Chapter 28

SELF-ORGANIZATION AND MAXIMUM EMPOWER

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In 1922, Alfred Lotka, with an acknowledgment to Boltzmann (1905), suggested that the maximum power principle was a fourth law of thermodynamics that constrained and guided the self-organization of open systems (Lotka 1922, 1925). The maximum power principle can be stated:

> During self organization, system designs develop and prevail that maximize power intake, energy transformation, and those uses that reinforce production and efficiency.

The idea is that over time a network that draws more resources and uses them better toward maintaining that network will tend to replace designs that have fewer resources with which to work. Martinez-Alier (1987), in a review, provided quotations tracing somewhat similar ideas of energy causality to writers in the mid–19th century.

Alone, words like these are not very good for defining network concepts clearly, which may be why many, if not most, people who read the maximum power principle don't understand it, much less see the compelling strength of the argument. We have used the energy systems symbol language since 1965, in addition to verbal descriptions, for relating designs of energy transformation networks to the thermodynamics of self-organization. This chapter summarizes these concepts of the way energy is involved in self-organization of any system and the common network patterns that result. Recognizing a universal hierarchy of energy forms that correspond to different scales of size and time, the thermodynamic quantities EMERGY, transformity, and empower are defined to relate energy from different system scales on a common basis. We found that EMERGY is a rigorous, scale-independent measure of work and a useful concept of value.

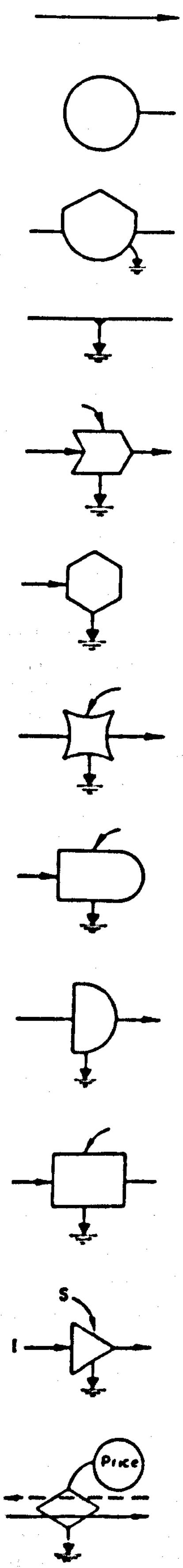
Energy Systems Language for Open System Thermodynamics

The principle of maximum power and its corollaries concern a system's network organization. Consequently, they cannot be expressed with single equations of classical thermodynamics, which concern only one energy transformation step at a time. A network language is required. Starting with ecosystem examples, I introduced a general systems "energy circuit language" (Odum 1966; Odum 1971; Odum 1972; Odum 1983b) in order to combine open system thermodynamics with system kinetics, while also representing hierarchy by position from left to right on diagrams. The symbols given in Figure 28.1 include explicitly or implicitly the energy laws and mathematical characteristics associated with each symbol, so that energy constraints are always linked to equations and simulation models. For example, the consumer symbol automatically includes the heat dispersal that represents the available energy required to maintain the ordered structure. For consumer organisms, biochemical structure and processes are maintained; for a consumer industry of an ecosystem or a society, manufacturing structure is maintained.

Energy Control of Basic Energy Transformation Configurations

Two basic designs can develop in self-organization, as shown in Figure 28.2 using the energy circuit language. One is linear, and one autocatalytic. The energy source, which is limited from the outside, supplies a steady flow of available energy in each case. The linear pathway, where the available energy disperses its potential in a simple process of diffusion, is shown in the lower part of Figure 28.2). Some of the input energy becomes unavailable, as required by the second law, and in this system diffuses out into the environment. This dispersal to the environment is represented by the "heat sink" pathway on the bottom of the interaction symbol. This low-grade energy no longer has the potential do work in the system except to drive the diffusion that disperses the energy according to the second law.

Parallel to the simple pathway and just above in the diagram is an autocatalytic configuration (#2) that draws on the same source energy. This autocatalytic pathway is competing with the linear pathway (#1) for the same resource. As we discussed earlier (Odum 1982; Odum 1983b), the



Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.

Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.

Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.

Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Switching action. A symbol that indicates one or more switching actions.

Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows. An example: a green plant.

Self-limiting energy receiver. A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within. An example: chloroplasts of a plant.

Box. Miscellaneous symbol to use for whatever unit or function is labeled.

Constant-gain amplifier. A unit that delivers an output in proportion to the input I but changed by a constant factor as long as the energy source S is sufficient.

Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 28.1 Energy language symbols. From Odum 1972 and Odum 1983b.

simple linear pathway prevails when energy concentrations of the inflow are small. At higher levels of available energy inflow, however, there is enough energy to support growth of the autocatalytic system against the depreciation inherent in its storage. The autocatalytic unit (which requires an initial storage) then is able to take the energy away from the linear pathway. Typical examples include consumer animals and consumer cities. In this case, the animal does not receive energy passively but invests some of its own energy into capturing more energy from the source, such as the difference between a sit-and-wait frog and an insect-seeking bat.

The autocatalytic design illustrates how the maximum power principle operates. The combination of energy transformation, storage, and feedback to interact with the source flow reinforces and increases the power flow through the system. This basic energy systems model represents living and nonliving systems at all scales of size and time, as will be demonstrated subsequently.

Bernard Convection Cells

A nonliving example of self-organization for maximum power is a Bernard cell convection (Figure 28.3). A dish of viscous fluid receives a steady flow of heat from a hot plate below. The gradient of thermal energy generated by the heat source causes convection of the fluid in the dish (Figure 28.3a) and the development of structure in the cellular fluid. The energy available to run the cell is calculated as the Carnot ratio (delta T)/T times the influx of heat. The structure that develops recycles cooler water to where it is heated more rapidly, making the thermal gradients larger and increasing the energy captured by the system through the process of autocatalytic reinforcement. The action of the structure interacts with, and amplifies, the input pathways as shown in the energy systems diagram (Figure 28.3b).

A cycle of materials is characteristic of most real systems where materials from a receptive, lower-energy state on the left (indicated by the storage tank symbol "N, Cool Fluid") are used to capture new energy in an interaction process. These interactions are production processes involving two or more necessary input quantities as indicated with the symbols definition (Figure 28.1). The transformed energy is stored in the materials of the fluid structure of the hot cells (the tank "C, Hot Cells," on the right). The useful power flow is measured on the production pathway designated "k_1" in Figure 28.3b, and this flow is increased by the development of the storage quantity. Energy transformed, stored, and made useful by the feedback interaction is useful power.

The equations given in Figure 28.3b follow from the use of the energy symbols and are typical for autocatalytic processes, living and nonliving. The model is logistic. Increasing the available energy increases the structural

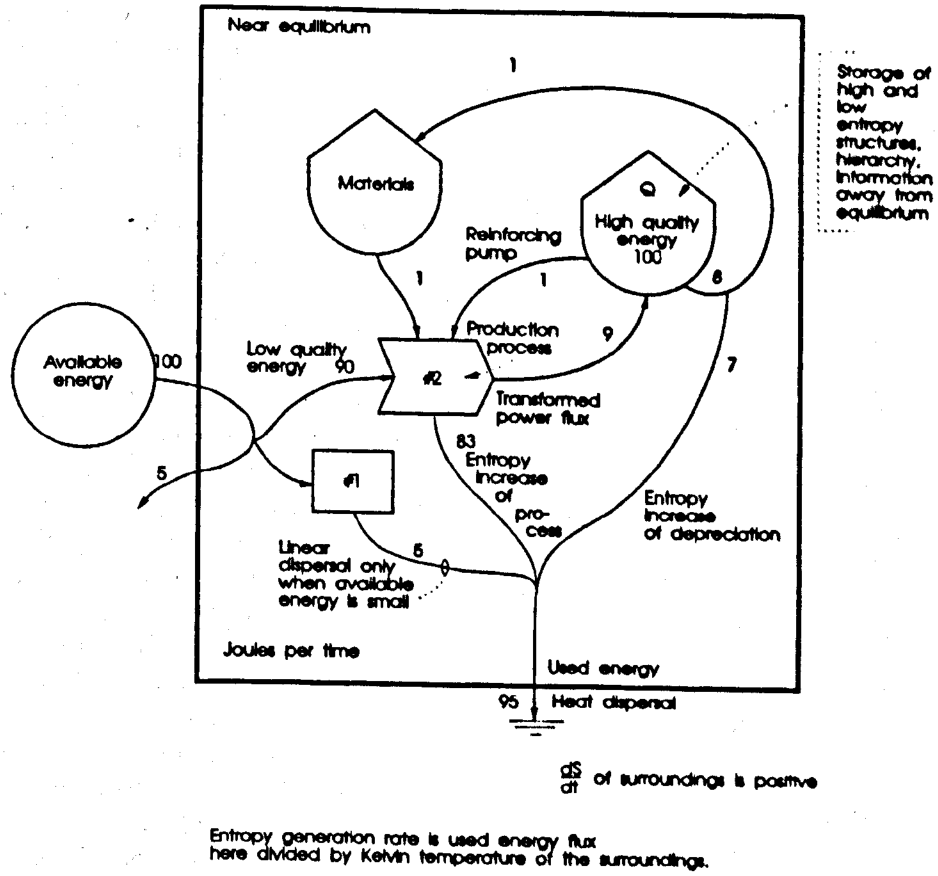


Figure 28.2 Typical energy flows in one unit of a self-organizing system on a source limited from the outside to a steady flow. Numbers are energy flows (Joules) at steady state.

storage and reduces the available material (cool water) available (Figure 28.3d).

The second law requires that storages of high-quality structure (Tank C) have depreciation (energy dispersal), which is shown by the pathway to the heat sink. However, the materials that are part of this process are dispersed within the system and are available for reincorporation into the production process. The background equilibrium state for the material is represented by storage tank N (for the cool water of the Bernard cell). Depreciation is a dispersal of the state of energy (represented in energy language by the "heat sink") because the energy that leaves the system has only enough potential remaining to drive its own diffusion and dispersal.

The material associated with the storage state in this system is retained in the container and is recycled. If one wishes to diagram only the storage and flux of recycling materials, Figure 28.3c results. However, diagramming material cycles alone leaves out the real driving forces associated with energy sources and the way that structure develops which increases the capture of input energy.

Entropy and Entropy Generation Rate

The simple case in Figure 28.3 has a high temperature and thus high entropy structure, which is maintained by the continued inflow of available heat gradient energy. It also maintains high information (high macroscopic entropy information) in the cellular structure of the hot cells. In more complex living systems, the structures that are maintained away from equilibrium include high-entropy temperatures, chemical complexities, and low-entropy crystals. (See diagram in Odum 1983b, Figure 17-9.) Schrödinger's famous little book (1947) describes life as maintaining its own low entropy by pumping in low-entropy food to be degraded. A more complete statement is that high- and low-entropy structures both away from equilibrium are maintained by the input of foods that are also away from equilibrium and that are degraded with an overall increase in entropy from their transformation. An even simpler statement is that potential energy storages are maintained against second law depreciations by the input of foods with potential (available) energy. In the degrading of most of the energy, some energy is transformed to a higher quality that contributes to feedbacks

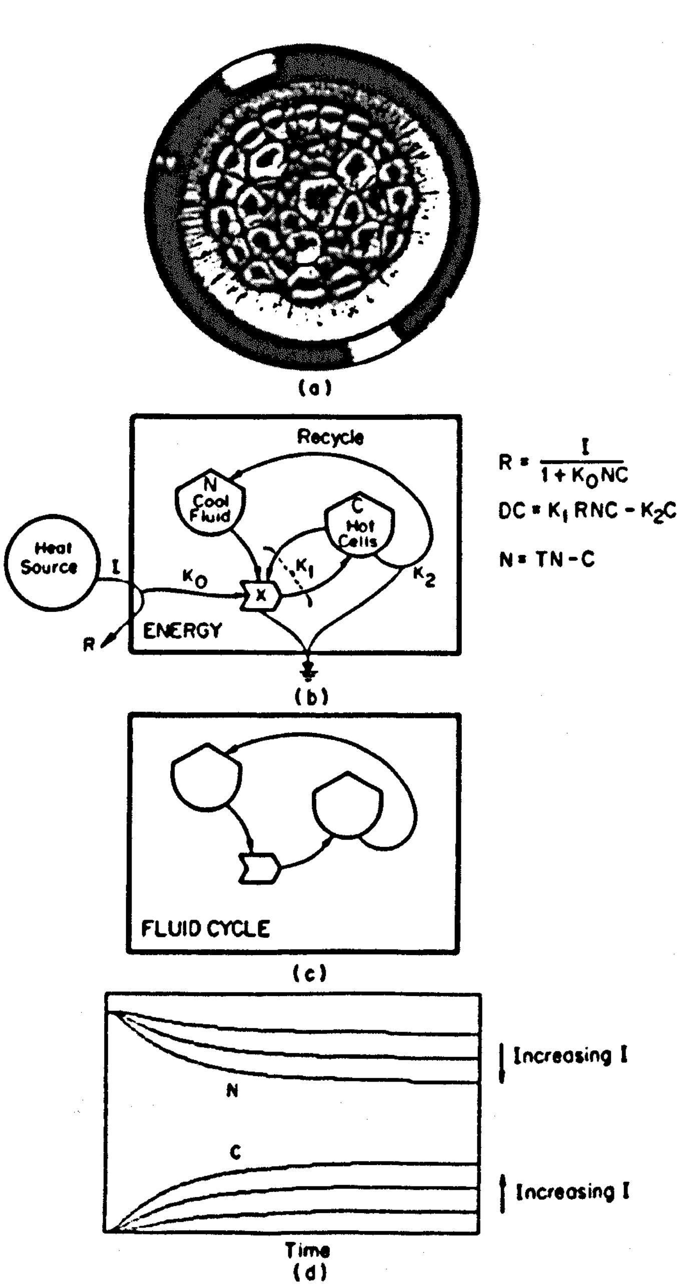


Figure 28.3 Nonliving Bernard cell microcosm with energy-driven material circulation through a convection cell structure maintained away from equilibrium; I, energy inflow; R, unused available energy; C, hot centers; N, cool fluid; (a) Sketch from Swenson 1989; (b) energy systems model; (c) material cycle; (d) graph of simulations for three intensities of available energy (heat flux from below at three temperatures). Figure 28.3(a) is from Swenson 1989. Reprinted with permission of the International Society for the Systems Sciences.

that reinforce the exploitation of the main external energy sources.

The hot upcurrents maintained within Bernard cells have a higher entropy than the surrounding room environment, but the gradient of high and lower temperature together constitutes a lower entropy than the same heat distributed equally. This gradient state away from equilibrium is maintained in spite of a steady depreciation (the cooling of the hot water) in which the potential energy and the low entropy of the temperature gradient is degraded by thermal diffusion through the heat sink. When one compares a hot plate with and without a Bernard cell on top, there is an overall increase in entropy as energy passes through the system, as required by the second law, because the increase in entropy in the environment (at the heat sink) is greater than the decreases in entropy that come about by maintaining gradients within the Bernard cell system.

Living systems operate similarly. Their stored assets are a mixture of low-entropy structures such as crystals and high-entropy structures such as the warm-bloodedness of animals. All require a continued input of available energy to maintain their structure.

Some scientists that have the viewpoints of statistical mechanics think that autocatalytic processes are driven by molecular populations following random processes. For example, the storage of transformed energy (hot cells) is said to be a "dissipative structure," one dragged miraculously into existence by the rapid dissipation of available energy. When they say that the structure emerges when energy is dispersed rapidly, they are stating the result of the maximum power reinforcement but without recognizing the mechanism of the network itself in maximizing its own power.

Few of those who use the language of dissipative structures made popular by Prigogine (1978) and associates acknowledge the relevance of the literature on maximum power that preceded their work by many years. To them, dissipative physical–chemical structures don't seem relevant to the structures that maximize useful power in living and economic systems. This is an example of where a general systems network language is required for seeing beyond the special languages of single disciplines to find principles that may be applicable to any and all systems.

The autocatalytic system of Figures 28.2 and 28.3 can be described in two ways that are equivalent. The physical chemist who emphasizes random processes that do not have causality tends to say: The faster the dissipation, the more structure generated. Or: *Self-organization maximizes rate of entropy generation.*

The biologist, thinking of development of living structure as the means, tends to say: The more structure, the faster the dissipation. Or: *Self-organization develops structure to maximize power.*

Sugita (1981) offered a similar concept from thinking about reactions. All the statements are correct, but they are potentially ambiguous without a network diagram to explain all of what is meant.

Minimum Entropy Generation Concept

When the concentration of the energy of a source is below the critical minimum value required to sustain structure (C in Figure 28.3b) against its normal rate of depreciation, the autocatalytic system changes back to a simple linear energy diffusion dispersal. Autocatalysis stops. For example, the complex material fluid circulation in the Bernard cell becomes laminar. In other words, at low concentrations of potential energy, the system design that will pull the most power is linear and does not build structure or storage. There is only simple energy dispersal (degradation of thermal diffusion). Living systems without enough energy resources to maintain their own structure die.

The behavior of a system with small available energy was described by Prigogine and Wiaume (1946) with their "minimum rate of entropy generation" principle as the general law for energy and open systems. Systems of low energy that are displaced from steady state generate more entropy per unit time while they return to the steady state. Closed systems with storages of weak concentrations of available energy decrease their rates of entropy generation as their processes decline towards equilibrium.

In the 1960s our attempts (Odum 1962; Odum 1967a; Odum 1967b) to get the maximum power principle generally recognized as the energy law controlling the development of structure in open systems were often criticized as contradicting Prigogine's minimum principle. Later on, Prigogine (1978) realized that the minimum concept was not general and that autocatalytic structures develop with higher energy (without, however, acknowledging the causal role of the network reinforcement that we call the Maximum Power Principle). Autocatalytic structure in nonliving reactions was a surprise to chemists trained to think of isolated reactions and random populations, but for us, these were more examples of the generality of the old maximum power principle.

Natural Selection by Reinforcing Designs

The concepts of natural selection were used by Lotka (1922, 1925) to explain why the designs for maximum power prevail, but network diagrams are required to avoid confusion as to the meaning of natural selection. Simple Darwinian selection, i.e., the classic "survival of the fittest," really means "self-selection," where one population outgrows another in a simple competition for consumer source. By ensuring the prevalence of maximum power usage as soon as possible, such competition helps maximize power in early stages of ecosystem growth before the development of networks with control patterns.

However, with self-organization, ecosystems soon develop hierarchical patterns with closed feedback loops, which reinforce those patterns with a diversity of mutually symbiotic sectors and a division of labor. With most of the externally supplied energy already in use, increases in useful power can be achieved only by reinforcing internal efficiency-producing mechanisms, such as by the division of labor through increasing species diversity. In this process, units at one level of organization are chosen in large part by the reinforcement action of some other unit from a higher level of organization, one with longer turnover time and territory. In energy systems language (Figure 28.4), the energy transformations from left to right are fed back with pathways that are represented from right to left to control and reinforce the units lower in the hierarchy. Those pathways that reinforce the intake and useful transformations of power by the entire system are retained. A priority for component species to become important is their contribution to another part of the system, a necessary part of being reinforced. For example, bees pollinating flowers while being fueled by the nectar from the flowers form a mutually reinforcing loop. Other examples are the components of nutrient cycles and population-regulation services of carnivores. Self-organization by pathway reinforcement is a kind of system learning. Ecological succession and biological evolution are examples, each on a different scale of time and space.

Energy Transformation Hierarchy

Figures 28.2–28.5 illustrate the way energy, as measured in constant-quality units such as joules (J), decreases through a transformation process, including the pathway of feedback control action, as required by the second law. To be sustainable, the transformed energy has to have a higher quality in the sense that a small amount fed back can amplify and reinforce the larger flow of lower-quality energy incoming from the source on the left. Similarly, the transformed energy can be transformed further, with an additional loss, while acquiring even greater effect when fed back as an amplifier. Thus energy transformation chains and webs develop (Figure 28.4) a special kind of division of labor, which reinforces the system's power and efficiency. An energy transformation chain is an energy hierarchy, in that much energy at one stage is required to develop a smaller flow at the next higher level. Energy transformation networks, such as food chains, have become part of the normal way of thinking in ecology and among those representing the energy flows of the economy.

Work, Transformity, and Exergy

Once it was recognized that the hierarchy of energy transformation networks is general to all systems because of the common processes of self-organization, traditional definitions equating work and energy had to be revised.

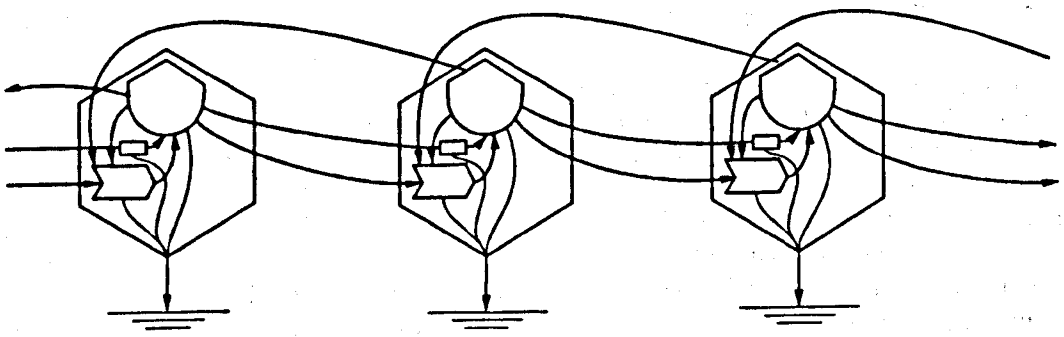


Figure 28.4 Hierarchical levels emerge in self-organization because of the reinforcement they provide to increase transformation power and efficiency. The pathways between storages with small boxes are linear pathways that can operate at low energy, making possible the start of autocatalytic growths and oscillations.

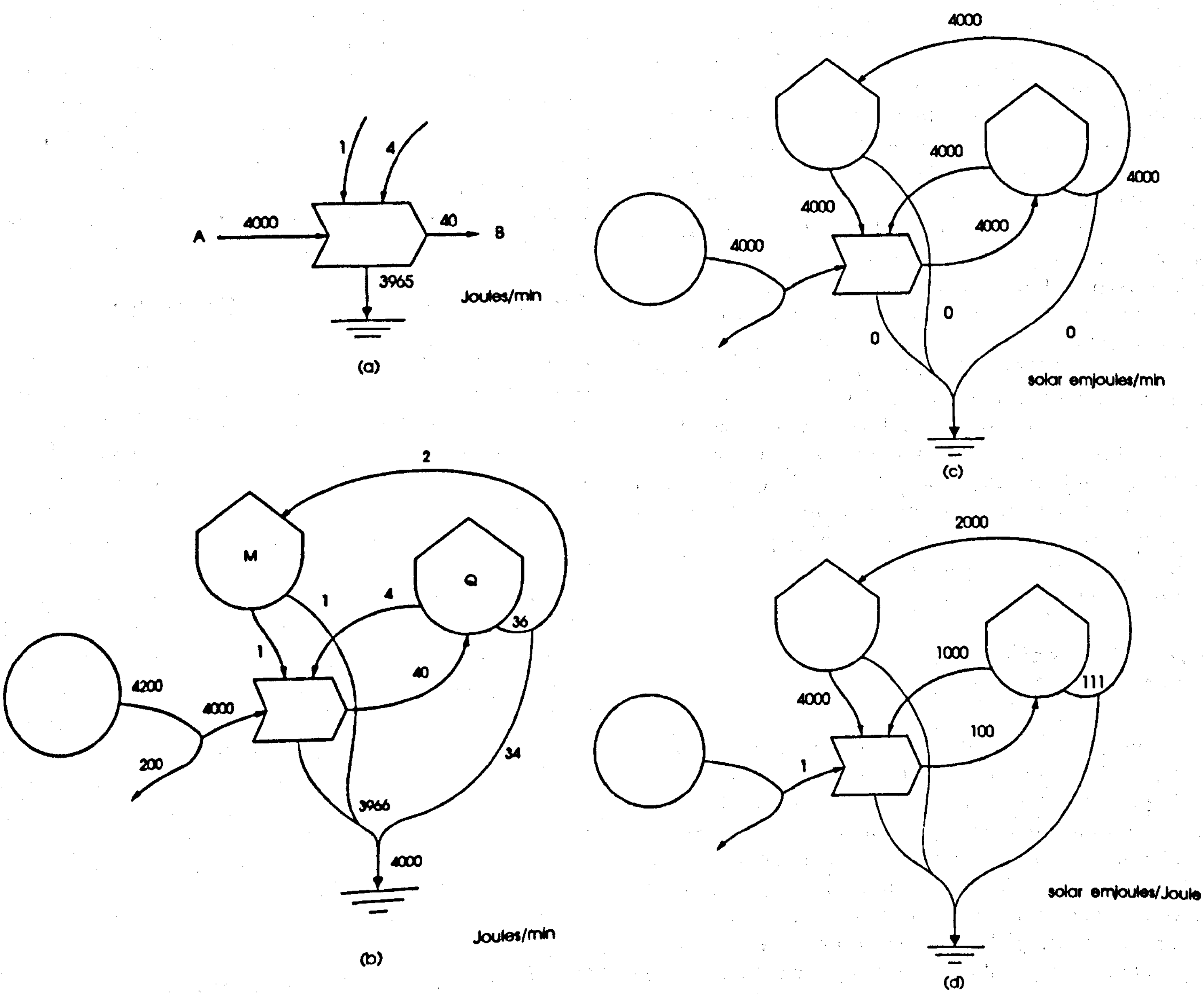


Figure 28.5 Energy flux and transformities in a material-closed ecosystem using solar energy: (a) energy flows in Joules through the productive process of the interactions symbol with energy conserved; (b) energy flows at steady state; (c) solar EMERGY flux in solar emjoules per minute pumped from the source flow by the interaction process; (d) solar transformities in solar emjoules per Joule based on solar EMERGY flux in (c) divided by the energy flux in (b).

Available energy of one kind at one level in an energy hierarchy was not equivalent to that at another level.

We redefined work as "an energy transformation," converting input energy to a new form or concentration capable of feedback reinforcement. We defined this process as a network concept where work increases the utility of energy while degrading and dispersing part of that energy (Figure 28.4). I first called this concept "energy quality ratio" at the award ceremony of the Prize of the Institute La Vie in Paris (Odum 1976), but later renamed it "transformity" (with units emjoules/Joule, not a dimension-less ratio) (Odum 1986; Odum 1987).

> Transformity is the available energy of one type required to generate a joule of another kind of energy in the universal energy hierarchy. The unit of transformity was defined as the emjoule. For example, if 4000 joules of solar insolation are required to generate a joule of organic matter, the solar transformity of the organic matter is 4000 solar emjoules per joule, abbreviated 4000 sej/J. (Odum 1988)

Defining available energy as the ability to do work is ambiguous except where one is comparing potential energy (available energy) of the same type. For example, engineering normally concerns mechanical work but tends to ignore work of different types and transformity, such as solar transformation and mental work.

"Exergy," as used by Ahern (1980), is defined to include only energy flows of similar qualities, that of mechanical work (Evans 1969; Evans and El-Sayed 1976). Thus the common practice of evaluating energy contributions in exergy units includes only energy flows of similar transformity. Because exergy analysis often omits the most important inflows, such as human services that require very large energy flows to maintain, comparing exergy is not a valid way to compare all the resources that are directly and indirectly required for a process.

As the intersection symbols in Figures 28.2–28.5 show, work generally involves a productive interaction of two or more energy flows, each of different kind and transformity. The main flow of energy from the left interacts with, and is controlled and amplified by, a smaller flow of higher-transformity energy from the right. Work is a network concept requiring an energy systems diagram to clarify the meaning.

As part of the protocol for the energy systems language, items are arranged in order of increasing transformity from left to right. Higher-transformity inputs to interactions (Figure 28.4) are drawn from the right so as to enter the top of the interaction symbol, whereas the more abundant but lower-transformity form of energy input is connected to the left of the interaction symbol. The interaction represents a production process where two or more inputs of different transformity are required. The output is a product, energetically, and often in the mathematical sense as well.

Work as an energy transformation usually involves a network interaction, as represented in Figure 28.5 as the normal pattern from self-organization. The highest transformity is the feedback, the output product is second, and the more abundant energy source from the left has the lowest transformity. High-transformity feedbacks usually interact as multipliers, and they achieve a large effect from a relatively small quantity of energy. In this way, effects are commensurate with the high energy flux required to develop a loop of higher-transformity energy.

The Energy Efficiency of a Transformation

Efficiency of an energy transformation is usually calculated as the quotient of the output energy divided by the flux of the input energy. According to the "time's speed regulator" principle (Odum and Pinkerton 1955; Odum 1983a), self-organization of energy transformations for maximum power reinforces those pathways that have the load of output compared to optional input energy. The efficiency that produces the maximum power output is intermediate between the highest and lowest efficiences possible. Our original derivation considered only the energy required to restore potential energy, without the additional consideration of the energy normally required to generate a higher-quality output compared to the input. At high efficiencies, the storage process is slow, and the system tends to stall; at lower efficiencies, the process, although rapid, wastes too much of the input potential energy as heat. At an intermediate loading, speed and efficiency are intermediate, and useful power is maximized. By reinforcing loadings that maximize power, self-organization selects optimum intermediate efficiencies. Many studies have shown the selection for optimal efficiency loading in muscle, photosynthesis, membranes, and power plants. See also examples in Hall et al. (1986), Odum (1967b), Odum (1968), Odum (1983a), Curzon and Ahlborn (1975), Caplan and Essig (1983), and Fairen et al. (1982).

There are also many day-to-day applications of the maximum power concept that we may do without even thinking about it, such as loading a grindstone or a chain saw for maximum output or shifting gears in an accelerating automobile. As taught in electrical engineering textbooks, matching resistances in electrical circuits generates an optimum efficiency for power transmission to the useful output process.

There is also an optimum organization rate for maximum power in rearranging parts in a mechanical system (Odum 1972). For example, there is an optimum rate for maximizing the desired result of reorganizing cars in a parking lot. If the work of accelerating cars and braking is done slowly, the work of arranging a useful pattern is delayed, and the power conversion is less. If the work is done too rapidly, more power is dissipated than goes into the reorganization.

Unfortunately, traditional calculations of efficiency using energy are misleading as to the resources actually required for an energy transformation, because the large quantities of energy used earlier to develop high-transformity (low-energy) inputs are not usually evaluated. For example, the prior energy requirements (4,000 sej) of the high-transformity feedback in Figure 28.5 are not appropriately evaluated by its relatively small energy flow (4 J/min). Tracking all of what is required for a process is a network concept. The denominator should include a quantity that is evaluated using the entire input network and include all prior use of available energy evaluated using some common basis.

EMERGY in Emjoules

As reviewed by Martinez-Alier (1987), concepts of embodied, or sequestered, energy have been under discussion for a century. In recent years, several measures involving energy have been quantitatively defined that represent the several ideas of how past contributions to a product can be evaluated. In our work on energy analysis that started in 1966, the energy of one kind was used as a common denominator with the names "energy cost" and "embodied energy" (Odum 1967b; Odum 1971). In 1983, the term EMERGY, spelled with an "M," was suggested by David Scienceman for our concept and emjoule or emcalorie as the unit. Scienceman (1987) provided a general paper on terminology. See also his chapter in this volume.

EMERGY is defined as the energy of one kind required directly and indirectly to produce a service or product. The unit of EMERGY is the emjoule or emcalorie of a designated energy type. For example, the production of green plants can be expressed in solar emjoules, which includes the solar energy required to make all the inputs to the plant, such as rain, wind, nutrients, cultivation efforts, seeds, and so forth.

Because the solar EMERGY of each input is a product of the energy flux and its solar transformity, the total EMERGY of a product is the sum of the [(energy)*(transformity)] terms of all necessary inputs.

In Figure 28.5a, the solar energy required to generate organic matter flux B is the solar EMERGY flux from source A. In this example, there are 4,000 sej in the organic flux B. Where pathways close a loop with their source in an upstream interaction (Figure 28.5b), the EMERGY of that source terminates. To add feedbacks to A would be double counting of the flux from A. If these flows were from a different EMERGY source, they would be added to that from A in order to evaluate B.

Having defined EMERGY, we can redefine transformity: Transformity is EMERGY/energy. For example, in Figure 28.5a, the solar transformity of the output organic matter is the total solar EMERGY of the input(4,000 sej/min) divided by the energy of the organic flux. EMERGY is a network measure, and adding the EMERGY flows required for a product requires a knowledge of the sources and inputs from the surrounding system that contribute to the generation of that product. An input to a product that is a closed-loop feedback and not an independent source is not added in a second time. Network knowledge is required to avoid double counting an EMERGY input.

Traditional efficiencies are calculated as the ratio of the output (P) over only one of the lower-transformity inputs (I). For example, in Figure 28.5a, efficiency is often calculated as P/I (40 J/40,000 J * 100 = 1%). Traditional efficiencies can be misleading, because high-transformity inputs with only a small energy content require large energy flows in their formation. A more appropriate measure of what is required for an output is the solar EMERGY of all inputs in emjoules of one kind of energy. The energy of an output divided by the total solar EMERGY of all inputs is a measure of direct and indirect energies required for the conversion. This quotient is the reciprocal of the solar transformity (solar EMERGY/energy).

EMERGY of Pathways

Drawing an energy systems model aggregates a more complex system according to the person's belief in what is interesting or important. Assigning EMERGY to pathways may depend on the pathway configurations of the model. Energy storages and fluxes of the various pathways are evaluated first from measurements, published data, or illustrative assumptions (Figure 28.5b). Then, one of two procedures may be used for evaluating the EMERGY flux through the pathway, which is the process of finding how much prior available energy (adjusted to equal tranformities) is contributing to that flux.

1. For old systems in which there has been a long period for self-organization (i.e., systems evolution), where amplifying feedback loops may have developed and where there has been the development of fine-tuned specializations through speciation or other processes of specialization, one perhaps may make the assumption that all the pathways are necessary, different, and mutually reinforcing. Then, as in Figure 28.5, the solar EMERGY flux of every pathway is equivalent, namely, equal to the sum of all the inputs or sources expressed as solar EMERGY (only one source is shown in Figure 28.5). Thus the solar EMERGY flux at each place in the food web is the product of the energy flux and the solar transformity of that energy type. The quotient of solar EMERGY flux and energy flux is the solar transformity of that place in the pathway. For example, solar EMERGY values in Figure 28.5b are

divided by the pathway energies in Figure 28.5c to obtain the solar transformities in Figure 28.5c.

2. For a system aggregated to contain splits and convergences of energy flows of the same type, where the system may be new, partially destroyed, or otherwise incomplete in its organization of possible feedback reinforcement loops, the solar EMERGY of each pathway may be calculated by summing the EMERGY tracked from each source along each pathway using that source up to the point where that track intersects itself in a closed loop. EMERGY flux from a source is split when energy of the same kind divides into two pathways, and it is added to another EMERGY flux when two pathways of the same energy type combine. When EMERGY flux passes through a production process where there are two or more outputs that are each different products, each necessary to some other unit, then each receives the same value of the EMERGY flux that is being tracked from an outside source. The sum of the solar EMERGY fluxes on a pathway tracked from all sources is the total solar EMERGY flux on that pathway.

These methods were given by Tennenbaum (1988), who also coded them into a computer program that calculates these values automatically. The result of such calculations done one at a time with this method is the same as in the procedure previously described in Paragraph 1, at least when the system is a fully organized one with every source connected directly or indirectly to reinforce every other unit.

EMPOWER

Maximizing EMERGY production and use at each level of hierarchy at the same time is required to maximize the combined economy of humanity and nature. This means simultaneously maximizing EMERGY production and use at each level's scale of time and space. The EMERGY flux of the whole system is maximized when the oscillation frequencies on each scale are adjusted for maximum average EMERGY (Richardson and Odum 1981).

An energy flux in a system that is self-organized for maximum performance includes transformation and feedback to an interaction where it is necessary and thus is an amplifier (Figure 28.5). The EMERGY of that flux is the energy flux multiplied by its solar transformity. EMPOWER is the name for a useful EMERGY flux. Perhaps the maximum power principle is well stated as the Maximum Empower Principle. Maximizing empower also maximizes power, because the high-quality sources and closed-loop reinforcements increase inputs and efficiency of conversion of lower-transformity sources, which usually have large energy flows.

EMERGY of Storages

The solar EMERGY of a storage is that required to develop the storage. For example, the solar EMERGY stored in a redwood forest that required 200 yr before it reached a climax level (the temporary steady state) is the sum of the solar EMERGY fluxes used from independent sources multiplied by the time required. This is principally the solar EMERGY of the water transpired during the 200 yr of development. The solar EMERGY of storage is also the energy stored multiplied by the solar transformity of that storage.

If a storage is in steady state due to the balance of a production flux and a yield flux, the solar EMERGY of the storage is constant. The solar EMERGY flux of the yield is the same as the production. Because the yield energy is less than that of the production, the solar transformity of the yield coming out of storage is higher than that of the production flux going in.

When an energy storage is decreased either by depreciation or removal, its solar EMERGY reduction is the product of the energy decrease and its solar transformity. When the previously available energy of a storage becomes unavailable due to this second-law depreciation, the EMERGY of that energy is lost. The empower of depreciation pathways that go into heat sink symbols is 0. Such flows of used energy have no further utility to the system.

Thermodynamics of Circulating Matter

As in the Bernard cell in Figure 28.3, material recycling is a necessary part of most operating systems. It is also a way that higher levels in the energy hierarchy feed back reinforcements to the production processes at lower levels.

In developing a homeostatic model for the earth's closed biogeochemical cycles in 1949 (these models are now called "Gaia"), I looked to a mechanism given by Lotka (1925), who showed that storages develop in front of rate-limiting processes (bottlenecks) and with a quantity inversely proportional to those limiting rates. The closed-cycle mechanism of accumulating storages is a self-organizing mechanism that eliminates any one pathway from being more limiting than others, thus contributing to the maximum processing of the available energy. This mechanism causes such cycles to organize a steady pattern spontaneously, with rates dependent only upon the availability of external energies. Lotka had already explained the way that reinforcement was a process of natural selection for designs with maximum power. My first experience with designs for maximum power was in applying the closed-cycle inverse storage–flux design to the earth's sedimentary cycle (Odum 1950; Odum 1951).

There are similarities in the distribution of recycling matter between the distribution patterns of matter in open systems and that predicted for closed equilibrium systems. Sillen (1967) found that equilibrium calculations seem to account for the distribution of chemical substances in the sea. Most of the water in the biosphere is in the ocean, which is where it would be if the system was in equilibrium — that is, with everything having gone literally downhill. Given that the biosphere, a major influence on geochemistry, is not in thermodynamic equilibrium, the question is, why does the distribution of matter in states of the open system resemble the distributions of an equilibrium state?

The mechanism of self-organization of cycles, as given by Lotka (1925), explains why most of the cycling materials are maintained at their low state of available energy. The process of self-organization eliminates any one step in the cycle of material from being limiting, so that the only control is the external energy sources. By maintaining the major part of a material cycle at its junction with incoming energy, the capture of energy is maximized. A large ocean area, with properties that absorb most of the visible and nonvisible solar insolation, maximizes the operation of the main atmospheric–oceanic heat engines on which everything else on this planet is dependent. Materials maintained at the low-energy part of the cycle require no maintenance energy, because there is no depreciation.

Self-Organization and Patterns Over Time

The homeostatic properties of Lotka's closed-loop kinetics (described in the previous paragraph) generate self-organizational mechanisms for maintaining sustainable steady states. In a dissertation done under Evelyn Hutchinson (Odum 1950; Odum 1951), I used this mechanism and data on strontium in fossils to suggest the processes that led to the long-term stability of oceanic chemistry and the world sedimentary cycle. Thus the concepts of homeostasis were extended to the biogeochemistry of the world.

In those days, ecological succession was usually described as reaching a stable plateau called the "climax." In our first closed microcosm studies, periods of rapid adaptation indeed were followed by a more stable period of climax. In 1950, I sought the historical antecedents and found Fechner's stability principle (Holmes 1948), which might be stated: *Self-regulating stable systems outlast transient changing ones.*

In later years, however, after I had considered more systems, it was apparent that over longer periods most systems vary and oscillate, sometimes responding to outside rhythms and sometimes by using internal mechanisms. The outside rhythms were usually the oscillations of the next larger system with longer periods. Because of their low frequency, larger territory, and greater EMERGY, these pulses, although recurring, are often regarded as catastrophes to those components (such as humans) on the receiving end.

These types of oscillating patterns can be generated readily through computer simulations. A chain of coupled autocatalytic populations, as in Figure 28.4, represents the hierarchy of self-organization in which each unit from left to right has a lower energy flux but is composed of units of larger territory and turnover time than the one before. Ever present are linear pathways that operate at low energy levels (represented in Figure 28.4 with the small box symbol). As storages increase, thresholds for autocatalytic acceleration are exceeded, and such chains develop oscillatory pulses (Alexander 1978; Richardson and Odum 1981; Odum 1981; Odum 1983b; Richardson 1988). When such models are simulated, relatively small changes in coefficients can change an oscillating steady state to a steady one, but there are thermodynamic reasons why self-organization may reinforce the oscillating patterns.

For example, it has been shown that photosynthesis was more efficient for the same light energy if it was flashing. Pulsing maintains a stronger gradient between energy source and the loading of the receiving unit, which transforms more energy. Typical oscillation involves the coupling of units of different hierarchical level, where rapid oscillations among smaller units are embedded in longer oscillations driven by higher levels of size and transformity. A pulse of consumption alternating with a longer period of production can make both processes contribute more. Examples are animal herds grazing grasslands and herring schools feeding on plankton.

Thus, it became apparent that there were loading patterns over time that affect power transformations. One might say that there are energy frequency niches that the units having the appropriate characteristics can exploit and from which they can derive more energy. Campbell (1984) considered the pulse-filtering characteristics of ecosystems that could maximize energy reception. Zwick (1986) considered units adapted to receive and utilize energy of acceleration against "backforces." Using hierarchical pulsing models, Richardson (1988) considered the optimum frequency for maximum power transformation and the effect of spatial arrangements of producers and consumers. Our civilization's frenzied consumption of resources that were accumulated over millenia appears to be an example of a pulsing oscillation that ultimately must alternate with a period of net restoration of resources. Whereas the maximum consumption period is not sustainable, the repeating regime of oscillating patterns may be. The term "climax" may still be useful to refer to the levels of maximum storage in each cycle of oscillation.

When rhythmic fluxes of energy passing through storages are large relative to the size of that storage, chaotic pulsing results because the storage alternates between excess net inflow and excess net outflow. The greater the energy flow, the more the number of states alternating in time. These bifurcations create a diversity of energy gradients that may contribute to maximizing power. This hypothesis that "chaotic states are designs that prevail because they contribute to maximum power" needs study.

Self-Organization of Diversity

Among the structures that increase power and efficiency are webs with hierarchical energy levels. With the collecting and concentrating of EMERGY, units are formed with larger transformity, size, territorial size, and turnover times, properties that reinforce pathways in ways not possible on a smaller scale (see Figure 28.4). The larger sized units on the right control and reinforce the large populations of smaller units on the left by feeding back high-transformity interactions. Each unit shown in Figure 28.4 has three pathways of contribution to the system, all of which form closed loops of reinforcement that eventually contribute to the unit's own support. In this example, one feeds back to the left to reinforce the fast, small units; a second reinforces its own autocatalysis; and a third interacts with higher levels of larger systems and is controlled and amplified by their feedbacks. Figure 28.4 shows how a chain to achieve maximum empower requires equal priority in assignment of a unit's resources to the lower-transformity supporters, to itself, and to support higher-transformity levels.

Each unit draws energy and contributes to the continuation of the system upon which it depends by feeding back high-transformity controls, services, and material reinforcement. Successful long-term agriculture succeeds because farmers feed back controls, soil enhancement, and useful service. Public fisheries often fail because fishermen draw upon energies of the lower-transformity units without feeding back reinforcing services.

Maximum power is obtained when all products and by-products are fed back to amplify some upstream flow with lower transformity so as to make a web of connectivity between the various units. Many of these units are partly in parallel and partly in series, which provides self-organizational flexibility. The development of hierarchical webs is accompanied by diversification of units that facilitate maximum power by contributing to efficiency or providing alternative pathways for changing conditions. Although facilitating energy processing, diversity also requires energy to maintain the variety. For example, in complex diverse ecosystems such as wet tropical forests, energy is required to maintain the plethora of colors, behaviors, and chemicals found there. There may be an optimum diversity for maximum power. Maintaining diversity is second in priority, often developing after the main storages and reinforcements for processing matter have reached the maximum possible without diversification.

As pointed out by Kay (1989), there is an energy limit to the length of an energy chain because there is less available energy remaining in each successive transformation. Thus the number of steps in an ecological food chain is limited by the amount of food available at the base. However, if entities of high transformity and great control ability per unit energy can be developed, the chain can be lengthened with additional performance elicited from more high-quality feedbacks. The entities that permit more transformations, higher transformities, and super control we recognize as "information."

Self-Organization, EMERGY, and Information

Information is defined here as "the configurations of the parts of a system." Information is in the real operating system, but it can also be separated out from the system as an isolated plan. The energy of isolated information is that of its carrier. For example, information may be carried by paper on which a plan is written, by a disk on which computer programs are written, or by DNA on which genetic information is coded. Information has very small energy but very high transformity and impact.

In ecosystems, development of behavioral programs fine-tunes adaptations of species to their resources; in human affairs, development of computer information processing gets more efficiency out of the same work force. Considered collectively, diversity is information by which systems of nature and of humanity maximize empower.

When systems emerge through evolution and self-organization, the designs that maximize power can be separated from their system as coded information. This information can be duplicated by reproduction and spread by communication or migration so that it is shared over large areas, helping larger systems maximize their performance. Solar transformities (EMERGY per unit energy of its carrier) increase as information in emergent systems is evolved, extracted, widely copied, and shared. The larger the territory of the shared information, the slower is its depreciation rate and the larger is its scale in space and time (Odum 1987; Odum 1988). Widely shared information becomes a large-scale controller at the top of the energy chain, analogous to the lion managing its food chain.

An example of shared information among humans is the widespread use of basic religious teachings, Bibles, and Korans that unify and focus people. An ecological example is the widespread distribution of worldwide species information. Whereas the individuals are short lived, the common elements of shared genetic information in a taxonomic category gives that taxon a long turnover time and slow depreciation.

A characteristic of information is that it requires less to maintain and copy than to be reformed again. In other words, information requires more EMERGY for formation than for copying. More EMERGY is required for information formation than for information maintenance.

Although information copying requires little EMERGY, correction of errors and keeping information functional requires that an information cycle be maintained. The cycle requires extraction of information from systems, duplication of many copies with variation, reapplication of these copies to operate systems, and a selective process of deriving future copies from the system operating with higher empower. Examples are the life histories of plants and animals. Similar cycles now exist in the storing, copying, teaching, and application of technological information. Maintaining an information cycle with all these components requires much EMERGY.

The annual solar EMERGY requirement for maintaining living information is that required to maintain the biosphere, about 9.4 E24 sej/yr (Odum in press). The solar EMERGY to generate the diversity of life on earth is much larger, about E32 sej (the product of the annual solar EMERGY budget of the earth and a billion yr time for evolution).

The science of biological classification, systematics, deals with the living information that has resulted from a billion yr of self-organization. When items of similarity are grouped together, it is usually because there are similarities of the coded information. Classification of evolution's information is hierarchical. The larger groupings of information represent longer periods of time developing and genetic information shared more widely.

The hierarchical data of systematics represent the territories of shared information; the higher the systematics category, the larger the territory of shared genes, and the longer the time of formation and turnover. The larger the territory of shared information, the more EMERGY was required in its formation and the higher the transformity. The higher the transformity, the greater the control action exhibited by these shared genes. For example, the information for the basic biochemical structures and processes of life have been shared, adapted, tested, and selected the world over for the whole period of living evolution.

A Simulation Model of Evolution

Figure 28.6 is a model of energy flow through an ecosystem that generates categories of shared information from the flows of energy, resulting in microevolution of species

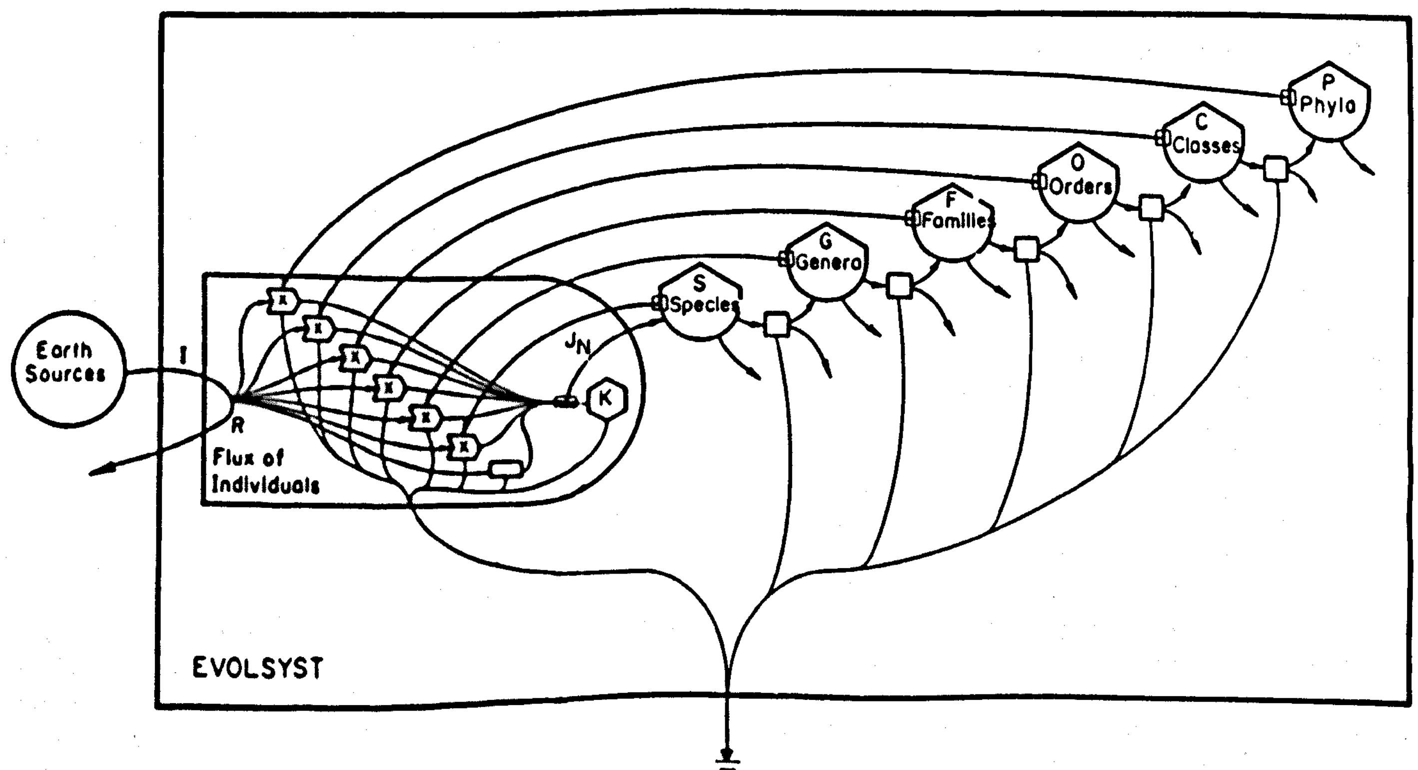


Figure 28.6 Energy systems model of evolution of the shared information categories recognized in taxonomic classification. From Odum 1989b. Reprinted with permission of the International Society for the Systems Sciences. Equations: R = I/(1 + K0 + K1*S + K2*G + K3*F + K4*O + K5*C + K6*P) ; J_N = (K7*R + K8*R*S + K9*R*G + K10*R*F + K11*R*O + K12*R*C + K13*R*P); DS = K14*J_N – K15*S – K16*S; DO = K26*F – K27*O – K28*O; DG = K17*S – K19*G – K20*G; DC = K30*O – K31*C – K32*C ; DF = K22*G – K23*F – K24*F; DP = K34*C – K35*P; where I = energy flow; K = individuals; R = unused energy; and J_N = speciation.

and macroevolution of higher taxa. The model makes specific the way ecosystems are regulated by designs for self-organizing and maximum power and how they generate a hierarchy of high-transformity, shared information — which we now classify with biological systematics.

Figure 28.6 includes equations that represent species generated from the flows of energy through living individuals (see symbol K in the production symbol). This represents microevolutionary processes that introduce small information changes. Species accumulate (storage tank S) with flow J_N in proportion to the production of individuals. The number of extinctions is proportional to the stored species, shown with the outflow pathway. In the same way, accumulating genera generate families; accumulating families generate orders; orders generate classes; and classes generate phyla.

In proportion to the number of new species, emergent new innovations are possible because the many small increments can be connected into new functions that have much greater generality. The new innovation spreads rapidly, displacing other species, and through adaptive radiation generates many new ones to replace the older ones. In the fossil record, this shows up as a saltatory jump, which has been called the Goldschmidt macroevolution (Goldschmidt 1940). An analogy in contemporary society is the microcomputer, evolving suddenly after accumulation of many small microevolutionary innovations among electronic components.

In Figure 28.6 macroevolutionary transformations are shown as the small boxes between each taxonomic category. The flux of new macroevolutionary information is in proportion to the accumulation of microevolutionary information. Something new emerges when enough small changes develop to provide new combinations that can have major effects. The massive substitution of species that occurs with the innovative change is macroevolution. Through the box between tanks S and G is the flux of macroevolutionary change with innovative new information. Innovative species cause many previous species to go extinct, represented by the depreciation pathway down from each macroevolutionary box.

A simulation model based on Figure 28.6 was calibrated, with the flows and storage values given in Table 28.1. The BASIC language program EVOLSYT is listed in Table 28.2 and explained in more detail in Odum (1989c).

On the screen, the program tallies the number of years since the start and also generates bar graphs on a logarithmic scale (Figure 28.7a), keeping the old bars as it prints the new bars on top. The species bar reaches its maximum quickly, followed at later times by the genera, families, orders, classes, and finally the phyla after a billion yr.

The input to the model was the solar EMERGY budget of the earth of 8 E24 sej/yr (Odum 1988). The derived solar transformities of the categories of systematics were

Table 28.1 Quantities for calibrating EVOLSYST in Figure 28.6

Unit	Flux/yr	Storage	Turnover, yr
Individuals	5 E16	—	1
Species	5 E2	5 E6	1E4
Genera	5	5 E5	1E5
Families	5 E–2	5 E4	1E6
Orders	5 E–4	5 E3	1E7
Classes	5 E–6	5 E2	1E8
Phyla	5 E–8	5 E1	1E9

obtained as the solar EMERGY required divided by the number of units of that category formed as follows:

species	E22 sej/species
genera	E24 sej/genus
families	E26 sej/family
orders	E28 sej/order
classes	E30 sej/class
phyla	E32 sej/phylum

See the graph of the number of units of a taxonomic category as a function of the solar transformity of that category in Figure 28.7b.

As with this example, we have developed microcomputer programs in BASIC that represent the main systems configurations common to various sciences, combining kinetics and energetics. These are available in teaching manuals with systems diagrams and explanations (Odum et al. 1988; Odum and Odum 1989, 1991, 1993; Odum 1989d), with accompanying disks. We call these general systems configurations "minimodels" because they are simple, but they represent large-scale phenomena of humanity and nature (ecological economics) as well as the processes of physics, chemistry, and biology. Full explanations and their precedents in mathematics were given in *Systems Ecology* (Odum 1983b), a book that in 1994 was revised and appropriately renamed *Ecological and General Systems* (Odum 1994).

EMERGY Simulation With EXTEND

The remarkable Macintosh computer program EXTEND (Imagine That, 151 Bernal Road, Suite 5, San Jose, California 95119; telephone 408-365-0305) allows systems representation, simulation kinetics, and EMERGY evaluations to be done all at the same time, as with real-world phenomena. With this program, you can prepare and store an icon and write a program for its kinetic and energetic behavior so that when connected with the mouse to other blocks, it not only shows the network and generates simulation graphs, but it also can calculate and transmit quantities from block to block according to laws for energy, EMERGY, matter, and information.

Table 28.2 BASIC simulation program EVOLSYST for IBM compatible PC

```
3 REM EVOLSYST (Simulation of the
    evolution of Systematic Categories)
5 REM For time graphs, set X= 0; for bar
    graphs, set X = 1:
6 X=1
7 CLS
8 REM GRAPHICS:
9 SCREEN 1,0
11 COLOR 0,1
12 LINE (50,180)–(230,180),3
13 IF X = 1 GOTO 40
15 LINE (0,0)–(319,180),3,B
18 LINE (0,30)–(320,30),3
20 LINE (0,60)–(320,60),3
25 LINE (0,90)–(320,90),3
27 LINE (0,120)–(320,120),3
30 LINE (0,150)–(320,150),3
40 REM Scaling factors
60 DT = 10000!
62 T0 = 100000!
64 S0 = 200000!
66 G0 = 20000!
70 F0 = 2000!
80 O0 = 200
90 C0 = 20
95 P0 = 2
100 REM Coefficients
105 K0 = 6
110 K1 = .0000004
115 K2 = .000004
117 K3 = .00004
119 K4 = .0004
120 K5 = .004
122 K6 = .04
125 K7 = 3000!
128 K8 = .000004
130 K9 = .002
133 K10 = .02
135 K11 = .2
137 K12 = 2
138 K13 = 20
140 K14 = 1
143 K15 = .00005
145 K16 = .00005
147 K17 = .000001
149 K19 = .000005
152 K20 = .000005
155 K22 = .0000001
158 K23 = .0000005
160 K24 = .0000005
162 K26 = 1E–08
165 K27 = 5E–08
168 K28 = 5E–08
170 K30 = 1E–09
173 K31 = 5E–09
175 K32 = 5E–09
177 K34 = 1E–10
180 K35 = 1E–10
182 REM Sources
183 I = 1
185 REM Initial conditions
187 S = 1
189 G = 1
191 F = 1
193 O = 1
195 C = 1
197 P = 1
200 REM PLOTTING GRAPHS:
201 IF X= 0 GOTO 245
205 LINE (50,180)–(50,180–5*LOG(S)),3
206 LINE (50,180–5*LOG(S))–(80, 180–
    5*LOG(S)),3
207 LINE (80,180)–(80,180–
    5*LOG(S)),3
209 LINE (80,180–5*LOG(G))–
    (110,180–5*LOG(G)),3
210 LINE (110,180)–(110,180–
    5*LOG(G)),3
212 LINE (110,179–5*LOC(F))–
    (140,179–5*LOG(F)),3
213 LINE (140,180)–(140,180–
    5*LOG(F)),3
217 LINE (140,179–5*LOG(O))–
    (170,179–5*LOG(O)),3
219 LINE (170,179)–(170,179–
    5*LOG(O)),3
221 LINE (170,179–5*LOG(C))–
    (200,179–5*LOG(C)),3
224 LINE (200,179)–(200,179–
    5*LOG(C)),3
226 LINE (200,179–5*LOG(P))–
    (230,179–5*LOG(P)),3
230 LOCATE 1,30: PRINT T
235 LOCATE 2,30: PRINT " years"
244 IF X= 1 GOTO 300
245 PSET (T/T0,180–S/S0),3
255 PSET T/T0, 150–G/G0),3
265 PSET (T/T0,120–F/F0),3
267 PSET (T/T0, 90–O/O0),3
275 PSET (T/T0, 60–C/C0),3
285 PSET (T/T0, 30–P/P0),3
300 REM Equations ;
305 R = I/(1 + K0 + K1*S + K2*G + K3*F +
    K4*O + K5*C + K6*P)
310 JN = (K7*R + K8*RS + K9*R*G
    +K10*R*F +K11*R*O + K12*R*C +
    K13*R*P)
320 DS = K14*JN – K15*S – K16*S
330 DC = K17*S – K19*G – K20*G
340 DF = K22*G – K23*F – K24*F
350 DO = K26*F – K27*O – K28*O
355 DC = K30*O – K31*C – K32*C
360 DP = K34*C – K35*P
400 REM Change Equations
410 S = S + DS*DT
420 G = G + DG*DT
430 F = F + DF*DT
440 O = O + DO*DT
445 IF O <1 THEN 0 = 1
450 C = C + DC*DT
455 IF C <1 THEN C = 1
460 P = P + DP*DT
465 IF P <1 THEN P = 1
470 T = T + DT
500 REM GO BACK AND REPEAT:
505 IF X = 1 GOTO 200
510 IF T/TO < 320 GOTO 200
```

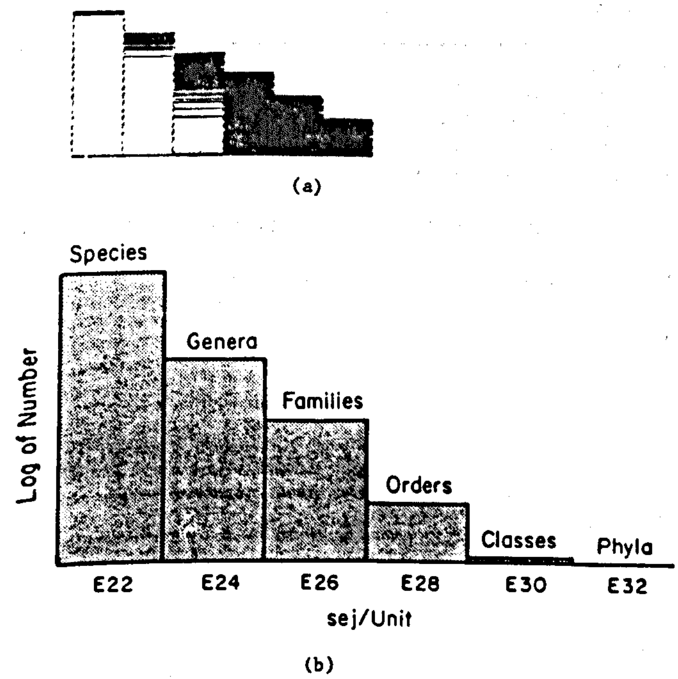


Figure 28.7 Results of computer simulation of EVOLVSYST model in Figure 28.6. Bars from left to right are systematics categories on a logarithmic scale after 2 billion yr—species, genera, families, orders, classes, phyla: (a) screen dump of bar graph after 1.01 billion yr; (b) bar graph of number of units of each taxonomic category as a function of solar transformity of each unit. From Odum 1989b. Reprinted with permission of the International Society for the Systems Sciences.

We have now programmed the energy symbols of the energy systems language, and these, available on disk, can be used with EXTEND. One set of symbols has pictorial icons of plants and animals for beginning classes in science to connect and simulate (see E. C. Odum et al., this volume). A second library has the general symbols with transformities and EMERGY. This library, with symbols shown in Figure 28.8, in addition to normal simulation, transmits transformities and, within each block, calculates the EMERGY storage or flux. For example, Figure 28.9 has an autocatalytic system to represent the thermodynamics of self-organization where the source is flow-limited.

When the connector of one symbol is joined to that of another with the mouse, the array of one block is set equal to that of another. Part of the array is set by the upstream block and used by the downstream block's program. Vice versa, other parts of the array are set by the downstream block and used by the upstream block's program. For example, Table 28.3 is the listing of the scripts of one block, the source, used in Figure 28.9a. Most of the lines in the script set up the arrays by which a descriptive code, the driving force, the flow, and the transformities are passed from one block to another. The transmitted code is used by the receiving block for special operations that depend on the nature of the connecting block.

In the example, Figure 28.9a, the model is connected to four plotters, so that four graphs are plotted (Figure 28.9b–e). Quantity of stored energy (Figure 28.9b) levels off, limited at its source. EMERGY, empower, and transformity of the storage stop changing when storages are

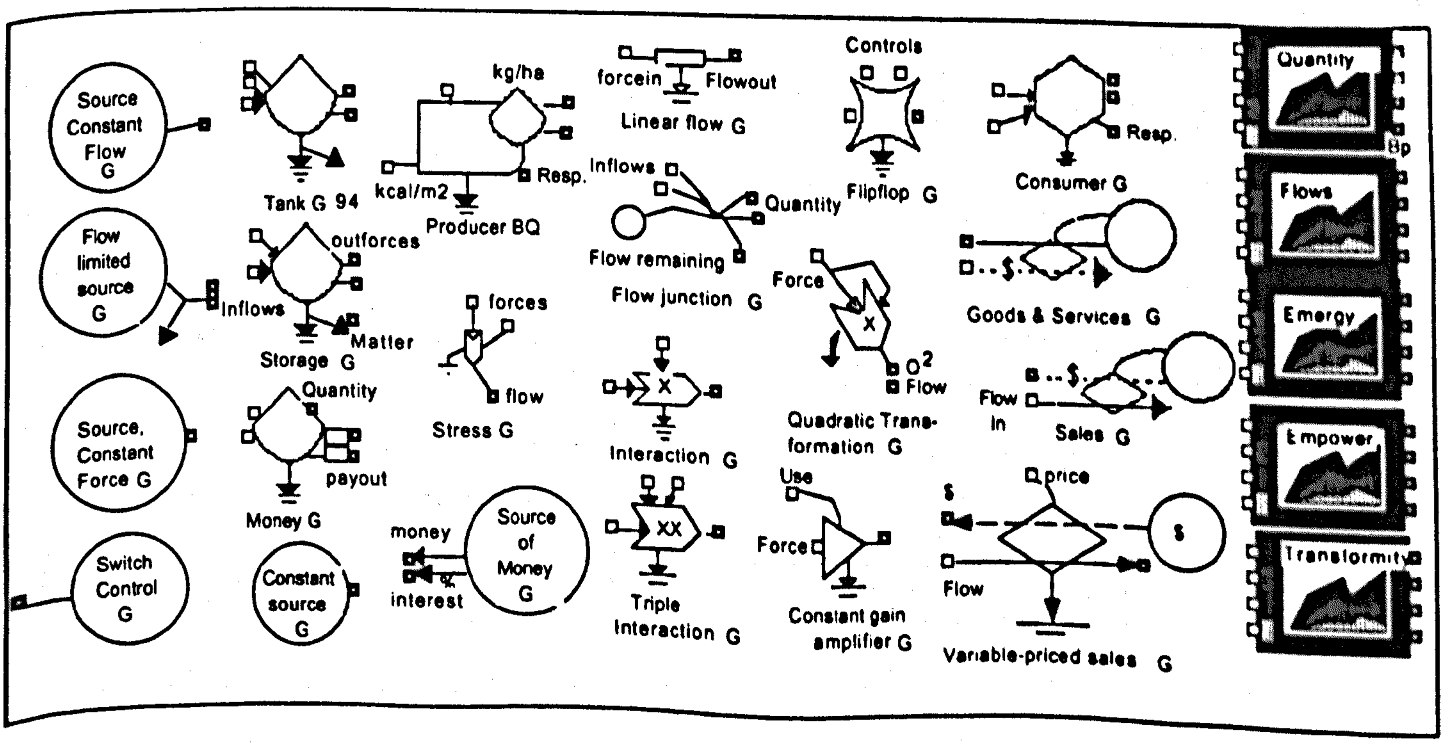


Figure 28.8 Icons of the EMERGY-calculating energy systems blocks for simulating energy systems language and energy relationships on the Macintosh program EXTEND.

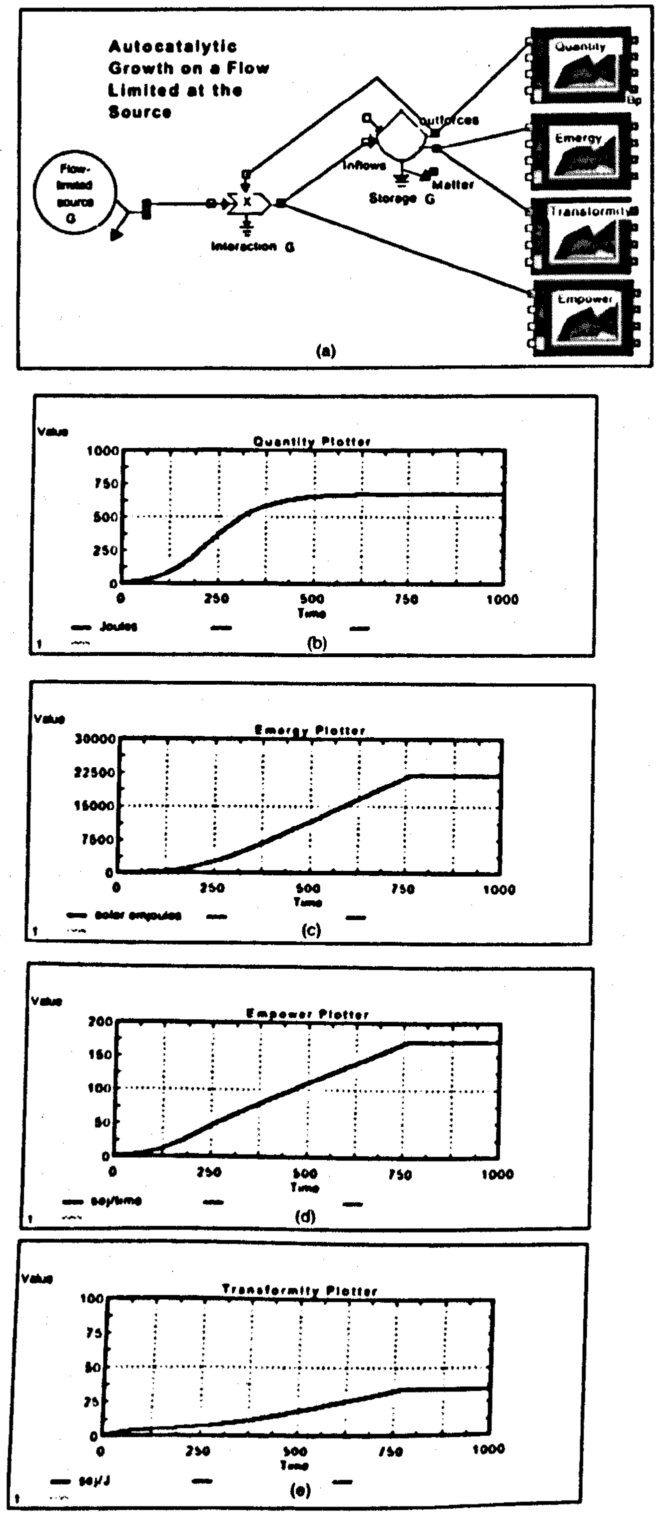


Figure 28.9 Example of use of energy systems blocks to simulate a model with EXTEND: (a) view of Macintosh screen with autocatalytic growth model using a flow that is limited at its source; (b–e) graphs generated by EXTEND simulating the model in (a).

Table 28.3 Script of block source

Use Limited E

```
Constant code is 0;
Constant force is 1;
Constant use is 2;**use is outflow used
Constant transformity is 3;

real R,N,ST,userusage, conarray[], Receivedarray[];

** This message occurs for each step in the
                                     simulation.
on simulate
{

Unusedout = R;

If (Not Getpassedarray(conout, receivedarray))
{
Conarray[code] = 1;
Conarray[Force] = R;
Conarray[use] = 0.0;
Conarray[transformity] = 0.0;
}
Else
{
Conarray[use] = receivedarray[2];

}
Userusage = Conarray[use];
R = sourceflow/(1 + Usersage);
If (R <.1)
R = .1;

Conarray[force] = R;
Conarray[code] = 1;
Conarray[transformity] = ST;

Conout = Passarray(conarray);
Unusedout = R;
}

** create block
on createblock
{

solartransformity = 1;

Sourceflow = 4000;**kilocalories per square meter
                                           per day
}

** Initialize any simulation variables.
on initsim
{
R = .1*sourceflow;
ST = Solartransformity;

Makearray(Conarray,4);
Conarray[code] = -1;
Conarray[Force] = R;
Conarray[Use] = 0.0;
Conarray[transformity] = 0.0;
}

** User clicked the dialog HELP button.
On help
{
showHelp();
}
```

Table 28.3 *(Cont'd)* Script of block source

Flow limited G

```
Constant code is 0;
Constant force is 1;
Constant use is 2;**use is outflow used
Constant transformity is 3;

Real R,N,ST,userusage,conarray[], Receivedarray[];
Real userusage2,con2array[],Received2array[],
     userusage3,con3array[], Received3array[];

** This message occurs for each step in the
                                   simulation.
on simulate
{

If (Not Getpassedarray( conout, receivedarray))
{
Conarray[code] = 1;
Conarray[Force] = 0.0;
Conarray[use] = 0.0;
Conarray[transformity] = 0.0;
}
Else
Conarray [use] = receivedarray[use];
Userusage = Conarray[use];

If (Not Getpassedarray(con2out, received2array))
{
Con2array[code] = 1;
Con2array[Force] = 0.0;
Con2array[use] = 0.0;
Con2array[transformity] = 0.0;
}
Else
Con2array[use] = received2array [use];
Userusage2 = Con2array[use];

If (Not Getpassedarray(con3out, received3array))
{
Con3array[code] = 1;
Con3array[Force] = 0.0;
Con3array[use] = 0.0;
Con3array[transformity] = 0.0;
}
Else
Con3array[use] = received3array [use];
Userusage3 = Con3array[use];

R = sourceflow/(1 + Userusage + userusage2 +
                                   userusage3);
If (R <1E-10)
R = 1E-10;

Conarray[force] = R;
Conarray[code] = 1;
Conarray [transformity] = ST;
```

unchanging. These blocks are programmed to stop changing when the growth slows to less than 5% (Figure 28.9c, 28.9d, and 28.9e).

Cosmic "Ecosystem"

The principles of self-organization and the maximum empower principle are ready for consideration in other sciences. At the invitation of the Royal Swedish Academy of Sciences, I gave an energy general systems representation of the cosmos at their symposium in 1989 (Figure 28.10). It might be called an astrophysical food web. With the use of the common systems structure for energy systems networks that we find wherever we look, a different perspective on a steady-state universe is found. It is not one of explosion and contraction but is more of an ecosystem of hierarchical stars and galaxies, one where dispersed low-energy Kelvin radiation and distributed matter converges stepwise to the intense centers of highest transformity, energy and matter recycling to form a closed loop, as it does on a much smaller scale where there is a Maxwell–Boltzmann distribution in a gas at equilibrium.

Epilogue

It has now been 45 yr since I started the effort to synthesize and generalize about the thermodynamics and kinetics of systems by studying ecosystems. The search for commonalities between ecosystems, helped greatly with a Rockefeller Foundation grant, soon led to my consideration of the larger systems of humanity and nature and the comparisons of ecosystems and economic systems (Odum 1983b, Chapter 23; Odum 1987). Clarification of thermodynamics of self-organization showed that revisions in neoclassical economics were necessary. In the past, humanity found the optimum for maximum power through self-organization by trial and error, followed by storage of the tested information in the mores of the culture. Now we have the means to find the optimum for maximum empower by overview modeling and EMERGY analysis, avoiding some of the waste of trial and error.

One of our techniques is ecological engineering, the human facilitation of nature's self-organization. For maximum symbiosis of the human economy and the environment, processes are allowed to self-organize together for maximum empower (Odum 1989a). Simulation models of ecological economics were developed (Odum 1989c). With EMERGY as a new value system, ecological economics gives us the means for recommending policies for sustainable human stewardship of the biosphere. Examples were given for agriculture and coastal resources (Odum 1984b; Odum 1984c).

EMERGY analysis of nations led to evaluations of international trade that showed great inequity as the cause of many of the world's problems of public welfare (Odum 1984a; Pillet and Odum 1984a; Pillet and Odum 1987; Huang and Odum 1991. These problems may be solved if international policies and treaties on trade arrange equity of emergy exchange (Scienceman 1989). Em$, an EMERGY based dollar, is defined as the part of the gross economic product that results from EMERGY. For example, EMERGY flowing in exports is divided by the

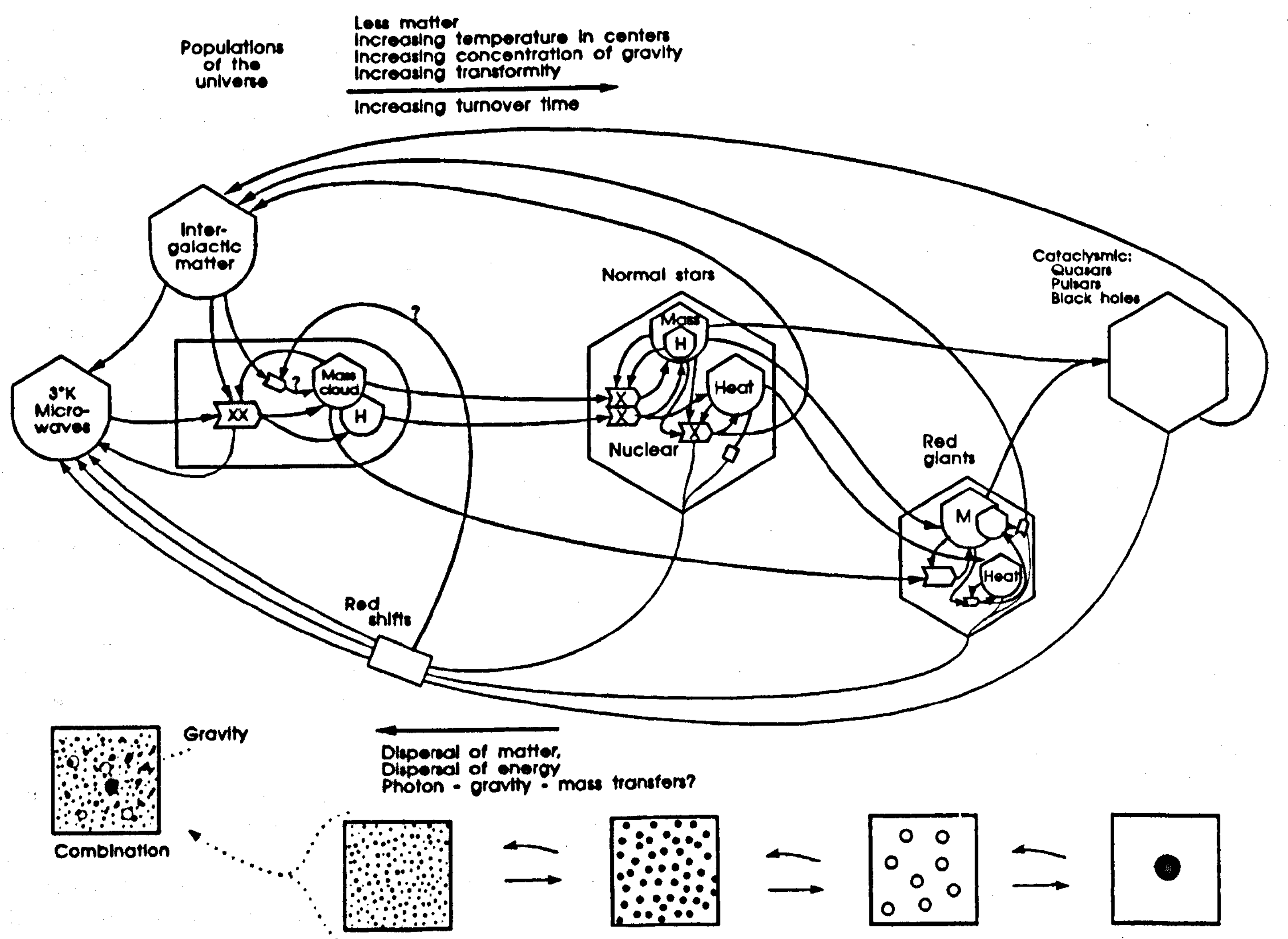


Figure 28.10 An energy systems representation of the universe. This systems concept has a closed energy cycle based on energy of electromagnetic radiation being extracted by gravitational forces, causing at least some of the observed red shifts that are usually attributed to the Doppler effect of rapidly diverging components of an expanding universe.

EMERGY/money quotient for the United States (1.4 trillion sej/1992 $U.S.) to obtain 1992 Em$ of that trade.

To summarize theories of self-organization for maximum empower, we offer the hope that global public policies toward a sustainable system of humanity and environment on many scales can be selected in advance by empower evaluation of holistically aggregated energy systems models of environment and society.

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