The relationship between information theory and thermodynamics: the second law of thermodynamics revisited

CHAPTER 6

TOWARDS MEASURES OF FUNCTIONAL ORGANIZATION

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(For discussion the mathematical relationships underlying this chapter, see APPENDIX 1: Maximum Entropy Principle, Minimum Cross Entropy Principle, Exergy & Statistical Mechanicsof *Self-Organization in Living Systems*.)

6-1 THE ISSUES

Central to this thesis is the idea that succession is the process by which an ecosystem moves away from thermodynamic equilibrium with its environment. But how can the "distance" from equilibrium be measured? In Chapter Two, the terms "degradation of incoming solar energy", "energy dissipation", and "maximize energy degradation" are used frequently. In the discussion of state variables on pp. 92-93, the idea of characterizing species in terms of their production-consumption role, that is their energy/mass transformation process, is put forward.

While all of these have some intuitive meaning no real progress can be made until the terms are translated into mathematics and thus explicitly defined in terms of measureable quantities. Once this is done it should be possible to identify state variables which define the operating point of an ecosystem. As stated in Chapter Two the quantities which need to be measured reflect the thermodynamics of the ecosystem.

Some attempts have been made to describe species and ecosystems from a thermodynamic perspective. These attempts can be loosely divided into a classic engineering descriptive approach which documents the energy and entropy flows and a collection of novel attempts to expand thermodynamics so as to explain the observed phenomena.

CLASSICAL ACCOUNTING

The International Biological Program undertook to document the energy flows in a number of species and ecosystems. This work is thorough and of sufficient volume that a separate bibliography would be required to provide appropriate references. However this work is largely in the vein of a classical engineering analysis which identifies all the energy flows in and out of the system and energy transformations in the system being studied. (See for example Tracey, 1975, for a complete study of the leopard frog.) Bormann & Likens (1979) extended this approach, in the vein of H.T. Odum's work, to include the biogeochemistry as well as the energy flows. Gates (1980) has written a textbook which describes the theoretical underpinning of such analysis. Another basic reference is Morowitz (1968).

While much has been done to undertake first law analysis of biological systems, not surprisingly, much less has been done in a second law context. Galoux (1978), as part of the IBP, undertook a second law analysis of an oak forest. Conrad (1977) developed measures of efficiency using the first and second laws.

ENTROPY AND LIFE

While these studies are all useful, they only identify flows is a steady-state situation. In general, they do not give any insight into the development and self-organization processes nor the stress-response of living systems. The obstacle to gaining a thermodynamic understanding of life is the correct interpretation of entropy and the second law of thermodynamics in the context of living systems.

Entropy is well defined, in terms of macroscopic variables, for equilibrium situations. Consequently the same can be said for the second law. However entropy, for far from equilibrium situations, particularly living systems, has not been clearly defined. As a result, for many years a debate has gone on as to whether or not life violates the second law of thermodynamics. Does entropy decrease with the development of life and if so, does this violate the second law?

Both sides have been argued in some detail. The book "What is Life" by the pre-eminent physicist Erwin Schrodinger (1945) and Brillouin's "Science and Information Theory" (1962) are the classic works. Reviews of the different arguments and definitions can be found in Gallucci (1972), Goodman (1975) (in the context of diversity), Smith (1975) and Zotin (1978). It is left to the reader to investigate these.

It suffices to say that no satisfactory resolution of the issues has been put forward.

WICKEN'S DEVELOPMENT OF ENTROPY

Wicken (1976, 1978a,b, 1979, 1980) pointed out that the information required to specify the state of chemical system is made up of three components.

$I_e = (E_i - A) / T$ (assuming a Gibb's ensemble)

where E_i = energy of the ith micro state of of the system; A is the ensemble average of the Helmholtz free energy and T, temperature. As I_e increases the state is further from equilibrium.

$I_{th} = -k \ln W_{th}$;

W_{th} = the number of thermal modes with energy E_i. As I_{th} decreases the number of thermal modes increases.

$I_c = -k \ln W_c$;

W_c = the number of configuration states for the energy state, E_i. As I_c decreases the number of configuration states increases.

For irreversible processes in closed, isothermal systems the second law becomes:

$$dI_e + dI_c + dI_{th} < 0 \qquad (1)$$

Changes in I_c and I_{th} are due to changes in the number of microscopic states which can make up the macrostate defined by E_i, T and A. As the number of microstates increases the information we have about which microstate the system is in for a given macrostate, decreases. Thus (1) links information about the macro and micro states of the system.

Furthermore Wicken argues that I_e decreases when the energy in the system becomes "randomized", that is less distinguishable from the average. Decreases in I_c correspond to more configurational states, that is the number of different molecular configurations increases, the state of matter is "randomized". (1) is a relationship between energy and matter randomization.

Wicken argues that in a pre-biotic soup, the solar energy impinging on it will cause I_e to increase. The second law (1) and chemical kinetics then dictate that overall I_c decrease. This is accomplished by matter randomization, that is the emergence of new complex molecular forms in the soup. Wicken argues that the need to satisfy the second law will eventually, through this mechanism, result in life (see the discussion in Chapter 2.3.1). He goes on to develop a set of hypotheses concerning how life will develop which are consistent with those of Chapter Two.[1]

Unfortunately this development put forward by Wicken hinges on assuming that the system is isothermal and that Gibb's canonical ensemble applies. Of course there is no reason this should be the case in general. Wicken's theoretical development is stymied because of the lack of a formulation of a far from equilibrium thermodynamics. However Wicken's work points the way to an explanation of the emergence of life and clarifies the role of the second law in the development of living systems.

PRIGOGINE

Prigogine's non-equilibrium thermodynamics provides a means of describing the behavior of some self-organizing systems (Nicolis & Prigogine, 1977).

Prigogine begins by observing that most of classical physics deals with equilibrium phenomena which is totally reversible. Classically, non-equilibrium states are considered anomalies, temporary instabilities which will be corrected. However systems in non-equilibrium can be at a lower entropy and exhibit more order or organization than a system at equilibrium. Furthermore there is a range of variables beyond which a non-equilibrium state is not just a temporary instability, but is in fact stable and can allow for the possibility that a system can organize itself so as to exhibit coherent space-time behavior. Such behavior can only be maintained if a sufficient flow of energy and matter is available to support the system's far from equilibrium state.

So how to describe such phenomena? The starting point of Prigogine's work is that the second law of thermodynamics is the only law of physics which gives direction to the arrow of time. Entropy in the only quantity, in classical physics, which indicates the direction a system will move along a trajectory. Thus a theory to account for the dynamics of non-equilibrium systems must center on the entropy changes in

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[1] In fact Chapter 2 was inspired by Wicken's work.

the system. It was the realization of this that lead Prigogine to develop his theory of self-organization in far from equilibrium dissipative structures.

Some of the important points of Prigogine's theory are now put forward. Most of the detail is left to the reader to obtain from his book "Self-Organization in Nonequilibrium Systems" (1977)[2].

To begin consider a system which exchanges mass and energy with its environment. Let dS_i be the entropy production in the system due to irreversible processes and dS_e be the entropy flux due to exchanges between the system and environment. The total entropy change in the system is given by

$$dS = dS_e + dS_i \tag{2}$$

The second law states that $dS_i \geq 0$. However if sufficient low entropy flux enters the system then $dS_e \leq 0$ and it is possible that $|dS_e| > |dS_i|$ which implies that $dS < 0$. If this is the case then the system will be driven away from equilibrium. It is also possible for the system to eventually reach a steady state ($dS = 0$). It is the process which leads to this steady state and the accompanying coherent behavior which Prigogine, for special cases, has developed a theory for.

Central to this theory is the Minimum Entropy Production rule. Let P = entropy production due to irreversible processes in the system and σ = local entropy production.

Then

$$P = \frac{dS_i}{dt} = \int \sigma \, dV \geq 0 \tag{3}$$

where the integral is over the spatial volume of the system.

Using Onsager's Reciprocity Relations it is possible to write

$$\sigma = L_{kl} X_k X_l \tag{4}$$

where X_k is the thermodynamic force acting on the system and the summation convention over repeated indices is in effect[3]. Substituting for σ, making several assumptions about the forces, and differentiating with respect to time, leads to[4]:

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[2] The notation used in this section is the same as used in the book.

$$\frac{dP}{dt} = \frac{2}{T} \int \frac{\partial \mu_i}{\partial \rho_j} \frac{\partial \rho_i}{\partial t} \frac{\partial \rho_j}{\partial t} \, dV \qquad (5)$$

The quadratic form in the integral can be shown to be positive semi-definite. It is zero at a steady state. Hence

$dP/dt < 0$ away from steady-state

$dP/dt = 0$ at a steady state.

This is the famous Minimum Entropy Production rule which governs the behavior of dissipative structures in the steady-state. It can be easily shown that this rule guarantees the stability of steady non-equilibrium states.

However the derivation of this rule depends on seven assumptions which I can identify.

1) Local Equilibrium Thermodynamics applies. The system must be well enough behaved that locally (spatially) equilibrium thermodynamics apply.
2) The fluxes can be expressed as a linear combination of the flows using Onsager's Reciprocity Relationship.
3) The L_{ij} used in the expansion of the fluxes are time independant.
4) The medium is isotropic.
5) The boundary conditions imposed on the system are time independant.
6) The system is isothermal.
7) The system is in mechanical and thermal equilibrium with its environment. Only mass flow occurs across the boundary.

This set of constraints means that the minimum entropy production rule and most of Prigogine's results apply to a very restrictive set of systems. A general far from equilibrium thermodynamics and theory of self-organization does not exist.

Any attempt to apply Prigogine's theory must be viewed with skepticism because of its lack of generality. For example, Johnson (1981) and Wiley and Brooks (1982) both try to apply nonequilibrium thermodynamics to living systems. However

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[3] Summation convention in effect for repeated indices. That is $\sigma = L_{kl} X_k X_l$ is taken to mean:

$$\sigma = \sum_{k=1}^{n} \sum_{l=1}^{n} L_{kl} x_k x_l$$

[4] It takes Prigogine 12 pages of text to develop the assumptions which lead to this result (eq 3.42, p. 43 of Self-Organization in Nonequilibrium Systems" (1977)). Going from (3) to (5), given all the assumptions are previously worked out, took me 7 pages of algebra and integration. It seemed merciful to spare the reader.

their extensions of the concept of entropy/information, to allow it to be massaged into a form which is suitable for developing arguments (for living systems) in analogy to Prigogine's, are on shaky theoretical grounds. More promising is the work of Gladyshev et al (1982, 1980), Zotin (Lamprecht and Zotin, 1978) and Volohonsky (1982, 1980).

However the fundamental problem still exists. The concept of entropy has not been generalized so that it can be used in non-equilibrium situations. Until this is done a general theory of self-organizing systems cannot be developed. (For an eloquent discussion of the issues in theoretical physics involved, see Jaynes, 1980).

THE BOTTOM LINE

If one accepts the fundamental argument of this thesis, that is that understanding the self-organization of living systems depends on understanding the thermodynamics of self-organization, then clearly no further theoretical development can be made until the conceptual and methodological problems of theoretical physics are resolved. Specifically, what the second law and entropy mean far from equilibrium, and how to measure entropy in terms of non-equilibrium macroscopic variables, must be determined before mathematical laws governing self-organization can be formulated. Until these issues are settled any attempt to define functional state variables for living systems seems somewhat futile, as we do not know what is relevant.

This is not to say that the situation is hopeless. What is needed, as Jaynes points out, is a fresh approach to the problems, a re-orientation of our thinking. What follows is a review of some of the ideas put forward in the context of the Jaynesian approach to thermodynamics. These ideas show promise of providing the necessary new outlook required for generalizing thermodynamics.

6-2 THERMODYNAMICS A LA JAYNES, TRIBUS AND EVANS.

In Appendix I the maximum entropy principle (M.E.P.), the cross-entropy, the minimum cross entropy principle, and their application to thermodynamics is discussed. The results of this discussion force one to reconsider the underlying principles of thermodynamics. Why do these purely mathematical analysis yield what are traditionally considered physical results? Why do these techniques work? What are the implications for the traditional ergodic view of statistical mechanics? Is statistical mechanics a branch of physics or mathematics? These issues and more have been explored by Jaynes and Tribus and Hobson (1971).

A brief summary of the main results of these authors is now presented. The purpose of the summary is to give the reader a flavour of the direction in which "predictive statistical mechanics", as Jaynes calls it, is developing. Much of the mathematical and philosophical detail is left for the reader to explore using the references cited.

JAYNES (1957)

In these papers Jaynes first put forward M.E.P. and derived some of the classical results of thermodynamics. In the second of these papers (p. 178) Jaynes discusses irreversibility and states "it is not the physical process which is irreversible, but rather our ability to follow it... the tendency of entropy to increase is not a consequence of the laws of physics as such...". Jaynes argues that entropy increase and irreversibility reflect our loss of knowledge about the system's state. Thus they represent observer dependant (i.e. subjective) phenomena rather than some objective change in the system due to physical laws.

TRIBUS (1961) & TRIBUS, SHANNON, AND EVANS (1966)

Tribus follows Jaynes' ideas to derive a number of results from thermodynamics using essentially mathematical arguments. Consider a box containing a fixed number of particles for every chemical type present. The energy levels e_i are a function of the state number (i) and the generalized coordinates $\{X_1 \ldots X_k\}$ of the box. We are given $<e_i>$ which is the internal energy (U). Using M.E.P.[5] we get

$$p_i = Z^{-1} \exp [-\lambda e_i] \qquad (6)$$

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[5] See appendix 1 for the mathematical details of M.E.P, particularly eq. 3,4.

The following relationships are easily derived

$\Sigma\, dp_i = 0$ (Since $\Sigma\, p_i = 1$) (7)

$d\langle e\rangle = e_i\, dp_i + p_i\, de_i$ (Since $\langle e\rangle = p_i\, e_i$) (8)

$dS = \ln [p_i]\, dp_i$ (Since $S = -p_i \ln p_i$ and (7)) (9)

$\ln p_i = -\ln Z - \lambda\, e_i$ (Using (6)) (10)

The change in internal energy (8) consists of two terms. The first term is due to changes in the probabilities and consequently affects the entropy of the system. The second term represents changes in the internal energy which do no affect the entropy of the system. Classically in thermodynamics, changes in internal energy which do not affect the entropy are associated with work performed on the system[6]. Thus the second term ($p_i\, de_i$) can be called dW. Changes in internal energy, which affect the entropy of the system, are associated classically with the transfer of heat to the system. Thus the first term ($e_i\, dp_i$) can be called dQ. Thus we have the following result from 8.

$$dU = dQ + dW \qquad (11)$$

This is often called the first law of thermodynamics. It is derived here using purely statistical arguments. The identification of dQ and dW is carried out in the same manner as the identification of the Lagrange multipliers with the traditional intensive variables.

Substituting (10) into (9) and using (7)

$$dS = \lambda\, e_i\, dp_i$$

Making use of (8)

$$dS = \lambda\, d\langle e\rangle - \lambda\, p_i\, de_i \qquad (12)$$

From thermodynamics[7], the generalized force $F_k[i]$ is given by

$$F_k[i] = \partial e_i / \partial X_k$$

Thus $de_i = F_k[i]\, dX_k$ and (12) becomes:

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[6] Reynolds and Perkins, p.165.

[7] Kittel, p.108.

$$dS/\lambda = dU - <F_k> dX_k$$

Recalling from Appendix I that $\lambda = 1/kT$

$$k\,T\,dS = dU - <F_k> dX_k \tag{13}$$

This is of course Gibb's equation. In the case that $dX_k = 0$, no forces are acting on the system and no work is done. Hence (11) leads to

$$k\,dS = dQ/T \tag{14}$$

The relationships (11), (13), (14) are fundamental to thermodynamics. They have been derived from purely statistical arguments. Physical arguments are used only to identify variables with measureable quantities. However the relationships between these variables does not depend on these identifications. The question these results begets is answered by the title of Tribus et al (1966): "Why Thermodynamics is a Logical Consequence of Information Theory". Is it?

JAYNES (1963, 1965)

Jaynes (1963) develops a similar result to that of Tribus, but using a different derivation. Jaynes, using M.E.P., derives the relationship:

$$dS = \lambda_k (d<f_k> - <df_k>)$$

If dQ_k is defined as $d<f_k> - <df_k>$ then

$$dS = \lambda_k\, dQ_k \tag{15}$$

If the problem investigated is the same as that defined by Tribus then $f_k = e_i$ and

$$dS = \lambda_k\, dQ_k = \lambda\, (d<e_i> - <de_i>)$$

$$dS = dQ/T = (dU + dW)/T$$

where Jaynes shows, as Tribus did, that $<de_i> = -dW$. So, once again, Gibb's equation is derived from purely statistical arguments.

Jaynes goes on to argue that (p.216, 1963): "... the correct statement of the second law is that spontaneous decreases in the experimental entropy, although not absolutely prohibited by the laws of physics, cannot occur in an experimentally reproducible process."

Jaynes (1965) follows up on this notion. First Jaynes notes that both the Gibbs and Boltzmann entropies are only related to macroscopic variables at equilibrium. Thus the statement of second law as "entropy increases" has meaning only at equilibrium, as this is the only state in which entropy can be measured.

He goes on to argue that the second law is a statistical rather that physical law. Specifically he examines moving a system adiabatically from one equilibrium state to another in a reproducible experiment. A reproducible experiment is one in which sufficient control over the state of the system is maintained so that the measured values of the variables are always the expectation values. This is what is meant by a reproducible experiment; it will always give the same results.

In moving reproducibly and adiabatically from one state with W possible and equally probable configurations to a new state, the new state must have at least W possible configurations, one for each of the original configurations to change to. Since $S = \ln W$ for equally probable configurations, the entropy of the new state must be at least that of the old.

Thus second law is: "The experimental entropy cannot decrease in a reproducible adiabatic process that starts from a state of complete thermal equilibrium" (p.397, Jaynes, 1965). The line of argument which leads to this conclusion is statistical in nature and Jaynes states that it can be applied to any reproducible process, whether or not it is thermodynamic in nature.

Furthermore Jaynes argues that entropy is an anthropomorphic concept. He begins by observing that there is no such notion as the entropy of a physical system. Rather the notion is of the entropy of a thermodynamic system. Any physical system can correspond to several thermodynamic systems depending on how the observer chooses to view the physical system. Thus a single physical system may have several entropies associated with it. Each entropy reflects the constraints the observer puts on the system.

Jaynes points out that one could argue that the true entropy is the one obtained when all possible constraints are imposed on the system. To do this would require that we completely specify the physical systems' state. But were this done we would no longer have any uncertainty about the system, the entropy would be zero.

Thus Jaynes concludes that the entropy of a system is a meaningless concept unless it is used in the context of specific questions which an observer has about the state of the system. Thus, Jaynes states, such general statements as "entropy measures randomness" or "biological systems violate the second law" are meaningless.

The main points of these two papers are that the second law is statistical in nature and is due to our requiring experiments to be reproducible, and that entropy is relative to an observer and has no absolute physical meaning.

CONCLUDING COMMENTS

Clearly the results presented in this section seriously undermine the foundation of classical thermodynamics and statistical mechanics. What do the p_i mean? Are the first and second law of thermodynamics physical or statistical rules? What does entropy mean? Are work and heat physical or statistical concepts? Why does the M.E.P. work? These questions are addressed in the next section.

6-3 STATISTICAL VS PHYSICAL LAWS OF THERMODYNAMICS

To begin consider two systems. These systems are in equilibrium if we cannot differentiate between them, that is any measurements we take do not provide us with any information concerning which system we are looking at. The concept of equilibrium is observer dependant in that systems may be at equilibrium for one observer while another, measuring different state variables, may detect a difference between the systems.

The p_i document our knowledge about the states of the systems. They reflect the physical constraints imposed on the system by us and nature. They are only meaningful in that they allow us to predict the expectation value of some state variables. The p_i do not reflect the frequency with which a system will be found in the ith state. In fact the microscopic state of the system is not measured or of interest.

A physical law is that if two systems are allowed to interact, that is if the constraints imposed on the systems which allow us to differentiate between them are removed, then the systems will evolve to equilibrium, a new state in which we cannot differentiate between the systems. This is a law of nature. There is no statistical argument that will tell us that the systems will move to equilibrium. This is the second law of thermodynamics.

A statistical consequence of this law is that entropy will increase. Obviously, if the removal of constraints results in an inability to differentiate between the systems, our uncertainty increases. However increase in entropy is a consequence of a physical law. It is not the law itself. Failure to separate the physical law from its statistical consequence has lead to much confusion.

The reason that M.E.P. correctly predicts the macroscopic states of a system is because of the tendency of systems to become indistinguishable. System will interact so that the constraints which were removed, leave no trace. Hence the constraints one need recognize to correctly predict the states of a system are time independant, in the sense that they need not include the past history of the system. If systems, after constraints were removed, did not become indistinguishable from systems which never had the constraints, then M.E.P. would not work, given that the only information provided is the current constraints on the system. Thus the fact that M.E.P. works is a consequence of the second law. A system will not spontaneously impose constraints upon itself, thus allowing us to distinguish between it and the system it is in equilibrium with.

When systems are allowed to interact, what is exchanged between them is energy. When systems are constrained it is the modes of energy transfer which are constrained. Different observers will be monitoring and constraining different modes of energy transfer between systems. Entropy is, in essence, a measure of the uncertainty about how energy is distributed in the system.

A physical law is if two systems exchange energy, then the total of all energy changes in one system must be accounted for by the total of all energy changes in the other system. This is the principle of conservation of energy, the first law of thermodynamics.

The energy added to a system (dU) can be broken into two parts, the energy which we lose information about when it is transferred to the system and the energy we do not lose any information about when we add it to the system. These are traditionally referred to as heat added (dQ) and work done (dW) on the system. Thus (11) is not a statement of a physical law but rather an expression of the information difference between heat and work. It should not be confused with the first law of thermodynamics.

EXERGY AND CROSS ENTROPY VS HEAT AND ENTROPY

Adding heat to a system increases our overall uncertainty about the energy content of the system. It seems reasonable that the entropy increase of the system would be proportional to the heat added, that is the amount of energy added that we have lost information about. Thus (14) is no surprise.

When work is done on a system our knowledge about the energy content of the system increases. Thus we are better able to distinguish between the system and its environment (the other system from which energy was removed). If the uncertainty we have about the environment is negligibly affected by the removal of energy from it, then the work performed on the system moves it further from equilibrium with the environment since the work allows us to better distinguish between the system and the environment. In fact the only way to move systems away from equilibrium is to perform work on them, which is in effect placing constraints on the energy content of the system so that we have more information about the energy content. The constraints make the energy more accessible to us.

MEASURE OF DISTANCE FROM EQUILIBRIUM

Thus the available work in a system is a measure of the ability we have of distinguishing between the system and its environment. It is the energy we have access to, because we have information about it. Therefore it seems reasonable to suggest that available work (exergy) is a measure of the distance of a system from equilibrium.

Just as entropy change is proportional to the heat added to a system, one should suspect that the total work extractable from a system should be proportional to the information we have about the system relative to its environment. The measure of this information would be the cross-entropy. If this suspicion were correct the constant of proportionality should be the same as in (14). But of course this is just the relationship observed by Evans as discussed at the end of Appendix I.

Furthermore just as a system moves closer to equilibrium as its energy is converted to heat and the entropy increases, a system whose energy is increased by work is driven from equilibrium and its cross-entropy is increased. Thus it would seem that any study of the thermodynamics of systems as they are driven further from equilibrium, should focus on the exergy content of the system and the cross-entropy, just as the study of systems coming to equilibrium should focus on the conversion of energy to heat and the increase of entropy.

Of course having made this claim is one thing. Developing a non-equilibrium thermodynamics based on it is another. Unfortunately such development is beyond the time constraints imposed on this Ph.D. student.

SOME QUESTIONS

Is predictive statistical mechanics only a branch of mathematics? The reason it works is because of the tendency of systems to become indistinguishable. This is the physical law which allows M.E.P. to work. Some of the constraints used in applying the M.E.P. are imposed by the experimenter and others reflect physical laws. M.E.P. is used to make predictions. (Hence the name Predictive Statistical Mechanics). If these predictions turn out to be incorrect then the experimenter has incorrectly identified the constraints (either his own or those imposed by nature), operating on the system which affect the variables he is measuring. If these predictions are correct then the experimenter has correctly identified all the constraints which affect the variables he is measuring. This does not mean he has identified all the constraints acting on the system, only those which affect what he is measuring. It is in this sense that predictive statistical mechanics is observer dependant.

Is work an anthropocentric concept? Our ability to extract work depends on our understanding the modes/constraints on energy transfer and making sure to control energy movement. When we discover new modes or methods of constraint we can more fully control energy transformations and thus "lose" less of it into a system at equilibrium. These modes correspond to the various "work effects" and a new mode corresponds to discovering a new work effect, for example magnetic spin.

What is the difference between exergy degradation and energy dissipation? Exergy degradation is the destruction of the available work in the energy coming into a system. It prevents the system from being driven further from equilibrium. Energy dissipation is the process of dumping energy out of a system thus also preventing the system from being driven further from equilibrium. Prigogine discovered the latter. The two are not equivalent. Degraded energy dumped out of a system has a very low exergy content relative to the input energy exergy content (for example waste heat from living systems). However dissipated energy may have high exergy content (the output of a laser for example). The two represent different modes of preventing system from being driven further from equilibrium.

What next? The next step is to develop the ideas put forward in this section into a rigorous treatment of classical thermodynamics and then to attempt to use exergy/essergy as measures of distance from equilibrium.

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