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REQUISITE VARIETY AND THE SECOND LAW

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ABSTRACT

Although the Law of Requisite Variety (LRV) speaks directly about entropy (of a set of disturbances to a system, and of the states and effects of a regulator), the relation of Ashby's principle to the Second Law of Thermodynamics does not appear to have been commented on. In this paper, it is shown that, when regulation is viewed as a temporal process, the LRV can be interpreted as a statement of, and, in fact, a consequence of, the Second Law. In essence, the regulator reduces the variety (entropy) of the system being regulated by a compensatory increase of variety (entropy) within itself. The total change of entropy in regulator plus system cannot, however, be negative.

Yet, while the LRV is a statement of the Second Law, it is one which casts the classical interpretations of the concepts of entropy and neg-entropy in a new light. Specifically, the LRV appears as a principle opposite, or more precisely, complimentary to what might be called the "neg-entropy principle" of Schrödinger, Bertalanffy, and others. These two principles set out alternative strategies for survival for an open system. To counter the tendency of internal order to degrade, a system may ingest neg-entropy from and/or excrete entropy into its surroundings (Schrödinger, et al). Or it may reduce entropy by shifting it, as it were, to a regulator subsystem (Ashby). Entropy has both "negative" and "positive" attributes - disorder and variety, respectively; so, too, has neg-entropy, which can imply rigidity as well as order.

1. INTRODUCTION

Ashby's Law of Requisite Variety [1,2] is one of the fundamental principles of cybernetics. Although this law speaks about entropy (of a set of disturbances to a system, and of the states and effects of a regulator), or, equivalently, about information, which is isomorphic to entropy in statistical mechanics [3,4,5], still the relation of Ashby's principle to the Second Law of Thermodynamics does not appear to have been commented upon. Indeed a recent article [6] notes that Ashby's law "has the same crucial significance for regulation and control as has the Second Law of Thermodynamics for physics," but goes no further, implying in effect that these laws are fundamentally distinct from one another. However, if we recast slightly the form in which the Law of Requisite Variety (LRV) is expressed, it becomes apparent that this principle is a simple statement of the Second Law.

2. AN INTERPRETATION OF THE LAW OF REQUISITE VARIETY

The LRV is usually given as $H(E) \geq H(D) + H_D(R) - H(R)$, where $H(E)$ represents the entropy in the essential variables of the system being regulated, $H(D)$ is the entropy in the disturbances to these variables, $H(R)$ is the entropy of the regulator, and $H_D(R)$ is the entropy of the regulator for a known (fixed) disturbance. $H_D(R)$ is zero for systems where R is a determinate function of D. For such systems, we rewrite the LRV in the form $[H(E) - H(D)] + H(R) \geq 0$, and here suggest a <u>temporal</u> interpretation, in which $H(D)$ and $H(E)$ refer to the initial and final states of the system, and $H(R)$ to the final state of the regulator. That is, if we can assume that for an unregulated system, the essential variables are in equilibrium with, and therefore have the same uncertainty as, the disturbances, then $H(D)$ and $H(E)$ can be taken to be the entropy of the system (its essential variables) before and after regulation. Similarly, $H(R)$ may be considered the entropy of the regulator after regulation, while before regulation the regulator may be considered to have some fixed resting state, and thus an entropy of zero.

Defining $\Delta H = H^{Final} - H^{Initial}$, the expression for the LRV becomes $\Delta H_{System} + \Delta H_{Regulator} \geq 0$. For successful regulation, ΔH_{System} is negative and $\Delta H_{Regulator}$ is positive. The net entropy change is positive or zero. This is simply the Second Law. Since the regulator cannot directly effect the disturbances impinging upon the system, it can reduce the system's entropy only by taking up some of this entropy itself. The relation of the LRV to the Second Law is perhaps more apparent if we modify our terminology, and call the regulator "the system" and what it regulates "the environment." We then have the more familiar, $\Delta H_{Environment} + \Delta H_{System} \geq 0$.

When $H_D(R)$ is not zero, the LRV can still be given the same interpretation. In this case we have $[H(E) - H(D)] + [H(R) - H_D(R)] \geq 0$. The second bracketed expression can be considered to be that <u>portion</u> of the final entropy of the regulator which was transferred to it from the system. It is given by the total regulator entropy, $H(R)$, minus $H_D(R)$.

The latter term is the regulator entropy for known/fixed disturbances, which represents, in effect, spontaneous entropy production within the regulator. Ashby's insight that $H_D(R)$ should be zero for optimum regulation, i.e., that one-to-many mappings from D to R should be excluded, corresponds simply to the realization that entropy in the regulator is of value only when it has been "siphoned away" from the system, and not when it arises from some independent entropy-generating process internal to the regulator.

These results should not be surprising. The Second Law is actually the very basis of the derivation of the LRV. It is introduced in the provision that, in the table which specifies the outcome, E, as a function of disturbance, D, and regulator state, R, no element appears twice in any column. Ashby justifies this convention by noting [1, P. 204]:

> From all possible tables let us eliminate those that make R's game too easy to be of interest ... If a column contains repetitions, R's play need not be discriminating; that is, R need not change his move with each change of D's move. Let us consider, then, only those tables in which no column contains a repeated outcome. When this is so R must select his move on full knowledge of D's move; i.e. any change of D's move must require a change on R's part.

But further on [P. 207] he observes that "the condition introduced above that no element shall occur twice in the column corresponds to the condition that if R is fixed or given, the entropy of E (corresponding to the outcome) is not to be less than that of D, i.e., $H_R(E) \geq H_R(D)$." This inequality, which is the starting assumption in the derivation of the Law of Requisite Variety, states simply that the entropy of the system cannot spontaneously decrease. The Second Law is here directly introduced and it is the physical content of Ashby's principle; the rest is just algebraic manipulation: The above inequality, plus the identity

$$H(D) + H_D(R) = H(R) + H_R(D)$$

and the relation $H(E) \geq H_R(E)$, yield the LRV.

Yet Ashby and subsequent writers make no mention of a thermodynamic basis for the LRV, treating it as an independent finding of cybernetics. Moreover, Ashby considers also the case where "even when R does nothing (i.e., produces the same move regardless of whatever D does) the variety of the outcome is less than that of D. This is the case in .... [regulation tables in which repetitions are allowed] ..." In discussing this possibility, and in his later remark that his theorem is a statement about possible arrangements of the D-E-R table and "has nothing to do with the properties of matter," or even "with the properties of the machine in the general sense," Ashby obscures the fact, that for physically realistic situations, columns do not contain repetitions, since entropy does not decrease spontaneously. (Indeed, the Second Law, also, "has nothing to do with the properties of matter," but can be viewed simply as a statement about probabilities.) The real nature of Ashby's result that only variety can destroy variety, is that entropy can only be destroyed by "shifting" it elsewhere, in this case from the system being regulated to the regulator.

Strictly speaking, the variety increase of the regulator <u>compensates</u> for the decrease of system variety; a transfer of entropy in the physical sense need not actually be demonstrated. (It is not suggested by Ashby's principle or, indeed, required by the Second Law.) Nonetheless, it is important to realize that thermodynamic entropy and information-theoretic entropy are not only mathematically isomorphous, but, in some cases, are physically interconvertable [3,5]. This cannot, however, be shown explicitly for regulation, because Ashby considers this process in very general terms, and omits discussion of the detailed interactions which must actually occur between regulator and system.

Of course, from a purely mathematical point of view, it is possible to allow repetitions in the table. If there are k such repetitions per column, and K = log k, and if we take for our starting inequality,

$$H_R(E) \geq H_R(D) - K,$$

then it is possible to derive an equation similar to the LRV.* Thermodynamically, this implicitly postulates the existence of an entropy "sink" adjoined to the system.+ Or, as Ashby notes, it might simply be the result of "luck," in that it just happens that for a fixed state of the regulator the consequences of the disturbances (the final states of the system) are less varied than the disturbances themselves. For systems obeying the Second Law, however, this is conceivable only as a statistical fluctuation, and not as long-term behavior.

3. DISCUSSION

Yet, while the LRV is a statement of the Second Law, it is one which casts the classical interpretations of the concepts of entropy and neg-entropy, especially as applied to living systems, in a new light. To counter the tendency of internal order to become degraded, either spontaneously or under the impact of external disturbances, an open system available to it two opposing strategies: 1) It can ingest neg-entropy and/or excrete entropy, as noted by Schrödinger [7], Bertalanffy [8], and others, and thus increase entropy in its external environment; or 2) it can reduce entropy by a compensatory increase of variety in an internal regulator subsystem, as proposed by Ashby. (Or it might pursue some mixture of both strategies.) Note that in the latter alternative, the living system as a whole might act as a regulator and reduce the variety of the environment, not merely its entropic effects on the system, in this case the environment being considered the "regulated system."

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*Note that one cannot assume $H_R(E) < H_R(D)$. For such cases, the LRV, or its analogues, cannot be derived; not surprisingly, since this assumption proclaims explicitly a violation of the Second Law.

+Ashby's discussion assumes that the regulator does not need the operation of additional elements to change the state of the system. In cases where such elements are involved, e.g., a furnace or air-conditioner controlled by a thermostat, the thermodynamic action of these elements will be relevant to the entropy analysis.

Thus, the widely prevalent idea that viable systems, whether biological or social, necessarily seek to preserve or perhaps even to maximize internal neg-entropy is not strictly true. It is only one half of a dialectical complementarity, the other half of which consists of the fact that entropy is necessary for adaptability. As Ashby has observed, variety and noise cannot be distinguished through any intrinsic property. Entropy is usually associated with noise, chaos, and randomness, but the "positive value" of entropy is expressed in the cybernetic notion of requisite variety, and in related principles of other disciplines.* For example, in ecology, "variety" is referred to as "diversity," which is defined in terms of the standard expression for entropy. Diversity, in ecosystems, correlates roughly with stability, and high diversity is generally a feature of mature stages of ecological succession [9,10].

In the cybernetic literature, moreover, variety is treated as being nearly synonymous with complexity, and is often viewed as increasing with evolutionary development [11]. Just as a thermodynamic conception of evolution might speak of systems evolving to greater neg-entropy, so a cybernetic view might speak of a tendency (in complex environments) towards increased variety. These two views are not different ways of speaking about the same thing, but are actually diametrically opposed, since variety means entropy, not neg-entropy.&

What is actually needed for viability is some synthesis or balance or perhaps a context-dependent choice+ between order (neg-entropy) and variety (entropy). A great deal has of course been written on this subject#: on the complementarity of order and disorder, and the need for both, suitably reconciled. This idea also is not new, but dates back at least to the Chinese Taoists.

Consequently:he who wants
Order without disorder,
Does not understand the principles
Of heaven and earth.
He does not know how
Things hang together.
Can a man cling only to heaven
And know nothing of earth?
They are correlative:to know one
Is to know the other.
To refuse one
Is to refuse both. -- Thomas Merton, after
Chuang Tzu [12]

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*Just as entropy has, for systems, both "negative" and "positive" aspects, so, too, has neg-entropy. The latter term is most traditionally associated with order and integrality, but it also implies rigidity and inflexibility, i.e., the absence of variety. The tendency of systems to rigidify is often incorrectly regarded as a direct consequence of the Second Law.

&Of course, the entropy of the regulator is controlled, the state of the regulator being specifically determined by the initial disturbance. Still, an optimal regulator which, for example, exists in all of its possible states with equal frequency, because of equally frequent disturbances, has actually the same variety as a regulator which selects its state randomly and thus effects no regulation at all.

The Law of Requisite Variety asserts that to reduce H(E) to zero, H(R) must equal H(D), but this is a necessary, not a sufficient condition. It indicates Second Law limitations on the efficacy of regulation, but provides no instructions for the construction of D-E-R tables.

+Such a choice might depend on the characteristics of the system's environmental niche. For stable environments, an emphasis on order may be optimal, but in turbulent environments, variety is necessary for adaptability.

#Some pertinent references are [13-20].

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