Self-Organization, Transformity, and Information

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Ecosystems and other self-organizing systems develop system designs and mathematics that reinforce energy use, characteristically with alternate pulsing of production and consumption, increasingly recognized as the new paradigm. Insights from the energetics of ecological food chains suggest the need to redefine work, distinguishing kinds of energy with a new quantity, the *transformity* (energy of one type required per unit of another). Transformities may be used as an energy-scaling factor for the hierarchies of the universe including information. Solar transformities in the biosphere, expressed as solar emjoules per joule, range from one for solar insolation to trillions for categories of shared information. Resource contributions multiplied by their transformities provide a scientifically based value system for human service, environmental mitigation, foreign trade equity, public policy alternatives, and economic vitality.

ON THIS BLUE PLANET EARTH, SELF-ORGANIZATION IS connecting parts and processes into a new kind of global system that includes earth, air, oceans, biogeochemical cycles, living species, human minds, and knowledge. A frenzy of processes seems to be accelerating, as millions of human minds are being linked with flows of money, electronic signals, and information. What principles explain these information storms?

Increasingly in recent decades, ecosystem study has generated concepts that may apply to all complex systems when appropriately generalized with network models, energy, and information. Observing self-organization in nature suggests how energy is related to hierarchy and information. New measures of energy hierarchy, transformity, and EMERGY (spelled with an "M") are used to evaluate environmental contributions to the economy and public policy alternatives.

Self-Organization

In 1955 we turned to simple ecosystems that develop in closed containers (*3*) to find the essentials of self-organization and develop basic models with which the larger ecosystems of forests, lakes, rivers, reefs, and oceans could be compared. We found that once seeded with many available species, microcosms such as the aquarium in Fig. 1a rapidly developed a basic ecosystem organization shown by the production-consumption-recycle model in Fig. 1c. As self-organization proceeded, more of the available energy was used.

The systems diagram shows the way energy is processed, some being dispersed into heat at each transformation as part of necessary work in generating units at the next higher level. Figure 1b shows the three-level energy hierarchy of sunlight, plant producers, and consumers (on the right). The consumers are higher in the hierarchy toward which products converge and from which services and valuable materials diverge as they are recycled, stimulating production again. This basic ecosystem plan is similar to the production-consumption model of economic systems except that the latter also has money circulation.

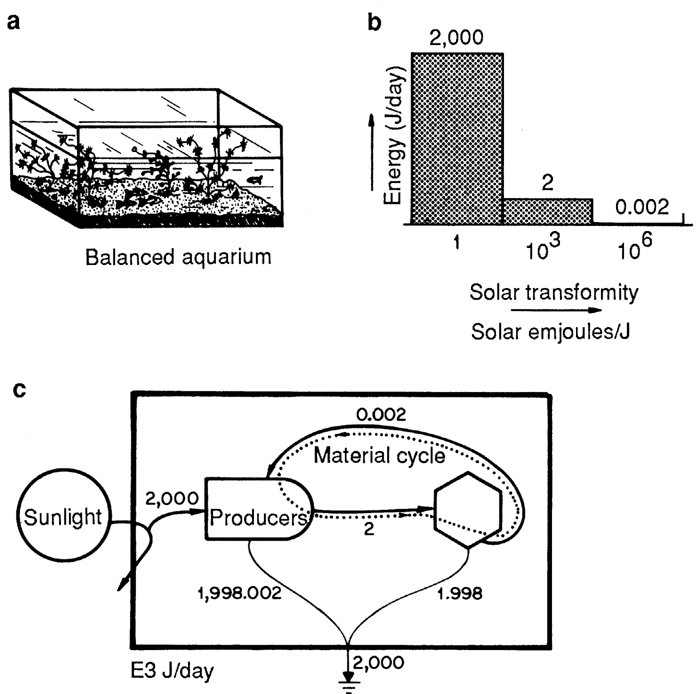

Fig. 1. Energy flow and transformation in a closed aquarium ecosystem. (**a**) Sketch of closed aquarium, (**b**) graph of energy flow as a function of solar transformity, and (**c**) energy systems diagram of the standard production-consumption model (*1, 2*). The cycle and reuse of chemical materials is shown with a dotted line accompanying the energy flows. Solar EMERGY and transformities are below; E3 means 10^3; similarly, E20 means 10^{20}.

Path	Energy (E3 J/day)	Solar EMERGY (E3 sej/day)	Solar transformity (sej/J)
Sunlight used	2,000	2,000	1
Organic produce	2	2,000	1,000
Material recycle	0.002	2,000	1,000,000

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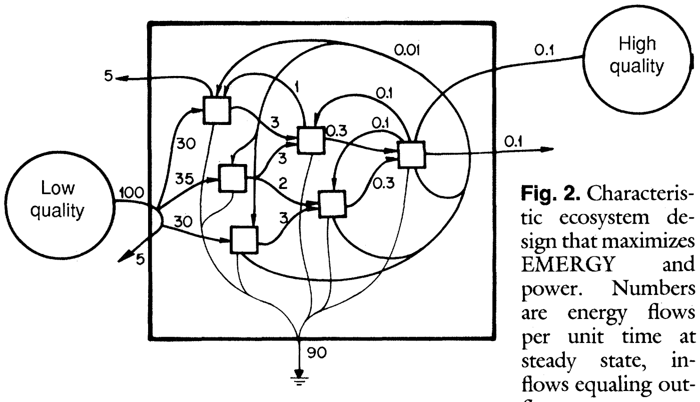

Fig. 2. Characteristic ecosystem design that maximizes EMERGY and power. Numbers are energy flows per unit time at steady state, inflows equaling outflows.

Hypotheses of self-organization. The hypotheses of energy transformation in self-organizing open systems, quite beyond classical energetics, involve concepts of self-development (such as evolution and systems learning) in energy terms. During the trials and errors of self-organization, species and relations are being selectively reinforced as more energy becomes available to those designs that feed products back into increased production.

Efforts to explain self-organization as a selection of designs for maximum power were begun long ago by scientific theorists, S. Podalinsky, L. Boltzmann, F. M. Ostwald, A. J. Lotka, and many others (*4*) starting in the last century, but these explanations ignored the different qualities of energy. Work of an intelligent human counted no more than that of a plant leaf. Now, however, insights from ecological food chains help us reformulate definitions of work and distinguish energy types quantitatively.

Energy transformation in ecological webs and chains. Characteristic ecosystem designs result from self-maximizing energy flow. The typical system design is a web of energy flows (pathways) and transformation processes (box units) represented in aggregated form in Fig. 1 and in somewhat more detail in Fig. 2, where there is a second outside energy source. Energy flows are given on the pathways at steady state with inflows equal to the outflows. At each transformation (box), most of the available energy is degraded and dispersed as a necessary part of generating a smaller amount of energy of another type to the right. Later in this paper items farther to the right are defined as higher quality because they require more resources to maintain. As in a military hierarchy, services and controls are moving back down the hierarchy (to the left). The higher quality but smaller quantity energy types feed back as controls, reinforcing (amplifying) the production processes. For example, large animals control the more numerous smaller organisms by their behavior, placing of waste products, ways of eating, and control of pollination, seeding, and reproduction.

The by-product materials released from each unit recycle back into the production process. These patterns emerge after the feedbacks have amplified (and thus selected) those pathways that are mutually reinforcing. In a forest hierarchy, for example, sunlight is concentrated by leaves, which converge their products to twigs and limbs and these to trunks, litter, and animals. In turn, the trunks, litter, and animals feed their support and materials back to limbs and these to the leaves. The connections between units of the systems in some cases are visible, such as roots in the soil, but most of the pathways of interaction are invisible and intermittent, as when bees pollinate flowers or animals communicate. Consumer units are useful because they feed back reinforcing materials, service, and information.

Ecosystems, earth systems, astronomical systems, and possibly all systems are organized in hierarchies because this design maximizes useful energy processing. These systems look different until they are drawn with energy diagrams. Most systems have a chain of energy transformations like an ecological food chain.

Mathematical pathway selection by power level. The essence of self-organization is automatic reinforcement of available choices. In ecosystems the multiple choices are the information in the species and their genetic variation, which allow many possible types of pathways to be tried out (*5*).

Provided the choices are available, the more available energy there is, the higher is the mathematical exponent of the pathway that dominates the energy competition (*6*). See Fig. 3 for the computer simulation. At low energy the simple linear pathway carries the most flow; with more energy available, the autocatalytic pathway prevails, and with higher levels of energy the quadratic-autocatalytic pathway predominates.

An example of the shift from linear to autocatalytic flow is the shift from nonliving processes when food is scarce to living units when food levels are higher. An example of the shift from autocatalytic to quadratic-autocatalytic flows may be the takeover of populations with intraspecific cooperation as studied by Allee (*7*). Physical examples of self-organization for maximum power utilization are the switches from laminar to turbulent flows at higher levels.

Emulation of goals of self-organized systems. The following is the hypothesis as to the way systems of various kinds are constrained into similar mathematics and energetics by self-organization: As illustrated by the one-source example in Fig. 3, there is a mathemati-

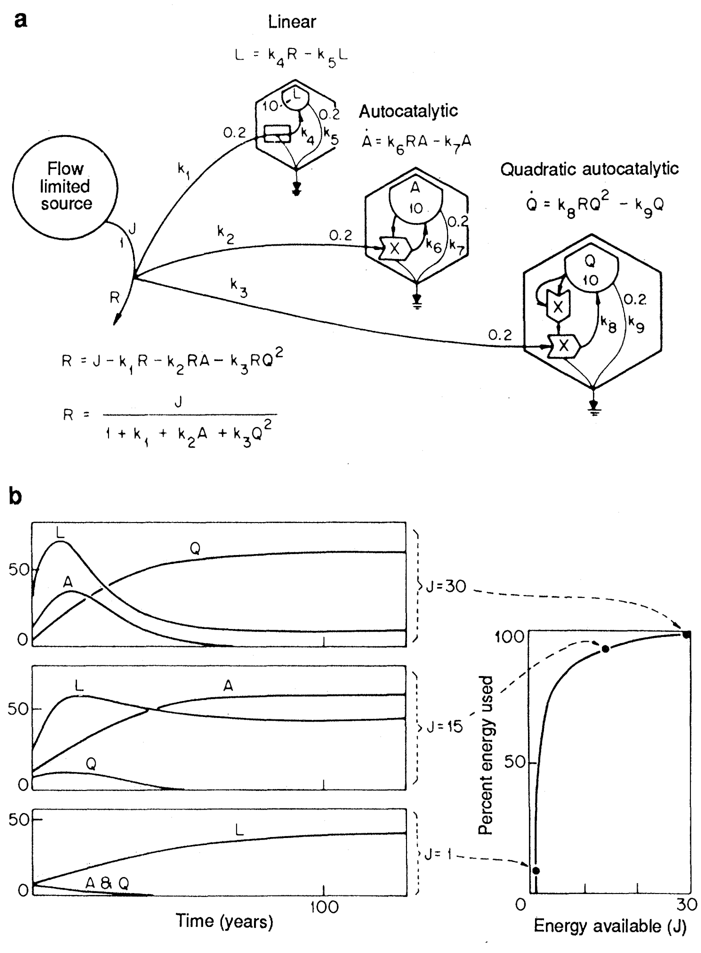

Fig. 3. Simulation of competing mathematical pathways in which higher powers (larger exponents) prevail with higher power sources (greater energy availability). Abbreviations: L, linear power flow; A, autocatalytic power use; Q, quadratic-autocatalytic power use; R, available remaining energy. (**a**) Energy systems diagram and (**b**) simulation graphs (*6*).

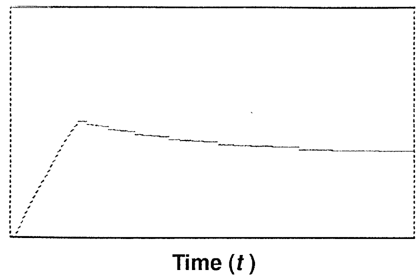

Fig. 4. Steady-state growth paradigm from simulation of model in Fig. 1c with equations:

$$N = K - k_3Q - k_6C$$
$$I = J/(1 + k_0NQ)$$
$$dQ/dt = k_1INQ - k_2Q$$
$$dC/dt = k_4Q - k_5C$$

where J is incident light; I, usable (unused) light; N, available phosphorus; Q, plant and detritus biomass; C, consumer biomass; K, total phosphorus in the container; t, time; and k's, pathway coefficients.

cally defined systems design that maximizes power (rate of useful transformation of available energy) for each available energy condition. Since designs with greater energy use displace other transient conditions, the trial and reinforcement process of self-organization continues until the mathematical property that maximizes power for that resource condition is reached. The details of the mechanisms operating are quite different in ecosystems, chemical reaction systems, turbulent systems, social systems, and stars, but energy and mathematical characteristics are common to all. If the designs (and their mathematics) that will prevail are determined by combinations and availabilities of the resource, details of the mechanisms by which different kinds of systems find the maximum power condition need not be known to predict the performance.

If designs keep changing during self-organization until maximum performance designs are reached, then self-organizing systems can be said to have energetic-mathematic goals. A considerable challenge is thus given to experimental science to help determine the maximum-power designs (and their mathematics) for the energy levels and source combinations more complicated than the simple example in Fig. 3.

If models of overall energy design can simulate systems without including many of the component details and mechanisms, prediction for complex self-organizing systems is simplified. The representation of various different kinds of complexity with a common overview model is here called "emulation." In the ecological modeling field, this is sometimes called top-down modeling.

Steady-state or pulsing paradigm. When production, consumption, and recycling of a system with a limited flow source are simulated with the model in Fig. 1c, we observe a classical growth paradigm that we observed in microcosms where the larger scale pulses are excluded (Fig. 4). Growth of production is followed by growth of consumption until both level in a steady state. The growth period may go through a maximum depending on the initial conditions, soon dampened out. In ecology the process of ecosystem growth and development is called "succession" and the term for the mature state is "climax." This model became a textbook concept for growth and climax in ecology (*8*).

Increasingly, studies in ecology and other fields are showing that a different paradigm, one that maximizes performance by pulsing, is the most general one in nature (*9*) (Fig. 5). Sometimes the pulses are generated by the consumer animals and in other cases by long-period oscillations from even larger systems such as floods, landslides, hurricanes, economic oscillations, and harvest cycles. A self-organizing system can organize around an available source of pulsing or develop its own. Periods of frenzied autocatalytic consumer growth cause pulsing alternation of production and consumption as in the simulation model in Fig. 5.

One can visualize why pulsing can maximize long-range performance with the example of farmer's cattle grazing a pasture. By keeping the number of cattle at a minimum level the grass can grow thick and maximize its use of sunlight, rain, and nutrients. Then consumption can be done quickly so as not to interfere with continued production. The materials are thus recycled without delay to stimulate another round. Pulsed consumption keeps production and consumption from interfering with each other.

Extensive computer simulations of the production-pulsed consumption model (*6*) show that over a wide range of conditions, power is maximized by the pulsing pattern. Increased performance with pulsing was observed in photosynthesis in flashing light, with the disturbance of ecosystem population and forests, and with the pulsing of batch processing in the chemical industry (*9*).

Pulse and hierarchical position. Consumers can be defined as units one or more energy transformations higher in the hierarchy than producers. If defined in this way, consumers represent a convergence, spatially, as suggested by Fig. 5c. The inputs of lower level units to higher units is spatial convergence (in the fluid dynamics sense). For example, food is converged spatially.

The actions of higher transformity units are spread over their territories and thus diverge spatially. For example, animals disperse nutrients, seeds, and regulatory services. Such consumers are a step larger, have longer turnover time, and larger territory of support and influence.

There is a correlation of size of units and their territories with time of turnover in units of biology, meteorology, zoology, and the like. Turnover time is the principal mathematical property that determines the frequency of pulsing, the time of pulsing correlated with size and hierarchical position.

Control of the small by the large. When the pulses of higher level consumption occur, the whole system is caused to pulse, whereas pulses in smaller realms are easily absorbed without much perturbation. The oscillations of phytoplankton are absorbed by the zoo-

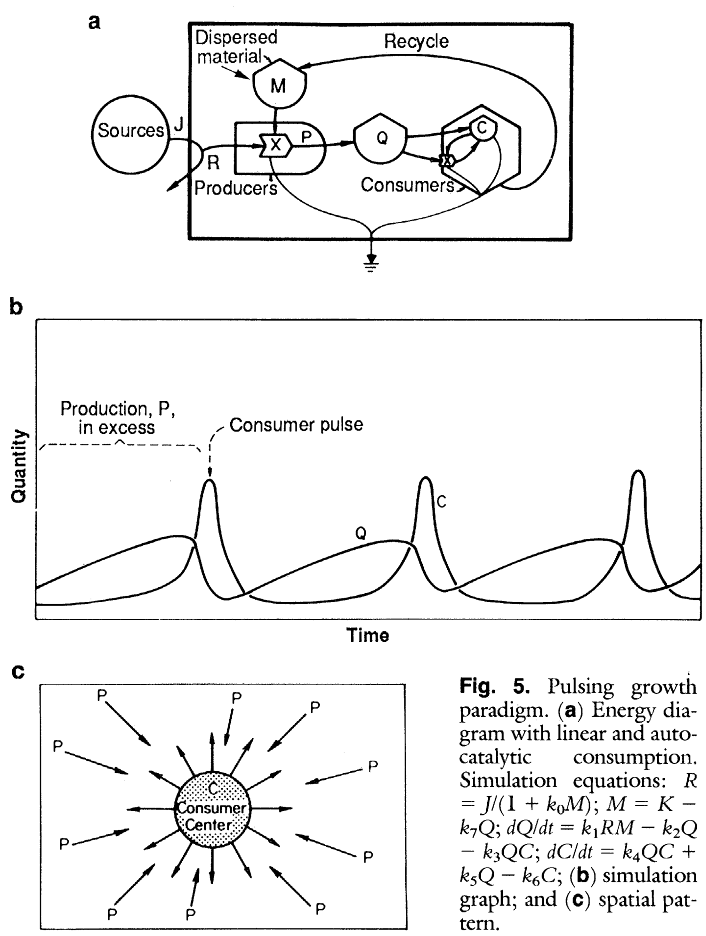

Fig. 5. Pulsing growth paradigm. (**a**) Energy diagram with linear and autocatalytic consumption. Simulation equations: $R = J/(1 + k_0M)$; $M = K - k_7Q$; $dQ/dt = k_1RM - k_2Q - k_3QC$; $dC/dt = k_4QC + k_5Q - k_6C$; (**b**) simulation graph; and (**c**) spatial pattern.

plankton consumers, whereas oscillations in populations of fishes cause every level to pulse, including the nutrients and phytoplankton. To small units with short turnover time the long sustained pulses from a higher level appear as catastrophes.

EMERGY and Transformity

Ecosystem studies lead us to the energy transformation rules for the natural hierarchies developed by self-organization. In other words, energetics of open system self-organization may explain why hierarchies are universal in physical and biological systems. To clarify concepts, the typical web (Fig. 2) is simplified further in Fig. 6a by the dropping out of one source and the omission of the feedback control and recycle pathways. Next, the web of connections is aggregated into a single-chain model in Fig. 6b to depict the energetics. Sunlight is successively transformed from light to plant organic matter to herbivore, to carnivores, and so on. At each stage, energy is degraded as a necessary part of transforming a lower quality energy to a higher quality one in lesser quantity. The energy flows decrease as one goes up the food chain (Fig. 6c).

The diagramming process shows an energy transformation hierarchy with large flows of low-quality energy being converged and transformed into smaller and smaller volumes of higher and higher quality types of energy. In designs that prevail after self-organization, it takes much energy of lower type to generate a small amount of higher type.

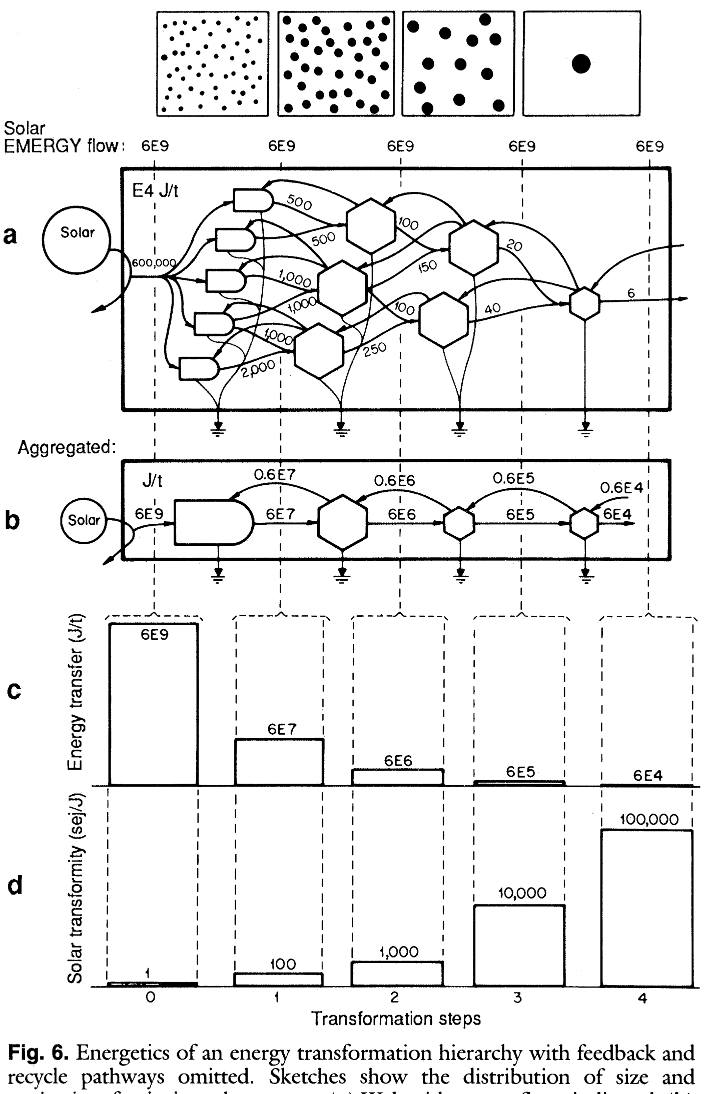

Fig. 6. Energetics of an energy transformation hierarchy with feedback and recycle pathways omitted. Sketches show the distribution of size and territories of units in each category. (**a**) Web with energy flows indicated, (**b**) energy transformation chain formed by aggregating the web, (**c**) graph of energy flows at each stage in the energy hierarchy, and (**d**) solar transformities for each level in the hierarchy.

Thus, it is incorrect to use energy as a measure of work where more than one type of energy is concerned. A joule of porpoise work and a joule of sunlight are located in different parts of the energy transformation hierarchy and more of sunlight is comparable to less of porpoise service. Engineering practice already recognizes that it takes 4 J from coal to make an electrical joule.

The series of energy transformations in the hierarchies formed by self-organization are cascades of successive energy fractions, which explains why Mandelbrot's fractals often describe nature (*10*).

Solar EMERGY and its maximum. In order to put the contributions of different kinds of energy on the same basis, we express all resources in terms of the equivalent energy of one type required to replace them. A new name is defined (*11*): EMERGY (spelled with an "M") is defined as the energy of one type required in transformations to generate a flow or storage. In this account solar EMERGY is used. Solar EMERGY of a flow or storage is the solar energy required to generate that flow or storage. Its units are solar emjoules. For example, all the flows (average considered as a steady state) in the aquarium in Fig. 1 depend on a solar EMERGY of 2000 E3 solar emjoules per day. Maximum EMERGY flow occurs when all products and by-products are fed back to reinforce source inputs and improve full power efficiencies. "To use" means to transform into a feedback source that reinforces. Having defined EMERGY, we can restate the old maximum power principle more rigorously as the principle of self-organization for maximum EMERGY use (*4, 12*).

Transformity, an energy measure of hierarchical position. Extending food chain concepts to thermodynamics generally, we defined a new quantity, the *transformity*, which is the amount of energy of one type required to generate a unit of energy of another type (in real competitive conditions of optimum loading for maximum power) (*12, 13*). It is not a dimensionless efficiency ratio. Transformity is the EMERGY per unit energy in units of emjoules per joule.

In this essay, solar transformities are used: Solar transformity is the solar EMERGY per unit energy. The solar transformity of each stage in the energy transformation chain is depicted (Fig. 6d). The solar transformities increase as the influences converge in the hierarchy. As the energy decreases, the solar transformities increase. In a hierarchy many units of smaller size and territory converge to a fewer number of larger size and territory. Larger items with longer turnover times have larger transformities. The small items are those of small territory, rapid turnover, and low transformity. For another example, see the aquarium hierarchy (Fig. 1b) where the solar transformities increase as the numbers in the hierarchy decrease.

Another hypothesis that emerges is that a transformation is useful only if it is to a higher quality that can amplify more with less energy. Work will not become part of a real world system unless it includes transformation to a product that can reinforce another flow. Thus, real world work is redefined as a useful energy transformation. Neither exergy nor Gibbs free energy can be used to measure the ability to do work if one is comparing items of different transformity. Different chemical compounds with similar potential energies have widely different transformities.

Solar EMERGY and value. EMERGY is a measure of value in the sense of what has been contributed. (One may use solar EMERGY, coal EMERGY, electrical EMERGY, or any other energy of one type, provided one is consistent.) It is a hypothesis that self-organizing systems use stores and flows for purposes commensurate with what was required for their formation. To do otherwise is to

Table 1. Typical solar transformities (solar emjoules per joule).*

Item	sej/J
Sunlight	1
Wind kinetic energy	623
Unconsolidated organic matter	4,420
Geopotential energy in dispersed rain	8,888
Chemical energy in dispersed rain	15,423
Geopotential energy in rivers	23,564
Chemical energy in rivers	41,000
Mechanical energy, waves, tides	17,000–29,000
Consolidated fuels	18,000–58,000
Food, greens, grains, staples	24,000–200,000
Protein foods	1,000,000–4,000,000
Human services	80,000–5,000,000,000
Information	10,000–10,000,000,000,000

*For sources and calculations, see (*15, 16*).

waste resources, making products without as much effect as alternative designs. Thus, EMERGY appears to measure the value of a flow or storage to a system in the long run after self-organizing selection processes have been at work. Energy is not a measure of value, because the highest valued processes such as human services and information have tiny energies, but EMERGY does measure these contributions appropriately.

As applied to the economic system, the more EMERGY use there is, the more real work is done, the higher is the standard of living, and the more money can buy. Thus EMERGY is suggested as the measure of contributions to the general economy, a means for evaluating environment, resources, and public policy alternatives.

Solar transformities of the energy flows of the biosphere. The first step in evaluating solar EMERGY flows is to determine the solar transformities of the main flows of the biosphere, a web not unlike that shown in Fig. 2. The aggregated energy flows of the earth in its support of the whole biosphere and the human economy are shown (Fig. 7). Notice the two main sources, the direct sunlight and the sources of radioactive and residual heat that drive the deep earth's geological convection. The sun's input is abundant but low in quality (transformity); the deep heat is at high temperature, high in quality (transformity). Expressed as solar EMERGY (after multiplying each by its solar transformity), the contributions of the two are similar. The solar EMERGY of the earth is used to determine transformities of higher quality flows that are part of the global system of the biosphere, which has several billion years of past self-organization (*14*).

A table of solar transformities. Solar transformities, some calculated from energy analysis of the existing web of energy flows on the planet, are shown in Table 1. For example, the transformity of chemical energy in rain as it falls (fifth item in the table) was calculated by dividing the global solar EMERGY per year from Fig. 7 by the estimate of average Gibbs free energy in terrestrial rainwater relative to seawater. The hierarchy of energy of the biosphere beginning with sunlight is shown by the increasing solar transformities as one goes to living organisms and then to humans.

EMERGY evaluation of environmental resources. The various flows and storages of the environment are readily evaluated on a comparable EMERGY basis, when one first determines the energy content and then multiplies by solar transformities (*15, 16*). As an example, resource inputs to the economy of Florida are plotted on a general spectral diagram using the coordinates of quantity and solar transformity (a "quantity-quality" diagram, Fig. 8). The upper graph is of annual energy inflow: the lower graph is the solar EMERGY. Typical of developed countries is the large hump in the middle of the spectrum representing the input of fuels and minerals from nonrenewable resources (*17*).

We have applied EMERGY analysis to a number of other states and countries (*15, 16*), evaluating the total EMERGY uses. The EMERGY use per year can be prorated on a per capita basis to get a measure of standard of living and on an area basis to get a measure of concentration and, thus, hierarchical position.

EMERGY values of currency value and international exchange. If total annual EMERGY use measures the real value, then it is the basis for the gross national product. The EMERGY value of the currency is obtained by dividing the dollars of gross economic product by the annual EMERGY use. The resulting EMERGY-to-dollar ratio can be used to estimate the EMERGY in services where data are in dollars. When EMERGY-to-dollar ratios are evaluated for several countries, higher values are found in rural and undeveloped nations where more of the support of people comes directly from the environment without payments of money. Money buys more real value in such areas.

Raw resources like fuels, agricultural products, minerals, and water contain much more EMERGY than is usually paid for them, because money paid is only for the human service, not for the work of the environmental systems. Thus international trade is often uneven in its contributions to the trading economies. For example, the United States received twice as much as it returned to Mexico in various exchanges (*16*). Table 2 shows advantages received in trade by developed countries.

If the total exchanges between two nations could be based on EMERGY rather than money, equity could be arranged, which might improve international cooperation, enrich the world economy, and foster peaceful relations.

Macroeconomic value for public policies. Money cannot be used directly to measure environmental contributions to the public good, since money is only paid to people for their services, not to the environmental service generating resources. Price is often inverse to

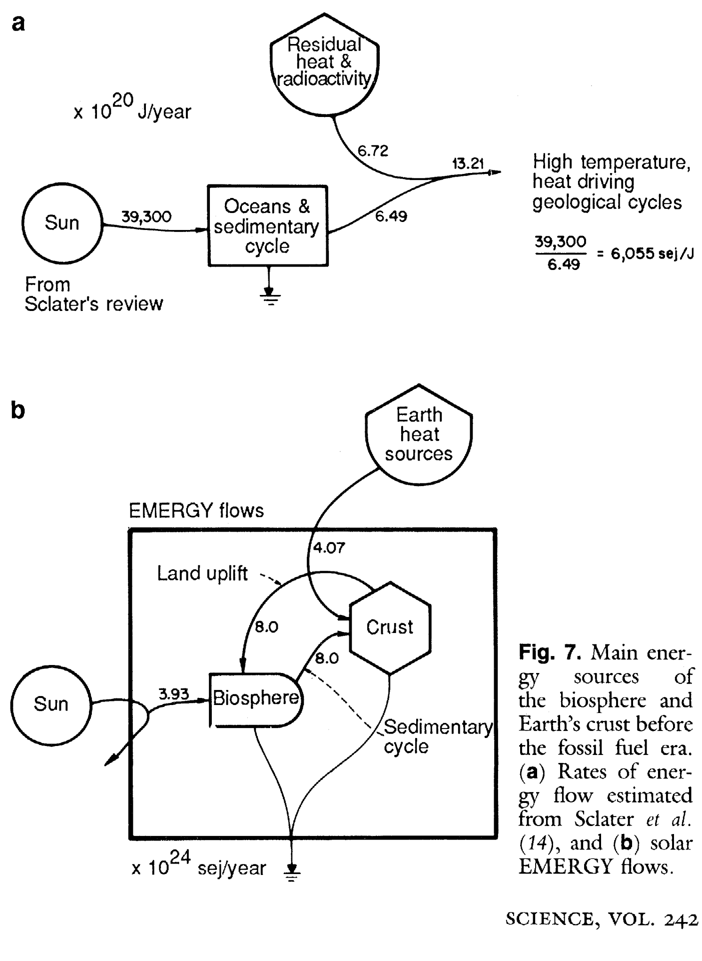

Fig. 7. Main energy sources of the biosphere and Earth's crust before the fossil fuel era. (**a**) Rates of energy flow estimated from Sclater *et al.* (*14*), and (**b**) solar EMERGY flows.

Table 2. EMERGY self-sufficiency and exchange (*15*).

Nation	EMERGY from within (%)	EMERGY received / EMERGY exported
The Netherlands	23	4.3
West Germany	10	4.2
Switzerland	19	3.2
Spain	24	2.3
United States	77	2.2
India	88	1.45
Brazil	91	0.98
Dominica	69	0.84
New Zealand	60	0.76
Poland	66	0.65
Australia	92	0.39
Soviet Union	97	0.23
Liberia	92	0.151

the contribution of a resource, because it contributes most to the economy when it is easily available, requiring few services for delivery.

A macroeconomic dollar value suitable for public policy discussions of resource alternatives is obtained by calculating the percentage of the national EMERGY use due to a resource. That percentage of the gross economic product provides the dollar value to the public economy. Macroeconomic value is not to be confused or substituted for regular economic values, which are microeconomic, market values based on individuals' willingness to pay.

These solar EMERGY evaluations provide new ways to give more accurate accounting to the values of works by nature, work of unpaid people, and products exchanged in foreign trade. Macroeconomic value is useful for public policy considerations but should not be substituted for market values for the microeconomic transactions of the marketplace.

Information

As one passes to the right in the energy transformation spectrum of Fig. 6, energy decreases, but the information and its processing often increase. Items of information on the right feed back to the left as control elements. Tribus and McIrvine found decreasing energy per unit information with more sophisticated, "high-quality" information processing electronics (*18*). By recognizing that information has high transformity, we have a new useful measure with which to study various kinds of information in relation to energy.

EMERGY as a measure of new information and copies. The solar EMERGY used up in the self-organizational process of trial and error is a measure of usable information. EMERGY of new information is that of making the choices, of making the selections based on testing use. It is large. Another defining characteristic of information is that it is easier to copy than to generate anew. EMERGY used to maintain information in storage is that required for copying. For example, genes are maintained by copying and discarding errors. A library repairs and replaces old books. The EMERGY of one copy is small.

Depreciation and resource limitations to information use. Information storage requires a carrier, such as the paper carrying text, the wires carrying telephone messages, the disks carrying computer data, and the brain tissues apparently carrying memories. Information can depreciate with dispersal of its carrier. Books are lost, people forget, and disks develop errors. Since information depreciates and has to be continually recopied and readapted, there is a substantial EMERGY requirement for its maintenance and use. There is resource limit to the information that can be maintained.

Separation of functional information from its user systems. The useful information of operational ecosystems and economic systems is tied to the real operation. However, the plan of the system's arrangements can be extracted from its operational system and written on paper, on a computer disk, or in coded genes. The isolated information may be miniaturized in small spaces such as brains, computer chips, and memory disks that facilitate copying, sharing, dispersal, and feedback control actions. The extracted information may be in a dormant, unused form, stored in a book, but the information can be reapplied to configure and operate a system again. When the functional information of a system is isolated and placed in memory storage, the energy associated with its storage is reduced, but its solar EMERGY is raised by the additional work done. Hence, the ratio of solar EMERGY to energy (the solar transformity) increases.

High solar transformity of the first or last copy. If there is only one copy of information in existence, it has all of the solar EMERGY of its development, which may be estimated from the EMERGY flow of the supporting territory for the time required. Although the energy in one copy is small, the solar transformity of a unique copy is high. For example, if one is evaluating the last members of a species, the solar EMERGY is what is required to regenerate it by evolution or others means from the most closely related species available.

Shared information. After information has been copied, it may be shared. The same information then has a larger territory, a greater area of influence, and a slower depreciation rate. Considerable additional work must be done to develop the shared status. With a larger support area, the shared information has higher EMERGY for maintaining its shared status. For example, shared genetic information in populations of birds and plants has broad territories due to bird movements and seed dispersals. Information shared by a

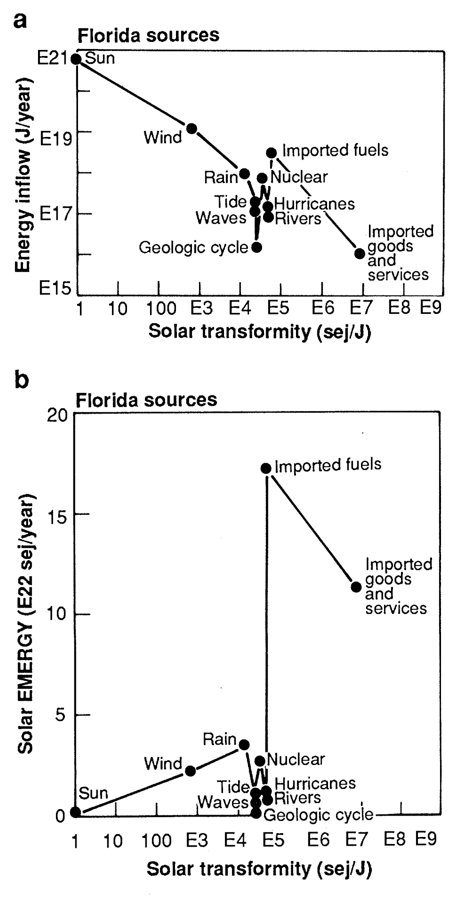

Fig. 8. EMERGY inputs to the economy of humanity and nature in Florida (*17*). (**a**) Energy as a function of solar transformity; (**b**) solar EMERGY as a function of solar transformity.

species has a larger territory than the individual organisms. Information in shared language and culture has large support areas, large turnover times, higher positions in energy transformation hierarchies. There are two transformities for shared information. One is the total solar EMERGY supporting the shared information divided by the energy flow in maintaining all the copies, all the shared information. This is a transformity of duplicates. Another, much higher transformity is the total solar EMERGY supporting the shared information divided by the energy flow for one copy. This is the transformity of a shared original. This measures what is required to maintain the shared status per one unit of the information shared.

Hierarchy and transformity of human education. A hierarchy of human information is given in Fig. 9. Many people at lower educational levels on the left are the basis for fewer people operating at higher levels. At the top of the hierarchy on the right are public leaders and others who are known to the public and are shared information with a large territory of support and influence. The annual EMERGY flow of the United States was divided by the number of people in each category and the annual metabolic energy per person to obtain a solar transformity of each. Throughout biological and later cultural evolution, humanity has moved toward higher transformities as more and more solar EMERGY has gone into shared information of society. Human progress is measured by passage from left to right on the information hierarchy. As successful shared new technologies emerge in self-organization of our society, transformities provide a scale evaluating what was required.

Since information is used to make more information, it is mathematically autocatalytic and acts as a pulsing consumer in Fig. 5. Just as meteorological storms are on the high-transformity end of the fluid turbulence spectrum (*19*), so shared information at the high-quality end of the information spectrum exhibits intense

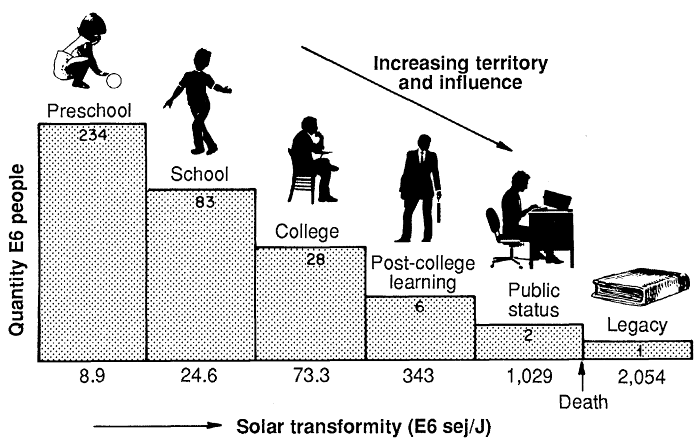

Fig. 9. Hierarchical levels of education attained in human growth and development. Population of the United States in each category is graphed as a function of solar transformity.

Solar transformities for human educational levels in Fig. 9.

Attainment	Individuals* (E6 ind.)	EMERGY share/ind.† (E16 sej/ind. per year)	Transformity‡ (E6 sej/J)
Total (preschool)	234	3.4	8.9
School	83	9.4	24.6
College grad	28	28.0	73.3
Postcollege ed	6	131.0	343.0
Public status	2?	393.0	1029.0
Legacies	1?	785.0	2054.0

*U.S. Bureau of the Census, *Statistical Abstract of the United States* (*22*). †Annual U.S. EMERGY use, 785 E22 sej/year (*20*) divided by number of individuals (ind.) in the category. ‡Annual EMERGY share/ind. per year divided by the energy per individual: (2500 kcal/day) (365 days/year) (4186 J/kcal) = 3.82 E9 J/ind. per year.

activity and emergent new informational structures that we call technology. Facilitated by human flexibility and self-organizational skills, the biosphere is now swirling with "information storms" centered in leading cities. The stock market surge and decline of the 1980s is an example.

A Christmas tree model of human history. The lights at night are a symptom of information processing, most concentrated in the cities. Viewed from a satellite, the centers of population show patterns of hierarchy of the landscape. Over historical time the rise and fall of cities and states as if viewed from satellite have been like the flashing of lights on a Christmas tree, small centers with short-term pulses; the larger centers with longer pulsing periods.

Pulsing paradigm on the Earth scale. With Fig. 5 the pulsing paradigm was suggested as a general self-organizing pattern for maximum long-range performance. With world-shared information occupying the whole world as its territory, the entire biospheric system has been drawn into a world-scale pulse of human economic consumption based on use of the accumulations of fuel and mineral reserves in previous periods of excess geologic production. The assets and infrastructure built in the first half of the 20th century seem to be the stores feeding information storms, now becoming a frenzied consumer unit at a high level dominating the last of the 20th century. When the model in Fig. 5 is calibrated for Earth production and frenzied urban consumption, it generates very sharp pulses that look like King Hubbert's blip (*1, 2, 20*).

Information for the prosperous way down. As the current large-scale global surge of information crests and recedes, the growth society changes to a declining society, learning to live in a period when Earth production processes will exceed consumption, restoring the reserves that will later support periods of growth and net consumption again. New public policies will be needed to make the economy vital while it is contracting. EMERGY evaluation may help set priorities.

Where ecosystems go through the pulsing pattern of ups and downs, the information is not discarded, but is carefully processed into storages of essentials (spores and seeds, for example) available for the next round of growth. The challenge ahead for human creativity and research is learning how to save and manage our information for the cycles yet to come (*21*).

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Space, Stars, C_{60}, and Soot

HAROLD KROTO

Although carbon has been subjected to far more study than all other elements put together, the buckminsterfullerene hollow-cage structure, recently proposed to account for the exceptional stability of the C_{60} cluster, has shed a totally new and revealing light on several important aspects of carbon's chemical and physical properties that were quite unsuspected and others that were not previously well understood. Most significant is the discovery that C_{60} appears to form spontaneously, and this has particularly important implications for particle formation in combustion and in space as well as for the chemistry of polyaromatic compounds. The intriguing revelation that 12 pentagonal "defects" convert a planar hexagonal array of any size into a quasi-icosahedral cage explains why some intrinsically planar materials form quasi-crystalline particles, as appears to occur in the case of soot. Although the novel structural proposal has still to be unequivocally confirmed, this article pays particular attention to the way in which it provides convincing explanations of puzzling observations in several fields, so lending credence to the structure proposed for C_{60}.

IN THIS ARTICLE SOME EXCITING NEW AVENUES IN THE chemistry of one element, carbon, which are a consequence of the premise that the C_{60} molecule has the high symmetry of a truncated icosahedron, are explored. We shall see that this novel proposal allows many pieces of the carbon chemistry jigsaw puzzle to fall neatly into place.

When David Walton, some years ago, introduced me to some polyyne ($\cdots C{\equiv}C{-}C{\equiv}C{-}C{\equiv}C{-}C{\equiv}C\cdots$) chain molecules that he and his colleagues had made (*1, 2*), they called to mind the problems that a microscopic baton twirler would have in catching a baton that was flexing wildly as it spun in the air. To study this process quantum mechanically we, with Anthony Alexander, made $H{-}C{\equiv}C{-}C{\equiv}C{-}C{\equiv}N$ (HC_5N) and measured its microwave rota-

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