CHAPTER 3

PULSING, POWER AND HIERARCHY

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The models we use to conceive of nature are the means by which we generalize in our quest for understanding. Concepts may succeed if they encompass real data yet are sufficiently aggregated to provide a simpler overview. Systems of nature and humanity are now visualized separately through concepts of kinetics, networks, energetics, statistical variation and entropy. However, these concepts increasingly are being interrelated. Phenomena of different realms of size, which were unrelated earlier, turn out to be special cases of general patterns of nature's hierarchy. In this chapter, computer simulations of energy language models are used to simplify our understanding of process and structure in time and space. This language represents kinetics, energetics and processing of material and information with the same pathways [1-3]. Simulation of basic designs suggests ways that self-organization can maximize energy use to meet conditions for competitive survival.

MAXIMUM POWER PRINCIPLE

The concept that struggle for existence is a struggle for potential energy was expressed by Boltzmann [4], and the survival of systems organized for maximum power was clearly formulated by Lotka [4]. Aspects of maximum power theory have been clarified in energy diagrams by Odum and Pinkerton [5] and Odum [1, 6, 7]. In short, the designs that prevail in self-organizing systems are those that maximize useful power. Useful power is power that feeds back to amplify. It implies autocatalytic organization in which energy transformations associated with gaining power feed back amplifier actions to further accelerate flow of energy of the same or different source. Or, where further acquisition of energy is not possible, existing budgets of energy feed back to maximize efficiencies through diversity, division of labor, prevention of losses, improvement of recycling, etc.

Equations for a Flow-Limited Source

Most energy sources are flows that are limited by their nature and that cannot be increased by the user system. Maximizing power use requires pumping demand from source flows. Although given earlier [8, 9], the energy diagram and the equations for source-limited flows may need some explanation, as given in Figure 1. A demand on the inflow is being made by pumping interaction from storage, Q. If there is an appreciable storage of the inflow at its point of use, it may be represented as Figure 1a; the arrangement is a limiting factor configuration of the Monod type.

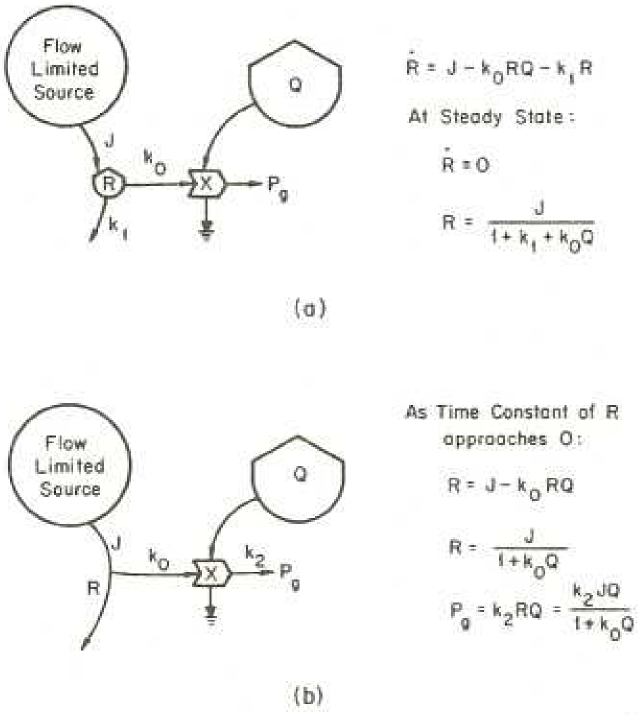


Figure 1. Configuration and equations for power use of an externally limited flow source: (a) Monod type limitation; (b) same, with very small time constant of storage at point of use.

If, however, the inflow material has a very tiny time constant relative to the user system, as with sunlight, then configuration in Figure 1b is appropriate. It may be visualized as the arrangement in Figure 1a as the time constant of R approaches zero. The equation is almost the same as the steady state of the system in Figure 1a. Use of this function for light limitation may be more natural than use of exponential attenuation functions.

Threshold for Autocatalytic Pumping

Figure 2 shows three designs for utilizing an available energy flow that is flow limited at its source. The design that prevails is determined by the quantity of the energy flowing from the source. The control of design by energy can be demonstrated by simulation or shown analytically. At low levels, the depreciation of the autocatalytic unit is greater than the energy required to maintain the storage. The flow is a linear diffusion of energy into degraded state. At higher energy levels, the autocatalytic system takes over and outcompetes passive pathways. At even higher energy levels, quadratic feedbacks become dominant in competition. There may be a general principle that the higher the level of energy, the higher the mathematical power of autocatalysis. Note also that the design that drives out ones previously dominant is one that draws and uses more power (Figure 2).

Minimum Power Principle

The concept of systems trending toward a minimum rate of generation of entropy was proposed by Prigogine and Wiame [10]. This is tantamount to a principle of minimum power. It states that systems trend toward the minimum rate of power use. This was regarded for twenty years as a theory contrary to the theory of maximum power. An example would be a closed system running down as its potential storage is used, or an open system in which a steady state is disturbed by a displacement. A displacement is an added storage that contributes to power until the displacement storage is used up, with the system then returning to its steady pattern. In these examples, power declines because the available energy to the system declines. They do utilize the maximum power available and so are not exceptions to the maximum power principle, even though power use declines [11].

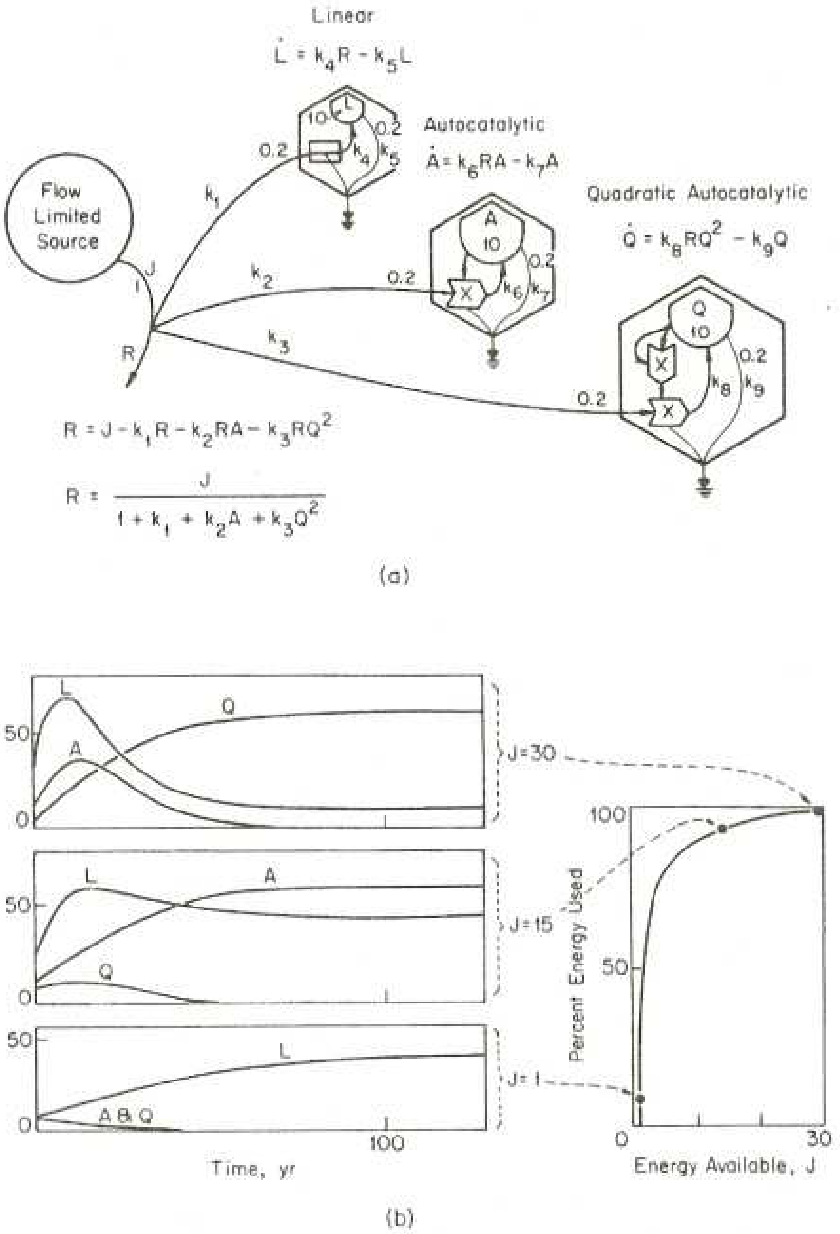


Figure 2. Effect of varying available power on designs that compete successfully for maximum power: (a) energy diagram and equations; (b) simulations of storage assets with increasing power availability.

The difference between the concepts of minimum power and maximum power is illustrated by the simulation in Figure 2. In Figure 2a, with low energy available and the source flow not far from equilibrium, energy degrades with a linear process and autocatalytic processes die out. A high percentage of available power goes unused. With more energy availability, autocatalytic processes prevail that feed back pumping action to draw more power.

Consensus on Maximum Power

In recent summaries, Nicolis and Prigogine [12], and Prigogine [13, 14] have restricted their view of the utility of the minimum entropy concept to situations of low energy, i.e., "near equilibrium." Energy disperses with linear processes like diffusion and laminar flow. Autocatalytic processes are described as patterns emerging with higher energy levels, as in Figures 2b and 2c. If autocatalytic growth prevails, this is maximization of useful power. Apparently, consensus is developing on the generality of the maximum power principle and the kinetic designs that result.

FEATURES OF SELF-ORGANIZATION THAT MAXIMIZE POWER

Odum [7] has presented corollaries of the maximum power principle that suggested system patterns favoring power utilization. Here, several features of ecosystems are simulated in minimodel form to study their role in maximizing power as follows: (1) parallel arrangement of pathway types; (2) hierarchical chain structure with recycling; (3) multiplication of high- and low-quality energy flows; and (4) pulsing control from high-quality sources.

Pathway Competition for Maximum Power

The increasing role of autocatalysis with increasing power availability observed for three competing designs in Figure 2 also is found in Figure 3 in a single system with three parallel pathways contributing to a common storage and depreciation drain. As in Figure 2, the linear pathway prevails at very low energy flow; the autocatalytic pathway at intermediate levels of energy availability; and the quadratic autocatalytic pumping at higher energy levels. In real systems, the variability of seeding may keep the various kinds of pathways available to pull jointly for maximum power. Although the pathways compete, the ultimate effect is self-organizing toward maximum power.

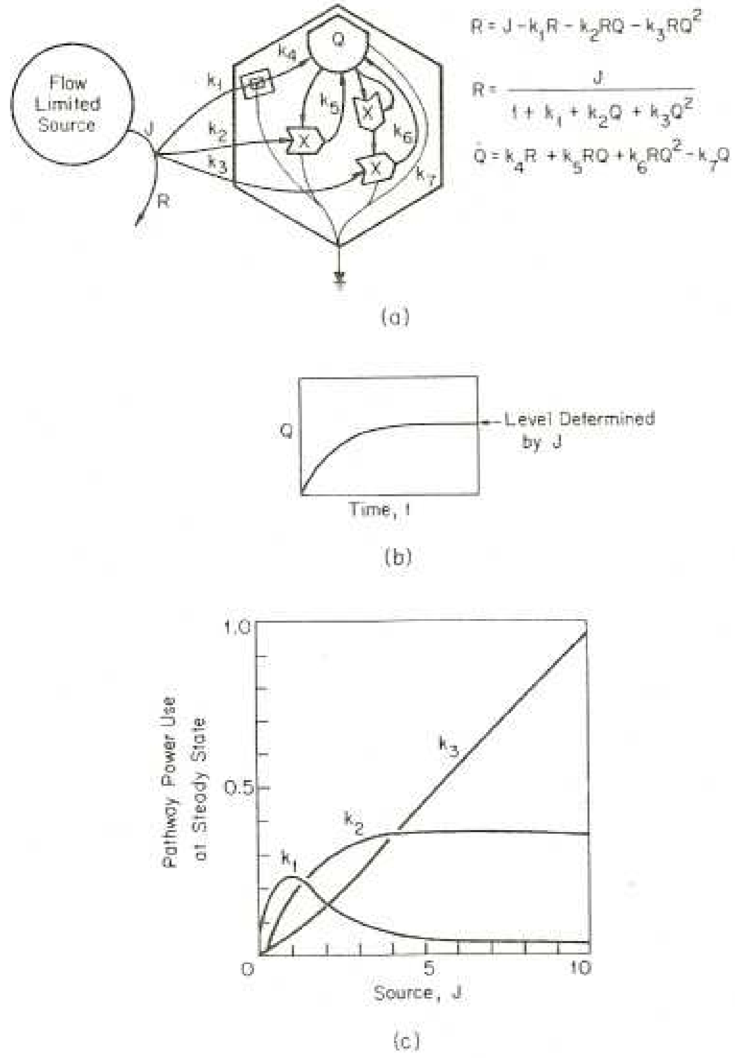


Figure 3. Parallel pathways for use of a source-limited energy source: (a) energy diagram and equations; (b) typical growth curve of storage; (c) energy flow in component pathways.

Hierarchy of Energy Convergence Chains

The output of successive energy transformations must be fed back as a reward loop if a chain (Figure 4) is to compete with alternatives. Therefore the small energy of surviving transformations must be of higher value in the sense of being able to amplify when it interacts as a feedback. For the energy to develop higher quality, it often requires concentration during transformation. However, the feedback must interact with the more dilute energy flows it must amplify over the broad area to which these energies are flowing. Therefore, the feedbacks diverge from the focal centers. Thus, the designs that tend to survive by generating more power are hierarchical, with spatial convergence and divergence (Figure 4c).

Recycle of Matter

Chains and webs, if supplied with feedback loops (Figure 5), also process matter in circular patterns, which helps to maximize energy utilization. These materials converge during their incorporation into storages away from equilibrium and diverge in their return to unused state at equilibrium.

Length of Chains Dependent on Energy Level

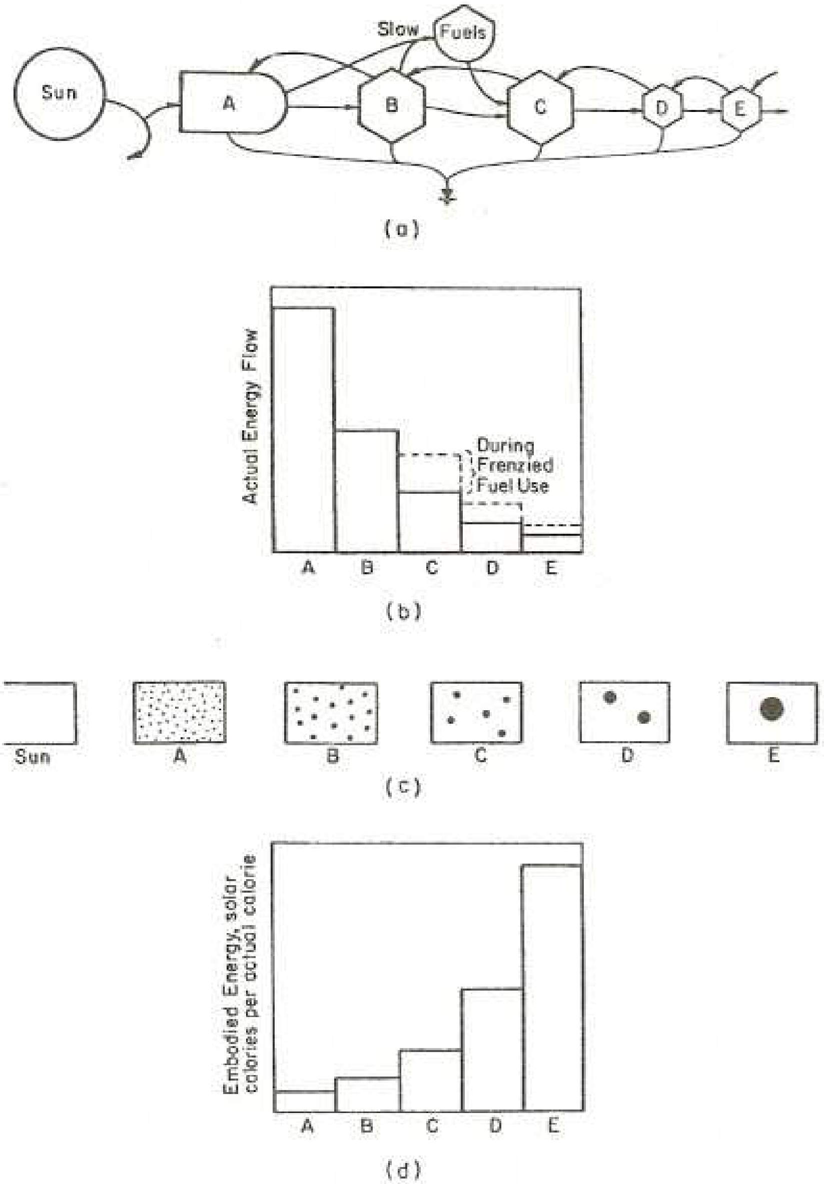
The larger the sources of energy, the longer the chains that may be supported. For the same quality of energy, larger quantities may mean a larger realm of area. With a larger area, more energy may be converged and more successive transformations may be supported (Figure 5). The simulation that is graphed as a function of available energy shows increasing stocks maintained at the right-hand end of the energy chain (C and F).

Producers and Consumers

In any chain of systems in which one is related to the other hierarchically, one unit may be regarded as the producer that converges energy and materials and transforms them into storages for use by the next system unit. The next unit is called a consumer, although it may have production processes as part of its own energy use and transformations. To stimulate production, its higher-quality outputs feed back as control and available scarce materials. Production-consumption models already are recognized by this name in ecology and economics, but exist also in chemistry, geology and possibly in all systems. The pattern is to be expected for any two or more steps in a hierarchy.

Models of Producer-Consumer Pulsing

Sharp oscillations are a property of many producer-consumer hierarchies and of the models being developed to explain them. The classic Lotka-Volterra prey-predator oscillator lacks energy or material constraints



gure 4. Hierarchical relationships of chains of energy transformation: (a) energy diagram of chain with a low- and a high-quality source; (b) decrease in actual energy flow with each transformation step; (c) increasing size of units and of territory per unit with each energy transformation step; (d) increase in energy transformation ratio with successive steps where ratios are expressed in embodied energy of the first type.

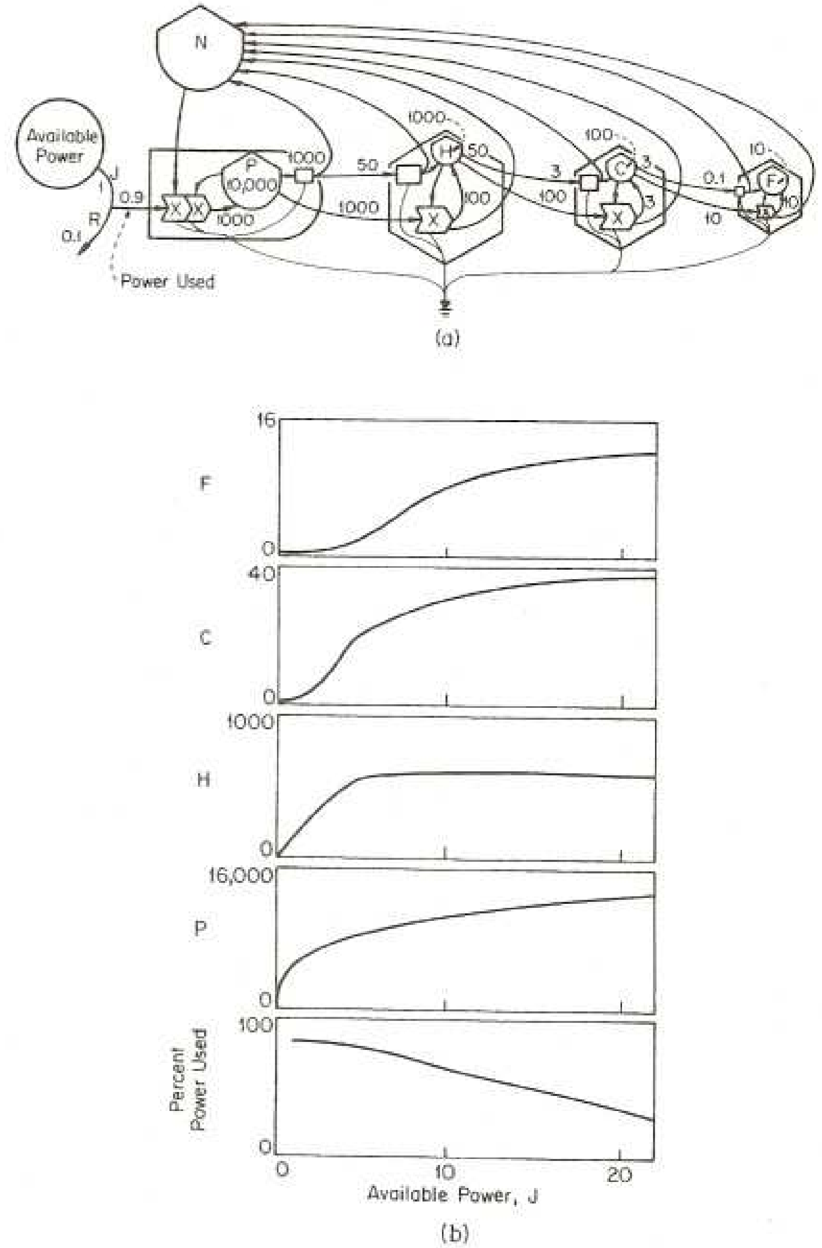


Figure 5. Effect of increasing power on the length of hierarchical energy chains: (a) energy diagram and equations; (b) graph of storages for various levels of available energy inflow.

Instead, it is dependent on initial conditions but is still used in textbooks to introduce oscillations because of its simplicity. Odum and Odum [3] have provided two models of pulsing epidemics in which frequency was related to energy level (Figure 6). Ludwig et al. [15] have provided models of spruce-budworm pulses, as given in Figure 7. When the single-state equations are combined, a higher-order equation for a surface results. This surface has folds and catastrophe points such as those described by Thom [16]. Representing pulsing models with surfaces is an alternative method of analysis.

Many empirical studies find ecosystems that have long periods of gradual buildup of the production products followed by sudden pulsed consumption and recycle. Fire climax ecosystems alternate growth and fire. Wiegert [17] found hot springs building up algal mats, which then broke off and restarted the cycle. His simulation model oscillated under some conditions.

Producer-consumer oscillations, such as the Kondratief and inventory storage cycles, have been described for economic systems [18]. Bormann and Likens [19] found evidence of waves of forest growth and consumption in New England. Dubois [20], O'Brien and Wroblewski [21], and Platt and Denman [22] found oscillatory models of plankton growth and outward dispersal of products in the sea, which were variations on Kierstead and Slobodkin's [23] model of red tide.

Using producer-consumer models for environmental catastrophes, Alexander [24] discovered pulsing properties of the model (Figure 8). He applied this to earthquakes and floods, patterns in which energies build up storages slowly and then discharge in frenzied autocatalytic surge, recycling materials and returning the system to start.

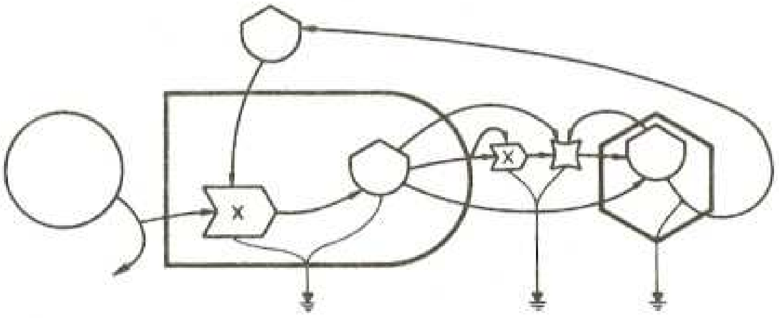
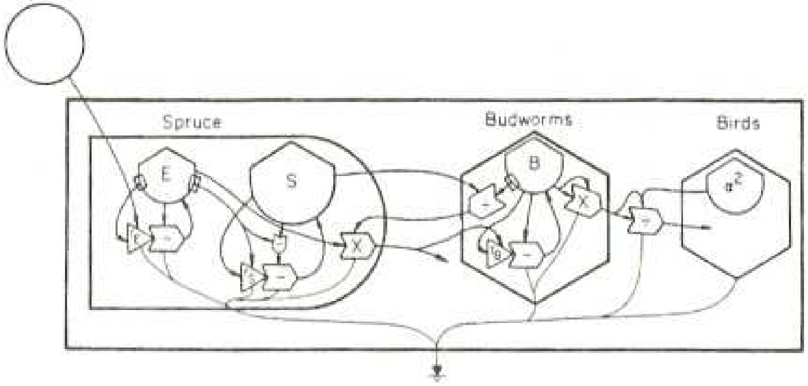


Figure 6. Threshold-controlled consumer epidemic model [3].

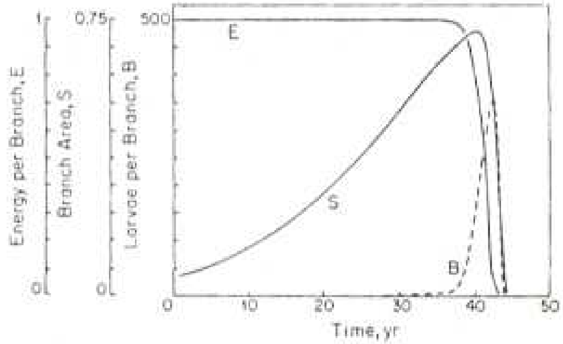


(a)

$$E = r_E E\left[1 - \frac{E}{K_E}\right] - P\frac{B}{S}$$

$$\dot{S} = r_S S\left[1 - \frac{S}{K_S} \times \frac{K_E}{E}\right]$$

$$\dot{B} = r_B B\left[1 - \frac{B}{K_B}\right] - \beta\left[\frac{B^2}{\alpha^2 + B^2}\right]$$



(b)

Figure 7. Model of spruce-budworm epidemics by [15]: (a) differential equations and energy diagram translation; (b) simulation.

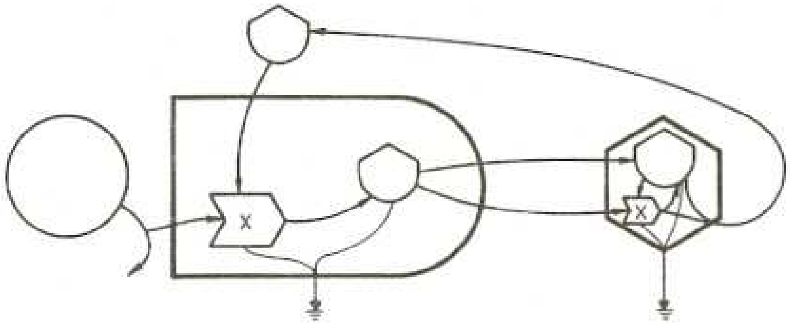


Figure 8. Model of catastrophic frenzy [24].

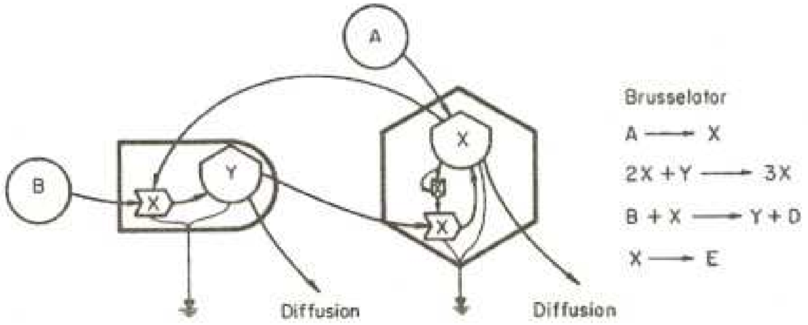


Figure 9. Brusselator chemical oscillator reaction [12].

Nicolis and Prigogine [12] studied a chemical reaction that has properties of oscillation and structure building in spatial manifestation (Figure 9). (Note the similarity in comparing Figures 8 and 9.)

A variation of the Alexander model was simulated with quadratic autocatalytic feedback. The result is shown in Figure 10 [25]. It was calibrated with data for carbon in biomass, both in soils and wood of the landscape. Minor changes in the efficiency of transferring organic matter to consumer changes the period between pulses. The longer the time between pulses, the larger the amplitude of pulse.

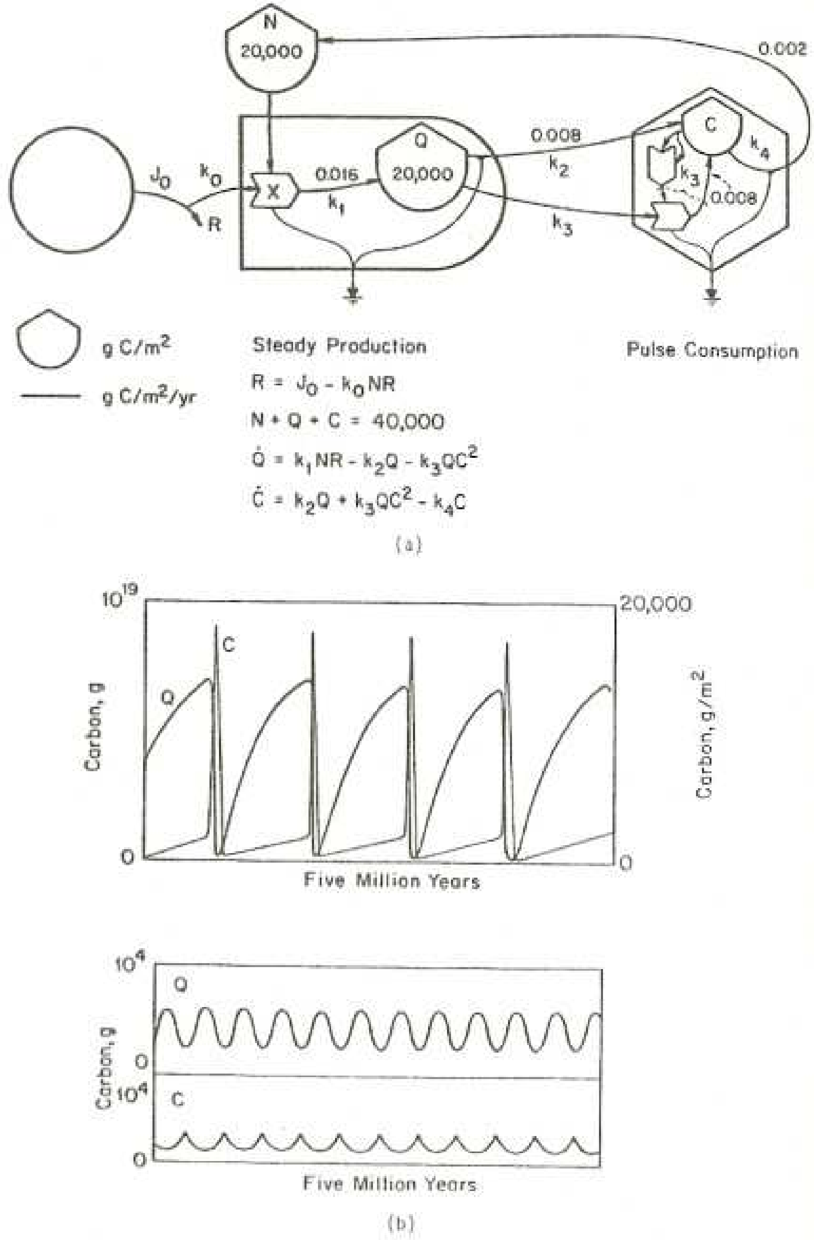


Figure 10. Pulsing model of production and consumption of earth biomass [25]: (a) energy diagram and equations; (b) simulation.

Pulsing and Maximum Power

The presence of pulsing in real-world producer-consumer systems raises these questions:

1. When does pulsing maximize power utilization?
2. What conditions favor organizational designs that pulse?
3. Under what conditions do self-organized systems pulse with internal oscillations?
4. Given external inputs that pulse, does self-organization utilize the external pulses for maximum power in place of self-generated ones?

While studying chemical engineering systems with nonlinear processes, Rinaldi [26] found more production with pulsing operations than with steady-state operations. Richardson and Odum [27] found maximum power with pulsing while studying a hierarchical model of production and consumption with recycle. The model was similar to that in Figure 10, except that the producer had autocatalytic production. The characteristic simulation regime had a long interpulse period with a very sharp pulse by the consumer unit, utilization storages and recycling materials ready for the longer period of production again.

Albedo for Evaluating Solar Power Use

As diagrammed in Figure 11, such source-limited flows of energy as solar insolation will pass out unused if not incorporated into production processes. Thus, the unused energy is an easy way to estimate relative ability of a system to maximize power use. For example, reading the albedo is an easy way to estimate total production. However, production includes meteorological and geological production, as well as biological production. Over the oceans, meteorological production of potential energy in air masses and waves predominates. Over the deserts, geological production of canyons, weathered rocks, isostatic uplift and exposed minerals predominates. Over humid regions, biological production of vegetation predominates. One may think of the desert as unproductive because the terrestrial albedo is high, perhaps 30%; however, the cloud albedo over the desert is small. Over the sea and over humid landscape the terrestrial albedo is small, perhaps 1-12%, but the cloud albedo is large. Hence, the regions are not as different in their conversion of solar energy to earth work as they might seem at first.

As the albedo model in Figure 11 suggests, there is an optimum in the supply of water to terrestrial regions that maximizes the power of biological production. Too much water increases cloud albedo; too little water decreases vegetation capacity to accept insolation. For evaluating the power utilization of models, the energy used–quantity (J-A) in Figure 11–is integrated over time.

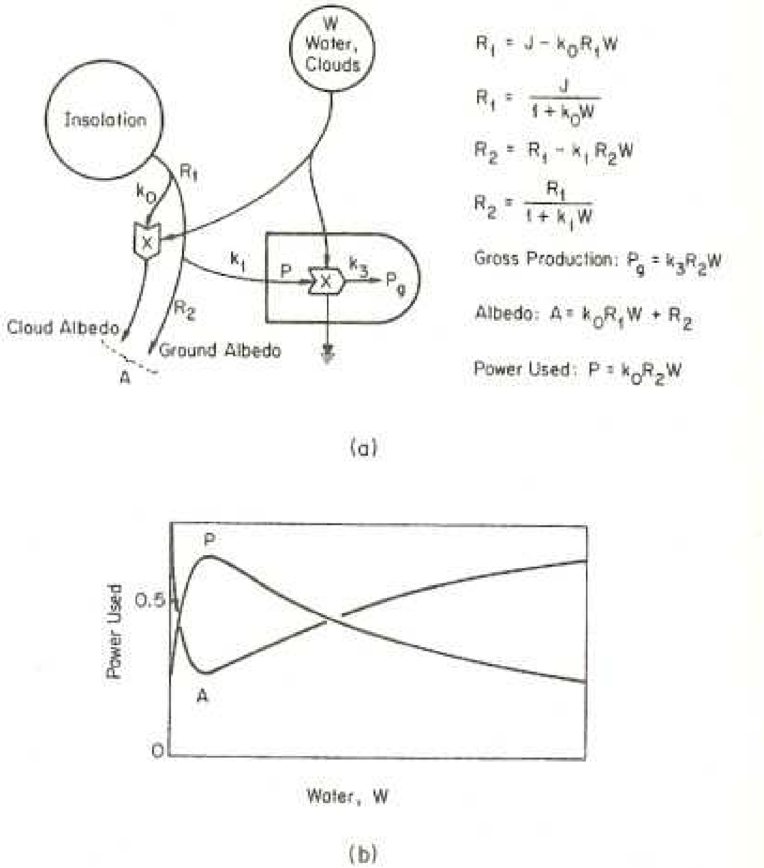
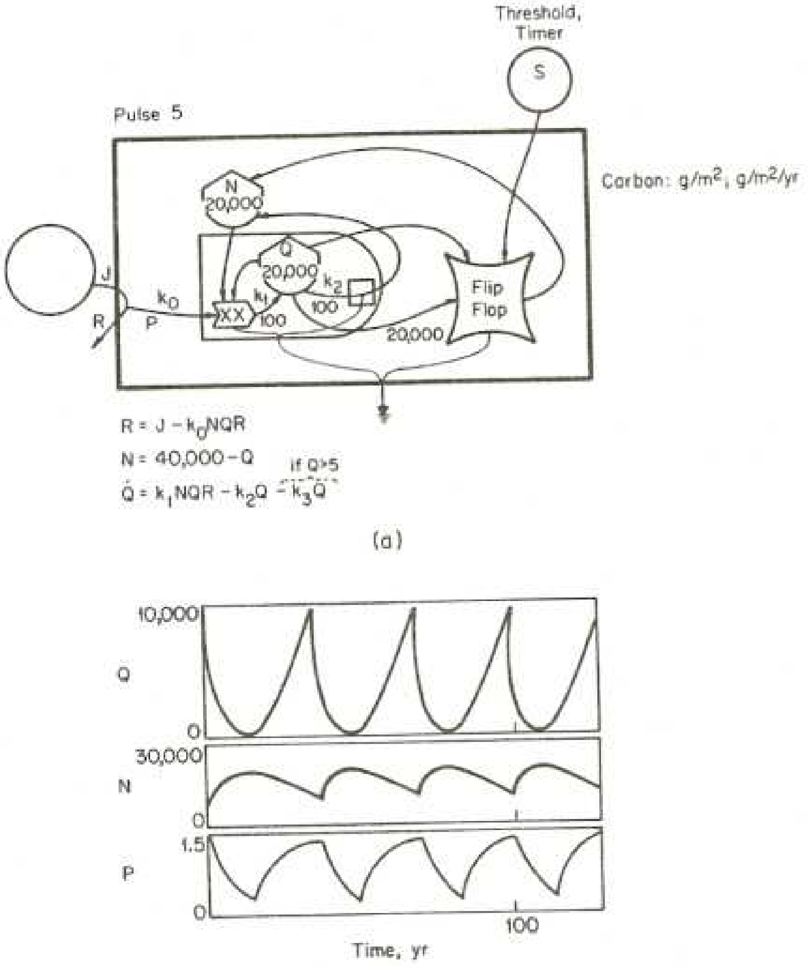


Figure 11. Relationship of albedo to the quantity of clouds: (a) energy diagram and equations; (b) simulation of model in (a) showing an optimal concentration of water and clouds for maximum production.

Frequency and Maximum Power in a Pulse Recycle Minimodel

Whereas the models in Figures 6–10 generate their own pulse as a function of internal properties, the minimodel in Figure 12 has an



$$R = J - k_0NQR$$
$$N = 40{,}000 - Q$$
$$\dot{Q} = k_1NQR - k_2Q \overset{\text{if } Q>5}{- k_3\dot{Q}}$$

(a)

(b)

Figure 12. Model of production with threshold control of pulsing recycle. (a) energy diagram and equations; (b) typical simulation curve.

external threshold control of pulsing. Thus, the frequency of pulsing may be varied to study the effect on power utilized. Raising the available energy or lowering the total amount of recycling materials causes production and power utilization to drop as the materials quickly become limiting. Under these circumstances, more rapid pulsing increases power by keeping materials recycling well.

However, if pulsing is so frequent that the stock of producers does not build up its autocatalytic feedbacks high enough to pump in available power, the power used is less than the maximum. If the pulsing consumer pulls the stocks too low during its frenzied pulse of consumption, too long a period passes before production begins to utilize much of the available energy. Oscillations with this pattern use less energy than is possible for the consumer's survival.

In other words, there is an optimum frequency and pulse duration for maximum power utilization where only production, consumption and recycle properties are considered. For some conditions, no pulsing maximizes power. Real systems have other kinds of feedbacks, several kinds of sources and other properties that are yet to be related.

Alternation of Production and Consumption

Pulsing of consumption and recycle apparently is a common property of systems. The minimodels help us understand why alternation of P and R may maximize power in many circumstances. Quick recycle minimizes the time that the productive functions are interrupted. It also maximizes power in the frenzied subsystem relative to competitive alternatives.

Since the earth has inherent diurnal and seasonal variations in sunlight, systems may develop with the properties that make the input frequencies the ones that maximize power.

Size of Units and Realms, and Time of Pulsing

As illustrated in Figure 4, larger units require larger energy realms and feedbacks to a larger territory. Larger units also have larger time constants for their replacement. Studies of space and time in the sea, which have been summarized by Platt and Denman [22] and Steele [28] show populations with longer periods of turnover occupying larger spaces. Similar patterns are found in other aspects of the earth and stars. Larger realms of size have pulses of larger dimension but of longer period between pulses. Minimodels of the class of Figures 6–10 can be used for any range of size and time. If scaled with larger time constants, there is a lower actual power flow through downstream high-quality units.

Embodied Energy and Energy Transformation Ratio

If energies of different types are related to each other by energy transformation processes in which potential energy is dispersed as necessary tax for the conversion, then a hierarchy of energy types exists, each related to the next by the energy required for the transformation (Figure 4).

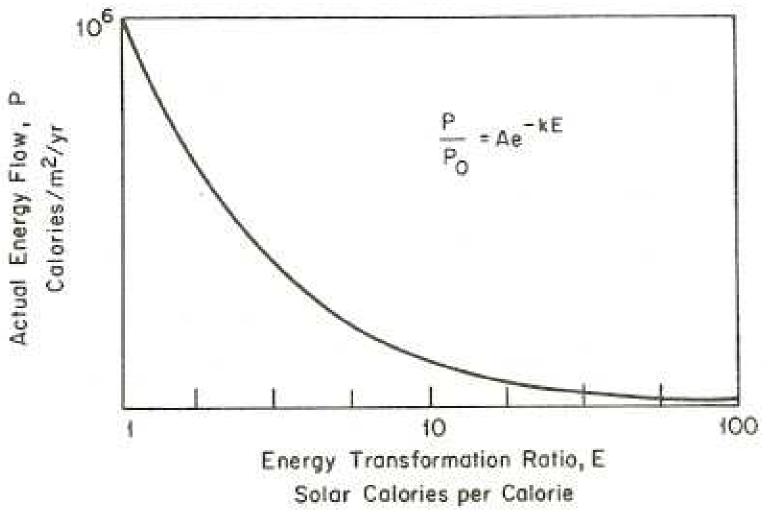


Figure 13. Generalized spectral graph of energy transformation chains.

The energy of one type required for the next is the *energy transformation ratio*. The energy of one type used to generate energy to other types is the embodied energy of the first type inherent in the others. Since the energy transformation ratio measures the position in the energy hierarchy, it may be correlated with size of realm and time of pulsing (Figure 13).

Control

As in Figure 2, competition for power favors those designs with properties of feedback amplification. It may be postulated [29] that energy-amplifier effects are selected to be proportional to embodied energy. After transformation, the high-quality energy achieves an effect commensurate with energy converged into it by feeding action back as an amplifier to interact with a larger quantity of low-quality energy. High-quality external sources may control smaller systems if the sources develop concentrated, high-quality interactions with the systems' productive processes.

One aspect of the control of high quality is the longer period (low frequency) of the higher-quality pulses, which, when amplified, cause the whole system to pulse. (For example, see the pulsing models of Brown [30] and Limburg [31].) They found that high-quality energies from outside cause dominating units to develop in the web on either side of the point of entry of the energies.

One reason why pulsing feedbacks of the right form presumably maximize power is because they deliver more energy in a shorter time. Thus, they prevail as controlling elements over those with less delivery of concentrated energy.

An interesting question is whether high-quality energy can be transported more readily. As part of a larger unit with larger territory to cover, high-quality transport may be characteristic. More embodied energy may be transmitted in higher-quality form than in lower-quality form. However, the high-quality energy after transport requires the low-quality energy to match and interact to achieve an output like the original flow of low-quality energy.

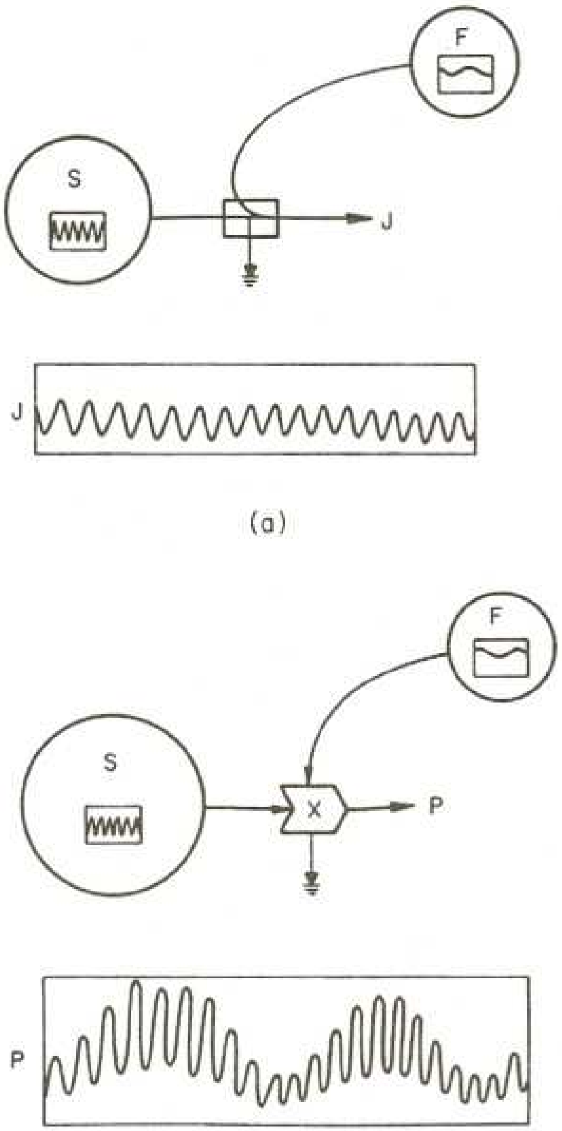
Combination of High- and Low-Quality Pulses

If the aforementioned concepts of pulsing are general for various size realms of natural hierarchies, then observed patterns with time are the result of the interactions of pulses of many sizes and frequencies. Collectively, the small fast pulses interacting with slow, larger pulses generate a time series with the kind of variation often regarded as random, in the sense of indeterminately variable. Yet each size realm has its own size and time dimension for which its feedback pulses are dynamic. Hypotheses of statistical randomness may not be necessary, although traditional statistical measures of variation still may be useful for many purposes.

As shown in Figure 14, summation of small energies of feedback with larger input energies is much less than multiplicative interaction of the two.

Linear Time Series Separations

The Fourier time series analyses, now in general use for analysis of records with variations of various frequencies, are one way of separating out the contributions from various size and time realms. Generally, amplitudes are correlated with period in graphs generated with Fourier analysis. However, these procedures subtract out oscillations of different frequencies as if the complex observed record were produced by linear additions. The theory that high-quality energies feed their pulses back as amplifiers in multiplicative interactions (as in Figure 4) implies nonlinear synthesis.



(a)

(b)

Figure 14. Patterns resulting from combination of high-quality, long-period, small-magnitude feedback pulses with a larger quantity of lower-quality, high-frequency input energies: (a) combination by addition; (b) combination by multiplication.

Subdivision and Exponential Distributions

If energy is transformed and divided successively to transform some small constant percentage at each stage, an exponential distribution results. Thus, energy distribution graphs tend to be exponential in the zone of energy upgrading. On the other side of the energy distribution graph, where inflowing energy is being degraded by depreciation, there also may be a successive, stepwise exponential reduction of the energy. In turbulence, this latter zone of the energy spectrum is the Kolmogoroff range.

Whereas these successive subdivisions are expressions of energy principles, there are other ways to carry out successive subdivisions mathematically that will yield exponential distributions without correct energy significance.

Mandelbrot [32] develops fantastic geometric patterns by successive division. Large units branch into small ones with a fixed percentage per stage of division. The result is a hierarchy, except one generated from the high-quality concentrated energy working down to the smaller component units. By contrast, the energy flows in a simple food chain usually are visualized as moving from the dispersed small units to the concentrated higher-quality units. Actually, either is correct. (Figure 4 shows source energy moving both ways.)

Generalized Spectral Graph

Since embodied energy and energy transformation ratio are measures of hierarchical structure, a generalized energy spectral-hierarchical diagram can be drawn in which the abscissa is the energy transformation ratio. (This refers to one type of energy, such as solar insolation.) The ordinate is the actual energy. The product of the two is total embodied solar energy available to the system.

Characteristic Shapes

The distribution of energy flows or storages on the generalized spectral graph is skewed with an exponential tail if the energy is supplied only from the low-quality end. By its successive transformations, the low-quality energy generates the declining quantity and increasing quality of energies of the hierarchy, as in the chain models (Figure 13). The spectral graph is exponential if the system is in equilibrium with energy distributed between low- and high-energy states according to the percentage of one required to maintain that of the other.

Ecological Examples of Energy Hierarchy Spectra

A number of the graphic representations of ecological phenomena are accounted for with energy hierarchy concepts. Age distribution graphs that have many young units that gradually are being transformed into a few older units are examples of hierarchy of energy transformations and convergence. The embodied energy of the older units is that used by the populations of younger ones in developing the older ones.

Rank-order graphs have many individuals of common species supporting fewer members of rarer species. The most valuable may be the rare species held in contingency for the future to be available for seed recovery after a catastrophic pulse in a larger system. Many models have been made to account for the shape of rank order curves [32].

If random divisions of a realm of space are made successively, an exponential distribution results. An example is the broken stick model for random dividing and ranking ecological niche space [33, 34]. However, the same graph may be derived from a web of energy transformations. Here is an example of a random model giving the same result as a deterministic energy theory. Energy chains are successive divisions of actual energy resource accompanied by successive upgrading of embodied energy and predicted value.

Money and Energy Quality

The role of money and free market prices seems to be to help maximize power by providing a flexible means for shunting resources to eliminate bottlenecks and to maintain closed-reward loops that maximize power. The ratio of dollars to actual energy is highest at the top of the energy quality hierarchy, being low or zero in lower-quality zones where the external energy base of an economy actually starts.

Whereas value often is regarded as determined by human preference, social groups ultimately may determine the norms of their values by what has been working and, thus, what is maximizing power. Therefore, embodied energy may predict economic value.

Order and Disorder

Words of verbal language often refer to a class of related concepts, which is part of their usefulness. When the word order is used in relation to structure it has two implications: (1) ordered, meaning simple as with molecules in rows requiring only a few bits of information for description, that is, entropy of state is low; and (2) ordered, meaning valuable structure that has required energy transformations to develop and that may depreciate. Complex structure often is made up of pieces that are simple internally, that is, entropy is large, and there is a large entropy change from equilibrium.

To reduce complex structure to a neater, simpler type of order is a gain of order in the first sense and a loss in the second sense. Cutting a natural forest and planting rows of corn is a loss of valuable structure. Thus, the words order and disorder are semantically useless for representing whether there is more or less useful structure, in situations in which use is related to functions for survival.

Oscillations as Order

In studying chemical reactions that develop banding patterns, Prigogine [14] and Haken [35] identified oscillators as devices that develop order in the sense of regularity. Pulsing in time and space are related in this way. Autocatalytic processes may develop bifurcations with more than one state. Prigogine regards some complex high-energy states as chaotic.

HIERARCHY AS A TOOL FOR INDUCTION

If every system is a part of larger ones, then every system is subject to pulsing control by the larger realms. The time of pulsing is a function of the size, and the frequency with which the larger system pulses the smaller one is predictable. Therefore, the outside pulsing of the larger systems, to which the smaller system may ultimately develop adaptations, is predictable. The smaller system may carry with it the information and maintain units that are not needed until a large external pulse arrives, requiring restoration to interpulse realm.

Models should include outside driving functions and internal adaptive structures for infrequent large pulses from the larger realms, as well as the smaller pulses whose time and space dimensions are those of the system under study.

Conventions Suggested for Diagramming

For energy network diagrams to represent hierarchical structure so that positions of units can become standardized in a natural way, and to minimize the pathway "spaghetti," the convention is suggested that energy sources be positioned in order of their energy quality. This is illustrated in Figure 15. Also, components are drawn inside with items of small unit size, high pulsing frequency and low embodied energy on the left, and items of high embodied energy, larger territorial realm and longer periods of pulsing on the right. This automatically reduces crossing of lines; causes diagrams by different persons to have same items in similar positions; and translates hierarchical information on paper as part of portrayals of models. High-quality feedbacks should be drawn upward and counterclockwise, connecting with the low-quality energy with which they interact.

In Figure 15, sources to the left have higher frequencies of pulsing than the largest component within the system. To the right, sources have larger realm and a longer period of pulsing than those within.

Universal Model

One way to deal with hierarchy of models is to use the same model, but change the time scale as a function of size. For the viewpoint of a system of a particular size, the pulses of the component lower-quality members appear as noise, whereas the pulses of the larger system of which it is part appear as catastrophes, seemingly capricious because the period without pulse is longer than any regularity within the system.

Since size, frequency of pulsing and embodied energy are related graphically, one may be estimated from the other. A general model with several levels of hierarchy should have a driving function with long period that represents the next larger system. The general form of the model should tend to be general for all systems, with the exception that the actual time represented will be different for molecules than for ecosystems.

THE PULSING OF HUMANITY AND THE EARTH SYSTEMS

Within the patterns of humanity are many levels of hierarchy. The ones of largest size and longest time period are those of culture, knowledge and civilization. They have much longer time periods than those to which individual humans contribute. Some of the earth systems are similar, such as earthquakes and volcanic action. Many of the earth systems have even larger dimensions of space and time, such as the ice ages and the oscillations in sedimentary cycles. By taking over the energy transformations of the earth systems in part, humans have increased their own position in the earth's hierarchy. Their endeavors now operate at a longer period with more control and with a larger area of coverage.

Most intriguing is the possibility that following a long productive period, power is now being maximized by humanity as a pulse by consuming drastically, which is the action necessary to prepare the system for slow growth again. The excessive consumption habits that might seem ill

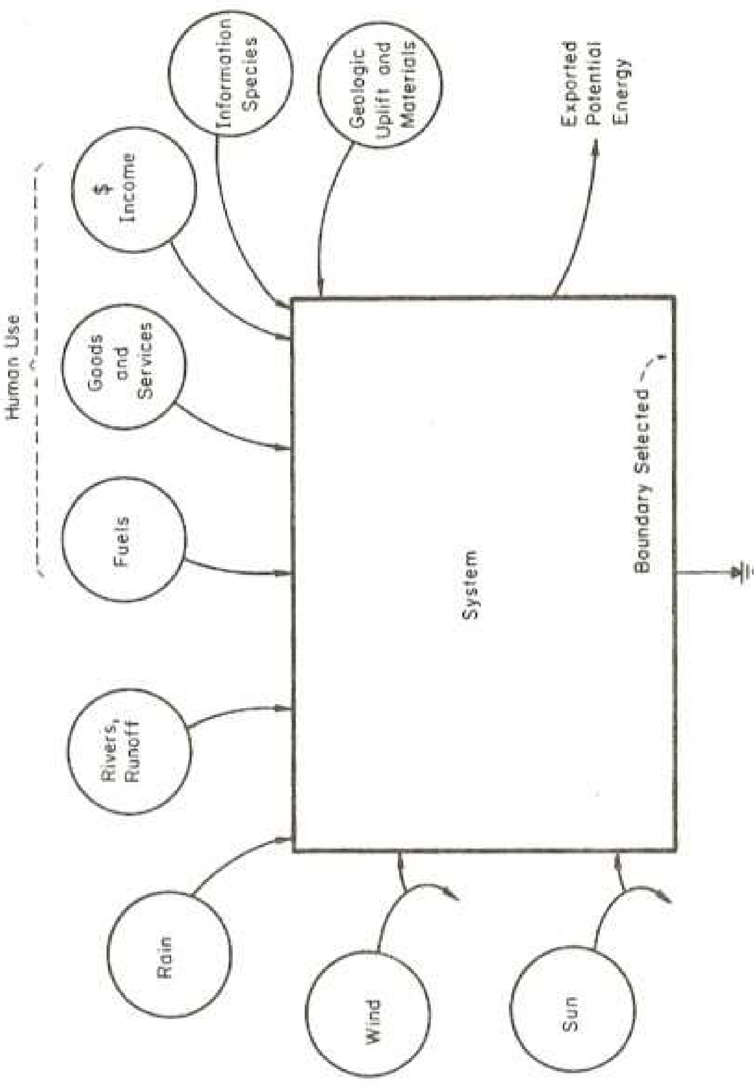


Figure 15. Conventions for diagramming, with energy quality increasing from left to right.

adapted to a period of declining energy may very well be the correct ones for proper service to the biosphere in better recycling, returning it quickly to a time of reconstruction.

REFERENCES

1. Odum, H. T. *Environment, Power and Society* (New York: John Wiley & Sons, Inc., 1971).
2. Odum, H. T. "An Energy Circuit Language for Ecological and Social Systems: Its Physical Basis," in *Systems Analysis and Simulation in Ecology, Vol. 2*, B. Patten, Ed. (New York: Academic Press, Inc., 1972), pp. 139-211.
3. Odum, H. T., and E. C. Odum. *Energy Basis for Man and Nature*, 2nd ed. (New York: McGraw-Hill Book Co., 1981).
4. Lotka, A. J. "Natural Selection as a Physical Principle," *Proc. Nat. Acad. Sci. U.S.* 8:151-154 (1922).
5. Odum, H. T., and R. C. Pinkerton. "Time's Speed Regulator: The Optimum Efficiency for Maximum Power Output in Physical and Biological Systems," *Am. Scientist* 43:331-343 (1955).
6. Odum, H. T. "Biological Circuits and the Marine Systems of Texas," in *Pollution and Marine Ecology*, T. A. Olson and F. J. Burgess, Eds. (New York: Wiley-Interscience, 1967), pp. 99-157.
7. Odum, H. T. "Combining Energy Laws and Corollaries of the Maximum Power Principle with Visual Systems Mathematics," in *Ecosystems Analysis and Prediction* (Philadelphia: SIAM Institute for Mathematics and Society, 1975), pp. 239-263.
8. Odum, H. T. "Chemical Cycles with Energy Circuit Models," in *Changing Chemistry of the Oceans, Nobel Symposium No. 20*, D. Dyrssen and D. Jagner, Eds. (New York: John Wiley & Sons, Inc., 1972), pp. 223-259.
9. Odum, H. T. "Macroscopic Minimodels for Balance of Man and Nature," in *Systems Analysis and Simulation in Ecology, Vol. IV*, B. Patten, Ed. (New York: Academic Press, Inc., 1976).
10. Prigogine, I., and J. M. Wiame. "Biologie et Thermodynamique des Phénomènes Irréversibles," *Experientia* 2:451-453 (1946).
11. Sugita, M. "Thermodynamical Analysis of Life. II. On the Maximum Principle of Transient Phenomena," *Phys. Soc. Japan* 8:704-709 (1953).
12. Nicolis, G., and I. Prigogine. *Self Organization in Non-Equilibrium Systems* (New York: John Wiley & Sons, Inc., 1977).
13. Prigogine, I. "Time Structure and Fluctuations," *Science* 201:777-785 (1978).
14. Prigogine, I. *From Being to Becoming* (San Francisco: W. H. Freeman & Company Publishers, 1980).
15. Ludwig, D., D. D. Jones and C. S. Holling. "Quantitative Analysis of Insect Outbreak Systems: The Spruce Budworm and Forest," *J. Animal Ecol.* 47:315-332 (1978).
16. Thom, R. *Structural Stability and Morphogenesis* (Menlo Park, CA: W. A. Benjamin, Inc., 1975).
17. Wiegert, R. G. "Simulation Modeling of the Algal-Fly Components of a Thermal Ecosystem," in *Systems Analysis and Simulation in Ecology, Vol. III*, B. C. Patten, Ed. (New York: Academic Press, Inc., 1975), pp. 157-181.
18. Forrester, J. W. "Business Structure, Economic Cycles and National Policy," *Future*, London (June 1976).
19. Bormann, F. H., and G. Likens. "Catastrophic Disturbance and the Steady State in Northern Hardwood Forests," *Am. Scientist* 67:660-669 (1979).
20. Dubois, D. M. "A Model of Patchiness for Prey-Predator Plankton Populations," *Ecol. Modelling* 1:67-80 (1975).
21. Wroblewski, J. S., and J. J. O'Brien. "A Spatial Model of Phytoplankton Patchiness," *Mar. Biol.* 35:161-175 (1976).
22. Platt, T., and K. L. Denman. "Spectral Analysis in Ecology," *Ann. Rev. Ecol. Systematics* 6:189-210 (1975).
23. Kierstead, H., and L. B. Slobodkin. "The Size of Water Masses Containing Plankton Blooms," *J. Mar. Res.* 12(11):141-147 (1953).
24. Alexander, J. F., Jr. "Energy Basis of Disasters and the Cycles of Order and Disorder," Ph.D. Thesis, University of Florida, Gainesville, FL (1978).
25. Odum, H. T. "Pulsing and Maximum Power," in *Proc. International Environmental Conference*, Paris (1980).
26. Rinaldi, S. "High Frequency Optimal Periodic Communities," in *NATO Conference Series, Section IV, Marine Sciences* (New York: Plenum Publishing Corporation, 1977).
27. Richardson, J. R., and H. T. Odum. "Power and a Pulsing Production Model," in *Energy and Ecological Modelling*, W. J. Mitsch, R. W. Bosserman and J. M. Klopatek, Eds. (Amsterdam: ISEM and Elsevier Press, 1981), pp. 641-647.
28. Steele, J. H. "Spatial Pattern in Plankton Communities," in *NATO Conference Series, Section IV, Marine Sciences* (New York: Plenum Publishing Corporation Press, 1977).
29. Odum, H. T. "Energy Quality Control of Ecosystem Design," in *Marsh-Estuarine Systems Simulation*, P. F. Dame, Ed. (Columbia, SC: University of South Carolina Press, 1979), pp. 221-235.
30. Brown, M. "Energy Basis for Hierarchical Distribution," Ph.D. Thesis, University of Florida, Gainesville, FL (1980).
31. Limburg, K. "Energy Basis for Ecosystem Design," M.S. Thesis, University of Florida, Gainesville, FL (1981).
32. Mandelbrot, B. B. *Fractals* (San Francisco: W. H. Freeman & Company Publishing, 1977).
33. MacArthur, R. H. "On the Relative Abundance of Bird Species," *Proc. Nat. Acad. Sci. U.S.* 54:293-295 (1965).
34. Pielou, E. C. *Ecological Diversity* (New York: John Wiley & Sons, Inc., 1975).
35. Haken, H. *Synergetics* (New York: Springer-Verlag New York, Inc., 1978).