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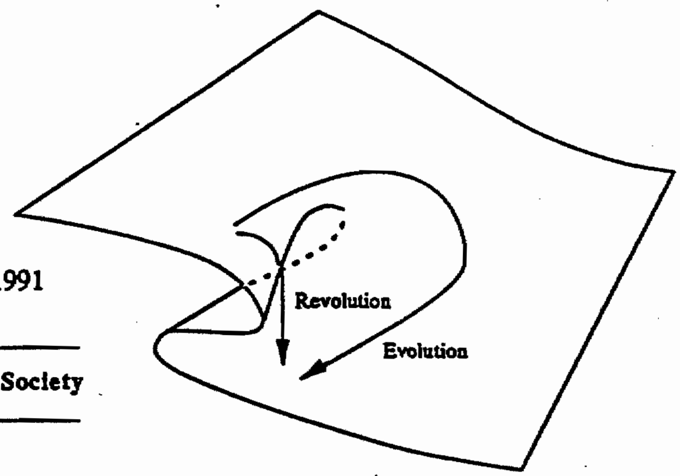

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Complexity: Toward Quantifying its Various Manifestations

Robert E. Ulanowicz

Introduction

Elsewhere in this issue of *WESScomm* Chandler provides a semantic analysis of the notion of complexity as a set of dynamic classes of behavior. He identifies eight manifestations of complex behavior -- closure, cyclicity, concatenation, conformation, convolution, contractability, coherence, and creativity--or what might be called the C8 description of complexity. Each of the observed modes of behavior is a way of recognizing or "knowing" complex behavior. Therefore, his approach is (properly) epistemic in nature.

As Chandler notes in his article, my own inclination is more toward developing a unified *quantitative* description of complex behavior. My approach, however, remains purely epistemic and phenomenological, because the basis for my narratives is information theory--the quantitative theory of knowledge, or what might be called "quantitative epistemology". What I wish to attempt here is a reinterpretation of Chandler's C8 narrative in terms of information theory. That is, I desire to establish quantitative criteria to define, identify, or otherwise illuminate each of Chandler's eight dynamical classes.

Describing Collections of Processes

In order to initiate the quantification of whole-systems phenomena, it is first necessary to adopt the perspective that evolutionary systems are not static configurations, like strings of letters or chains of chemical monomers ([Dawkins 1976] notwithstanding). They resemble more highly interrelated *processes*. Or as [Popper, 1990] so aptly put it when he restated the ideas of Heraclitus, "We are, like all cells, *processes of metabolism*; nets of chemical processes, of highly active (energy-coupled) chemical pathways."

With this cue from Popper, an evolutionary system may be represented as a network of n nodes. The nodes may be populations, cells, industries, chemical constituents, or whatever. Connecting these nodes are arcs that represent the influence that a particular node i exerts upon node j, that is, the *process* by which i affects j. It is important that all processes somehow be quantifiable, preferably in terms of some common units. The easiest situation to demonstrate occurs when each process involves an exchange of a conservative medium (i.e., mass or energy). For convenience I will restrict my subsequent narrative to networks of such conservative processes; however, the application of information theory is by no means limited to this subclass of evolutionary systems.

If T_{ij} represents the rate of transfer of medium from i to j, then the totality of all such processes occurring in the system becomes:

$$T = \sum_i \sum_j T_{ij}$$

Equation (1)

T is called the total system throughput, and it gauges the aggregate activity level of a system. (The Gross National Product is a related variable that measures the activity level of the national economy.) The fraction of the overall activity comprised by T_{ij} is T_{ij}/T, so that the complexity of the manifold processes according to the familiar Shannon-Weaver formulation for uncertainty [Shannon, 1948] becomes

$$H = -\sum_i \sum_j (T_{ij}/T) \log (T_{ij}/T)$$

Equation (2)

Of course, these transfers do not just occur hither and yon--there is a degree of order to the pattern in which they are connected. In a very real sense, this pattern of connections is also a blueprint of the constraints on the flows. That is, once one knows how the flows are hooked up to each other, transfers are no longer arbitrary. If one's attention is focussed upon a given compartment, then egress from that compartment (in general) can no longer be to any other compartment, but only to a delimited subset of other compartments. This means that the system no longer is as complex as an arbitrary configuration. Some of that potential complexity (expressed in equation (2)) has been resolved by the system constraints. That amount can be quantified by a component of (2) called the average mutual information [Atlan, 1974], [Rutledge et al., 1976].

$$I = \sum_i \sum_j (T_{ij}/T) \log (T_{ij}T/T_{.j}T_{.i})$$

Equation (3)

where a dot replacing a subscript signifies that the missing index has been summed over its full range. The quantity I measures the degree of order inherent in the juxtaposition of processes comprising an evolutionary network. It is possible to show that H is an upper bound on I, which, like H, is strictly nonnegative. If one measures the processes in the network at some time, and at a later time finds that I has increased, then the system has become constitutively more ordered, i.e., it has developed.

Actually the structure of a system cannot be fully appreciated by knowing I alone. System size is also a very important factor in its evolution, so that elsewhere ([Ulanowicz 1980], [Ulanowicz, 1986]) I has been scaled by T to define a combined measure of a network's size and organization, called the system **ascendency**. A system of increasing ascendency is said to grow and develop. I now wish to suggest that Chandler's eight facets of evolutionary dynamics appear as components of a system with increasing ascendency, and thus can be precisely quantified.

Figure 1 portrays three hypothetical mini-networks all with the same T. In 1a there is maximal uncertainty about the destination of a quantum of medium leaving a particular compartment. It is the temporal average of the totally arbitrary system referred to above, and I for this configuration is identically zero. In 1b there is less confusion, and I increases to one bit. Finally, in Fig. 1c there is no uncertainty about where a particle will flow next, and I reaches its maximal value of 2 bits. The configuration in Fig. 1c also can be regarded as strictly **concatenated**, so that the relationship between information theory and one of the C8 elements is thereby established.

As can be seen from equation (3), the algebra necessary to exposit information theory can become cumbersome. To assist those readers unfamiliar with the calculus of information theory, it is helpful to resort to defining subsequent terms using appropriate Venn diagrams. In this representation, the uncertainty about a particular attribute will be represented by a circle. Thus, Figure 2a depicts the respective uncertainties of the inputs and outputs on Figure 1a. Our uncertainty regarding where a quantum is coming from and going to can be quantified by H_{in} and H_{out} respectively, where

$$H_{in} = -\sum_j (T_{.j}/T) \log (T_{.j}/T)$$

Equation (4)

$$H_{out} = -\sum_i (T_{i.}/T) \log (T_{i.}/T)$$

Equation (5)

The independence between H_{in} and H_{out} is represented by the absence of any overlap between the two circles in Figure 2a. One may substitute into eqs. (2), (4), and (5) to verify that in this case, $H = H_{in} + H_{out}$ and $I = 0$. In configuration 1b, some of the uncertainty about sources and destinations has been resolved. For example, if a quantum is leaving component 1, we know that it is going to 2 or 3, but not to 1 or 4. This partial resolution of uncertainty is represented in Fig. 2b by the overlap between the two circles, and is quantified by I as expressed in equation (3). In other words, $H = H_{in} + H_{out} - I$. The overlap likewise represents the extent of concatenation in the network under consideration. When a system is fully concatenated, i.e., when a knowledge of a source determines unequivocally the destination (Fig. 1c), the two circles fully coincide. In the network in Figure 1a, this uncertainty is completely disconnected from our uncertainty, H_{out}, of whither the medium is flowing.

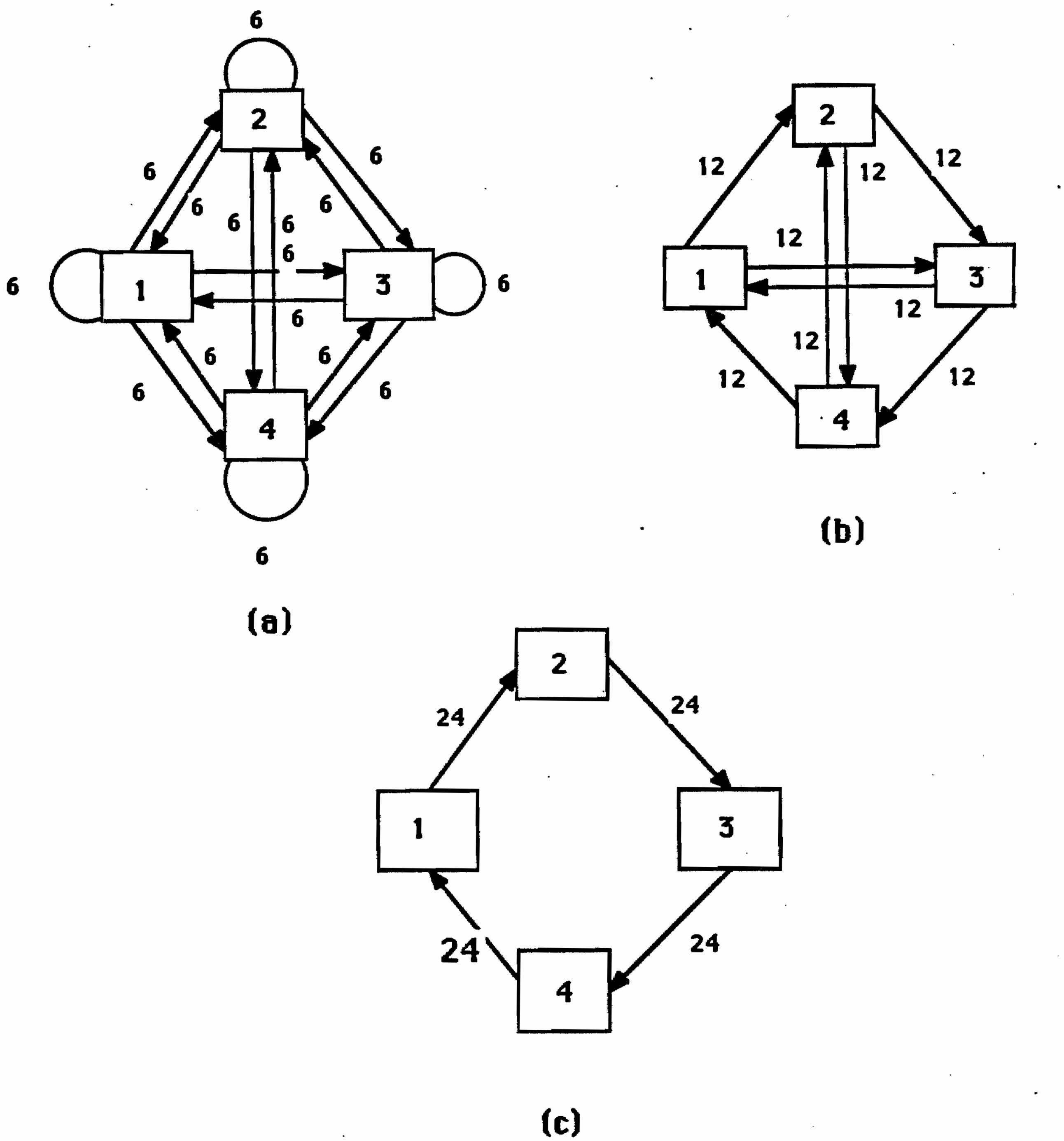


Figure 1. Three examples of hypothetical networks with the same T.
(a) Maximally unconcatenated.
(b) Intermediate concatenation.
(c) Maximally concatenated.

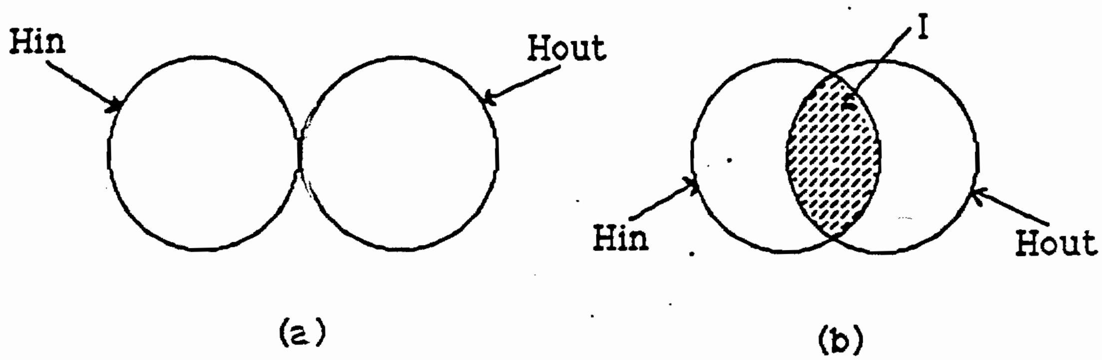


Figure 2. Venn diagram representations of information shared by inputs and outputs for the corresponding hypothetical networks in Figure 1. (a) Maximally unrelated. (b) Partially correlated.

Thus far, we have not considered exogenous transfers. To introduce communication with the external world, let the subscript 0 (zero) represent all outside influences. That is, T_{0i} is an input to compartment i from outside the system, and T_{i0} is an export from i leaving the system. The uncertainty about inputs to the system can be segregated from the other terms in eqn. (1) by collecting all terms with the first index zero (i=0) separately from the others and calling the grouping H_o. In terms of Venn diagrams we will represent this uncertainty as a rim around the uncertainty of all inputs, as shown in Figure 3. Chandler's **closure** now may be quantified as the relative amount of H_{in} that is not expressed as H_o, or $H_{in} - H_o$. Presumably, as a system evolves, its closure with respect to inputs increases, as represented either by a diminution in the difference $H_{in} - H_o$ or by the shrinking of the rim in Figure 3.

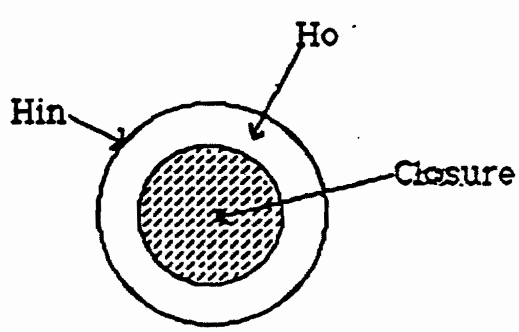
Dynamical Systems

Until now, we have not treated the actual dynamics of a system. That is, the T_{ij} have been considered to be either constant over time or else averaged over a long interval. However, the remainder of the C8 attributes involve explicit dynamics, so that it becomes necessary to expand the quantitative presentation to represent temporal variations in the exchanges. Thus, let T_{ijk} represent the transfer of a quantum of medium from i to j during the brief time interval k (i,j = 0,1,2...,n; k = 1,2,3,...,m).

One sees that to treat fully dynamical systems will require the calculation of information measures from data arranged in matrices having three dimensions. Fortunately, the algebra of three dimensional information measures has been treated in numerous texts (e.g., [Abramson, 1963]). As previously mentioned, I will not go fully into the algebraic exposition of information measures in three dimensions but instead will represent these measures in terms of regions on appropriate Venn diagrams. I wish to emphasize here, however, that any and all segments of these Venn diagrams can be assigned a unique magnitude by operating on the array T_{ijk} with an appropriate formula from information theory. That is, I am writing about concrete numbers, not vague heuristics.

Information measures in three dimensions can be represented as overlapping regions of three circles, as shown in Figure 4.

Figure 3. The input uncertainty partitioned into external and internal (closure) components.

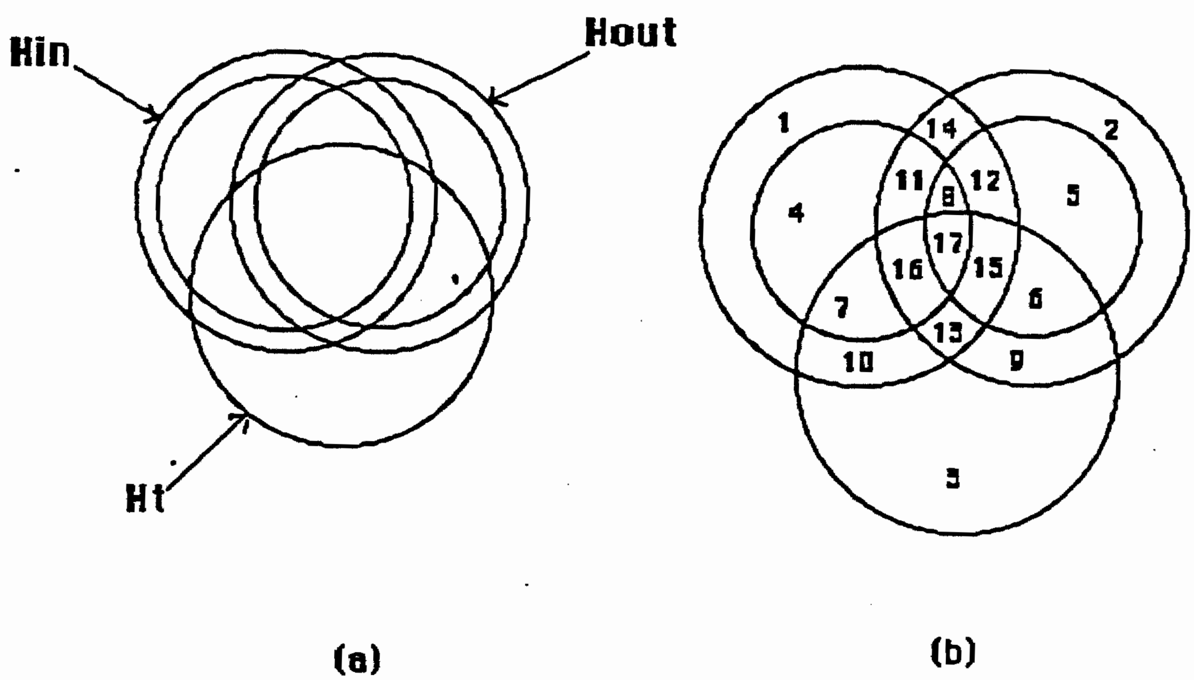


The three circles represent the uncertainties in inputs, outputs and temporal variation in activities. I have complicated the diagram slightly by also representing the segregation of uncertainties engendered by exogenous exchanges as circular rims on the input and output uncertainties. We now turn our attention to the different regions in Figure 4a as they pertain to identifiable aspects of evolution in complex systems. To facilitate the narrative, I have arbitrarily numbered each of the 17 divisions as shown in Figure 4b.

All temporal structure is represented by the shaded region in Figure 5. Looking more closely, one can make distinctions among temporal structures. For, by **cyclicity** Chandler is referring to order in the temporal domain. Such order is most apparent when it is dominated by a single frequency, but it can be shown through Fourier analysis that all temporal structure can be approximated by superpositions of elementary cycles. (When applied to chaotic or aperiodic behavior, such representation is sometimes impractical, but conceptually possible.) For example, the rim arc consisting of regions 10, 13, and 15 quantifies all cyclicity in the input flows; regions 9, 13, and 16, the cyclicity in the outputs. Region 13 measures temporal coherence between exogenous inputs and outputs, etc. Any increase of one or more of the eight areas comprising the shaded domain in Figure 5 represents an increase in cyclicity.

Conformation specifies an interrelationship between parts of a system and its environment. The extent of conformation is quantified by the four regions 11, 12, 15, and 16 as shaded on Figure 6. Obviously, there is an inverse relationship between conformation and closure, both as implied in their definitions and as shown in the Venn diagram. Regions 15 and 16 represent temporal coherence between the closure and the environment, whereas 11 and 12 represent conformation to other factors, such as spatial conformities between plant cover and soil types, etc.

Figure 4. Venn diagrams representing the intersections of uncertainties in inputs, outputs and temporal behavior: (a) without enumeration and (b) with enumeration for identification.



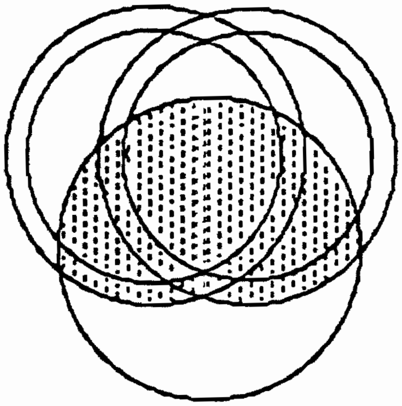


Figure 5. The region of the 3-D Venn diagram representing temporal structure, or cyclicity.

Convolution as described by Chandler is a temporal change in the conformation that evolves through continued mutual interaction between the closure and its surroundings. It is represented by a change in the magnitudes and relative sizes of the same four regions shaded in Figure 6. Convolution might occur via reconfiguration of internal relationships so as to increase the conformity (a nonautonomous process depicted in Fig. 7a); but it is more likely to appear as the closure regions themselves grow in relation to the environmental influences (co-option), so that the conformity shrinks in relation to other activities (Figure 7b).

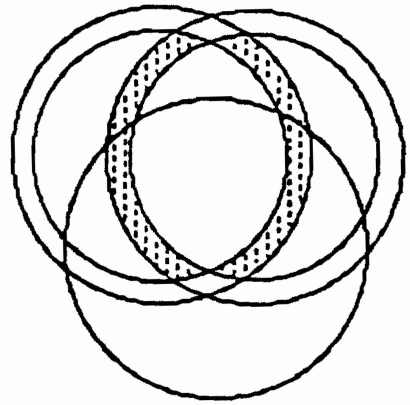
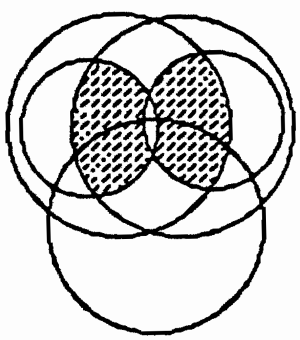
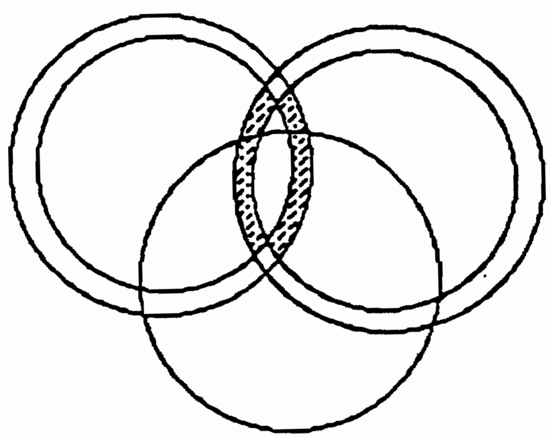


Figure 6. The overlap region of the 3-D Venn diagram representing conformation.

According to Chandler **coherence** "generates and maintains a quasi-stable form by acquiring resources and channeling its flows within the telaclosure". I translate this to mean that flows within the closures are coordinated with respect to each other and with respect to time. Graphically, coherence within the closures is gauged by areas 6, 7, 8, and 17, or by the shaded region in Figure 8. Any increase in the aggregate of these four regions can be said to represent an increase in system coherence. Notice that an increase in coherence can occur either through further concatenation (areas 8 and





(a) (b)

Figure 7. The process of convolution. Compare shaded areas with that in Fig. 6. (a) Non-autonomous (b) Co-option

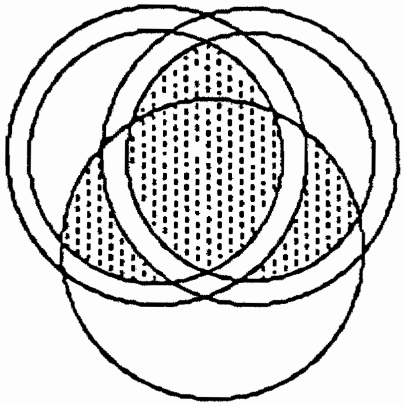
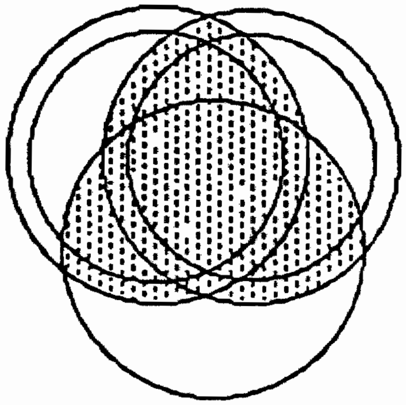


Figure 8. Areas of 3-D Venn diagram representing coherence.

17) or through more temporal cyclicity (areas 6 and 7) or via both avenues at once. It is interesting at this point to consider the union of all the regions discussed thus far in quantifying six of the elements in the C8 description. Said union is represented by the shaded area in Figure 9. (Actually, the union doesn't include region 14, but this set is null in most treatments.) Pahl-Wostl [Pahl-Wostl, 1991] has suggested that this area represents the most appropriate extension of the notion of ascendency into three dimensions. Thus, an increasing network ascendency appears to be an apt description of the growth and development of complex systems, because it encompasses the major modes of complex evolution.

Two attributes from Chandler's C8 description remain to be treated. Creativity is notoriously

Figure 9. Area of 3-D Venn diagram representing all regions of overlap, i.e., the normalized ascendency.



difficult to describe, in either semantic or quantitative terms. One can say, however, that creativity requires *both* stochasticity and constraint before it can happen [Atlan, 1974]. Thus, a system without enough disordered behavior and functional redundancy (as represented by regions 4, 5 and possibly 3, see Figure 10) will not possess a sufficient repertoire of candidate solutions to solve the problem of adapting to novel perturbations. At the same time the ensemble must possess a rich and coherent enough structure (Fig. 8) into which to incorporate the new adaptation and to stabilize its response.

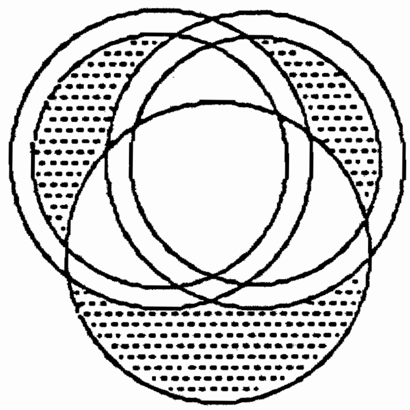


Figure 10. Regions of the 3-D Venn diagram that represent residual disorder, a prerequisite for creativity.

Finally, there is the factor which Chandler calls **contractability**, or "the capability of a system to represent itself in some skeletal form". This property differs from the other seven in being more epistemic in nature, i.e., a result of how one views the system. Hirata and Ulanowicz [Hirata and Ulanowicz, 1985] have shown that one naturally aggregates (contracts) ecosystems in ways that minimize any loss of information about the operation of the system. That is, one seeks to group those system compartments that are functioning similarly. For example, most of the cells within a particular organ of the body are behaving in much the same way, especially in contrast to the ways cells in other organs are performing. To be more precise, cells in the liver carry out quite different processes from cells in the pituitary gland; however, within each of these organs there is significant parallelism in what the individual cells are doing. These analogies suggest a way to test how contractable a given system might be: aggregation or contraction of the system nodes never increases the information about the system--at best an aggregation will leave the information unchanged whenever identically functioning parts are grouped [Hirata and Ulanowicz, 1985]. Hence, if a system is a candidate for contraction, there will exist groupings of elements that will decrease the dynamical ascendency (Fig. 9 and Eqn. 7) only minimally, but will decrease the redundancy (embodied in regions 1, 2, 3, 4, and 5) disproportionately. When to stop the contraction is ultimately a matter of judgment. My brief experience with the procedure has indicated that there comes a point when any further contraction induces a precipitous drop in network information, and the aggregation process should be broken off just before that point. Those wishing to quantify the stopping criterion are referred to Kullback [Kullback, 1968].

The reader should note that the attributes of complex behavior discussed here mostly have involved combinations of several regions of intersection, or overlap (as enumerated in Figure 4b). Obviously, there are many other combinations of the 17 regions than could be discussed -- some of which might portray recognizable aspects of complex behavior useful for taxonomic purposes. Such possibilities demonstrate the wisdom behind Chandler's statement that the C8 descriptors are necessary but probably not sufficient to describe fully all manifestations of complex behavior.

Conclusions

Rutledge et al. [Rutledge et al., 1976] have suggested a quantitative method for expressing conditionalities within ensembles of processes that leads to very useful comparisons. Building upon their information-theoretic approach, we assign specific numbers to aspects of complexity that heretofore were subject only to semantic narration. Such quantification is an initial step along the path of scientific progress in treating complex behavior, but perhaps even more importantly, it forms a bridge between the "hard" and "soft" sciences across which much useful dialogue may now pass.

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