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Macroscopic Minimodels of Man and Nature

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I. Introduction

Man is embedded in a complex world of confusing cues threatening to overwhelm him psychologically as much as physically. His finest role in the mechanism of this planet may be to become its steersman–*if* he can learn to cut through the plethora of detail his knowledge has brought and "see" the essence of man–nature interactions. Science is unlikely to help if it continues to focus on atoms and the short term. But science is beginning to show some adaptation in the recent shift to systems thinking and methods.

The thesis here is that complexity must be reduced to essentials if complexity is to be overcome as an impediment to understanding and correct action, and this means modeling. The specific tool envisioned is overview models that are macroscopic in viewpoint but minidimensional in complexity–"macroscopic minimodels."

There is a type of orthogenesis within our scientific system that sometimes says a proposed new outlook, theory, or process is more advanced, more sophisticated, and thus better if it is more complex. This is false whenever the new thing is not as energy conserving as a simpler one. It is also false if the complexity causes a communication failure with the human being with which the new science must interface. A science of detail must in the long run be self defeating if, from time to time, useful means of synthesis and summary are not sought. Just as an artist seeks to capture an impression of what he views, scientists also must find ways to suppress detail and formulate the subjective, qualitative essence of facts and figures.

Macroscopic minimodeling is seen as one way to do this, a way that can be freely operationalized on modern, high-speed computers. Such abstract condensations of the real world, it is held, will be useful if they include most of the energy forcings and dominant pathways pertinent to particular considerations. A simulation minimodel of a large system may be the only way to assess consequences of human acts when the system is too complex and ill-defined for direct, controlled experimentation. This chapter presents an approach to such models.

Examples will be given for some of the main issues of uncertainty about systems of man and nature. Generalization to other systems where energy flow and structure are involved will be self-evident. The approach is modular: the main configurations of macro-minimodels have characteristic performances which are implied by systems diagrams in energy circuit language. The diagrams become, in effect, a new kind of mathematics, or at least a substitute for existing mathematics.

The chapter presents performance characteristics of certain minimodels as determined by analog computer simulations. The approach is abstract and general, and related to applications important to current survival issues of man and nature. The models discussed include: money and energy; order and disorder; producer–consumer symbiosis and competition; recycling and mining; succession with declining energy reserves; power titration with war, disease, and diversity; regional development optima; auxiliary power and diversity; and systems with mixtures of constant force and constant flow energy sources.

Included is a section describing basic module performance as an aid to interpreting the energy circuit diagrams.

II. Methods

A. FORMULATION OF BASIC MINIMODELS

There are two approaches toward realizing basic macro-minimodels. In the first, large complex diagrams are drawn representing in detail all relevant components of the system and all outside forcing functions (energy sources). In our experience, this diagram was often done by a group of people with varied backgrounds, a class, or a panel of decision makers. Then, the large model of perhaps 50 units and many pathways is redrawn over and over again, condensing and compartmentalizing, but retaining the key classes of mechanistic configurations, the main energy sources, the state variables of concern, and all constraints of energy, matter, and information.

In the second procedure, a priori interesting configurations for generalizing about systems theory are considered, scanning the varied world of man and nature for examples of their application. Such simple models constructed in advance aid in the recognition of central mechanisms and driving forces that tend to be hidden from the human eye in all the confusions of too much data, too much macroscopic noise, and too close proximity of view from within.

Once a model is defined in simple form, it can be quantitatively parameterized from whatever data are available, translated from energy circuit language into other (mathematical and/or programming) languages, and simulated. Simulations, providing contact with computer software and hardware, facilitate communication between individuals who do not think naturally in terms of energy flow language. However, the prime thrust of the modeling effort is to establish macroscopic minimodels and their diagrammatic language. Energy circuit diagrams, once understood, can be the focal point of communication between scientists and laymen, and in many respects they are more precise than some other systems languages that may be used to represent the same model.

B. ENERGY CIRCUIT LANGUAGE

The diagrammatic energy circuit language evolved for macro-minimodeling serves a variety of purposes. It provides a symbolic general systems lexicon with built-in attention to energy constraints and to dual force–flux laws of single force and population drives. It allows combining energetics and kinetics, formalizing maximum power selection, and generally extending features recognized in ecosystems to other systems, and vice versa. As such, it makes possible unification of principles known in many fields under different names and expressed in different formalisms, it reduces semantic arguments, and facilitates the general process of discourse. Above all, it forces a change in reductionist thinking to synthetic thinking.

Published discussions of different aspects of energy circuit language include the following:

1. description of basic modules and models (Odum, 1967, 1968, 1972a);
2. a general book surveying applications (Odum, 1971);
3. nonmathematical introductions (Wetterquist *et al.*, 1972; Leaird, 1972; Jannson *et al.*, 1971);
4. geochemical and marine models (Odum, 1971c, 1972d, 1975);
5. rainforest minimodels (Odum and Pigeon, 1971);
6. climax man (Odum and Peterson, 1972);
7. economic model (Odum and Bayley, 1975);
8. environmental impact statements (Odum, 1972b; Odum *et al.*, 1972; Littlejohn, 1973; Gilliland, 1975; Zucchetto, 1975).
9. a book for junior college that uses the energy language to explain energy, economics, and environment (H. T. Odum and E. C. Odum, 1976).

An excellent example of application to ecosystem analysis appears elsewhere (Lugo *et al.*, this volume).

Since one of the main technical discussions of basic energy circuit modules is in a previous volume of this series, the reader is referred there (Odum, 1972a). Simple basic configurations not included there are presented here to help in understanding the minimodels that will be described. Figures 1–4, pp. 255–257, summarize the modules and their translations into equation form. It is noted that the equations do not necessarily carry all the information in the diagrams. For example, there may be more than one module possible for a given equation and, in general, the equations do not possess the energy constraints, or exact details of force–flux relationships, or immediate perspective of function beyond the simplest (often linear) cases. A set of differential equations is another way of writing an energy circuit diagram, but the translation is often qualitatively incomplete. In this chapter, mathematical representations are provided on the energy circuit diagrams for clarity, but this is redundant since the language already specifies these quantities implicitly. Each module and pathway has a function transfer coefficient, derivable from data on storage and flow.

C. SIMULATION

At the time *Environment, Power, and Society* (Odum, 1971) was written in 1968, most of the models described therein had not been simulated. Discussions were based on perspective thinking facilitated by the energy circuit language.

Now, however, most of those models have been simulated, and in addition approximately 200 others contrived by various scientists, engineers, and students using the approach. At the University of Florida, we use an Electronic Associates, Inc. (EAI) Miniac analog computer for small models, and for larger ones a variety of machines including EAI 580 and 680, and Applied Dynamics AD-30 and AD-80. Some of our group use digital simulation, implemented by languages such as Fortran, Dynamo, and CSMP, but for macroscopic minimodels most prefer the advantages of hands-on contact and instant turnaround provided by analog computers.

In our use of analog simulation we have developed a number of shortcuts that save time, reduce errors, and increase interaction with the minimodel itself, as opposed to its machine intermediary. Two of these techniques are described below.

1. *Quick Scaling*

Voltage and time scaling are the most difficult parts of analog simulation. They impose a mechanical rigidity on the process that the minimodeler does not want. One approach is to bypass scaled equations (and associated errors) entirely and scale directly on the analog computer diagram. The diagram is arranged so that all potentiometers are arrayed in a column along the left margin of the paper. Opposite each of these a quotient is constructed, with two sets of parentheses in the numerator and two sets in the denominator. In the numerator (left) is written the coefficient value as determined from data. In the numerator (right) the scale factor of the amplifier upstream to the potentiometer is written. In the denominator (left) is put the scale factor of the amplifier (integrator) into which the potentiometer is directed. The remaining set of parentheses is left blank at first (value = 1).

The quotient value is the potentiometer setting. If all the potentiometers fall within a settable range (0.001–1), then scaling is complete and no time scale factor is necessary. A unit of time in the data becomes one second on analog output. If, however, one or more potentiometers cannot be set, all are divided by an appropriate factor to make this possible. This factor, entered in the denominator (right), becomes the time-scaling constant. That many units of computer seconds corresponds to one time unit in the data.

2. *Use of Energy Circuit Diagrams for Debugging and Explanation*

After patching is done energy circuit diagrams can be used directly in place of standard analog computer programs. This increases contact with the primary model and speeds debugging enormously. Amplifier and potentiometer addresses are written directly on the energy diagram and the analog program put aside. Simulation manipulations proceed directly with reference to the energy circuit model. The latter, furthermore, is simpler since half the pathways are eliminated; there are two analog wires for most single pathways on the energy circuit diagram.

Analog simulation has another benefit specific to the minimodeling approach. Even with large analog or analog–hybrid installations, models ought to be kept to a small size (relative to the complexities of macrosystems). This ensures that real tests of essential system properties can be made in a small amount of time and at minor computer cost. Even a moderate-sized analog computer model, with 20 storages, 15 multipliers, and perhaps 100 coefficients, would have of the order of 10^4 combinations of meaningful manipulations. This is not so easily explored digitally. Often, complex digital computer models are only explored in a few combinations. The exercise becomes a computational rather than a theoretical and predictive endeavor.

All models and modules in this chapter have been simulated and explored to determine coefficient sensitivities in varying combinations, tendencies to display oscillatory or unstable behavior, and the relative importance of different pathways. Many of the configurations appear frequently in different applications so that generalizations are beginning to emerge. Most of the time behavior shown was traced from oscilloscope displays.

D. BASIC MODULES AND CONFIGURATIONS

A sampling of some (not all) basic modules and configurations of the energy circuit language, and associated behavior, is shown in Figs. 1–6. To the extent that basic performance curves become mentally associated with network configurations do larger diagrams of systems begin to take on a dynamic perspective.

Figure 1 has force and flow sources, heat sink, and basic pathway equations. Figure 2 defines the storage module and the storage capacity factor. Also given there is a derivation of the interesting truth that the two-thirds law of metabolism and size can be derived from the normal force–flux of first-order systems. The laws of metabolism turn out to be based on the same basic relationships as Ohm's law. Figure 3 has many of the intersection functions commonly used. Figure 4 shows some of the simpler autocatalytic modules (with work looping back from storage to pump in additional energy) and their time dynamics. Depending on the nature of the source (input), some of these will level while others will grow exponentially.

Pairs of self-maintaining units (autocatalytic pairs) are shown in several designs in Fig. 5. Some of these are competitive and some cooperative. Well-established in microbiology and population ecology is the competitive exclusion principle by which exponential growth at high energy levels leads to

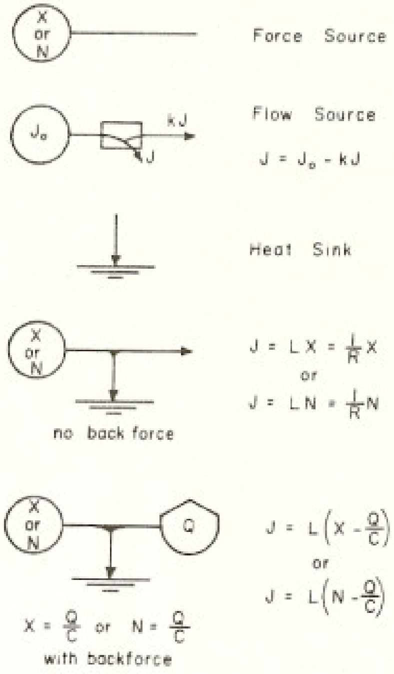

FIG. 1. Basic energy source modules and pathways.

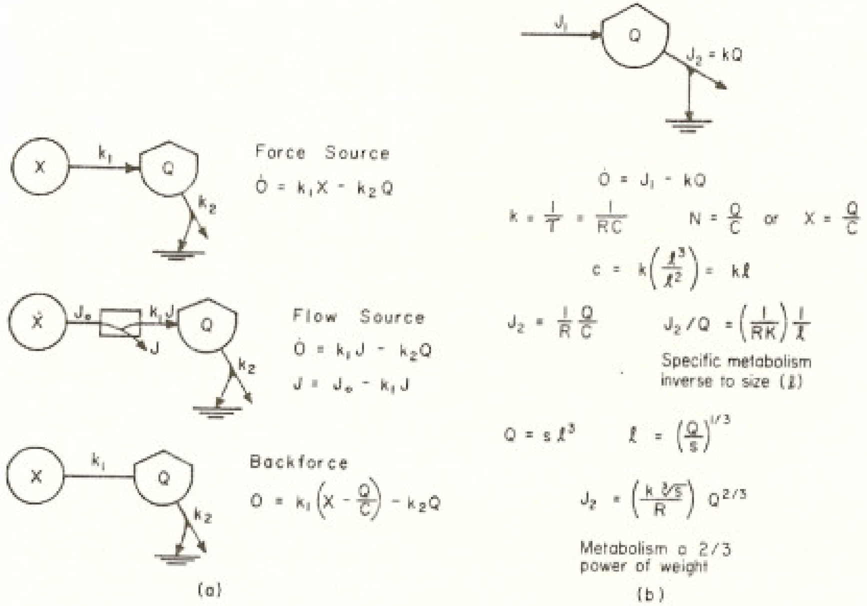

FIG. 2. Basic storage module and its relationship of (a) force and flux and (b) size and metabolism.

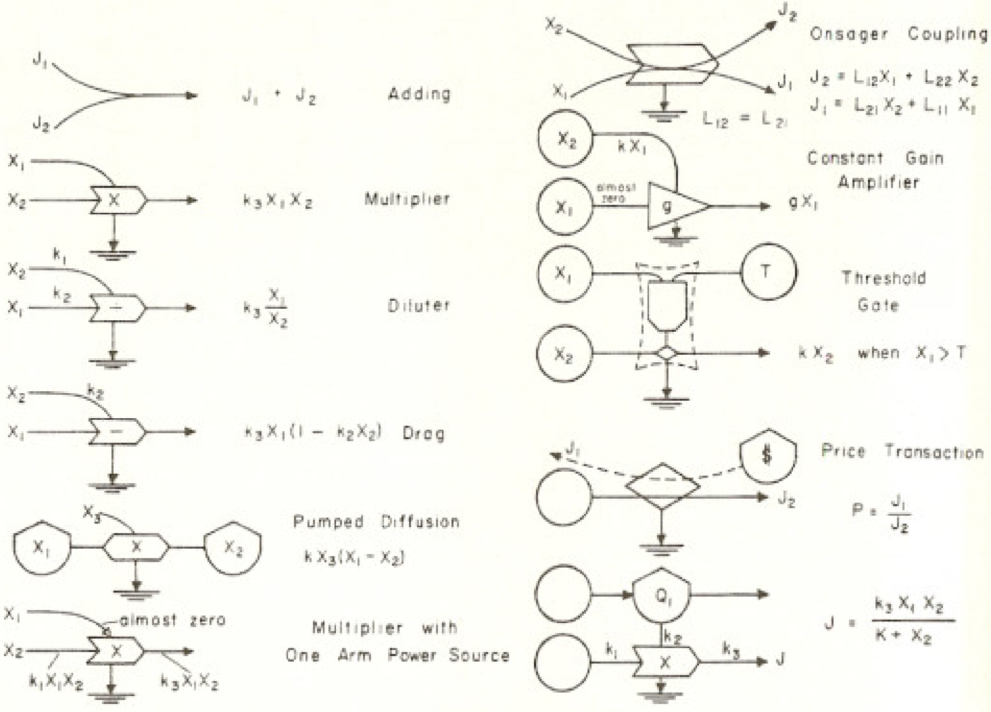

FIG. 3. Basic intersection modules.

only one competitor surviving and absorbing resources. Two designs for this are given in Fig. 5. A pattern that allows continuance of both interactive units is also shown. Most of the more complex designs of minimodels avoid competitive exclusion (i.e., are stable). Finally, in Fig. 6 are several configurations whose behavior is derived from the manner of coupling flow and force-type sources.

III. Macroscopic Minimodel Examples

A. SYMBIOSIS OF ORDER AND DISORDER

If order is defined as a higher state of stored potential energy and lower entropy (less randomness) than average in a system, and disorder as the opposite, then a general symbiosis can be said to exist between ordered and disordered storages. Figure 7 illustrates the essence of this property, showing disordered parts as reactants to incoming potential energy that interact to generate order. The pattern of order is selected that maximizes inflow by feeding back

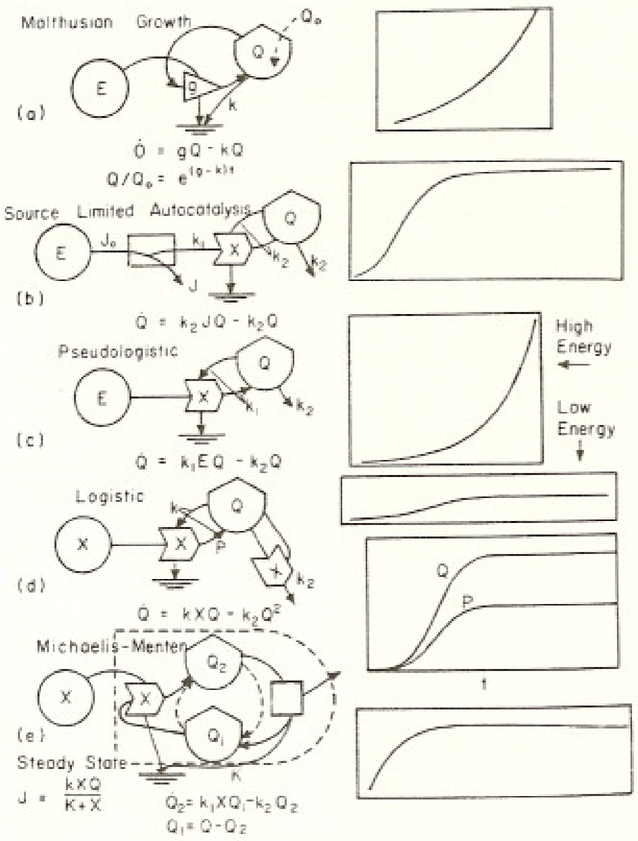

FIG. 4. Basic loop modules.

high-grade, organized potential energies; the power of the system is maximized together with its competitive advantage.

However, as storage energies rise and power flow increases, a shortage of disordered parts to interact with the high power develops and becomes limiting. Increasing disorder is generated as power flow increases, due to entropy-generating tendencies inherent in any high energy state or flow. Thus, disorder stimulates reordering, and reordered energies stimulate disorder. Shown in Fig. 7 (bottom) is a representative response of a system diverted from its steady state. It promptly returns. In some ways the model simulates both Schrödinger's "ordering by disordering" and Lotka's maximum power principle of selection, choosing order from disorder. The model is really a generalization of the P and R ecosystem model in which organic structure is the organized state and regenerated nutrients are among the disordered states stimulating reordering.

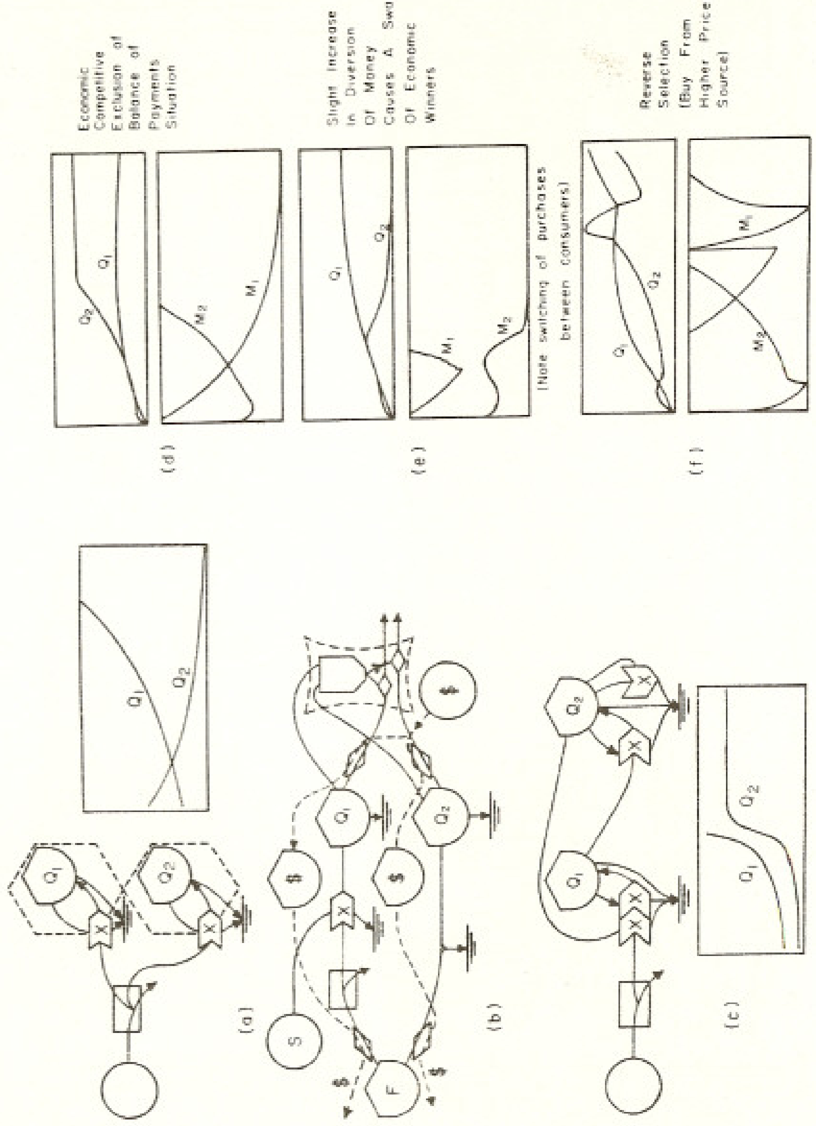

FIG. 5. Configurations of paired subsystem modules.

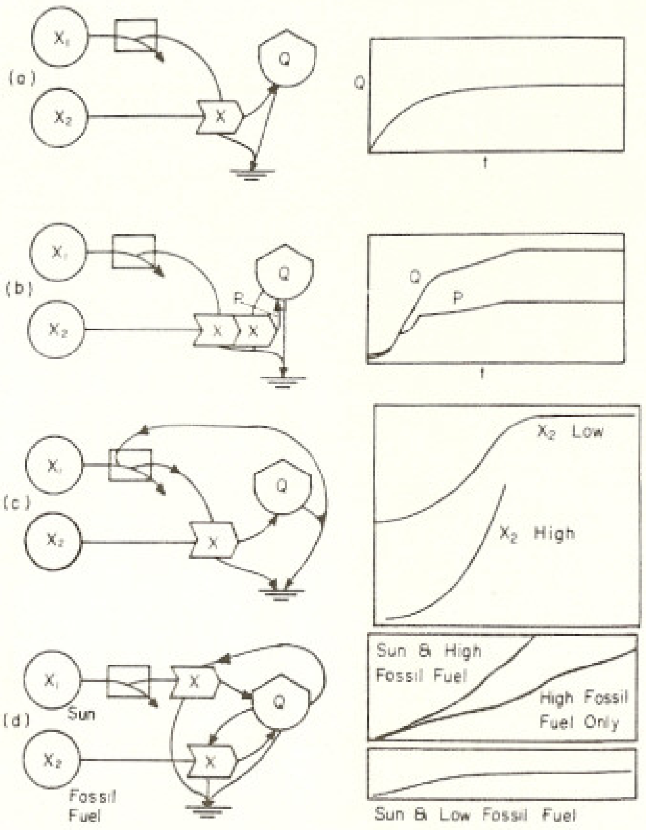

FIG. 6. Interplay of dual energy supports.

Another example of great recent interest is the war states in Vietnam in which the organizing energies of sun, wind, waters, and tides develop vegetation, mangroves, marine communities, and, with fossil fuel inputs, towns and agriculture. With this there also develops a normal disordering tendency that keeps lands, peoples, and materials in slow recycle. Superimposing on this scenario the organized disorder of war, the steady state shifts to a higher disorder–order ratio. It becomes progressively more difficult to disorder further as the ordering potential is increasingly stimulated by more fallow lands, loose building materials, photosynthetic sunlight, and people without occupations. If the disordering energies are turned down, reconstruction is very rapid. We saw this in Germany, Japan, and Italy after World War II, and it will happen in Vietnam also if disordering energies do not continue to be applied.

Another example is the effect of noise, fire, explosions, and so forth, on ecosystems. Richey (1970) showed experimentally that relatively small energies are required to divert order to disorder, but the disorder stimulates very prompt recovery of the more ordered condition. Photorespiration is a further example, disordering in this case being aided by the sun (Odum *et al.*, 1971). Kelly (1971) simulated models of high-temperature disordering that stimulated recycling.

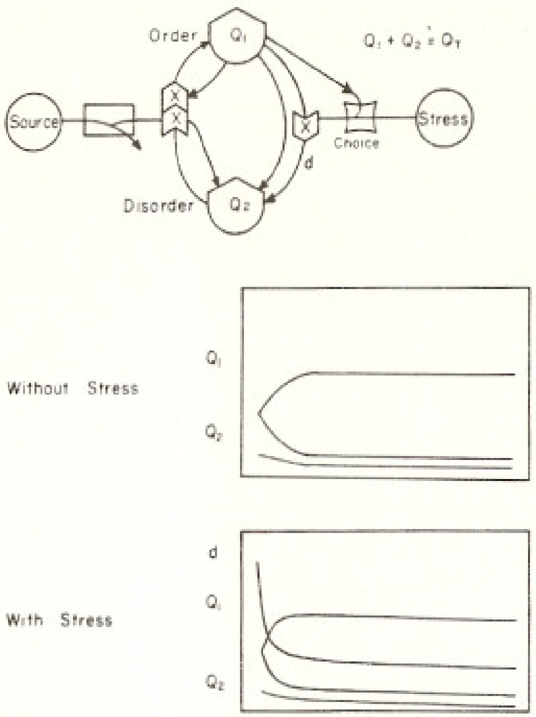

FIG. 7. A model of the symbiosis of order and disorder.

The following dual view of order–disorder seems appropriate. An anthropocentric view of the world generally favors paths from disorder to order. To man, entropy-generating tendencies are "bad." This shows up culturally in various forms: in religion disordering activities are actions of the devil, in economics the antithesis of goods is "bads", in ecology perturbing influences are stresses, and so forth. One wonders if there is not a true general symbiosis of order and disorder, with both essential to the other. Is it too human to regard as good only the ordered half? Is the word "order" suspect since disordered states ultimately have as much amplifier value as ordered states in the total process? A principle of order by energy selection may be as fundamental as the second thermodynamic law of energy degradation, as suggested by Lotka (1922).

B. WAR TITRATION OF DISORDERING ENERGY*

Whereas the essence of war's action as a special disordering energy is embodied in Fig. 7, there are additional roles of war such as in power titration for setting of boundaries between two regimes. Given in Figs. 8a and 9a are models that have some features of the Viet Nam situation, such as two large energy sources that tend to match each other in terms of energy effectiveness impinging on an area (Viet Nam). The essence of the order–disorder recycle symbiosis of Fig. 7 is also included. From one side money is added to purchase material and fuel for reconstruction, but added energy may also bleed off into further war. Figure 8b shows adaptation to war and Fig. 9b a simulation in which a 5-year pulse is introduced, representing the surge of energies, manpower, and money of the U.S. war effort; a matching effectiveness is injected for the opposition, accomplished on the analog computer by a comparator function. The simulation shows a surge of disorder and a new order–disorder balance achieved, which subsequently returns to an older state as the energy pulse fades. It is a property of this model that it is quite impossible to drive the order to zero, a characteristic commented upon by many in the adaptation of the countryside to war.

There are many situations and sizes of systems to which this macrominimodel may apply: for example, fire fighting of brush in pine ecosystems, cops and robbers, and competition between two ecosystems, each of which has soldier species whose preferences in behavioral action are programmed for antistatic actions against foreign members.

C. LEVELING TENDENCIES OF SYSTEMS RECEIVING COMBINATIONS OF CONSTANT FLOW AND CONSTANT FORCE ENERGY SOURCES

Summarized in Figs. 2 and 4 are basic energy consumption modules and their performance with time when supplied from constant force or constant flow energy sources. First there are the growth patterns of a single tank storage (von Bertalanffy module; first-order system) in response to both kinds of source. Steady states are reached as the linear density-dependent outflow equals inflow. Another variation of this has a backflow pressure included. Figure 6a shows the effect of multiplicative interaction of both kinds of sources, as in photosynthesis on an infinite nutrient pool. It also levels.

More realistic for self-maintaining modules are models that include one or more reward loop feedbacks under conditions of competition and maximum power selection. Stored energies have reward loop actions as required to offset

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* This section by C. Swallows and H. T. Odum.

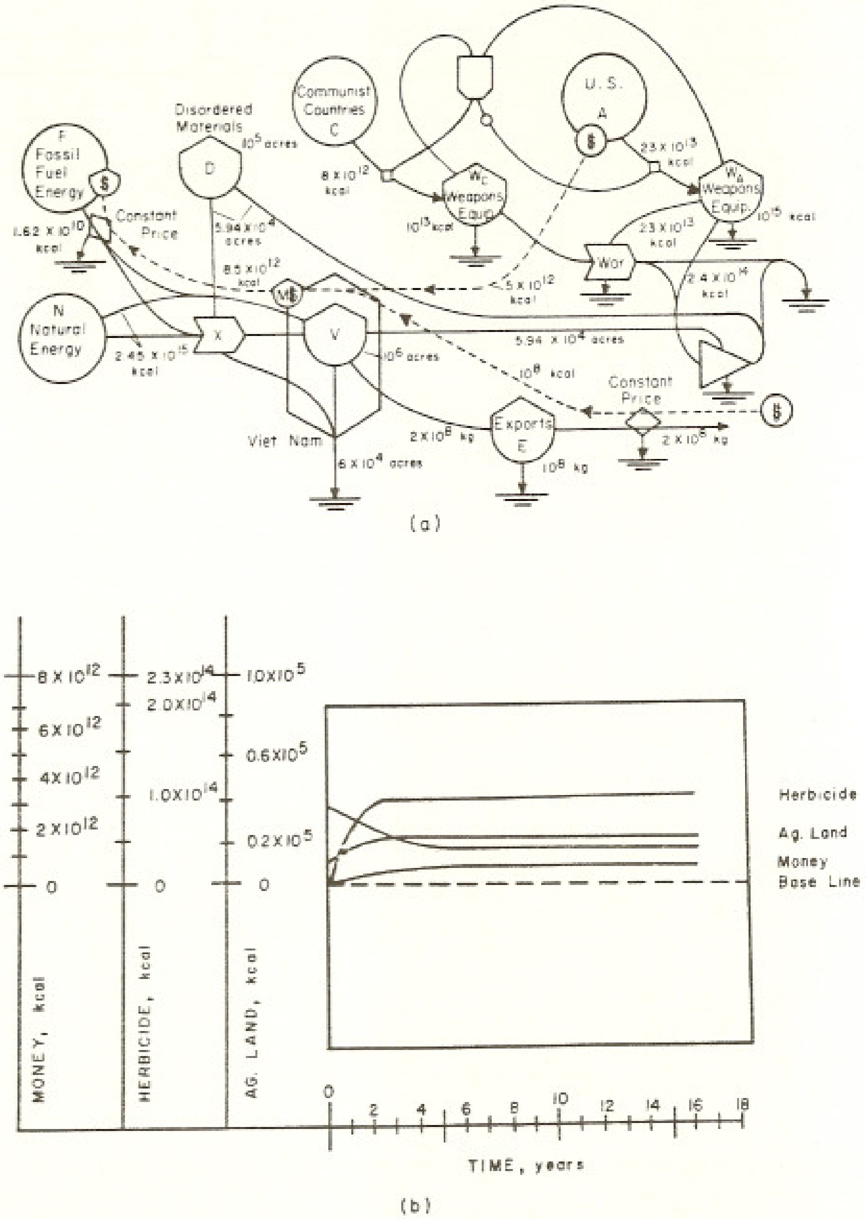


FIG. 8. (a) Minimodel of a steady-state Vietnam-type war. (b) Representative simulation.

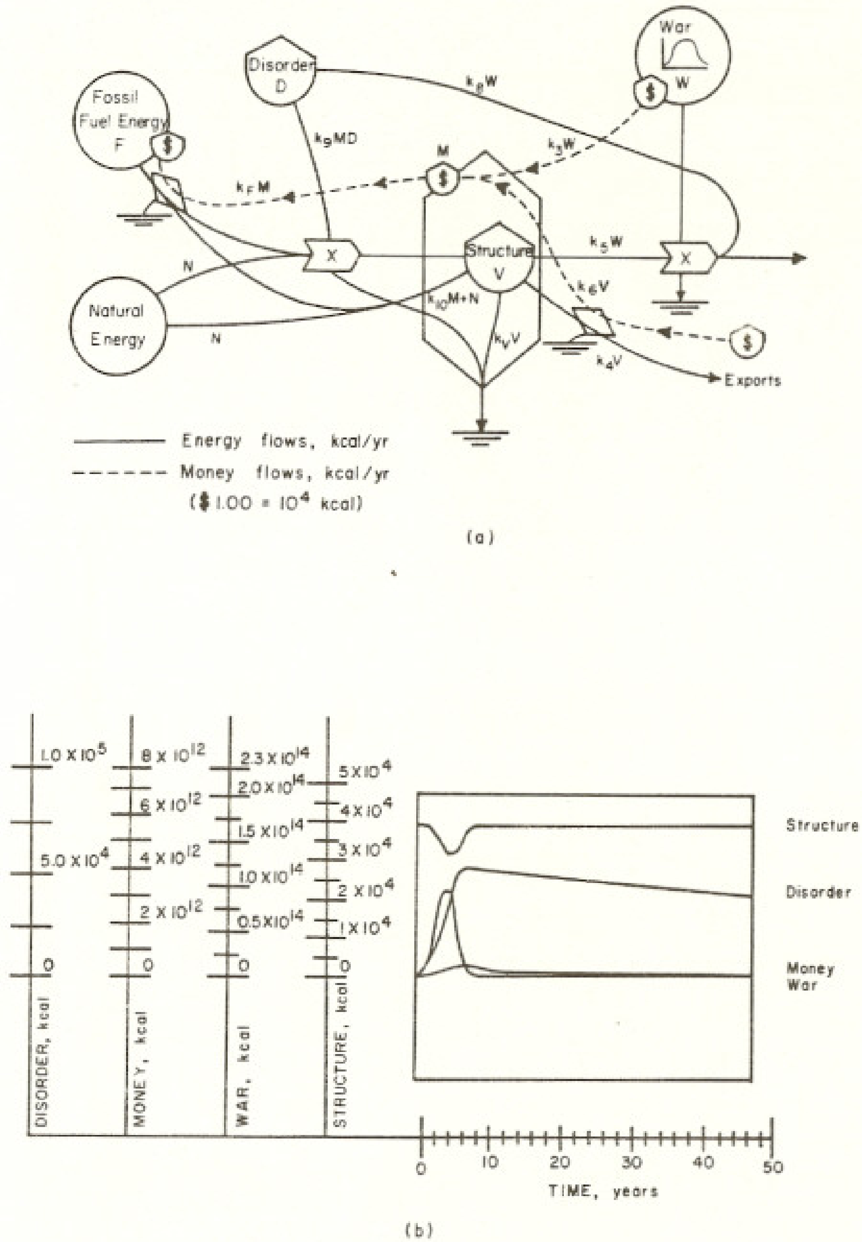


FIG. 9. Pulse of war: (a) A minimodel of disorder–order symbiosis upon structure as stressed by a Vietnam-type war. (b) Representative simulation.

their own drain. The behavior of these units drawing on constant flow and constant force sources is shown in Fig. 4. The constant flow source automatically levels, but the constant force source drives the basic self-maintaining module into exponential growth once power levels exceed a low threshold value. By analogy, when man shifted from solar energy (constant flow source) to fossil fuel (that behaved at first like a constant force source), his system shifted from a relatively steady-state pattern to exponential growth.

If, however, as shown in the Fig. 6 models, the system requires some of each type of input, then the two energy sources are not additive and alternative, but multiplicative and thus essential. In the latter case the system levels to steady state, with limiting energy from the second (fossil) source. But, if the unlimited source can be fed back to do the work of the necessary constant flow source (Fig. 6c), then the system can maintain exponential growth again. Such a system would actually inhibit the steady flow source by preempting the lands and overgrowing the mechanisms.

In nature, systems compete for service and feedback selection control. The system that gets the energy is the one that uses it most effectively. The most effective use is feeding back to auxiliary energy sources, developing energy sources in addition to the primary source. Thus, the first two systems of Fig. 6 get more energy than the third. The power-maximizing system is one that taps all energy sources, not just one.

Suppose the system is one such as man's civilization in which money flows and energy is purchased with a balance-of-payments mechanism that fine tunes the maximum power principle. In this case (Fig. 5b) a system increases its balance of payments for its work if it best uses auxiliary sources of energy. Such a system has a selective advantage in diversifying the energy sources upon which it is dependent. Making good use of auxiliary energies, such as environmental subsidies, levels growth.

D. DIVERSITY AS AN AUXILIARY ENERGY GENERATOR AND HIGH-POWER REGULATOR

Whereas autocatalytic modules with linear, density-dependent drains can level at steady state with low energy inflows, they switch into exponential mode with high energy inputs (Fig. 4c). However, as energy storages rise, square function outflow terms begin to develop. These include backforce interaction with the feedback loop (Odum, 1971, p. 316), and drains due to interactions of dense populations (including conflict, frictions, wrecks, noise, organized waste removal, and so forth). It may be a general rule that high energy levels generate square terms.

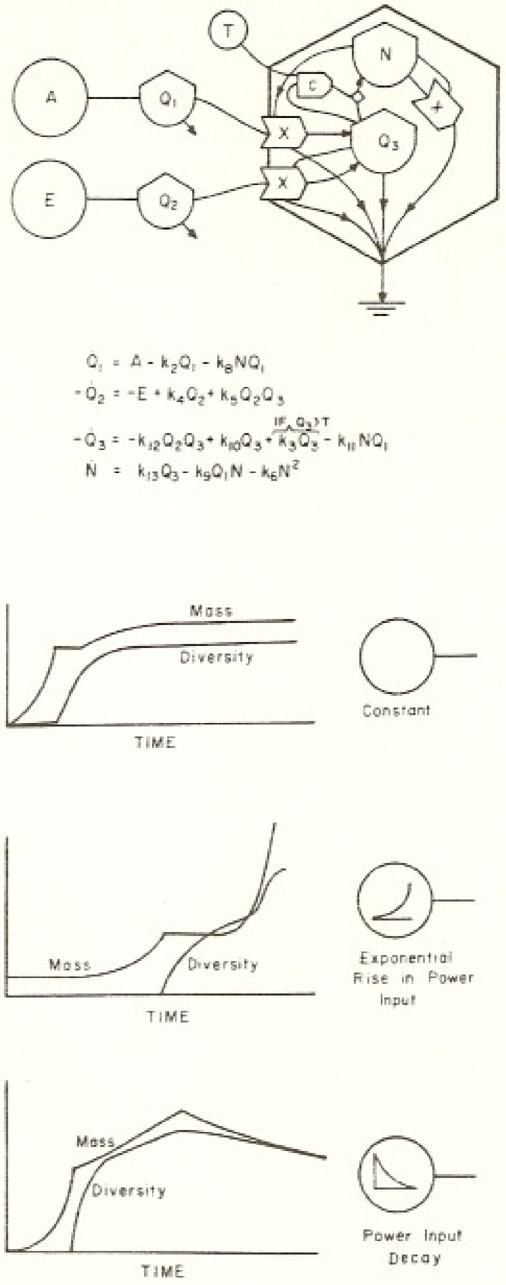
In many energy storage devices such as water tanks, capacitors, and flywheels, storages increase as the square of the quantity carrying the energy storage. High levels of such energies may generate proportional losses. In other words, higher storages have higher maintenance costs, proportionally, expended to prevent losses. In simulating minimodels, autocatalytic subsystems with unlimited energy inputs and no square terms in their drains are soon recognized for their explosive growth characteristics. Such systems are adaptive when rapid growth is adaptive, for example, during successions or epidemics.

When the drain on an autocatalytic module is a square function of the storage quantity *Q*, the module's growth is that of the standard logistic model (Fig. 4d). To some extent, the wide use of such models indicates some generality of quadratic terms in units leveling on high energy support. However, if such terms merely drain a system, it may be selected against in competition with systems using square terms to gain energy from auxiliary sources or to increase efficiencies.

One kind of square term that improves efficiency and taps additional energies is diversity. The maintenance cost of diversity may be in proportion to interaction between the diverse members, and this is a function of the square of the number of types. As shown in Fig. 10, diversity feeds work back to tap other energies, but with increasing costs in the form of regulatory structures, Parkinsonian losses, and general noise.

In Fig. 10 the diversity unit serves as a quality index, a bellwether of the energy condition of the system, and an indicator of high net energies flowing into informational types of processes. The system that grows until leveled by the square costs of diversity outcompetes one that grows until limited by more destructive square terms characteristic of less organized or younger systems. The climax system thus maximizes its total power while using it all in the process, being ultimately the most efficient input processor and least efficient net storage or output processor. The Fig. 10 simulation model develops mass and diversity alternatively during succession, and levels at a diversity allowed by the balance between energy inputs and losses (which are not a part of diversity).

In human systems, with rapid growth based on a succession of new fossil fuel sources, there has been diversification of occupations, specialization, organization, and a trend toward a diversity structure that captures additional sources of energy. Super strains of crops capture more light. Super technology is developing nuclear power. There is a trend toward better land use, better use of the natural energies of ecosystems that support man. The excess energies of wars may draw more energies into the economic and political spheres of influence. Efforts to couple these auxiliary energies may cost more energy than is gained, but at least frivolous expenditures are minimized. Care must be exercised in identifying which parts of human endeavors induce energy savings and auxiliary energy capture. Too little is known, for example, about how activities such as sports, the arts, hobbies and leisure pleasures couple with the total energy inputs and conservation.



$$\dot{Q}_1 = A - k_2Q_1 - k_8NQ_1$$

$$-\dot{Q}_2 = -E + k_4Q_2 + k_5Q_2Q_3$$

$$-\dot{Q}_3 = -k_{12}Q_2Q_3 + k_{10}Q_3 + \overbrace{k_3Q_3}^{\text{IF } Q_3 > T} - k_{11}NQ_1$$

$$\dot{N} = k_{13}Q_3 - k_9Q_1N - k_6N^2$$

FIG. 10. Diversity and succession (Odum and Peterson, 1972).

E. SUCCESSION AND CHANGE IN DECLINING ENERGY SOURCES, NUCLEAR ENERGY, AND RECYCLING

Figure 11 simulates the main features of succession to steady state on solar energy. The fossil fuel world of man is like the fuel supply of a dead log or hay infusion microecosystem. Available fuel declines from the start, firing the successional development of a consumer (heterotrophic) order that builds structure, develops diversity, and finally recedes as the energy disappears. The system that ultimately remains is one that shifts to other energies. The nature of such patterns is given in the minimodels of Figs. 12–14. Each of these shows patterns of exponential growth, sigmoid decay of reserves, and finally decline of processes leaving only some of the remnant structure of the system.

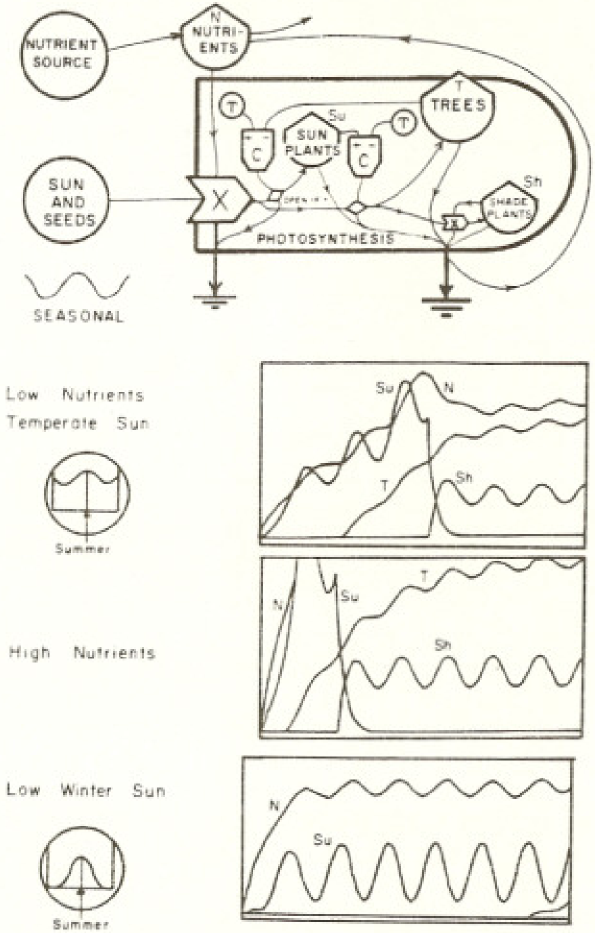


FIG. 11. Succession and vertical structures.

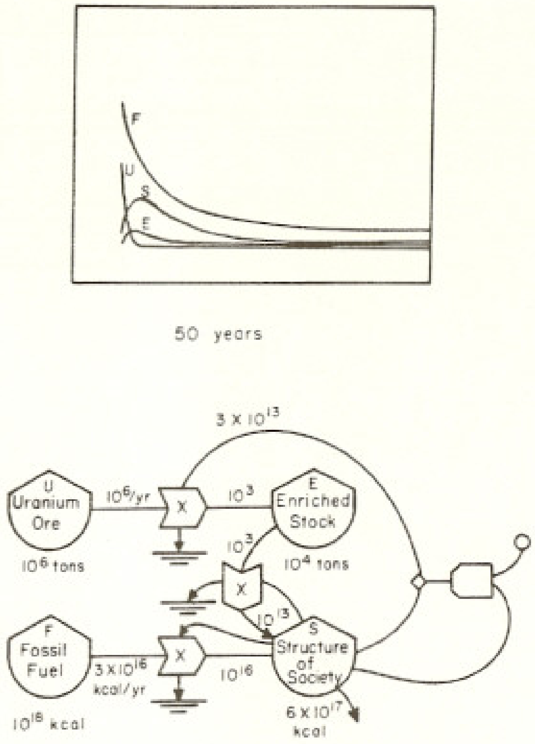


FIG. 12. Nuclear energy and auxiliary energy.

Figure 11 shows the progress of diversity during the rise and fall of a seasonal pulse. Figure 12 shows the pattern for nuclear power as it is now heavily subsidized by fossil fuels. If new processes (such as breeder reactors) with wholly different levels of conversion do not become new yielders, the nuclear power will run out before the fossil fuel, just as diversity disappears before all flow of life in a decaying log. Figure 13 includes material recycling as an alternative when scarce materials become more expensive to obtain from primary sources than the costs of recycling. This is another example where the main energy source is used to supply auxiliary energies, and where scarce materials have the amplifier release action by which necessary materials are recognized as auxiliary energy sources.

A word about net energy. Familiar to ecologists are the contrasting concepts of gross and net production, gross being input from synthesis and net being what remains after some feedback work has been done. The difference is not so familiar to the public, nor to leaders now showing concern for power policy. Usually when large fossil fuel reserves have been estimated gross energy was

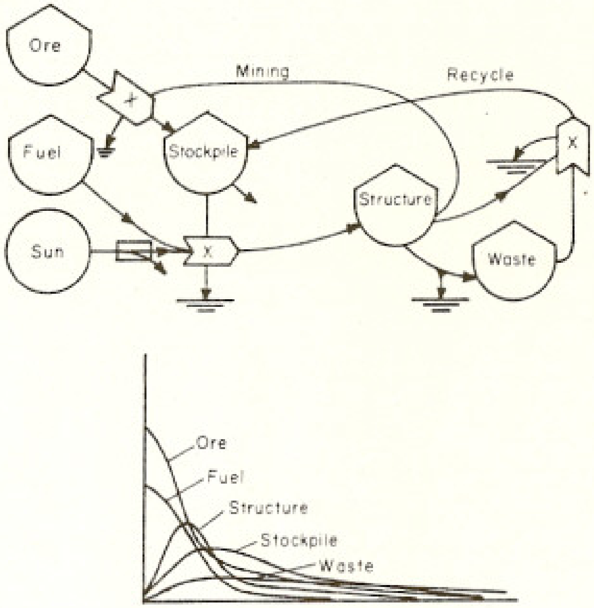


FIG. 13. Recycling and mining.

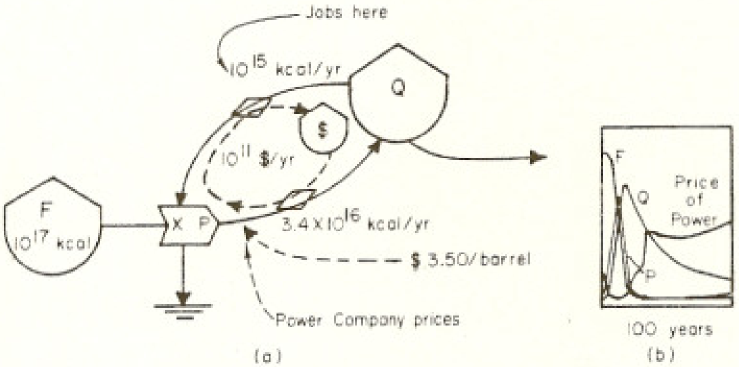


FIG. 14. Basic money–energy relations.

measured; the costs of concentrating and distributing were not subtracted. Much of the presently discussed reserves may actually be negative when the costs of delivering them for use are read in. When there are excess supplies of rich energy it may pay to expend some to develop less rich sources. But as rich energies decline the non-net paying energies must be dropped. Thus, if the new nuclear processes cannot be brought to new levels of magnitude of *net* yield in time, they may have to be dropped entirely.

F. THE REWARD LOOP AS A CONSTANT VALUE CIRCLE, AND COUNTERCURRENTS OF MONEY AS POWER-MAXIMIZING MECHANISMS

The energy theory of value described in *Environment, Power, and Society* (Odum, 1971) apparently caused some confusion because there are two values to be associated with any energy flow, both correct. Figure 14 shows a reward loop feedback system in which entering energies are gradually dispersed into heat sinks according to the second law of thermodynamics. If the feedback flow of energy from *Q* were diverted and its heat content evaluated, 10^{15} kcal would be found if it were used alone. However, reward loop feedback energies are of very high quality. The energy diverted from *Q* has the special and unique property of being able to release input flow of raw fuels at *P*. The flow may be a special nutrient, some information, a technological development, and so forth. If the feedback flow acts as *P* it becomes part of the energy flow of that multiplicative process and is as much responsible for the 10^{16} kcal output as the fuel flow itself. Thus, the feedback path shares a potential energy value of 10^{16} kcal with the fuel flow as it acts and while it is en route. The energy lost to heat sinks in developing the high quality of energy is needed to maintain the action releasing value constant within the closed loop value circle. Since other, open loop pathways handicap the energy sources they draw upon, natural selection will tend to retain those path loops that provide equal multiplier value to the upstream action in exchange for the energies they drain.

Money in human systems flows in the opposite direction of energy around a value loop. It serves as a lubricant, rapidly adjusting the choices of pathways (feedback loops) for total maximum power of the system. Since natural systems have the same value loops without money, money can be taken as an evolutionary refinement of effective value calculations to harness man's mind and energy for system function. Money patterns may follow from energy patterns and serve to distribute power optimally within the system for survival. Money causes those energy paths to interact that best release more power loop values.

Within the constant value loop there is an overall constant ratio of potential energy value to money. The simplest such loop is shown in Fig. 14, with a countercurrent of money. In general, money flows from a site in proportion to its storage, and is spent soon after it is acquired. Its turnover rate may be two to four times per year, representing the tendency to reinvestment. This is a fast turnover relative to the system in which the flow is a countercurrent, and thus money may show noisy fluctuations in the same way that scarce nutrients do in plankton systems.

1. *Variable Price Models*

Equations for a system of energy and money flow may be forced on a model system using empirical inverse curves for the relationship of price (energy per unit money) and supplies of energy stocks. A simulation with this kind of model was given by Odum and Bayley (1975). However, the model discussed next suggests that these properties emerge from energy flow loops without being forced into the model.

2. *Prices Determined by Energy Flow*

Consider a world system in which the feedback goes to the fuel-processing industry and the storage is the main structure of society. Suppose the amount of money circulating is constant, and the system is putting all its work into developing feedback multipliers to maximize power. Instead of forcing a price relationship into the model, let the price emerge as the ratio of the energy flow and money flow systems. In effect, this assumes expenditures in proportion to concentration. In the Fig. 14 minimodel, price emerges as an inverse function of energies available for purchase and monies available to be spent. With both money and energy flowing according to their stock, their ratio (price) develops in relation to stocks, as in classical (supply–demand) economics. Man, with "tunnel vision," may actually achieve the macroenergetic needs for system survival through greed about money, and culture is apparently selected to do so.

3. *Inflation from Declining Energy*

Now consider the money–energy model of Fig. 14, with a constant supply and turnover rate of money, but with declining energy reserves. When energy is (initially) plentiful, fuel prices are low and money tends to accumulate with the processors of power. Few work services are needed to get the fuel and so the money paid to feedback services is large. People have high salaries and wages, and there is surplus energy to put into higher living standards and seeking auxiliary energies. As fuels decline, feedback work to maintain the system is required. Gross energy consumption may increase but net energies soon begin to drop. Then fuel prices become high and payments for services low. The net energy circulating within the loop is less and the ratio of money to energy is high. This is inflation.

How much of world inflation is due to the declining concentration of fuels? Many economic indicators seem to show economies expanding because gross energy input is increasing. But, as more and more resources go back into securing power inputs, the net effect is less work value for the same energy. Net energy and standard of living depend on energy concentrations.

4. *Economic Competitors in World Fuel Monopoly*

The model shown in Fig. 15 features two economic competitors for fuels, each with a balance of payments with which to buy the fuels. A comparator function selects the pathway with highest fuel prices for the fuel processor to sell to. Another comparator selects lowest prices for purchase of feedback goods and services. The two systems have auxiliary energy sources such as environmental inputs. The one with the greater environmental subsidy is able to sell its services more cheaply, thereby gaining more money for fuel purchase. This element should win the competition. But, later in time, the competitor with higher levels of structure based on the earlier preferred energy position has increased energy losses and less cash. The other system begins to take the

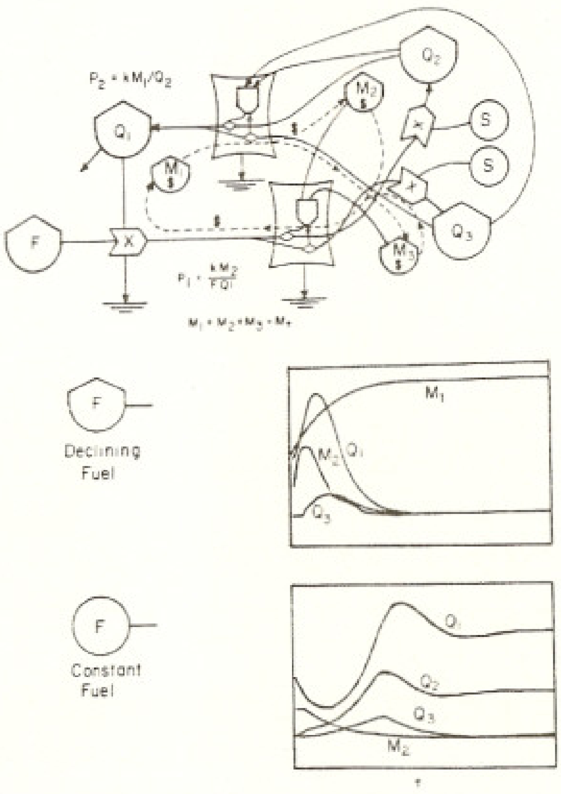


FIG. 15. Competing economic systems.

energies. There is an alternating action of first one buying and then the other (as indicated on the computer by flashing of comparator lights). The net effect is to maximize the coupling of both fuel energy cycles, giving maximum power flow for the whole system.

In this model the monies end up with the monopoly fuel supplier. The model was run with a constant energy source and also one of declining concentration.

G. DISEASE AND DIVERSITY

Diseases often regulate populations. Collectively, diseases generate diversity by eliminating dominance of energy flows. In steady-state situations diseases take relatively small energies, but enough to suppress populations to levels where they are present and available. When host stocks become large, the disease becomes epidemic and repressive square terms begin to operate through such mechanisms as increased probability of infection and increased virulence due to mutation. Diseases, like carnivores, may provide continual energy tests to organisms. A host organism with energy reserves generally dissipates the disease so long as its energy inputs are large. Old age, starvation conditions, or unbalanced density–resource ratios are properties that may set disease into nonequilibrium action.

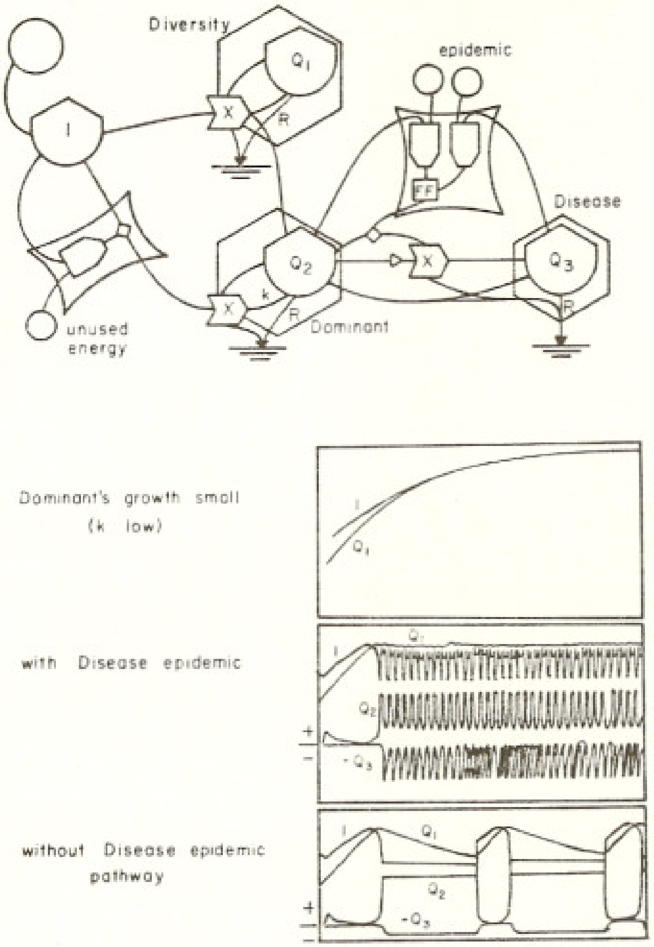


FIG. 16. Disease and diversity.

In Fig. 16 some properties of disease and diversity interactions are incorporated into a minimodel that has provision for epidemic response when stock thresholds of a dominant host are high. There is also a threshold for disease disappearance when host levels become very low. The model can develop dominance first, followed by diversity, with disease acting to ensure that the diverse stocks replace the dominant. By this action the total energy budget of the system is increased through greater efficiencies. The disease is part of the energy-augmenting auxiliary work. The Fig. 16 simulations show oscillations, with period determined by energy flows into the dominant's growth. Disease action produces a faster system with more stability, and the highest energy levels are without the tendency to overdevelopment with the energies going into diversity.

With declining energies available to human systems, disease can be expected to increase as less energy is invested in eliminating the population control role.

H. DESIGNS FOR SIMULTANEOUS COMPETITION AND SYMBIOSIS, ENVIRONMENT, AND FOSSIL FUEL

If competition is defined as two systems drawing on the same energy source in parallel, and symbiosis as two systems that are serial parts of a constant value loop, then a number of systems become easily distinguishable, as represented by examples in Fig. 5. The *P–R* model (Fig. 17) is a cooperative, reward loop linkage that has been much used to simulate diurnal and seasonal patterns in ecosystems. If matter is conserved and recycled, the system becomes a Michaelis–Menten module (Fig. 4e). The parallel competing models and predator–prey models in Fig. 5 were among the first models (Lotka–Volterra) in population ecology. In these, competition is distinct from symbiosis.

When larger systems like estuaries or world energy sources are diagrammed, opportunistic designs that switch to different combinations of energy sources begin to emerge. These systems may have cooperative and competitive pathways at the same time. Figure 18 shows a simple case of two parallel (competitive) modules in respect to nutrient use when there are only two energy sources. When there is only one source the units become symbiotic and recycling.

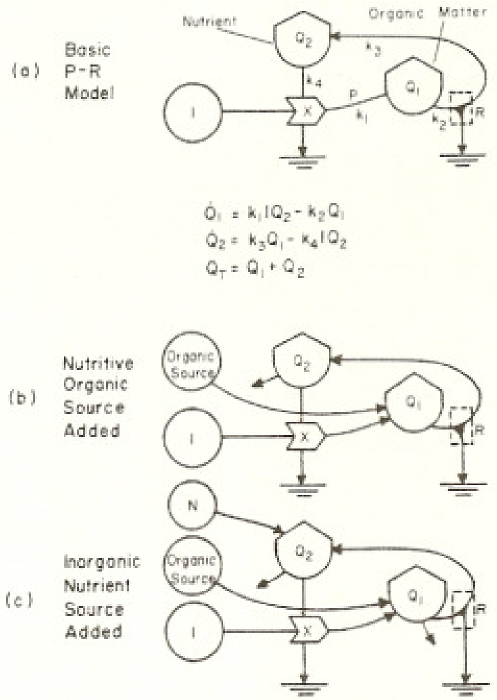


FIG. 17. (a) Basic *P* and *R* recycle model for closed system and its variation with (b) organic and (c) inorganic advections.

Estuaries of the central Texas coast sometimes receive river organic inputs from the land, which leads to bacteria–plant competition for nutrients. When these inflows are zero, the heterotrophs use only plant output and become recycling consumers. With converging food chains higher animals in these situations switch to exploit both chains as the energy source ratios change from plants to microconsumers.

The worldwide man–nature system is similar, with organic inflows from fossil fuels supplementing solar energy, both contributing to man's urbanism as a switch consumer mechanism. Without fossil fuel man is symbiotic with the solar-based environment; with it his relationship takes on competitive aspects. Viewing the system's overall maximum power, however, the design with both competitive and cooperative pathways allows flexibility in drawing from many energy sources, thereby optimizing survival. Switching between energy sources when competing for scarce nutrients in effect allows a continuous selection for maximum power.

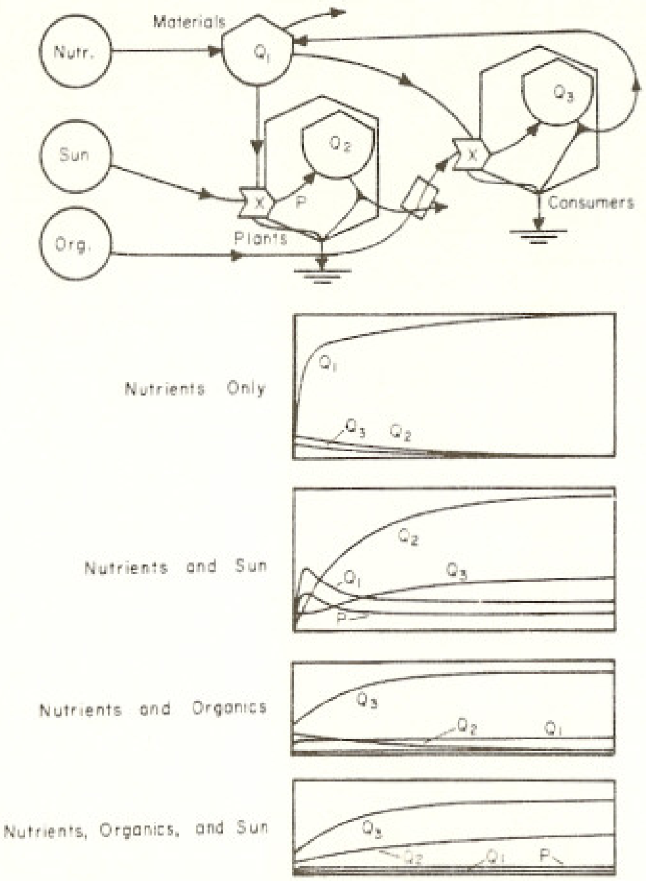


FIG. 18. Mixture of parallel and series.

The time dynamics curves in Fig. 18 indicate consequences of the system (same parameter values) operating with energy supplied in four combinations from two sources: on, off, and each alone. Whereas the model is simple and clear enough, attempts to describe it in terms of symbiosis and competition concepts lead quickly to semantic problems. The history of ecology is replete with semantic debates caused by lack of adequate models to expose essential relationships. Language clarification is another benefit of macroscopic minimodels.

The flexibility of serial–parallel designs in switching a system between different inputs in whatever combinations they occur makes for optimality. The system is doing something like automatic linear programming for maximum power.

I. ENERGY VALUE TABULATIONS

Macro-minimodels can also be used to calculate value in large-scale applied problems involving public decisions. We refer to this procedure as an energy cost-benefit method because all flows in the system (matter, information, money, and so forth) are converted to energy equivalents.

Figure 19 shows a simple example of energy evaluation in which parts of the system's transactions are accompanied by money flows and other parts are not.

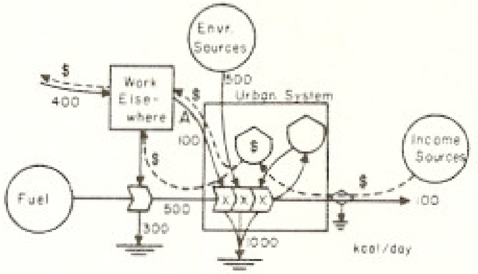


FIG. 19. Diagram for energy analysis.

As in Fig. 19, flows of various kinds of energy are shown in Calories of heat they release when degraded. According to the first energy law, the inflow energies ultimately balance outflow energies. However, the value of these energy flows in causing work differs because the kinds of energy flow are different (sunlight, food, human service, and so forth).

Energy analysis is done by converting the Calories of energy flow of various types and quality into equivalent Calories of the same type such as coal. Money flows as a countercurrent to some of the flows of energy. Money value is believed to equal the energy flow in the opposite direction when that energy has been expressed in units of equal quality. On the average, in 1975 20,000 Calories (Kilocalories) of coal equivalent energy was used per dollar spent. Converting money data to energy data allows one to evaluate high quality goods, services, and labor contributing to the work of a system.

Next, energy flows of the first diagram are multiplied by energy quality factors to put them all on the same basis such as Calories of coal equivalents. For example, sunlight is divided by 2000, because 2000 Calories are required to develop a Calorie of coal. A car built in Detroit with energy flows there brings high energy value with it elsewhere. Its value is measured by the energy required to replace it. Where several energy flows interact energy value is that of their collective action.

After the energy evaluations are tabulated they may be compared with diagrams for alternative plans. Systems with more energy flow can prevail. More energy flow results if more income can be attracted. More income is attracted if there are good, free, environmental energies as matching energy. Therefore, the level of investment that can be economic is determined by the level of environmental sources. Maximum energy flow occurs when economic development is at an optimum intermediate density.

IV. A Note on Symbolic Languages

Most scientists think pictorially, and ecologists are no exception. The diagramming of energy flows as a means to represent ecological systems started early in this century when vague food chain arrow diagrams were first drawn. Gradually, as ecology became more quantitative, these diagrams were made more quantitative. Such evolution is not unique to ecology; dozens of diagramming languages have developed in the highly mathematical engineering sciences (signal flow graphs, block diagrams, electrical networks, etc.).

In 1963. Forrester (1963) introduced a symbolic simulation language in connection with Dynamo, a digital computer language now widely established in programming libraries. The initial applications were industrial and urban problems, but this has now extended to world simulation (see preceding chapter), culminating recently in the best-seller status of "The Limits to Growth." The symbol diagrams of Forrester's language are now extensively used in systems ecology. The basic modules are illustrated in the right-hand side of Fig. 20.

Energy circuit language may be compared to the Forrester scheme. Correspondences between symbols are indicated in Fig. 20. Energy circuit language is less empirical and based more on certain physical and biological principles. Conservation of energy, for example, is built in as heat sinks. Forrester's language visualizes a system as a set of material subsystems linked with cross system coefficients or functions, and influenced from outside through such functions. Energy circuit language shows all paths in a system as energy flows explicitly governed by energy laws. The natural selection principle for maximum power is represented by feedback multipliers on all pathways, making linear models unreal for most purposes (next chapter). Energy force constraints prevent developing a model with more or less action than the energies involved. Switching processes are explicitly represented. In short, energy circuit language is consistent with important principles under which macroscale natural systems

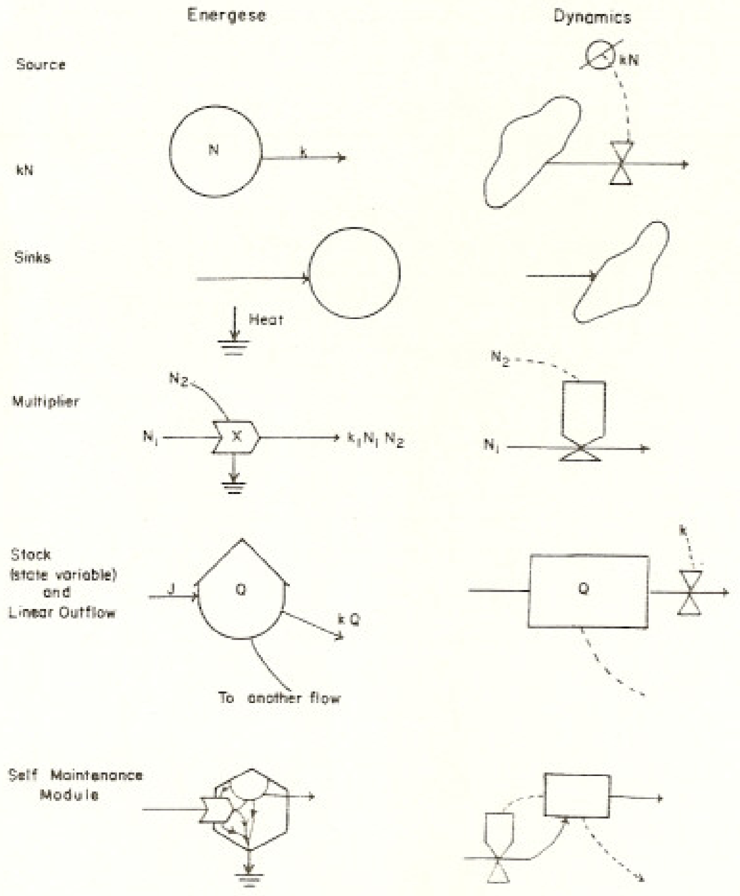


FIG. 20. Forrester translations.

operate. Since these principles are built into the language, the language can be used without conscious attention to them.

As such, it becomes a medium for rapid broad-brushing of the essential aspects of complex systems. It is a tool for suppressing detail and expressing the essence of systems' global operating features. It is a means of gaining quick insights at the whole system level by minimizing the scientist's reductionist tendency. Operationalized on computers, energy circuit diagramming of man–nature systems offers the possibility of piercing complexity, visualizing questions important at the system level, evaluating alternative human actions also at the system level, and in general makes possible a macro approach to man's energetic relation to this planet. Such is the role visualized for macroscopic minimodels.

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