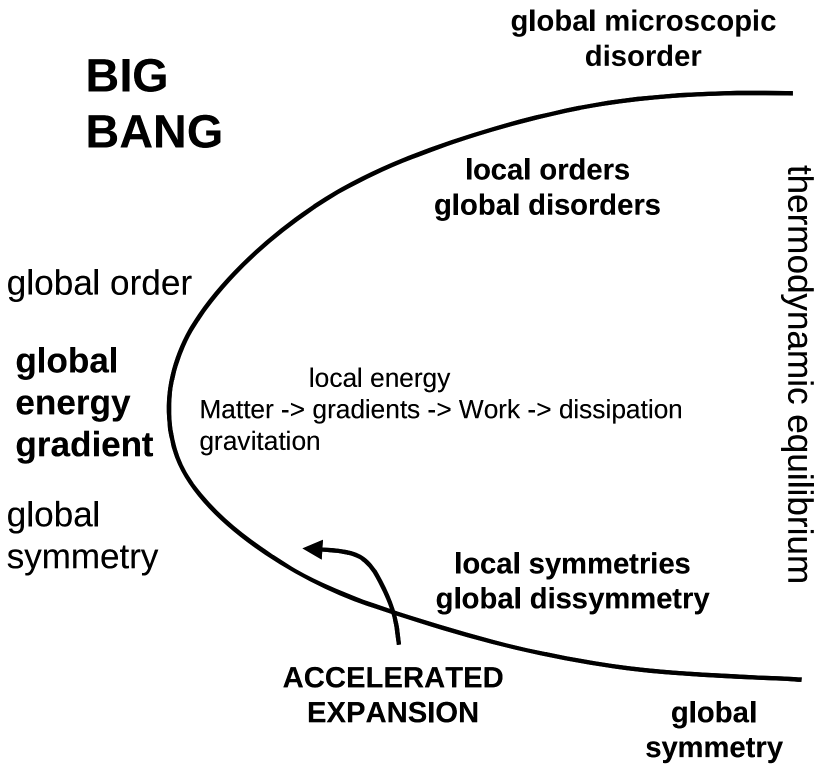

Figure 2. A thermodynamic perspective on the Big Bang expansion, noting both the production of disorder (entropy) via dissipation, and the regaining of symmetry lost as a consequence of cooling.

The work of order production results, by way of accidents / mutations, in a plethora of different forms, tending ultimately to produce increases in macroscopic informational entropy (i.e. variety) in its vicinity. With the origin of living systems, work involved an increasingly more organized degradation of gradients, and mutations led to the appearance of new kinds of energy consumers, increasing informational entropy in the form of biological diversity [26], as well as opening up possibilities for the dissipation of still untapped energy gradients, as in the use of fossil fuels by human economies. The inefficiency of work also produced / produces more kinds of energy gradients in waste products, giving rise to the possibility of the elaboration of ecological food chains and food webs. These waste gradients get dissipated gradually along food chains in the branches of food webs. It is sometimes claimed that this gradual process of dissipating the original energy gradient 'slows down' the dissipation. This does not take into account that without the food chain the dissipation would be even more greatly delayed, being remanded to microbial action. In biology / ecology, work therefore affords increases in species richness and diversity. Food webs increase entropy production beyond what would be possible in a simple food chain, not only tending to increase the local rate of energy degradation, but also improving the overall Second Law dissipation all the way to heat energy. And so we can model (using set theory format) the consequences of the Big Bang as:

{physical processes {chemical affinities {biological forms {societal organizations }}}}

giving us a specification hierarchy [16, 27], with more complex integrative levels viewed as emerging from prior existing simpler ones.

Thus:

{physical basis --> {chemistry --> {biology --> {sociality }}}}

whereby I conjecture that each step was accompanied by an ever stronger Second Law entrainment of dissipation -- increasing the average or typical '>' in 'dS > or = 0' in open systems -- reflecting the increasing departure of the universe from thermodynamic equilibrium that these emergences of new realms of nature represent, as increases in orderliness. So the headstrong expansion of the Universe entailed the ultimate production of forms as well as the simultaneous tendency to dissipate them.

The Evolution of Energy Efficiency

Abiotic dissipative structures are little more than transient pathways for increasing the rate of energy gradient degradation in the service of Universal equilibration. And they exist only as long as their local supporting gradient survives. The energy flow diverted to the work of generating these ephemeral forms could be said not to be deducted from entropy production at all since the active system itself dissipates rapidly. So energy efficiency is a concept that cannot even arise in the context of abiotic dissipative structures. Hurricanes and tornadoes slurp up temperature and pressure gradients and spew them out immediately as kinetic fury. On Earth (at least) a new sort of dissipative structure appeared when living systems invaded and coopted some of the preexisting abiotic ones. This sort of dissipative structure acquired such exceptional stability that it survived the gradients it dissipated, allowing incremental growth and eventually the generation of propagules. This stability was afforded by the genetic system, which provided information for the healing of ruptures and the repair of broken extensions. These living dissipative structures not only had form, but also an extended lifetime, characterized by a drawn out developmental pattern, increasing the length of the definitive stage (mature stage, Figure 1) compared to their abiotic precursors, which merely burgeoned and then immediately senesced as a consumed gradient was spent. In the living, stability between bouts of access to external energy gradients is made possible by an extended period of energy assimilation orchestrated internally [e.g., 7, 28]. Such an extended period between energy capture and use logically implies energy storage.

The mode of running on internal energy stores between access to uncertain or delayed external energy gradients gives rise to the logic of energy efficiency, while efficiency (slower than maximum dissipation) implies the possibility of shortage, which implies an embodied agency, which in turn implies potential stability into the future. Internal efficiency and delayed dissipation also affords ecological specialization upon scattered localized gradients, as well as giving rise to the possibility of a significant mature stage in the life history of dissipative structures, a stage that became reserved for reproduction. Stability requires -- despite the Second Law -- some efficiency of energy use, so that moderated energy flows may be deployed toward different functions as needed. Increasing energy efficiency requires increased control and moderation of the rate of energy throughput. In biology, for example, while meso- to macroscopic work still needs to be done, relatively cold dehydrogenation, for example, has been enlisted to replace burning microscopically. A recent discovery of interest here is that the rate of energy conversion in the photosynthesis of thermophylic bacteria does not rise exponentially with temperature, but is moderated by way of protein forms, giving similar yields to that found in mesophytes [29]. Faster rates of energy conversion would obviously be dangerous to the cells.

None of this, however, implies transcendence of the Second Law. Sluggards are not tolerated in the physical world. The biological work of growth and reproduction is underwritten in animals by efforts expended in the search and capture of energy gradient, which are carried out as strenuously as possible in the interest of competition for resources. We can also add to their striving competition for mates, as well as the urgency of healing and fighting off infections, and also in some cases the demands of searching for or building shelter in an inhospitable world. During striving, living systems maximize frictional entropy production to the degree possible short of disrupting themselves. Internally excess energy is harbored in forms like ATP, as well as in longer lasting lipid storages, allowing suddenly urgent action to occur without regard to the presence of external energy gradients.

It should be noted that this general picture is true of tornadoes as well. They too do not disrupt themselves. If stronger gradients face them, they just get bigger, moving up, say, to being hurricanes, with an end found not even (one supposes) in the likes of Jupiter’s Red Spot. What we have in energy flows are possible phase transitions, from slow conduction to rapid convections to, finally, explosions, which no forms can survive (see more below and Figure 3). Conduction is too undirected to underwrite form, while explosions tear it apart. Form is found only in connection with what we can now identify as relatively moderate energy flows. At the scale of organisms, typical flow rates reflect moderated power, and at the scale of hurricanes they reflect scaled up -- but still somewhat moderated -- power. In neither case is the energy dissipation explosive, which in both cases would destroy the dissipative structuration.

It is interesting to note here that the most stable internal condition for dissipative structures generally is the immature stage in their development [16]. This has two components: trivially, in those cases where a system can return to an earlier stage after disruption (as in ecosystems -- e.g., 30), this stage can be reconstructed comparatively rapidly if disrupted, and so, over long periods of time would tend to be the most persistent situation at some locale. More significantly from the present point of view, as well as more generally relevant, is the fact that the immature condition is one combining relative simplicity of form with a tremendous dynamism mediated by high intrinsic energy throughputs (Figure 1). The result is that an immature system is not easily deflected in its development by forces of about its own scale. Of course, the fact that immature individuals tend to be relatively smaller than other stages in many kinds of systems (not ecosystems) can tend to work against their stability inasmuch as it is generally assumed that systems are adapted to their environments primarily in their definitive condition. Indeed, I have reason to believe [31] that natural selection is not very effective in the early developmental stages of living systems. Immature stability can be boosted by special protections (as with the embryonic stages of organisms) as well as by large production of propagules, tending to guarantee some survival after culling. So, immature systems are the most dynamically stable stage of a dissipative structure, and are as well the stage with a proportionally larger intrinsic entropy production resulting from their work (Figure 1). It is plausible to see these properties as being linked, with the latter guaranteeing the former, since it increases during repair.

Hierarchical Structure

Herbert Simon [32] argued (with the watchmaker metaphor) that a compositional (scale) hierarchy [27, 33] is the most stable structure for a material system because, having modular organization, collapse of one component would not necessarily lead to collapse of a whole system. The relative stability of the material world could likely to be due to its having this basic organization, with higher scalar level entities having a greater stability, by changing more slowly relative to lower level ones. All material systems do appear to have this structure [34]. This modular organization, with multiple smaller scale entities or processes nested within, or entrained by, fewer larger scale ones may well be the form that packs the most information into a given locale, given only that we acknowledge information to exist at many scales. None of the accepted definitions of information appear to prohibit this. For example, information as the reduction of uncertainty is general enough for this, as is information as embodied in constraints on entropy production. Furthermore, given the restless dissipative shifting of forms within locales in any material system, this increases a locale’s informational entropy as well, providing in its smaller scales the variety requisite for adaptive flexibility [35] at higher levels [36], as well as providing the overhead capacity for recovery from perturbations [37]. This lower level informational entropy also underwrites the adjacent possible configurations a large scale system might access to provide for its evolution [38]. Thus we have a system with rapid adaptive dynamics in its components and even more rapid dynamics within its components’ components, while remaining relatively stable at its own, larger scale.

I now consider whether, In light of the Lotka/Odum maximum power principle, scalar hierarchical structure might also be favored materially as the form which best maximizes the overall rate of entropy production [39]. Note again that all material systems appear to be structured as scale hierarchies, with dynamical rate breaks between levels of around order of magnitude. Obvious examples can be shown in the hierarchies: [organism [cell [macromolecule]]], or [supercell [tornado [water phase changes]]], (interpreted as [higher level [lower level]]). Energetically, this form involves parsing energy flows among dynamics at different scalar levels. Consider a simplified thought experiment using a model of energy gradients organized as chunks of different scale nested within each other in, say, three levels. The largest chunks are held together by gravitational forces affecting the middle level chunks. These in turn are held together dynamically by dissipation of the smallest bits (they are dissipative structures), which bits, finally, are directly affected by the Second Law tendency to scatter. Chunks at all levels tend to scatter as much as possible, but gravitation prevents anything more than just fluctuations at the larger scales. The smallest bits would scatter uniformly, but are held within larger chunks, except for those that are released by dissipative activities in the middle level.

Now, entropy production would be maximized in such a system if it could just explode, destroying all chunks larger than the smallest bits. This is prevented by there being no energy gradients (chunks) bigger than the largest at the highest of the three levels here. This came about because the centripetal, ’gravitational’ force here was not strong enough to pull together the largest chunks, given their tendency to scatter. If it had been, the system before us just could not exist at all, as it would have exploded. Another route to explosion here would have been if large enough energy gradients could have formed because meso level dissipative systems had not formed. But these formed locally by way of fluctuations, and once they existed their entropy production locally satisfied the global Second Law tendency by degrading nearby lesser energy gradients at a fast enough average rate. Eventually meso level energy gradients will become scarce enough because of their continued degradation so that dissipative structures could no longer form in sufficient numbers to prevent the largest chunks from growing to explosive size. This would destroy the system (unless the 'gravitational force' could increase in synchrony with gradient size increase so as to hold it together).

Thus, given some level of centripetal (gravitational) force, the entropy production of a resulting system of levels would be maximized short of exploding the system itself (in which case there would be nothing to consider) by way of continued dissipation by mid level dissipative structures, which prevent the growth of energy gradients to explosive size. We can use the canonical triadic form of a scale hierarchy [34] to show the basic organization of dissipative structuration (Figure 3). Note that middle level, meso- to macroscopic dissipative structures, mediate the lower level production of heat energy by speeding it up, as shown in Figure 4. So, orderly convection associates with dissipative form, potentially constraining moderated energy flows characterized by a modicum of energy efficiency, which defuses the possibility of spontaneous explosions.

I conclude that the compositional hierarchical structure of natural dissipative systems is the material organization that (a) maximizes system stability to perturbations, (b) maximizes the amount of information by way of levels of chunking, and, with scale differences between dynamics at the different levels, (c) maximizes local entropy production short of disrupting the dissipative structures, while affording the possibility of work in the interest of stabilized mid level subsystems.

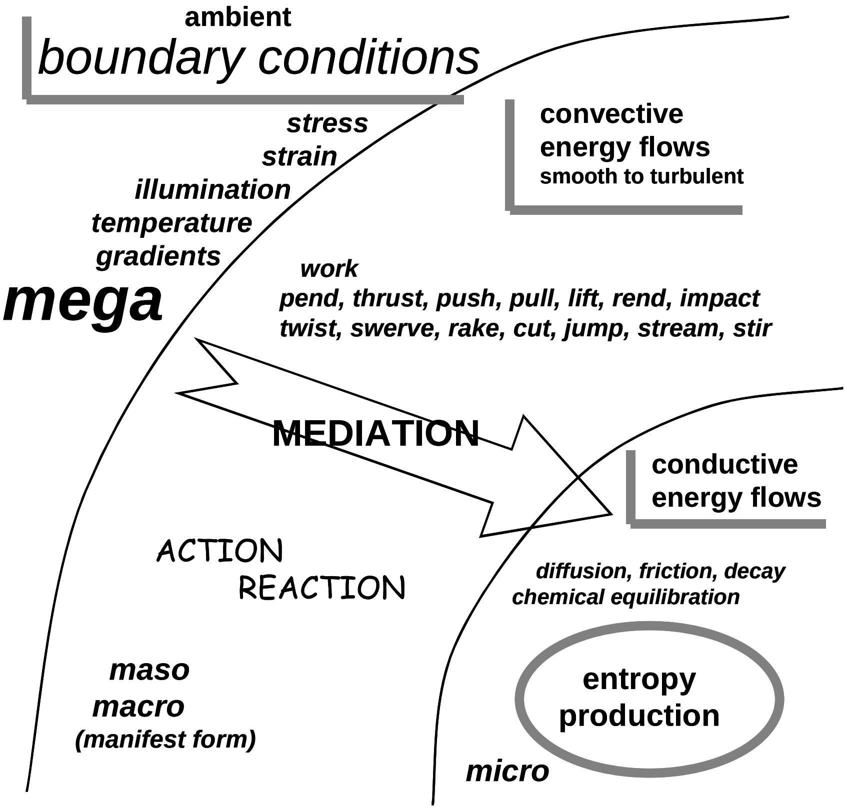

Figure 3. Energy dissipation frameworked in a scale hierarchy format. The middle level becomes spontaneously interpolated between primal upper and lower levels whenever supporting energy gradients become large enough to maintain the dynamical forms involved in convective dissipation. This mediation by work prevents the buildup of large energy gradients to explosive size.

Work Revisited

Recall that energy efficiency is a concept associated with work. What work generates directly is accelerated activity. All acceleration is produced by harnessing dissipation, which is afforded by the radical disequilibrium of -- and therefore the presence of energy gradients in -- the universe. These gradients are at best metastable because the continued expansion of the universe creates an increasing vacuum, inviting their dissolution in the interest of filling that vacuum to equilibrium (the Second Law). Thus: universal expansion --> local energy gradients --> continued expansion --> gradient degradation --> work and efficiency, tied to local interests, plus entropy.

At the lowest level, of energy conduction, accelerations occur when randomly moving particles collide. We assume that there are no microscopic agents, or even dissipative forms, and so these accelerations are not attributed to work being done. At the large scale of explosions, the outward burst itself is an acceleration, and, again, is not, unless harnessed (as in dynamite or bombs) by the interests of some mid level dissipative structures, supposed to represent work. Only mid scale dissipative structures are held to have the possibility of working, minimally just by preserving their form. But, as noted previously, natural dissipative structures (like tornadoes) are not seen to be working, even though there is no physical difference between what they do and what genuine workers do. Here we can see that workers (we ourselves) are members of a larger class of systems, which in the evolutionary perspective, must be taken to represent our distant ancestors. Thus we can formulate:

{entropy production {energy gradient degradation {work}}}

as the framework within which we have evolved, and the evolution can be shown by

{dissipative structures --> {organisms --> {people}}}.

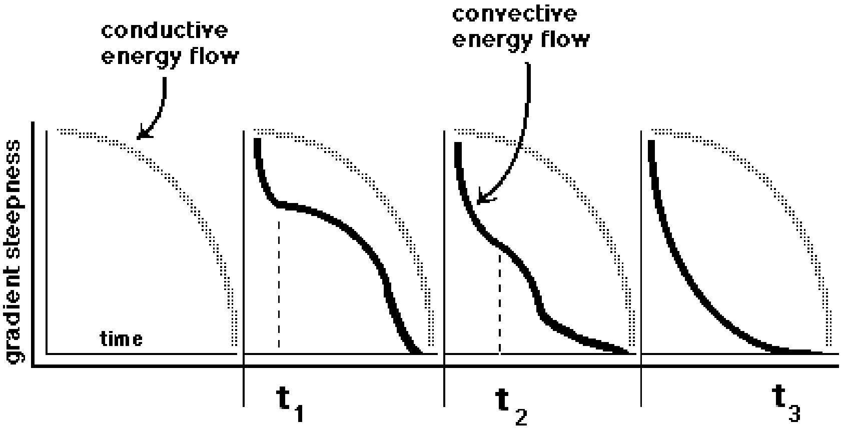

Figure 4. Time course of degradation / dissipation of a finite energy gradient. The left hand image shows the pattern for conductive dissipation. It increases with time as the gradient becomes increasingly exposed by degradation. The other three figures represent three stages in the dissipation when convective flows are involved as well as conductive. The purely conductive pattern is shown throughout for comparison.

I have argued [39] that the interpolation of new levels in a scale hierarchy occurs when such an increase in global extensional complexity, effecting dynamical streamlining, allows an increase in the overall rate of entropy production by a hierarchically organized complex adaptive system. The new level participates in the self-organization of a system to the edge of chaos [40], or to a window of vitality [41]. This requires the work of construction and maintenance of forms, which requires as well the minimizing of internal entropy production, while yet maximizing entropy production to the degree possible during degradation of external gradients, thus furthering MEP to whatever degree possible locally. This combination of internal entropy production minimizing with external maximizing is what allows work to occur, inasmuch as that combination preserves the forms that constitute the dissipative structures. We can see from this that mid level dissipative structures are essential as the basis for agentive action. We do not acknowledge microscopic agents, nor yet again megascopic ones, leaving agency and work as characteristics of mid level systems.

Coda on MEP

In this context it is curious to note that the relativistic equivalence principle, interpreting gravitation as spacetime curvature, eliminating the presence of acceleration, implicitly reduces dissipation solely to the microscopic scale. This implicit elimination of mid level accelerations obviates the possibility of understanding the dissipative cause of the universal scale hierarchical structure that is associated with energy efficiency and living systems, while being inconsistent with MEP as well.

Lineweaver [19] has argued that living systems could not be said to maximize entropy production globally unless they could be shown to be reproducible in the way that stars, planets and abiotic dissipative structures would be in another Big Bang. This does not impact my arguments above because I am suggesting that living systems only further MEP locally to an extent possible given the constraint of their survival. Lineweaver did acknowledge that living systems could transiently achieve MEP locally. Abiotics he conceives as “reproducible macrostates” -- that is to say, types, while biotics are taken to be historical individuals. But every tornado is uniquely different in some way from every other one. He does suggest that there might be a less complete description of biological forms, moving them in the direction of types. It is likely that from the thermodynamic perspective the historically acquired uniqueness of species typically has little or no bearing on their energy relations. For thermodynamic purposes I believe one would need some type-based description of living forms -- that is, forgetting most of their uniquenesses. On this head, it is well to remember the really widespread parallel and convergent biological evolutions we know about, but are not important in NeoDarwinian discourse, based as that is on historically generated genetic information. One type-based approach to the living would be as metabolic categories, e.g., homeotherms versus poikilotherms, or large size versus small, or immature versus senescent, and so on. There are well established relationships here in terms of energy throughput. There is at least a plausible possibility, I think, that these would be reproducible on planets like ours. For example, birds largely ‘reproduce’ mammals metabolically, and vice versa, as warm blooded vertebrates. Of course, it took some millions of years to evolve these groups, and prior to that, there would have been none. So this points to ‘stages’ in the evolution of a planet’s surface, which would have to be characterized as well, and which, presumably would not be a factor with abiotic dissipative structures. In short, I think living systems might well turn out to be ‘reproducible’ in the sense required by Lineweaver.

Conclusion

The Big Bang gave rise to universal thermodynamic disequilibrium, activating the Second Law of thermodynamics, represented locally by the maximum entropy production principle (MEP). Since the requirement of their embodiment prevents achievement of MEP, abiotic dissipative structures can be said instead to act to degrade macroscopic energy gradients as rapidly as possible, dissipating some of the energy and exposing the degraded remains to further dissipative forces. That is, in agreement with previous authors, degradation of energy gradients can be interpreted as a local nonequilibrium proxy for the Second Law, which is thus acting as a final cause of this activity. Given that some local systems do not just explosively dissipate, modular (scale hierarchical) structure makes possible the function of mesoscopic dissipative structures in furthering the dissipation of energy gradients. Organismic work is homologous to the energy utilization of abiotic dissipative structures, the results of which are also homologous to the work products of living systems. That is to say, work of any kind furthers the thermodynamic equilibration of the Universe.

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References and Notes

1. Salthe, S.N.; Fuhrman, G. The cosmic bellows: the Big Bang and the Second Law. *Cosmos and History* **2005**, *1*(2), 295-318. http://www.cosmosandhistory.org
2. Hoelzer, G.A.; Smith, E.; Pepper, J.W. On the logical relationship between natural selection and self-organization. *Journal of Evolutionary Biology* **2006**, *19*, 1785-1793.
3. Salthe, S.N. Entropy: what does it really mean? *General Systems Bulletin* **2003**, *32*, 5-12.
4. Pielou, E.C. *The Energy of Nature*, University of Chicago Press: Chicago; 2001.
5. Giampietro, M.; Mayumi, K. Complex systems and energy, In Cleveland, C., Ed.; *Encyclopedia of Energy,* Academic Press: San Diego; 2004,Volume 1, pp. 617-631.
6. Odum, H.T. *Systems Ecology: an Introduction***,** Wiley Interscience: New York; 1983, p.116.
7. Haynie, D.T. *Biological Thermodynamics,* Cambridge University Press: Cambridge, UK; 2001.
8. Lotka, A.J. Contribution to the energetics of evolution. *Proceedings of the National Academy of Science* **1922**, *8*, 147-151.
9. Schneider, E.D.; Kay, J.J. Life as a manifestation of the Second Law of thermodynamics. *Mathematical and Computer Modelling* **1994**, *19*, 25-48.
10. Swenson, R. Emergent attractors and the law of maximum entropy production: foundations to a theory of general evolution. *Systems Research and Behavioral Science* **1989**, *6*, 187-198.
11. Swenson, R. Autocatakinetics, evolution, and the law of maximum entropy production. *Advances in Human Ecology* **1997**, *6*, 1-47.
12. Dewar, R.C. Maximum entropy production and the fluctuation theorem. *Journal of Physics, A Mathematics and General* **2005**, *38*, L371-L381.
13. Martyushev, L.; Seleznev, V.D. Maximum entropy production in physics, chemistry and biology. *Physics Reports* **2006**, *426*, 1-45.

14. Bejan, A.; Marden, J.H. Constructing animal locomotion from new thermodynamics theory. *American Scientist* **2006**, *94*, 342-349.
15. Zotin, A.I. *Thermodynamic Aspects of Developmental Biology,* S. Karger: Basel; 1972.
16. Salthe, S.N. *Development and Evolution: Complexity and Change in Biology*, MIT Press: Cambridge, MA; 1993.
17. Prigogine, I.; Wiame J.M. Biologie et thermodynamique des phénomènes irréversible. *Experientia* **1946**, *2*, 451- 453.
18. Odum, H.T.; Pinkerton, R.C. Time's speed regulator, the optimum efficiency for maximum output in physical and biological systems. *American Scientist* **1955**, *43*, 331-343.
19. Lineweaver, C.H. Cosmological and biological reproducibility: limits of the maximum entropy production principle. In Kleidon, A.; Lorenz, R. *Non-equilibrium Thermodynamics and the Production of Entropy: Life, Earth and Beyond,* pp. 67-76. 2005.
20. Cho, A. Long-awaited data sharpen picture of Universe's birth. *Science* **2006**, *311*, 1689.
21. Riordan, M.; Zajc, W.A. The first few microseconds. *Scientific American*, May 2006, 34 - 41.
22. Turner, M.S. Quarks and the cosmos. *Science* **2007**, *315*, 59-61.
23. Wilczek, F. Did the Big Bang boil? *Nature* **2006**, *443*, 637-638.
24. Prigogine, I. *From Being to Becoming: Time and Complexity in the Physical Sciences,* W.H. Freeman: San Francisco; 1980.
25. Salthe, S.N. Energy and semiotics: the Second Law and the origin of life. *Cosmos and History* **2005**, *1*, 128 - 145.
26. Brooks, D.R.; Wiley E.O. *Evolution As Entropy: Toward a Unified Theory of Biology,* (2nd. ed.) University of Chicago Press: Chicago; 1988.
27. Salthe, S.N. Summary of the principles of hierarchy theory. *General Systems Bulletin* **2002**, *31*, 13-17.
28. Harold, F.M. *The Vital Force: A Study of Bioenergetics,* W.H. Freeman: San Francisco; 1986.
29. Shlyk-Kerner, O.; Samish, I.; Kattan, D.; Holland, N.; Maruthi Sal, P.S.; Kless, H.; Scherz, A. Protein flexibility acclimatizes photosynthetic energy conversion to the ambient temperature. *Nature* **2006**, *442*, 827-830.
30. Holling, C.S.; Gunderson, L.H. Resilience and adaptive cycles. In Gunderson, L.H. and Holling, C.S., Eds; *Panarchy: Understanding Transformations in Human and Natural Systems,* Island Press: Washington, DC; 2002, Chapter 2.
31. Salthe, S.N. Natural Selection in relation to complexity. *Artificial Life Journal.* (in press)
32. Simon, H. The architecture of complexity. *Proceedings of the American Philosophical Society* **1962**, *106*, 467- 482.
33. Salthe, S.N. Two frameworks for complexity generation in biological systems. In Gershenson, C.; Lenaerts, T., Eds. *Evolution of Complexity, ALife X Workshop Proceedings.* Indiana University Press: Bloomington, 2006, pp. 99-104.
34. Salthe, S.N. *Evolving Hierarchical Systems,* Columbia University Press: New York; 1985.
35. Ashby, W.R. Requisite variety, and its implications for the control of complex systems. *Cybernetica* **1958**, *1*, 1-17.

36. Conrad, M. *Adaptability: The Significance of Variability from Molecule to Ecosystem*, Plenum: New York; 1983.
37. Ulanowicz, R.E., *Ecology, the Ascendent Perspective,* Columbia University Press: New York; 1997.
38. Kauffman, S.A., *Investigations*, Oxford University Press: New York; 2000.
39. Salthe, S.N. The origin of new levels in dynamical hierarchies. *Entropy* **2004**, *6*(3), 327-343. http://www.mdpi.net/entropy/list04.htm
40. Kauffman, S.A. *The Origins Of Order: Self-organization and Selection In Evolution,* Oxford University Press: New York; 1993.
41. Ulanowicz, R.E. The balance between adaptability and adaptation. *BioSystems* **2002**, *64*, 13-22.