working in our laboratory, has prepared serum from LBN rats injected with antibody from Lewis rats injected with BN antigen which had been lightly aggregated with gluteraldehyde. This serum specifically blocks a mixed lymphocyte interaction between L and LBN leukocytes, and the blocking activity is specifically reduced by absorption with L spleen cells. This serum also forms precipitin lines in gel with those serums from Lewis rats injected with BN antibody that effectively enhance kidney survival but not with those that are ineffective. Although we cannot confirm that the material causing suppression in any of these models is in fact antibody to receptors, in each case the material was obtained under conditions which we believe might be appropriate for the formation of antibody to receptors.

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Information and the Ecology of Scholars

Thomas R. Blackburn

"What is that very large body with hundreds and hundreds of legs moving across the horizon from left to right in a steady, carefully considered line?"

"That is the tenured faculty crossing to the other shore on the plane of the feasible."

"And this tentacle here of the Underwater Life Sciences Department . . ."

"That is not a tentacle but the department itself."—DONALD BARTHELME, "Brain damage" (*1*).

As the behavior of biological ecosystems becomes increasingly familiar, one is tempted to use ecological phenomena as metaphors for human behavior. The apt and often amusing insights so produced have seemed, however, to offer little basis for the serious consideration of quasi-thermodynamic systems models for society. My object is to suggest a logical basis for the use of ecological concepts in modeling a special subculture: that of scholars (and, in particular, scientists), who produce, barter, and structure information as an ecosystem produces, exchanges, and structures biomass. To go beyond mere analogy, however suggestive, it will be necessary to discuss ecosystems as open, dissipative thermodynamic systems and to point out the relationship between material (thermodynamic) and conceptual (informational) structuring.

I begin with the common observation that the orderly structures found everywhere in nature may be classified into two groups: equilibrium structures, epitomized by crystals, and dissipative structures, epitomized by living cells (*2*). Both kinds of order represent relatively low-entropy states for the matter of which they are composed, although both may persist unchanged for long times. Since only the equilibrium structure represents a local free-energy (or other appropriate potential) minimum state, only such a state may

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persist in a closed system. Dissipative structures depend for their persistence on a flow of energy; if this energy flow is cut off, the structured matter begins immediately to relax toward a state of equilibrium, in accord with the second law of thermodynamics for a closed system. (The energy released by this relaxation may, of course, serve as the enabling energy flow for the formation of a lesser ordering elsewhere.) Low-entropy states of matter may also, through information theory and statistical mechanics, be characterized as states of high information content and of low probability. I use all four expressions (order, low entropy, high information, low probability) as equivalent, bearing in mind that the existence of quantitative correlations among the four allows such interchanges to be made in fact for particularly simple situations (like ideal gases, telegraph messages, or statistical distributions among a priori equally probable states) and in principle for complex ones (solutions in condensed phases, genetic and behavioral information, or social organization). In doing so, I try not to extend the meaning of the four concepts beyond the realm of discourse in which they are well defined.

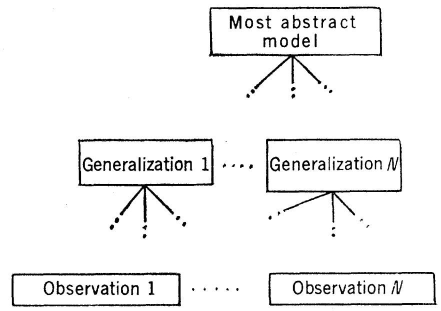

Fig. 1. A generalized informational hierarchy, in which the data of immediate experience give rise to working models that are themselves the input data for more abstract and general models. The spontaneous direction of information flow in such a system is "downhill" (deductively), from the more abstract to the more particular.

Ecosystems as Dissipative Structures

Although the size, complexity, and comprehensiveness of dissipative structures range enormously—from hydrodynamic vortices to biological assemblages—the largest and most important dissipative structure known is the biosphere, an ordered arrangement of matter supported ultimately by the degradation of solar energy from short to long wavelengths. Because the entire biosphere is, after all, an inconveniently large system to discuss, it is customary to isolate, conceptually, parts of it, such as a forest, a watershed, or the microbial flora in a single animal's intestine, and to call these ecosystems. By this term I mean a group of living organisms that are related to each other by their common access to some particular, well-defined energy flow (such as the sunlight, which falls on an entire watershed, or the flow of food through the digestive tract, in the case of the intestinal ecosystem) and by their participation in a web of nutrient and informational flows. Examples of informational flows in a biological ecosystem would include genetic information passed from parents to progeny, as well as such behavioral information (territorial marking, social ordering, mating behavior, hunting habits, and so forth) as is necessary for the efficient use of the common energy flow (*3*). Like those of any other thermodynamic system, the boundaries of an ecosystem may be chosen arbitrarily, and for most ecosystems the boundaries are open to material flow. The term "ecology" refers here to patterns of nutrient and informational relationships among organisms of a given ecosystem.

Since ecosystems are examples of dissipative structures, it should be expected that they will have properties in common with other such structures—for example, hydrodynamic vortices, candle flames, or the motion of a bowed violin string (*4*). Following are four properties that seem to me central to the characterization of dissipative structures, particularly ecosystems, and that I use as a basis for the discussion of scholarly groups.

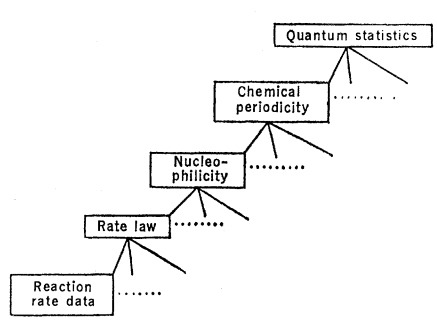

Fig. 2. An intellectual hierarchy from the field of chemical theory. At each level, possible other input data (for example, thermodynamic and stoichiometric information) are indicated by the dotted lines.

1) *Dependence on energy flow.* I have already discussed this property, and it remains only to reiterate that any ordered structure may be recognized as a dissipative one by its disintegration when the supportive energy flow is cut off.

2) *Homeostasis.* Because dissipative structures must be open to, and persist in the face of, energy flows large enough to disrupt them, negative feedback loops preserve their structure in spite of (moderate) changes in external conditions. Thus a skilled violin player (using a negative feedback loop that includes ear-hand coordination) maintains a uniform timbre and loudness in spite of variations in the physical properties of his instrument at different pitches and bow positions; a candle flame maintains a relatively constant pool of molten wax as the candle burns down because the flame size (and heat production) is negatively related to the size of this pool; chemical pollution of a watershed selects for just those organisms that are able to metabolize the pollutant and eventually return the water to its original chemical state.

3) *Succession.* Candle flames, bowed strings, and other dissipative structures show a change in their properties from their inception until a stable state is reached, in which characteristic parameters (for example, temperature, vibration frequency) attain constant values, or cyclic values with a regular frequency, that are determined weakly by external conditions (ambient temperature, bow pressure) and strongly by the properties of the structured matter itself (the melting point and heat of combustion of the candle wax, the length and weight of the string) (*5*).

Similarly, ecosystems display succession toward climax states, in which their properties tend to remain constant for as long as external conditions do. The changes that occur during ecosystem succession have been listed and discussed by Margalef (*6*) and by Odum (*7*), among many others, and it is superfluous to recount these in detail. However, for purposes of later discussion, I note some of their major conclusions. In mature, as compared to immature, ecosystems, the following generally hold: (i) the quantity of genetic and structural information maintained per unit of energy input is relatively large; (ii) the net rate of production of new structure is relatively low (approaching zero); (iii) the degree of diversity and niche specialization are relatively high; (iv) sizes and life-spans of individuals are relatively large; and (v) the nutrient budget is efficient and primarily from within the system, as compared to the prodigal and externally subsidized nutrient budgets of immature ecosystems.

4) *Limitation by rate of mass transport.* Dissipative structures reach climax states when as much matter as possible has been entrained into material cycles. Thus a bowed violin string reaches a stable pitch when the entire string vibrates in the same pattern; a convective vortex stops growing when all of the available fluid has been entrained. If there is a net flow of matter through the system, the properties of the stable state reached will be strongly determined by mass-conservation limitations on flows. As a quite general proposition, it is characteristic of dissipative structures, as opposed to equilibrium structures, that both their growth and their final forms are kinetically determined. For relatively simple dissipative flow structures, the kinetic determinants of form are shaped by simple input flow rates, since in such systems (for example, vortices or flames) there is little or no possibility of matter being diverted into storage, or of internal control mechanisms regulating the rate at which matter passes through the system. An instructive comparison is that between a gas flame, whose size (and, to a smaller extent, form) is completely determined by the rate of supply of fuel, and a candle flame, which is partly self-regulating through the effect of flame size on the level of molten wax surrounding the wick.

Physiological structures, by contrast, operate more efficiently when they are well within the extreme limits set by external mass transport (*8*). Animals, for example, do not metabolize to the point of collapse between meals, or between breaths. In ecological communities, behavioral mechanisms may mediate mass and energy flow; for example, in the division of nutrient flow among species-specific trophic niches. Such behavioral mediation may cushion the physicochemical boundaries of community stability and thus appear to be conceptually independent of such boundaries. However, behavioral specialization simply allows more matter to be entrained in the cycles of the biological community, and thus allows the domain [in ecological hyperspace (*9*)] occupied by living matter to fit more efficiently within whatever physicochemical limitations (for example, of temperature, insolation, or chemical potential) may bound a habitable hypervolume.

In summary, it seems reasonable that the increasing selective advantage of biological (behavioral) control of a system just within physicochemical limitations, as more and more matter is entrained, accounts for the successional trend toward greater structure and higher efficiency in the use of energy. It also seems (*6, 7*) that net productivity tends to zero because of the energy cost of maintaining that structure. I shall return to this idea later.

Social Structures and Intellectual Structures

Turning to the community of scholars, one can see several kinds of structuring. Most obvious are the literal structures: institutions and facilities and human beings. Second, there are the social structurings in these physical objects: faculties, professional societies, departments, roles and specialties, contracts, leaves of absence; the stuff, in short, of academia. Neither the literal nor the social structurings would make the least sense without the third structure, which is wholly intangible: the intellectual structure of scholarly thought itself, its language and models and logic. Since all three of these kinds of order would disintegrate if the flow of fossil fuel energy (in the form of electrical power, money, and food) were cut off, they are all dissipative structures, coupled to each other, although conceptually separable. The creation and maintenance of these structures is one of the many ways in which solar (including fossil fuel) energy is stored pending its ultimate dissipation into space. I now consider in more detail a specific model of intellectual structure (Fig. 1). Depending on what sort of scholarship is involved, and the degree to which a formal deductive structure is possible under its paradigms, such a hierarchical pyramid may be many, or only a few, levels "high." A hierarchy from chemistry is shown in Fig. 2. The object of scholarship in most fields is to structure the data of immediate experience and to distill from them meaningful generalizations that, on the one hand, summarize much information at the level of experience and, on the other, serve as data for generalizations at the next higher level. Clearly such a general model is applicable in only a general way to any one of the spectrum of scholarly efforts, ranging from literary criticism to the proof of mathematical theorems.

I have chosen a hierarchical model because it points up the informational ecology of scholarship. From the point of view of information theory, a meaningful generalization is a highly improbable statement, one that is selected out of all the possible statements about a given set of experiences, quite as a distillation selects an improbable, low-entropy, pure substance out of a mixture. A correct, fruitful, generalization contains in a small space much information about experience on lower hierarchical levels for the same reason (absence of an entropy of mixing) that the chemical free energy of a pure substance is much greater than that of the same quantity of substance in solution. At the same time, a correct generalization makes redundant some (in the case of a perfect generalization, all) of the information on lower levels of the hierarchy (*10*). If one were speaking of the concentration of nutrients in a trophic chain, one would say that the general preys on the particular.

Since the spontaneous direction for the flow of information in such a logical hierarchy is from the general to the particular (as it is, for example, in the proof of a theorem), the fact that generalizations arise out of particular experiences requires one to seek the compensating increase in entropy—that is, the enabling energy flow. In the case of most scholarship, two kinds of energy flow are required: the quite literal expenditure of fossil fuel energy, to maintain expensive facilities, and the input of mental effort, which is difficult, perhaps impossible (*11*), to quantify. While a complete discussion of the human motivation to create informational hierarchies would certainly go beyond both the subject of this article and my competence to comment, I note that, at the creative level in science, the high concentration of information in generalizations of broad scope has both logical and esthetic value: an extremely "powerful" generalization is also "elegant."

Perhaps this is the place to remark on the value of speculative information in science, since, in the case of urgent problems pertaining to complex systems (for example, in the discussion of man's impact on the biosphere), only speculative information may be available as a basis for action. In the academic sphere, information plays the role of nutrient; a guess, then, is a dilute source of nutrients, containing less useful information than, from the standpoint of information theory, its individual words give scope for. Even a dilute source of information, however, may be more useful than no information at all. To put this notion on a sounder basis, consider the following model: suppose one could formulate one's knowledge about some topic as a distribution of probabilities among all of the possible answers to a well-defined question (or set of questions). Perfect ignorance corresponds to considering the truth of each answer equally probable; in the case of N possible answers, each would be assigned the probability $1/N$. Perfect information amounts to the (correct) assignment of unit probability to one answer (*10*). In most cases, and certainly in all quantitative experimental questions, the actual situation lies somewhere between these two extremes: some finite probability must be assigned to a spread of possible answers (Fig. 3). Even with a paucity of experimental data, it is usually possible to hazard a guess about the right answer, and this situation corresponds simply to a relatively broad spread of uncertainty. A guess may be refined by the proper expenditure of energy (whether physical or mental) to narrow the spread of probabilities—by obtaining more information. In the same way, an impure substance may be refined, for example by distillation, through the input of energy. The refined guess contains more information by virtue of its narrower spread of probabilities; the refined substance has a lower entropy of mixing by virtue of its narrower spread of available microstates; and the same equation governs both processes.

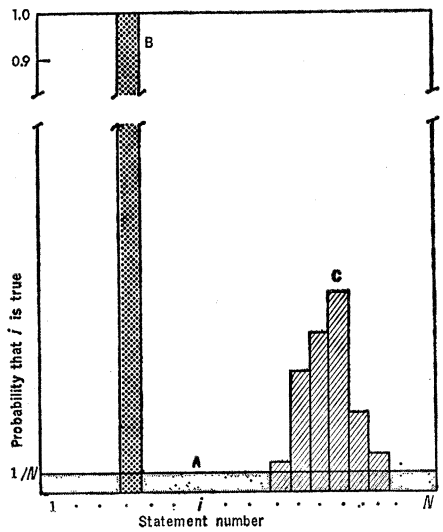

Fig. 3. Distributions of probability of the truth of a given answer to some well-defined question for the case of (A) total ignorance; (B) perfect information; (C) moderate certainty.

A Quantitative Example

In order to lend concreteness to the argument, let me give an example of how information is produced and incorporated into a trophic hierarchy in a simple case and how producing this information was achieved only at the expense of producing greater entropy elsewhere. Consider, then, the measurement of the mercury content of a lake sediment (*12*). Such a measurement produces at least two kinds of information: the geographical location of the sampling station and the mercury content of the sediment at that station. A calculation of the quantity of information produced by this measurement is possible, provided that the expected range of values and an estimate of the uncertainty are known for each value. Then (*10*) the information produced is

$$I = k \sum_i \ln (R_i/d_i) \text{ erg deg}^{-1}$$

where k is Boltzmann's constant, R_i is the maximum range expected for the ith variable, and d_i is the uncertainty in the measurement of the ith variable (*13*). In a typical case, one might know the geographical location to within 1 percent of the lake's width in each of two dimensions and the mercury content of the sediment to within 5 percent of the expected possible range. The information produced by these measurements would be 1.7×10^{-15} erg deg^{-1} (this quantity corresponds to 17.7 bits).

How great an increase of entropy in the fossil fuel economy is required to pay for this information? If a small limnological vessel with a 100-kilowatt (134-horsepower) engine were used in collecting samples, the entropy production resulting from that alone would amount to 10^{13} erg deg^{-1} per sample, assuming ten samples taken per hour. The ratio of information production to entropy production (ignoring all other energy use during the treatment and analysis of the sample) is, then, of the order of 10^{-28}. I shall return to the consideration of this remarkably unfavorable efficiency later. By making certain assumptions about language redundancy (*10*), it is not difficult to calculate that a man sitting and reading English prose at the rate of 300 words per minute by the light of a 100-watt bulb enjoys a considerably more favorable ratio of information to entropy production: 5×10^{-21}. Finally, note that, based on a calculation by Morrison (*14*), these ratios are comparable to the ratio of information to material entropy produced in the biological creation of such ecological information as colored identification patterns or social ordering.

It is evident that science, or any other scholarly art, can hardly afford to operate with the prodigally low efficiency demonstrated above. It is at this point that the power of a correct generalization becomes evident. To continue the mud-mercury analysis, suppose that a systematic study of the mercury content of no more than ten samples makes it obvious that a particular dentist's office in a lakeside town is a source of mercury pollution in the lake. Dental mercury constituted 4.1 percent of all mercury used in the United States in 1968 (*15*). I estimate a world dental mercury use of roughly 400 of the 9000 metric tons of mercury used in the world each year, with a direct spillage during the process of cavity-filling of 10 percent, or 40 tons. The sampling and analysis postulated above might typically have detected 4 micrograms of this, or 10^{-13} of the total. To account for all 40 tons, one could continue to sample or one could go up a step in the logical hierarchy to the generalization, "Mercury spilled down the dentist's drain will reappear in natural waters and sediments," thereby saving considerable time, effort, and consumption of fossil fuel energy. By accounting for all spilled dental mercury, not just a few micrograms, this generalization has made further measurements redundant by embodying the information they generated. (Of course, this statement assumes that the generalization is correct; as in all empirical generalizations, only a given statistical confidence level of its truth can ever be attained.) It has also improved the ratio of information to entropy production in this project by a factor of 10^{13}. Intellectual structuring tends to lead to a less wasteful information economy.

I have here considered an information-trophic model of the intellectual structures discussed earlier and shown how information is concentrated as it moves up the trophic pyramid. I now turn to the related social structures of scholarship to see how this nutrient supports a series of structures whose behavior and survival strategies reflect the common problems encountered by dissipative structures in the face of the randomizing dictate of the second law of thermodynamics (*16*).

The Social Ecology of Academe

There is a formal resemblance between the community of scholars and what biological ecologists have been willing to call ecosystems. Consider the definition of ecosystem in this article: an ecosystem is a group of living organisms related by their common access to a well-defined energy flow and by their participation in a web of nutrient and informational flows. No problem should present itself in categorizing scholars under this definition, if it is remembered that the supportive energy flow includes the flow of information according to the hierarchical structures discussed above and that what distinguishes the academic ecosystem from other units of the fossil fuel economy is just this additional peculiarity.

A consideration of the four properties of dissipative structures, as exhibited by ecosystems, should serve to test this conclusion.

1) *Dependence on energy (and information) flow*. It is hard to see that more needs to be said here. The physical structures of academe require maintenance energy in the form of electrical power, physical work, and money. The social structures require, all too clearly in this era of academic underemployment, money, but also psychological motivation of the sort discussed above. A man becomes a biologist, say, and a member of a biology department. He works to make both roles satisfying, because to do so earns him a salary and because he wants to understand biology. Only the intellectual structures survive on motivational energy. (One would, of course, be tempted to distrust such an opaque term as "motivational energy" except for the fact that this is a quasi-thermodynamic, not a mechanistic, model. Lacking human motivation, the intellectual structure ceases to grow and ultimately disappears, and that fact is sufficient to identify it as a dissipative structure and to validate the term "motivational energy.")

2) *Homeostasis*. Academe has survived war, famine, plague, Christianity, prosperity, and, so far, the SDS (Students for a Democratic Society) and the FBI (Federal Bureau of Investigation) with remarkably little change in structure or method for over 2000 years in the West. This stability probably results in large part from a strong historical tradition (embodied, for example, in the institution of the textbook), as well as from the fact that the human mind appears to be constrained to build constructs according to a nearly invariant logic, using models derived from daily experience.

3) *Succession*. Within the nearly constant framework just mentioned, there occur cycles (both on a local scale and, on a few occasions, encompassing the whole system) of greater or lesser productivity. The dynamics of these cycles have attracted the attention of sociologists (*17, 18*), and a few common features have been pointed out. Generally, a period of high scholarly production follows the advent of an entirely new model—in Kuhn's term, a new paradigm—that serves as the basis for a new way of looking at the world. In terms of the hierarchical model of scholarship, a new paradigm appears high in the hierarchy, and much subsequent work is devoted to assisting the consequences of this change to propagate downward through the logical structure. A biological system would experience a similar effect from a sudden pulse of nutrients or other form of energy. The response of the biological system is to return to a less mature state (*6, 7, 19*). It has been my observation, and it is documented in a more scholarly way by Griffith and Mullins (*18*), that groups of scholars react to a new paradigm in ways that, according to the ecosystem model, can be characterized as a return to (ecosystem) immaturity. Lines of communication become short and rapid; motivational and fossil fuel energy flow are high; diversity within the active research group decreases, as all members share enthusiasm for the new paradigm (*20*). Naturally, such a state cannot be maintained for long. As the group grows, administrative structures tend to grow with it, energy is diverted to maintenance of the larger structure, paperwork multiplies. At the same time, ties to the larger world of scholarship are reestablished. In the words of Griffith and Mullins (*18*, p. 963):

> . . . even the most expansive groups ultimately grow so large as to dilute personal ties and influence. Institutionalism (for example, creating a department of molecular biology or a departmental slot for an operant conditioner) reduces levels of antagonism and group identity and generally marks the group's return to the normal loose networks of science. Thus the "penalty" of success . . . is the death of the group as a distinct social and intellectual entity.

The informational pulse, in short, is metabolized and elaborated into a complex and flourishing structure, in which information webs grow up to replace the simple, linear patterns of direct (and excited) oral communication.

4) *Kinetic limitation of growth*. The economy at large is limited in its growth and productivity by material scarcities; the academic ecosystem, tied as it is to expensive facilities and mortal men, shares this limiting factor. A much more crucial and interesting factor is that academic systems are also limited by the rate at which the consequences of new paradigms can be worked out. In biological ecosystems, kinetically regulated nutrient scarcity gives a competitive advantage to specialized species, which helps to account for the increase in species diversity as the amount of biomass grows up toward the limit that the available fluxes of sunshine and nutrients will support. In academic ecosystems, kinetically caused information scarcity gives a competitive advantage to intellectual specialists. After all, there would be no advantage to specialization if the logical consequence of any paradigm or the optimum use of any technique could be perceived quickly by anyone. It is common experience that the longer an academic field matures, the more intense and diversified the degree of specialization within its ranks. It seems perfectly consistent to attribute this successional phenomenon to the slowness with which the human mind produces new paradigms and works out their consequences; that is, to an ultimately materially determined limit to the rate of nutrient flow in the academic ecosystem. The high structuring, the scarcity of information, the slowness of thought produce niches (to use an ecological word for the phenomenon) that are remarkably constant

from one field to another: artist, critic, graduate student, archivist, bench worker, the seemingly inevitable handyman to whom is assigned the care of audiovisual equipment. Such niches tend to be shifting or absent in the small and democratic "hot" groups that first gather around the personal or geographic center of a new paradigm (*17, 18*).

Research Institutions

A research institution is in the business of producing and structuring information, as a farm or a forest is in the business of producing and structuring nutrients, given certain energetic and material throughputs. It appears that the productivity of a research institution is not governed solely by the size of those throughputs (in spite of the necessity of *some* throughput and the tendency of funding agencies to reward large information outputs a posteriori). With increasing maturity, biological ecosystems tend increasingly to substitute behavioral and physiological controls on their production rate for physicochemical ones. Perhaps the same is true of academic ecosystems. If that should be the case, an interesting dilemma arises: it is in the direct interest of the personnel of such an institute that the productivity be as high as possible—that is, that the institution resemble Griffith and Mullins' "coherent groups." On the other hand, there is a real human tendency, especially in large groups, to devote physical and mental energy to the creation and maintenance of more and more intellectual and organizational structure. No wonder, then, that the progress of science shows alternations of structure-breaking new paradigms with structure-building quiescence. It may not be too farfetched to suppose that the tendency to become increasingly committed to the known complexity of a "developed" paradigm is a result of man's psychological fittedness for life as an integral member of a climax forest community (*21*).

In any event, the indulgence of this drive works against the interest of the institution as an economic entity, and a good director will seek to disrupt too comfortable an ambience (for example, with nutrient pulses in the form of provocative seminar speakers or by discouraging the creation of divisional boundaries within the institution) and to push in the direction of (ecosystem) immaturity. Evidently, a question of optimum strategy arises, in which the free productivity of immaturity is balanced against a psychological preference for the comfortable complexity of maturity. It may be possible to account for the differences among institutions by referring to how successfully they have solved this dilemma.

Summary

Groups of scholars often behave in ways that are startlingly reminiscent of the behavior of groups of plants and animals in a biological ecosystem. I have tried to show that the parallel may have its basis in two fundamental considerations: (i) the similar properties of stable dissipative structures in a wide variety of contexts and (ii) the mathematical similarity of information to chemical (nutrient) free energy.

A particularly intriguing problem is that of successional trends arising from the kinetic limitation of information flow through the intellectual and social structures created by scholars. The "strategy of ecosystem development" may have implications for the strategy of academic administration. In this connection, it is worth bearing in mind Marglef's dictum (*6*, p. 77): "Probably the hypothesis holds everywhere that the less mature ecosystem feeds the more mature structures around it."

References and Notes

1. D. Barthelme, *City Life* (Bantam, New York, 1971).
2. P. Glansdorff and I. Prigogine, *Thermodynamic Theory of Structure, Stability and Fluctuations* (Wiley, New York, 1971); G. Nicolis, *Adv. Chem. Phys.* **19**, 210 (1971).
3. H. J. Morowitz, *Energy Flow in Biology* (Academic Press, New York, 1968).
4. L. Cremer, *Catgut Acoust. Soc. Newsl.*, No. 18, 13 (1972); *ibid.*, No. 19, 21 (1973); J. Schelleng, *J. Acoust. Soc. Amer.* **53**, 26 (1973).
5. Not all dissipative structures are stable in this way. In particular, an exploding reaction mixture, a flag flapping in the breeze may never reach a state of constant internal parameters such as the temperature and frequency used as examples above. A thorough discussion of the criteria for stability of dissipative structures is given by Glansdorff and Prigogine (*2*).
6. R. Margalef, *Perspectives in Ecological Theory* (Univ. of Chicago Press, Chicago, 1968).
7. E. P. Odum, *Science* **164**, 262 (1969).
8. See W. Calder and J. Booser, *ibid.* **180**, 751 (1973); B. Heinrich and P. Raven, *ibid.* **176**, 597 (1972); B. Heinrich, *J. Comp. Physiol.* **77**, 49 (1972).
9. G. E. Hutchinson, *The Ecological Theater and the Evolutionary Play* (Yale Univ. Press, New Haven, Conn., 1965).
10. L. Brillouin, *Science and Information Theory* (Academic Press, New York, 1962). See also M. Tribus and E. McIrvine, *Sci. Amer.* **225**, 179 (Mar. 1971) and bibliography therein.
11. C. G. Jung, *On the Nature of the Psyche* (Princeton Univ. Press, Princeton, N.J., 1960), pp. 3–66. In this essay, "On psychic energy," Jung attempts a quasi-thermodynamic analysis of "psychic energy," in terms of the first and second laws, by invoking, respectively, conservative and unidirectional processes in the unconscious. It is doubtful that the quantitative rigor for which Jung hoped can emerge from "depth" psychology (or, on the other hand, that behavioral psychology will succeed in quantifying human motivation in any deep sense).
12. T. R. Blackburn, *Schwei. Z. Hydrol.*, in press.
13. The numerical value for information resulting from this equation is dependent on the values chosen for R_i. It is easy to produce infinite information by claiming total ignorance about this range and allowing it to be infinite. However, prior knowledge (for instance, that one is on the surface of the earth and, indeed, on a definite body of water) makes most of that infinite information redundant and spurious. The small uncertainties in I produced by legitimate ignorance of the true geographical and chemical ranges to be encountered do not affect the validity of the argument.
14. P. Morrison, *Rev. Mod. Phys.* **36**, 517 (April 1964).
15. F. D'Itri, *The Environmental Mercury Problem* (Technical Report No. 12, Institute of Water Research, Michigan State University, Ann Arbor, 1971); J.-P. Vernet and R. Thomas, unpublished manuscript, 1972.
16. A citation analysis by J. R. Cole and S. Cole [*Science* **178**, 368 (1972)] makes it clear that, at least in the case of physics, the social structure of information exchange does not parallel the hierarchical intellectual structure. No such parallelism is implied by the model proposed in this article.
17. T. S. Kuhn, *The Structure of Scientific Revolutions* (Univ. of Chicago Press, Chicago, 1962).
18. B. Griffith and N. Mullins, *Science* **177**, 959 (1972).
19. G. Woodwell, *ibid.* **168**, 429 (1970).
20. Griffith and Mullins (*18*) refer to this effect as a "high level of organization." However, it is clear that what is meant is a drastic simplification of structure along a one-bit criterion like that of Ken Kesey's Merry Pranksters: " 'There are going to be times,' says Kesey, 'when we can't wait for somebody. Now, you're either on the bus or off the bus. If you're on the bus, and you get left behind, then you'll find it again. If you're off the bus in the first place—then it won't make a damn.' And nobody had to have it spelled out for them. Everything was becoming allegorical, understood by the group mind, and especially this: 'You're either on the bus . . . or off the bus' " [T. Wolfe, *The Electric Kool-Aid Acid Test* (Farrar, Straus & Giroux, New York, 1968), p. 74].
21. Some such psychological predisposition may account for the literary power of the myth of Arcadia and for the emotional overtones of environmental conservation issues. The Sierra Club's slogan, "Not Man Apart," is, in effect, an appeal for the complexity of a mature ecosystem. The role in scientific thinking of literary and psychological archetypes is a subject that deserves more attention.
22. I thank Dennis L. Meadows and Joan S. Davis for a helpful discussion of candle flames as dissipative structures.