The Crafoord Prize

in the Biosciences
1987

CRAFOORD LECTURES

Global stress in life-support ecosystems mandates input management of production systems

by

Eugene P. Odum

and

Living with complexity

by

Howard T. Odum

THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Anna-Greta and Holger Crafoord Fund

The **Crafoord Fund** was established in 1980 by a donation to the Royal Swedish Academy of Sciences from Anna-Greta and Holger Crafoord.

The purpose of the fund is to promote basic scientific research in Sweden and in other parts of the world in the following disciplines:

- mathematics and astronomy
- the geosciences
- the biological sciences with particular emphasis on ecology
- rheumatoid arthritis.

Support to research takes the form of an international prize awarded annually to outstanding scientists, and of research grants to individuals or institutions. The awards are made according to the following rota:

Year 1 mathematics
Year 2 the geosciences
Year 3 the biosciences
Year 4 astronomy
Year 5 the geosciences
Year 6 the biosciences
Year 7 mathematics
and so on.

The research grant for rheumatoid arthritis is made every third year, but the prize is awarded only when a special committee has shown that scientific progress in this field has been such that an award is justified.

A certain portion of the grants is reserved for appropriate research projects at the various institutes of the Academy.

When the prize and the research grants are to be awarded in mathematics, astronomy, the geosciences or the biosciences, the first step is to define, in the light of current international scientific development, a research area of particular interest. The prize and the research grants are then awarded for work in this area.

The award - the **Crafoord Prize** - consists of a sum exceeding 1.3 million Swedish crowns, a gold medal and a diploma.

The Crafoord Prize is awarded at a ceremony held at the Royal Swedish Academy of Sciences on a **Crafoord Day** in early autumn. On this occasion, the prizewinner gives a public lecture, the **Crafoord Lecture.**

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His Majesty the King of Sweden (to the right) together with (from the left) Mrs Elizabeth Odum, Mrs Martha Odum, the prizewinner Howard T. Odum, the donor, Mrs Anna-Greta Crafoord and the prizewinner Eugene P. Odum. Photo: Boo Jonsson, Svensk reportagetjänst.

The Royal Swedish Academy of Sciences has awarded the Crafoord Prize for 1987 jointly to Professor Eugene P. Odum, University of Georgia, USA and Professor Howard T. Odum, University of Florida, USA for their pioneering contributions within the field of ecosystem ecology. Their fundamental findings have strongly promoted our understanding of the dynamics of natural systems and formed a scientific base for the long-term exploitation of the natural resources including pollution abatement.

On September 23, 1987 the prizewinners Eugene P. Odum and Howard T. Odum received the Crafoord Prize from the hands of His Majesty the King of Sweden at a ceremony at The Royal Swedish Academy of Sciences.

Eugene P. Odum has through numerous works formed the present basic picture of the structure and function of ecosystems. His textbook "Fundamentals of Ecology" published in 1953 has had an enormous impact on the scientific progress of ecology. Here the established foodweb structure of the natural systems were coupled to be the circulation of oxygen, carbon, nitrogen, phosphorus and other elements to a total structural system of nature.

Howard T. Odum's epochal contributions to ecology counts a series of basic studies of the importance of solar energy for the biogeochemical cycles and the development of ecosystems. His unique ability to explain events or processes from a total system perspective is demonstrated in how classical studies of rivers, lakes, coastal systems, coral reefs and tropical rainforests. H. T. Odum early recognized the consequences in nature of man's use of fossil fuel, contributing an energy subsidy to the ecosystem besides solar energy. On the basis of the laws of thermodynamics he has formulated an unifying systems theory including the socioeconomic field which has initiated an animated research activity which can be expected to change society's valuation of the living natural systems.

Eugene P. Odum and his younger brother Howard T. Odum were the first to in depth comprise the activities of man in the studies of natural systems.

Crafoord Prizes Awarded

1982 in **mathematics** within the field of nonlinear differential equations
Vladimir I. Arnold, Moscow State University, USSR and
Louis Nirenberg, New York University, USA for their outstanding achievements in the theory of nonlinear differential equations.

1983 in **geosciences** within the field of large-scale movements of the atmosphere and the sea
Edward N. Lorenz, Massachusetts Institute of Technology, USA and
Henry Stommel, Woods Hole Oceanographic Institution, USA for their fundamental contributions in the field of geophysical hydrodynamics that in a unique way contributed to our understanding of the large-scale circulation of the atmosphere and the sea.

1984 in **biosciences** within the field of coevolution – the mutual adaption of organism populations in the natural environment
Daniel H. Janzen, University of Pennsylvania, USA for his imaginative and stimulating studies on coevolution, which has inspired many researchers to continued work in this field.

1985 in **astronomy** within the field of the interstellar medium including star formation and interaction with stars
Lyman Spitzer, Jr., Princeton University Observatory, USA for his fundamental pioneering studies of practically every aspect of the interstellar medium, culminating in the results obtained using the Copernicus satellite.

1986 in the **geosciences** within the field of isotope geology
Claude J. Allègre, L'Institut de Physique du Globe, France and
Gerald J. Wasserburg, California Institute of Technology, USA for their pioneering work in isotope geology.

1987 in the **biosciences** within the field of ecosystem ecology
Eugene P. Odum, University of Georgia, USA and
Howard T. Odum, University of Florida, USA for their pioneering contributions within the field of ecosystem ecology.

Crafoord Lectures

1982 **Vladimir I. Arnold:** On some nonlinear problems.
Louis Nirenberg: Mathematical methods in nonlinear problems.

1983 **Edward N. Lorenz:** Irregularity: a fundamental property of the atmosphere.
Henry Stommel: The delicate interplay between wind-stress and buoyancy input in ocean circulation: the Goldsbrough variations.

1984 **Daniel H. Janzen:** The most coevolutionary animal of them all.

1985 **Lyman Spitzer, Jr.:** Clouds between the Stars.

1986 **Claude J. Allègre:** Isotope geodynamic.
Gerald J. Wasserburg: Isotopic abundances:inferences on solar system and planetary evolution.

1987 **Eugene P. Odum:** Global stress on life-support ecosystems mandates input management of production systems.
Howard T. Odum: Living with complexity.

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Living with complexity

Howard T. Odum

Environmental Engineering Sciences
University of Florida, Gainesville, FL, USA

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 shared information. 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 this complexity?

Increasingly in recent decades, studies of ecosystems have generated concepts that may apply to all complex systems. The new concepts, when appropriately generalized in terms of energy, information, and network models, may apply to other systems in physical science and especially to the human economy and its pattern with the biosphere. In this essay we use these general systems principles concerning energy, information, and hierarchy to help understand the super-ecosystem of the biosphere. General principles of self-organizing systems suggest the future of humanity on earth, less as a matter of human choice, and more as a scientific paradigm of earth complexity within which human works are being adaptively programmed.

Part I introduces energy concepts for hierarchy and complexity; Part II introduces energy emulation modelling; Part III connects the new energy concepts to information; Part IV indicates significance for physical sciences; and Part V explores significance for human society. Details are given as endnotes (1).

Systems Ecology and Opposing Viewpoints

Because ecological systems with trees, birds, fishes, rocks, and winds are evident around us, it is easy for the science of ecosystems (systems ecology) to concentrate on basic principles, whereas most sciences have had to struggle with elaborate apparatus to see their systems. For four decades, along with our colleagues the world over, we have sought general theories of the ecosystem by the comparative measurements of contrasting ecosystems of the earth, by large scale experiments and by study of microcosms. Simulation models have been used to relate parts and mechanisms to the designs that emerge on a larger scale. The generic models found have been extended to larger and smaller systems, the subjects of other sciences.

However, many scientists in ecology and economics do not believe there are general scientific principles for the system of humanity and nature and don't look for them. Opposition to teaching unified general systems science has been strong. Table 1 has some of the statements sometimes given by opponents. Consequently, progress was slow. Even more rarely were systems principles sought from ecologic-economic complexity for application to classic sciences.

Table 1. Objections to Ecosystems General Systems Theory

(1) Understanding how parts interact is enough to explain larger scale phenomena; synthetic models are not necessary.

(2) Smaller phenomena are basic and larger phenomena merely application.

(3) Laws governing how parts are controlled to perform is teleological and therefore not scientific and thus must not be studied.

(4) Patterns are subject to random influences and therefore are indeterminate, that is, without natural law.

(5) Because human minds are brilliant, there are no constraints on human choice in developing systems, that is, there are no natural laws involved in human roles.

(6) General principles may inhibit science if they make some measurements unnecessary and training obsolete.

(7) Empirical correlation is objective and safe; models and theory are not scientific.

(8) General systems theory has been so creative, in so many directions, and with so many languages, and so little related to the ral world that it is more art than science.

(9) Species and humankind are irreplaceable and of infinite value and therefore not subject to any numeric evaluation.

(10) Pattern in ecology and economy can be fully explained by comptetive struggle for existence among unorganized members and individual strategies; higher level organization does not exist.

(11) Organisms in nature are not connected with wires and pipes and therefore are not a system.

(12) Ecology only applies physics, chemistry, and thermodynamics and is not capable of showing the older fields new basic principles of energetics and information.

(13) Since the new ecosystem energetics redefines energy, work, energy quality, and information in new ways, not given in physics and chemistry, it must be wrong.

(14) Ecology only applies models developed by mathematicians and is not capable of generating new abstract languages constrained by energy.

(15) The technocrat movement in the 1930's tried to use energy as a measure of value and failed, therefore an energy concept of value is not valid.

PART 1. ENERGETICS OF SELF-ORGANIZING COMPLEXITY FROM ECOSYSTEMS

Let's start with the green ecological systems of the earth to illustrate the principles by which complexity is related to energy and concepts of EMERGY and TRANSFORMITY.

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Green Simplicity and Complexity

With Figure 1 we can see how nature's complexity has been viewed. Figure 1a shows a field crop and is regarded as simple. Most people see the green crop as beneficial, representing the good useful works of humanity. Maintaining a simple pattern is considered good. In cities the quest for simplicity produces grassy lawns, even where their purposes are not clear.

In nature there are repeating patterns of growth called *succession* shown by the growth curve in Figure 1. The first stages of succession are often like the field crops, simple, with many individuals of a few types that have fast net growth of little lasting quality. Agriculture is really a domesticated version of simple, first stages of succession.

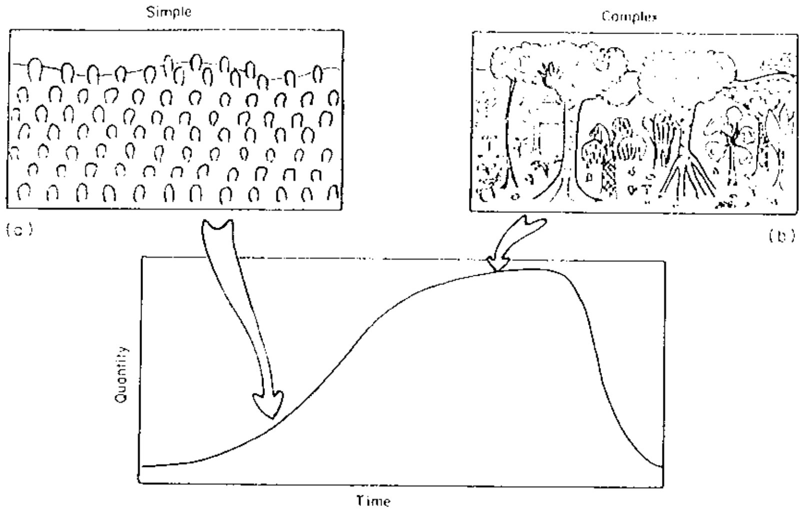


Figure 1. Patterns of simplicity and complexity in the green cover of the earth. (a) Simplicity of early stages of succession or domesticated crops; (b) complex vegetation.

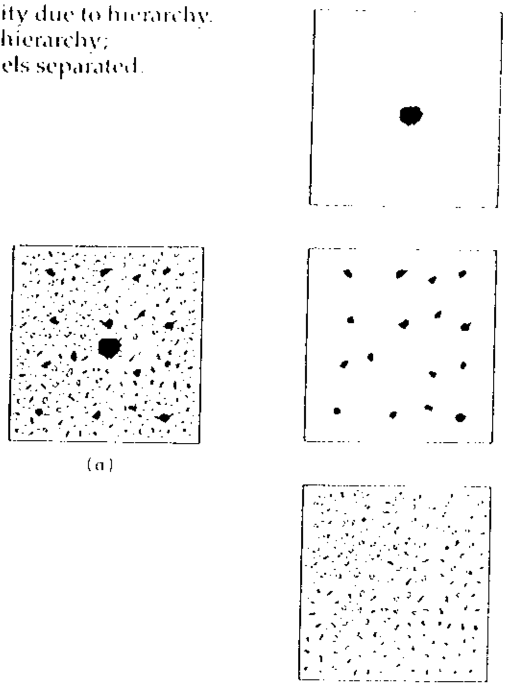
Figure 1b shows the self-organized vegetation of a later stage ecosystem which is complex. The complex division of labor is responsible for the good works it does in maintaining watersheds and soils, but these services by nature are indirect aids to the economy, an underestimated benefit. Tendencies in present cultures are to simplify the complexity, "to clear the bush".

Both simple and complex systems are useful to the landscape. Both require resources to maintain, in one case to keep simple and in the other case to keep complex. Both patterns can form without human management.

Organizing Complexity from Simple Components

When simple units are combined to make a larger scale functional pattern, complexity emerges. When viewed as a whole in Figure 2a, the complexity hides relationships. If viewed without knowledge of the mechanisms, the complexity might be regarded as useless and disordered, a pattern to be discouraged and replaced.

Figure 2. Complexity due to hierarchy.
(a) Superimposed hierarchy;
(b) hierarchical levels separated.



(a)

(b)

When the parts of Figure 2a are shown separately in Figure 2b, the systems now appear simple again. There are units of three size levels. Referring back to Figure 1b, we can understand the complexity there is like Figure 2, an organization of parts of many dimensions of size.

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 humans speak to each other.

Complexity from Hierarchy

Apparently all systems of the universe are hierarchical, although one cannot prove such a generality. The complexity that we showed in Figures 1 and 2 is due to parts combined in hierarchies. Figure 3 shows what is meant by a hierarchy. A military organization is a familiar example. Many privates report to each corporal; several corporals report to each sergeant; several sergeants report to each lieutenant, etc. Control goes in the opposite direction from lieutenant, to sergeant, to corporal, to private. There are many privates and few lieutenants, but each is necessary to the functioning of the other and to the performance of the whole system.

Simple Patterns of Complexity

The military hierarchy is an example of organizing parts with simple rules for relationships. Once the simple rule for organizational pattern is known, the

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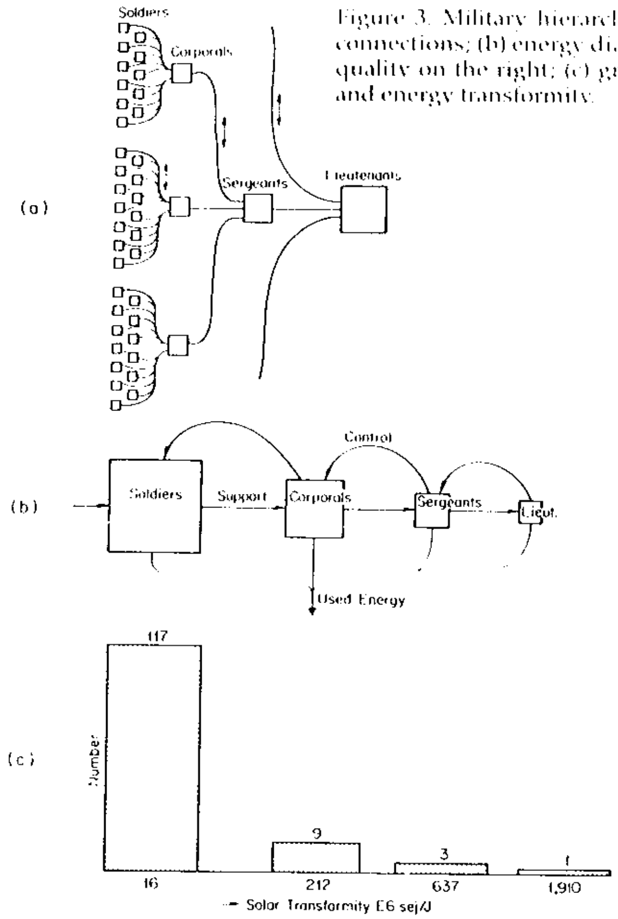

Figure 3. Military hierarchy. (a) Sketch of connections; (b) energy diagram with high quality on the right; (c) graph of quantity and energy transformity.

pattern to the human mind again is'simple. Perhaps all of science is the search for the simple rules by which the complexity of the real world is comprehensible to human understanding.

Stating rules for hierarchical organization simply and mathematically is a field called fractals from Mandelbrot (2), well known to generate complex and beautiful patterns like those in nature. Simple principles can generate complexity.

The Energy Systems Rules for Hierarchical Complexity

However, unbridled mathematical creations are not nature, and principles concerning the real world must come from systems constrained by the realities of energy laws of real self organization. Here we look to the manifestations of energy as they operate in self-organized ecosystems. Here we find the simple rules by which nature's complexity is expressed.

Simple Ecosystems in Microcosms

In 1955 we turned to simple ecosystems that develop in closed containers 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 rapidly developed complex organization, showing hierarchies, but simpler than in the unconstrained big ecosystems outdoors. See microcosm hierarchies in Figure 4 and simulation of their metabolism in Figure 5 (3).

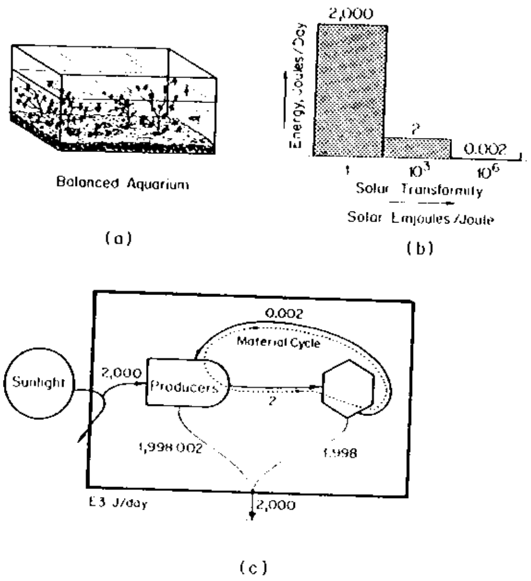

Figure 4. Energy flow and transformation in a closed aquarium ecosystem. (a) Sketch of closed aquarium; (b) graph of energy flow as a function of solar transformity; (c) energy systems diagram of the standard production-consumption model. The cycle and reuse of chemical materials is shown with a dotted line accompanying the energy flows. Solar EMERGY and transformities are below:

Path	Energy E3 J/day	Solar EMERGY E3 sej/day	Solar Transformity sej/J
Sunlight used	2000	2000	1
Organic produce	2	2000	1,000
Material recycle	0.002	2000	1,000,000

Aquarium Hierarchy

The model of the aquarium ecosystem in Figures 4 and 5 is shown as a short, three level energy hierarchy with much sunlight, supporting plants (producers) on the left supporting a few animals (consumers) on the right. The figure 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. Each level feeds services or raw materials back to its supporters (from right to left in the diagram). The production-consumption minimodel illustrates some of the basic plan of ecosystems.

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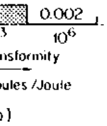

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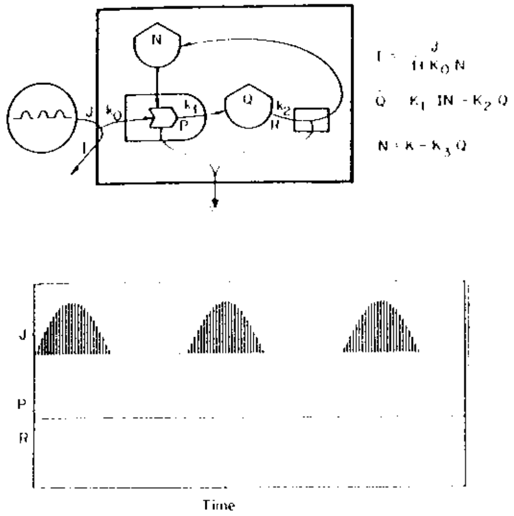

$$I = \frac{J}{1 + K_0 N}$$

$$\dot{Q} = K_1 IN - K_2 Q$$

$$N = K - K_3 Q$$

Figure 5. Simulation of the balanced aquarium in Figure 4 with a model that has linear consumption. (a) Energy diagram and equations; (b) simulation response to alternation of light and dark.

Laws of Self Organization

The study of ecosystems suggests principles by which energy flows generate hierarchies in all systems. From these it was clear that energy laws controlling self organization were principles of open systems quite beyond classical energetics, involving a generalization of concepts of evolution in energy terms. During the trials and errors of self organization, species and relationships were being selectively reinforced by more energy becoming available to designs that feed products back into increased production.

Efforts to explain self organization as a selection of designs for maximum power had been developed by scientific theorists, Boltzmann, Ostwald, Lotka, and others (4), starting in the last century, but these 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 an energy-basis of self-organized hierarchy that may apply to all fields.

Energy Transformation Webs and Chains

The concepts of successive energy transformation in ecosystems applicable to any kind of system are given in Figure 6. The web of connections is aggregated into a single chain model to help understand the energetics. As in a closed aquarium, sunlight is successively transformed from light to plant organic matter to herbivore, to carnivores, etc. 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 (Figure 6c).

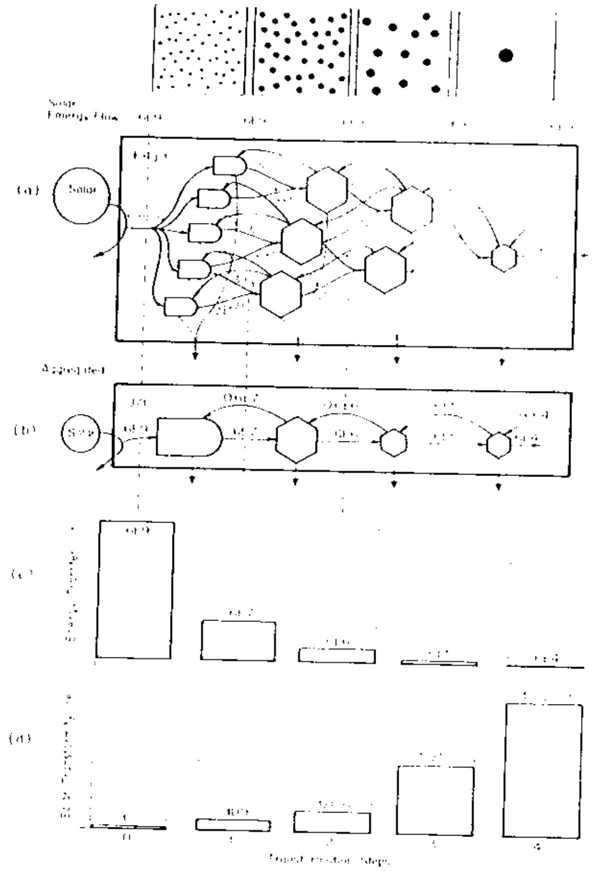

Figure 6. Energetics of a food web above: sketches show the distribution of size and territories of units in each category. (a) Web with energy flows indicated (feedback control pathways omitted); (b) energy transformation chain formed by aggregating the web; (c) graph of energy flows at each stage in the energy hierarchy; (d) solar transformities for each position in the hierarchy.

Like the military organization, services and controls are moving back down the hierarchy. Large animals control the more numerous smaller organisms by their behavior, by their placing of waste products, by their ways of eating, by their control of pollination and seeding, and reproduction of those under their control.

A forest is a hierarchy with the sunlight being concentrated by leaves which converge their products to twigs and limbs and these to trunks. In turn, the trunks feed their support and materials back to limbs and these to the leaves.

Ecosystems, earth sytems, astronomical systems, and possibly all systems are organized in hierarchies because this design maximizes EMERGY use (see explanation below). These systems look different until they are drawn with energy diagrams. Most systems have a chain of energy transformations like an ecological food chain, where plants feed consumers, which feed second level consumers, and these even higher level carnivores.

Solar EMERGY

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 (5):

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EMERGY (spelled with an "M") is defined as the energy of one type required for 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 Figure 4 depend on a solar EMERGY of 2000 E3 solar emjoules per day.

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 another type (in real competitive conditions of optimum loading for maximum power) (6).

Transformity is the EMERGY per unit energy.

In this essay, solar transformities are used:

Solar transformity is the solar EMERGY per unit energy.

In Figure 6d is graphed the solar transformity of each stage in the energy transformation chain. The solar transformities increase as the influences converge in the hierarchy. As the energy decreases, the solar transformities increase.

For another example, see the military hierarchy in Figure 3c where the solar transformities increase as the numbers in the hierarchy decrease.

Mississippi River Stream Hierarchy

Another example of an energy hierarchy is given in Figure 7 adapted from Diamond (7). Here the geopotential energy of rain is used by the streams as they are transformed to higher quality of larger concentrations. Solar transformities increase as the energy decreases.

Size and Turnover Time Increasing with Transformity

In a real hierarchy many units of smaller size and territory converge to a fewer number of larger size and territory. Larger items have longer turnover times also. For example, in Figure 2b the small items are those of small territory, rapid turnover, and low transformity. What sometimes appeared as incomprehensible complexity (Figure 2a) is the manifestation of simple hierarchical organization.

EMERGY and System Performance

By using transformities to find the solar equivalents for all kinds of energy flow, all flows of energy can be compared by expressing them in quantities of energy of one type. The energy of one type required for another flow is defined as the EMERGY of that type. Thus the concept of solar EMERGY was recognized as the solar energy required for any process (directly and indirectly).

Self organization appears to develop designs that maximize EMERGY use because such designs produce more, consume more, are limited less, and can prevail more. In other words, EMERGY appears to be a scientific measure of value in contributing to survival success of a system's designs.

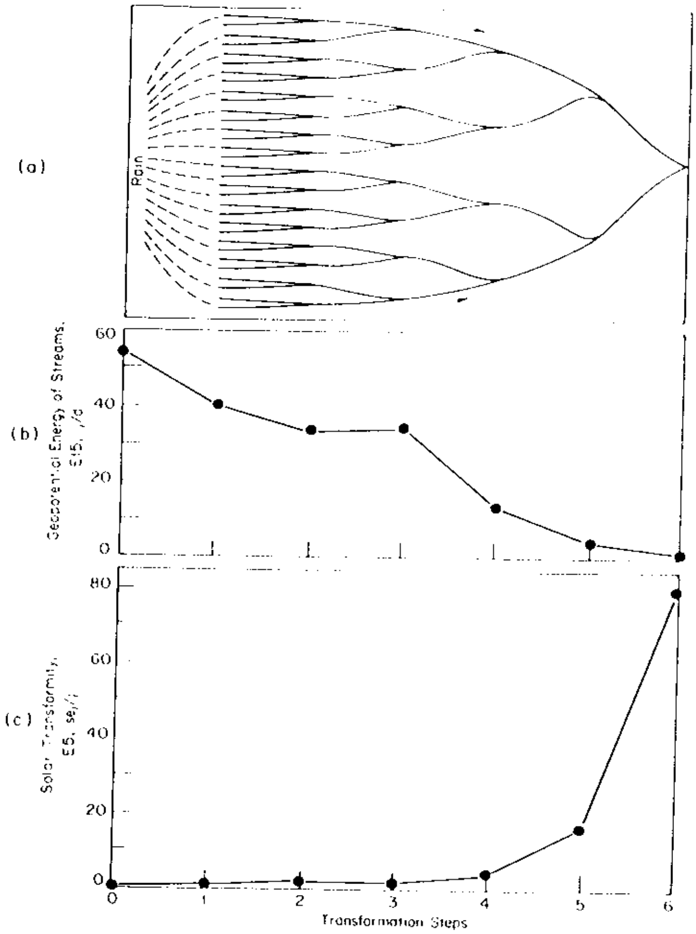

Figure 7. Hierarchy of water flows in the Mississippi River basin adapted from Diamond (7). (a) Sketch of converging streams; (b) energy flows; (c) solar transformity.

Self-organized Designs for Maximum EMERGY Use

The principle of design for maximum EMERGY use explains why systems of many kinds are similarly organized. This is a more rigorous expression of the old maximum power principle. By developing networks of cooperatively interacting units arranged hierarchically, all work goes into products and services that further improve available resources and efficient use. See, for example, the producer-consumer plan typical of most ecosystems found in small aquarium microcosms (Figure 4).

Energy of sunlight drives the photosynthetic part of plants which contribute products to the consumers in parthway from left to right, which feed their byproducts back as necessary nutrients to stimulate the plants. There is a symbiosis between one end of the food chain and the other. Each is mutually stimulating.

Figure 5b is a computer simulation. As the light goes on and off with day and night there is a pulse of stimulation alternating between the production and the consumption. Without the coupling of production and consumption the total use of sunlight would be less. The organization of processing in-

Figure 7. Hierarchy of water flows in the Mississippi River basin adapted from Diamond (7). (a) Sketch of converging streams; (b) energy flows; (c) solar transformity.

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creases power. All solar-driven ecosystems that have been examined have this organization.

Autocatalytic Designs Expressing EMERGY Reinforcement

The feedback of a product of energy transformation to amplify production is autocatalysis, an expression used for many years for one class of chemical reactions. Autocatalytic designs result from EMERGY-maximizing self organization. The real webs that are observed not only have the energy transformation chain of the model in Figure 6, but have the feedbacks (right to left pathways) shown in Figures 8a and 8b. These use a small amount of high quality energy to amplify (usually with multiplicative kinetics) the production processes (shown with the pointed-block interaction symbol) on the left. Another kind of feedback is the recycle of necessary materials to make a "mineral cycle". See for example, Figure 4 of the closed aquarium.

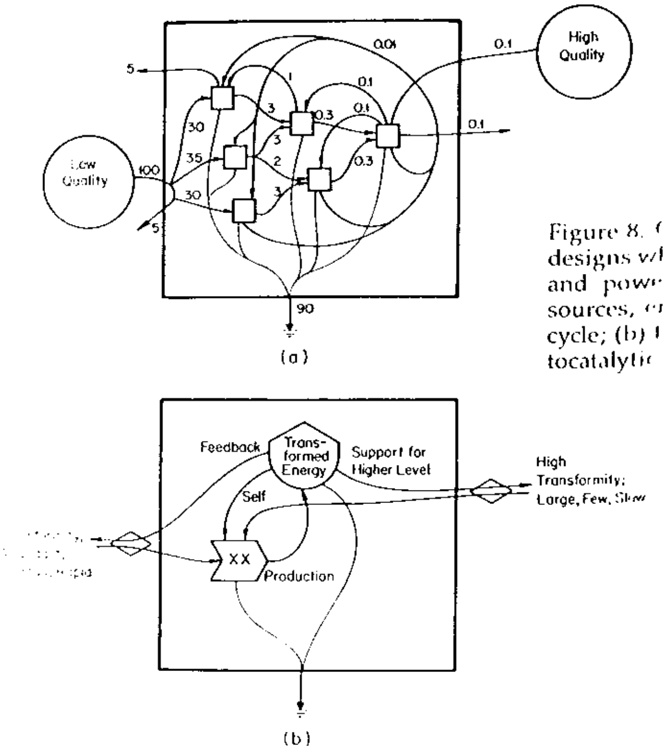


Figure 8. Characteristic ecosystem designs which maximize EMERGY and power; (a) design with two sources, energy hierarchy, and recycle; (b) typical details of one autocatalytic unit (box) in (a).

Elimination of Limiting Factors by Application of Resources

Ecosystems and economic systems tend to provide more of whatever is limiting to maximum production and useful consumption. Thus, in different situations they may build biomass, store nutrients, develop variety, become complex, earn profit, generate information, export products, or circulate more money. Redirecting resources to eliminated limiting factors is a common mechanism of self organization for maximum power.

Solar EMERGY and Value

EMERGY is a measure of value in the sense of what has been contributed. It is an hypothesis that self-organizing systems use stores and flows for purposes commensurate with what was required for their formation. To do otherwise is to 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. See Part II.

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.

We may restate the maximum power principle that systems designs prevail that develop maximum EMERGY use. Perhaps the appropriate name is maximum EMPOWER (5).

Useful Work as Energy Transformation

Often the early workers in a field are closer to the truth than those who follow who elaborate on some one aspect of detail with precision, but mistake the particular for the general. Early investigators such as Maxwell defined work as an energy transformation, whereas many thereafter dealt with the particulars of mechanical work only. The more general definition of work as an energy transformation applies to all kinds of energy changes. Since systems will not long continue energy transformations unless their products feed back to increase mutual coupling and maximum power, most work that is continued is useful, where useful means that the product or service is linked to other parts of the system so as to reinforce and increase system performance (maximum power principle) (6).

For work, an energy transformation, to be useful it must have some properties of higher quality that make it capable of being an amplifier. It may be a more flexible type of energy, a more concentrated one, or one with more stability, force, or transmissibility. It follows that work in real systems normally generates higher quality energy while dispersing part of the energy input.

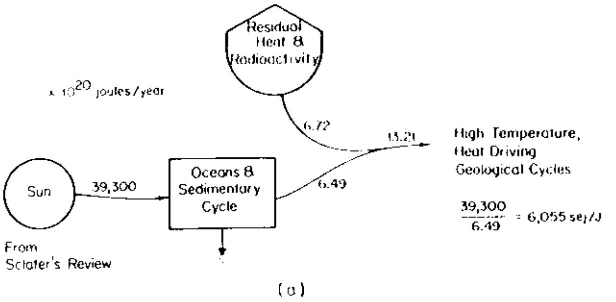
Energy Quality and Solar Transformity

With the concept of transformity we have a scale of energy quality that indicates the position in the energy "food chain". The solar transformity is the solar energy required to generate one unit of energy of another type. The higher the quality of energy, the higher the transformity. Solar transformity increases as one goes from sunlight to plankton to fishes, to people, to humans, to information, etc. (8).

Solar energy may be accumulated in one square meter for a year to obtain a concentration of the transformed product, organic matter. Or, the solar energy products for one day may be gathered from 365 square meters to that one square meter with similar result. There is a space-time equivalence in energy transformation.

Solar EMERGY Basis of the Earth

In Figure 9 is the web of energy flows of the earth in its support of the whole biosphere and thus the human economy. 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; the deep heat is at high temperature, high in quality. 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 (9).



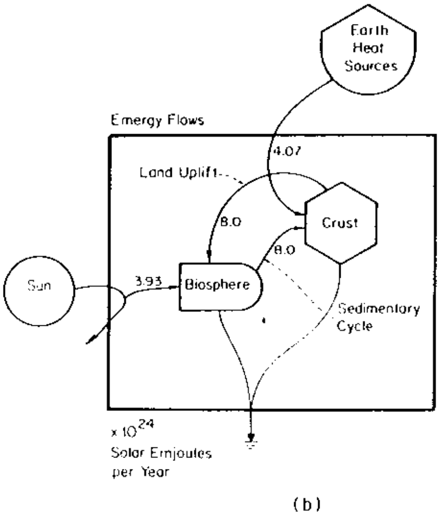


Figure 9. Main energy sources of the biosphere and earth's crust before the fossil fuel era. (a) Rates of energy flow estimated from Sclater et al. (9); (b) solar EMERGY flows.

A Table of Solar Transformities

Given in Table 2 are solar transformities calculated from energy analysis of the existing web of energy flows on the planet. For example, the transformity of chemical energy in rain as it falls (5th item in the table) was calculated by dividing the global solar EMERGY per year from Figure 9 by the estimate of avreage Gibbs free energy in terrestrial rain water relative to sea water. 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.

A forest receives direct sunlight, wind, and rain, each resource contributing a different form of energy. When these are all expressed in solar EMERGY units, the rain is often found to be the largest. In other words, more sunlight is involved elsewhere on earth over the oceans in bringing the rain to the system than is received by the forest directly (10).

Table 2. 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	18,000–40,000
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 Note (11).

Goals of Self-Organized Systems

If the self-organization process generates designs that maximize power, then we can say that self organization sets aggregate performance goals by reinforcing those parts which contribute. The designs that maximize performance are necessary complexity of existence. If performance of parts is predictable from designs and mechanisms at a higher hierarchical level, models at the higher level may predict performances of the lower level.

It may be time that the anti-teleology taught to biologists (teleological thinking is a sin) be put aside, recognizing that mechanisms of a larger system, by reinforcing those components which contribute, give the smaller units goals. Perhaps many scientists carefully tutored to deny that systems have goals are thus blinded to important generalizations. Only by making measurements do we get answers to questions posed to nature, but only through models on a larger scale can we find the questions to ask.

Functional Complexity

After arrangements of parts and connections have been selected by trial and error testing to make a system function best, complexity may result that facilitates the system's process. Since all processes involve a flow of energy, complexity is useful when its arrangements facilitate energy flow. Beacuse we can see parts and what they are doing in the ecosystem and economic system, we can be more definite about the important roles for complexity in these realms. Whether complexity in other aspects of nature is functional or not is a controversy, which is considered in Part IV after general models are considered next.

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41,000
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18,000–40,000
24,000–200,000
1,000,000–4,000,000
80,000–5,000,000,000
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PART II. MODELLING COMPLEXITY

Concepts of science, expressed in rigorous language, become models; and if mathematics can adequately represent principles of energy causality, then generalized models may represent many kinds of living and non-living systems. If the self-organization mechanisms that maximum power in all kinds of systems can be modelled correctly, then computer simulations can predict the parameters to which the systems of various types are guided during self organization. In Part II models that may emulate self organization are considered, deriving clues to designs from the comparative study of ecosystems and their performances.

Models Unite Structure and Time

Human minds use computer simulation models to represent the way self-organizing systems change with time. If a model represents the major relationships correctly, graphs of properties with time resemble the observed ones. Thus, the design of relationships in the structure of models is also a way of representing performances in time.

Calculators or Emulators

Some people use mathematical models to combine observed facts as a way to predict – in other words, as a calculator. This may not show the future because the real ecosystem reorganizes with different species and new patterns not predicted by a model describing past characteristics.

A different kind of model *emulates* self organization and maximum power reinforcement. The emulation model generates the performance into which the parts are constrained to become organized so as to maximize power. In other words, the successful model has the mathematics of maximum power organization that reinforces production and coupled consumption processes.

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 allows many possible types of pathways to be tried out (12). Hence models should have many kinds of mathematical terms, one for each type of energetic pathway, so that the system can automatically use the pathway combination that draws maximum power. As simulation proceeds, each pathway increases in flow during that part of the time when it is mathematically appropriate. For example, Figure 10 has three pathways in parallel, each of which dominates the power use for a particular range of available energy (R, unutilized energy flow).

Modelling from the Top Down

With emulation, main processes of ecosystems are to be represented by models that contain all the mathematical pathway types that go with self organization. These configurations may simulate the overall performance without dealing with details of all the separate species. The species and mechanisms which achieve the maxium performance may be different in each case, representing fine tuning of self organization. To predict the detail, one may first model the performance and then separately identify the species which are adapted to that circumstance. This has been called modelling from the top down. Not all ecologists believe this is possible (13).

Certainly, we do not yet have all the configurations of self organization mathematically identified, but some designs universal to energy processing seem empirically and theoretically established.

Autocatalysis

A design that uses power to reinforce production is autocatalytic. See example in Figure 10. After energy is transformed into a new product, this higher quality energy is used back in the production process again. In feedback amplifier actions that reinforce flows, a small amount of energy has a large effect as a multiplier. Things that reproduce such as living species and economic units are autocatalytic. The components of ecosystems are autocatalytic, as well as the designs of these components in the ecosystem (Figure 7).

As also shown in Figure 10, the feedback may be a higher order feedback amplifier with a quadratic (proportional to storage squared) or higher power. These become more important at higher available energy levels.

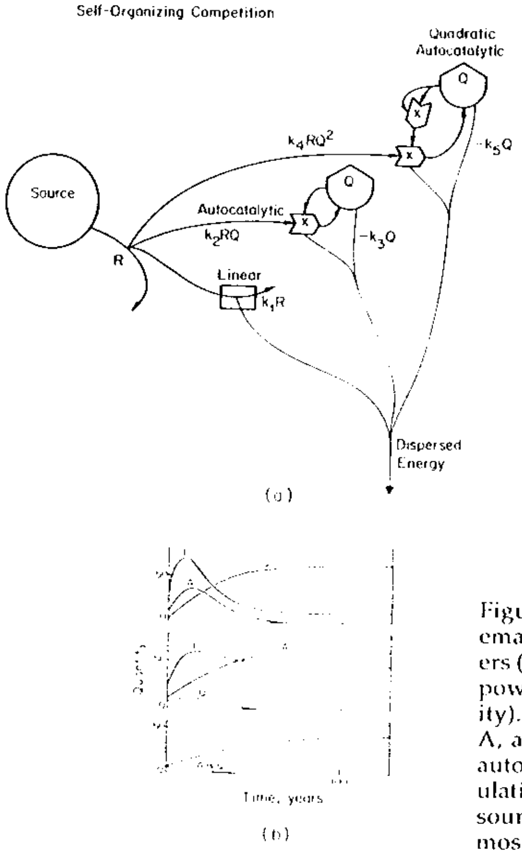

Figure 10. Simulation of competing mathematical pathways in which higher powers (larger exponents) prevail with higher power sources (greater energy availability). Abbreviations: L, linear power flow; A, autocatalytic power use; Q, quadratic autocatalytic power use. Lowermost simulation graph has the least available source energy; uppermost graph has the most source energy.

Mathematical Pathway Selection by Power Level

When a systems model is provided several kinds of pathways each of higher complexity for its production and consumption, the one which carries the most flow is a function of the energy provided. At low energy the simple pathway mathematically carries the most flow; with more energy available, higher complexity pathways take the predominant flow. See Figure 10b (14).

Other phenomena that fit these mathematically defined, energetic dependent criteria are the switching from laminar to turbulent flows, the shift from non-living to living units, and the switch from simple feedback growth to cooperative actions of populations such as those studied by W.C. Allee (14).

Although Figure 10 is useful for showing how mathematical competition can self organize maximum power input, real systems have hierarchy and recycle pathways like those already shown in Figures 4 and 8. Special properties of autocatalysis result.

Autocatalysis in Hierarchy Requires Linear Inflow

When an autocatalytic unit is part of a production-consumption system with a feedback necessary to lower level production as in Figure 11a, the system will not operate. Since the production depends on the consumer's feedback and vice versa, the system cannot get started in growth. If, however, there is a steady, linear flow from production products to the autocatalytic unit as in Figure 11b, then both production and consumption can grow until a level is reached at which higher order processes can function. At that point consumption accelerates as a frenzy. The linear-autocatalytic consumer unit is shown as part of a producer-consumer model in Figure 12.

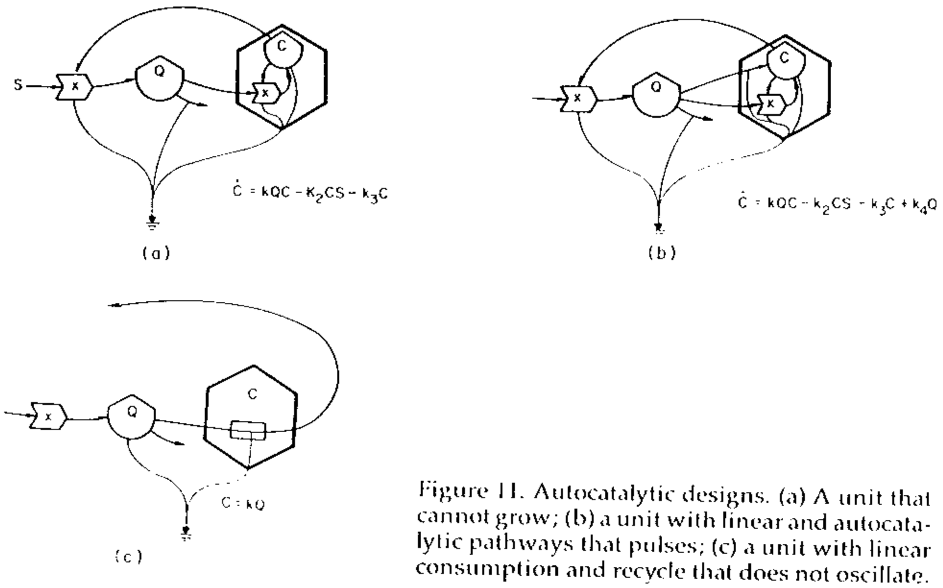

Figure 11. Autocatalytic designs. (a) A unit that cannot grow; (b) a unit with linear and autocatalytic pathways that pulses; (c) a unit with linear consumption and recycle that does not oscillate.

This may be why consumer populations in ecosystems have two or more modes. One is a benign consumption like forest leaf herbivores that takes only about 7% of the products and can maintain a presence; the other is an epidem-

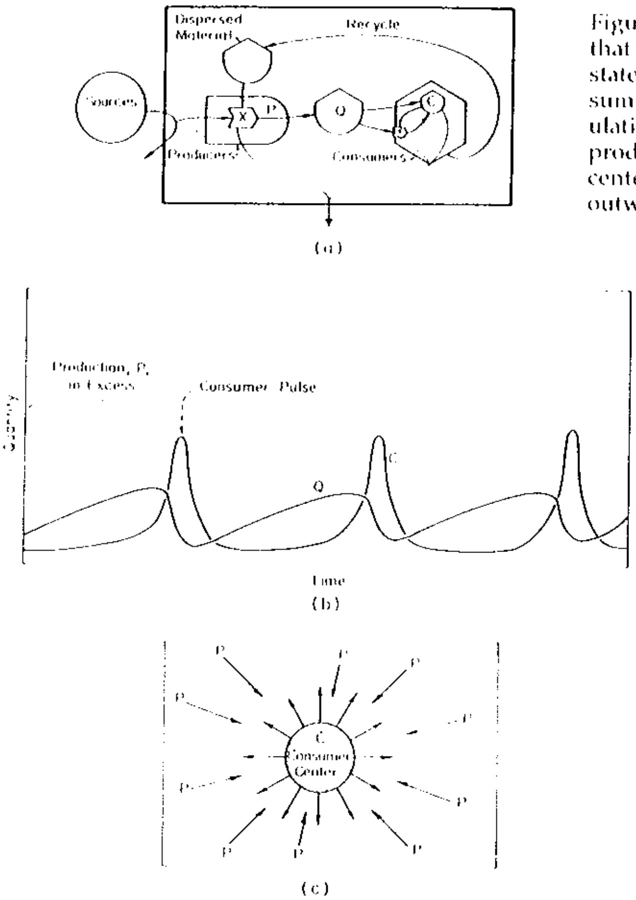

Figure 12. Simulation model that generates pulsing steady state of production and consumption. (a) Diagram; (b) simulation; (c) spatial flows of rural production (P) into hierarchical center, and recycle feedback outward to larger support area.

ic phase in which rapid autocatalytic growth rapidly consumes available storages after which it has to return to benign mode. The switch in some cases represents a substitution of species. In other cases such as locusts, it is a physiological switching within one species. This example shows how energy-constrained models explain why the species patterns have become organized as they are. The model emulates the system's overall performance without involving the component mechanisms because the performances of the parts are constrained by the larger scale design.

Temporary Role of Malthusian Growth and Competition between species

Because autocatalytic feedbacks maximize power when energy levels are high enough, they are capable of periods of sharp, nearly exponential explosive growth with accompanying decimation of available foods or fuels. This property described by Malthus is a model of what happens when there is no further organization. Unlimited growth does contribute to larger system functions in early succession by getting life started as quickly as is possible. Only in these brief, unregulated pioneer stages is unlimited competition useful in generating maximum power. See Figure 1a.

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Priorities for Maximum Power Altruism

After initial periods of simplicity (Figures 1a and 10), self organization forms system designs organized hierarchically. Each unit connects with the realm of smaller components that contribute to their support and to the larger realm of which they are a part, which has consumers of larger dimension and effect (Figures 6 and 8). Continuing the maximum power arguments, we conclude that the designs that continue become symbiotically coupled both to the smaller and the larger realms, because the additional pathways and division of labor increase total system power and efficiencies.

Figure 8b shows the symbiotic exchange connections which enable an autocatalytic consumer unit to maximize larger system power. After transformation of input energies into production and storage, each unit's products and services are fed back (to the left) to the lower level in the hierarchy and forward (to the right) to the next level in the hierarchy. Both of these outputs reinforce the return flows that converge on the unit's production process (P). We can call the maximum power designs that promote system continuation, system altruism.

The Self-organizational Tuning of Production Functions

When more than one input of different type and energy quality is required to generate production, each is a potential limiting factor. Performance is maximum when the feedbacks of high quality resources are assigned so that no one of the necessary inputs is more limiting than the others. Known in both ecology and economics is the principle that production is maximized when the partial derivatives (marginal effect) for contributing inputs are the same. In other words, maximum performance occurs when no input is more limiting than any other.

Tripartite Altruism for Units in Hierarchy

In Figure 8b are three inputs to a unit's own production process, the selfish input of its own, the return flow from the left, and the return flow from the right. Production is maximized by dividing the outputs from the output among the three pathways so that no one of the returning inputs is limiting. In other words, a three way distribution of output may generate maximum performance and continuation. This might be called "tripartite altruism" – one third for the producers, one third for self, and one third for the larger systems controllers. Supporting the rest of the larger system is the higher selfishness.

The Production-consumption Model

With Figures 4 and 5 we viewed the ecosystem with an aggregated model containing a symbiosis between production and consumption coupled with service and recycle. The consumers are higher in the hierarchy toward which products converge and from which services and valuable materials diverge. The economic system is similarly simplified as a coupling of production and consumption with the circulation of money as well as materials.

With linear consumption-recycle pathways (Figure 11c) models are stable, responding to on and off energy inflows by charge-up and discharge of storages (first order equations in textbook fashion). Patterns are like that in Figure 5. Variations of this model have been successful in representing the rise and fall of oxygen and carbon-dioxide during the day and night.

The linear consumer pathway can represent populations of autocatalytic consumers if they are tiny with fast turnover times relative to the time scale of the system. For example, populations of bacteria collectively maintain a pathway with flow in proportion to storage even though their own growth is autocatalytic on a shorter time scale. BOD (biochemical oxygen demand) procedures are based on this concept.

Steady State Paradigm

When the production – linear consumption model (Figure 5) is simulated for a longer period (Figure 13a), there is a period of growth of production, followed by growth of consumption until both level in a steady state with energy processing through the system and materials recycling. The growth period may go through a maximum depending on the initial conditions, soon dampened out. We found these patterns in some microcosms where there were no long-period autocatalytic consumers (3). This model became a textbook concept for growth and climax in ecology (15). The consumer pathways are linear and this is appropriate where pulses of growth and oscillation are only among small consumers, too small in time and space to affect the overall material budgets on the time scale of study. They cancel each other, are averaged out, and appear as noise.

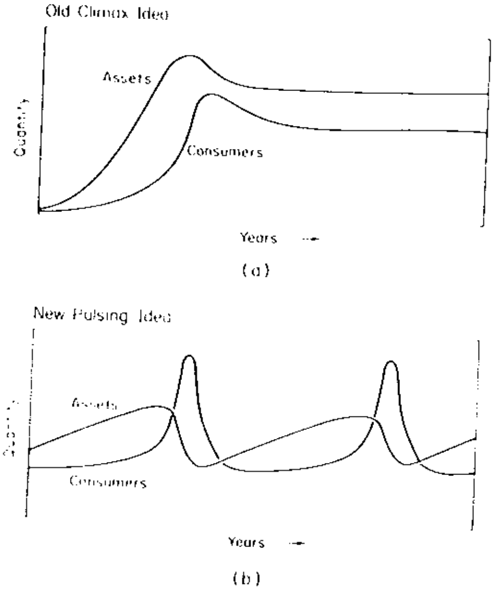

Figure 13. Comparison of two paradigms for self organization and growth. (a) Net growth followed by climax state; (b) pulsing alternation of production and consumption.

A Pulsing Paradigm

However, if available consumers are larger and thus with longer turnover times, the production – consumption model in Figure 12a is appropriate. The autocatalytic units develop surges of growth and cause the system of produc-

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ers and consumers to develop a different pattern, one of pulsing alternation of production and consumption. The simplest model for this, provided by John Alexander (16), had a linear and simple autocatalytic pathway. As shown in Figure 12, periods of net production are separated by periods of frenzied autocatalytic consumption.

A similar one in Figure 14 includes a quadratic autocatalytic pathway (17). Depending on the coefficients, that model generates either the classical climax paradigm (Figure 13a or the pulsing paradigm 13b). In other words, minor changes in rates and setting that correspond to presence of different species can switch the system from one pattern to the other. The maximum power theory suggests that whichever regime draws more resource with more efficient use, is reinforced and prevails.

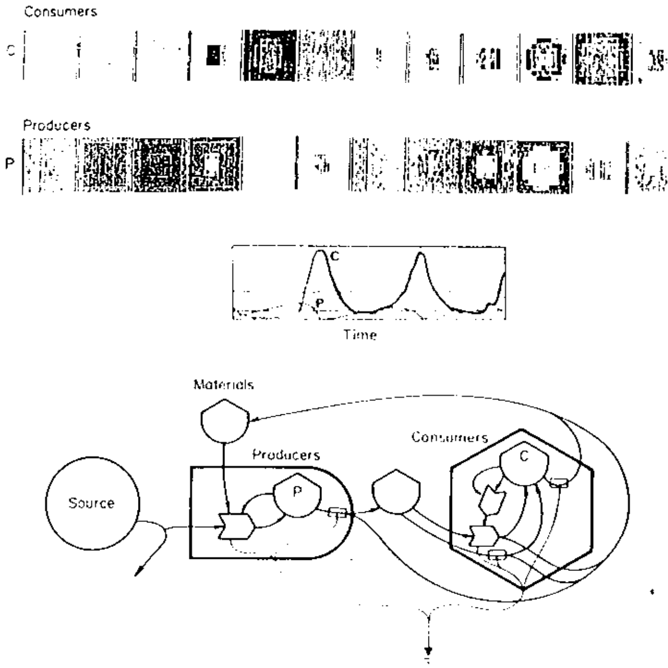

Figure 14. Example of pulsing spatial simulation by John Richardson (17) in which each spatial cell received input from the pulsing consumer and intercell diffusion. Above: succession of spatial patterns with Producers (P) in broad support area and Consumers (C) in hierarchical center; middle: time graph; below: energy systems diagram.

Optimum Frequency for Maximum Power

Extensive computer simulations of the production-pulsed consumption model (Figure 14) by John Richardson (17) show that over a wide range of available energy, power is maximized by the pulsing pattern. There is an optimum frequency for maximum power, but the design draws full power over a wide range of coefficient settings. Frequencies are controlled by small changes in coefficients of the kind that represent substitution of species. Hence, self organization occurs for optimum frequency. In other words, there are frequencey niches for speices.

There is precedent in other sciences for increased performance with pulsing. See, for example the studies of photosynthesis in flashing light, the pulsing of batch processing in chemical industry, papers of Rinaldi, etc. In ecology there is now a large literature showing that pulsing is the normal pattern. If the system maximized power when tuned for pulsing, it will be the design that generally emerges in self organization.

One can visualize why pulsing can maximize long range performance with the example of farmer's cattle grazing a pasture. By keeping 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. Pulsing keeps production and consumption from interfering with each other.

Increasingly, studies of ecosystems are showing a pulsing paradigm as the most general one in nature (Figure 13b). 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, and harvest cycles. A self-organizing system can organize around an available source of pulsing or develop its own.

Pulsing in Time Correlated with Territory and Hierarchical Position

Consumers can be defined as units one or more energy transformations higher in the hierarchy than producers (to the right in energy systems diagrams). Spatially consumers represent a convergence as suggested by the sketch at the top of Figure 6 and Figure 12c. Consumer feedbacks are a divergence. Consumers are a step larger, have longer turnover time, and longer territory of support and influence. Size-time correlations are long established for biological units, atmospheric units, geological units, etc. In other words, there is a correlation of size of units and their territories with time of turnover. Since the turnover time is the principal mathematical property that determines the frequency of pulsing, the time of pulsing is correlated with the hierarchical position and transformity of the consumer centers.

Models for All Scales

A general systems simulation modellike the pulsing one in Figure 12 (see also Figure 28b) can represent any scale of size-time. For the same model running on a computer, a second may represents a microsecond or a billion years. However, when one changes the time scaling, one changes the EMERGY that the flows represented by that factor. Time scaling is energy scaling. The energy scaling factor is the transformity. Mathematically and energetically defined, self-organization-emulating models may apply to all scales of size and time.

Patches and Complexity

Since the territory of a pulsing unit is proportional to time of pulsing, a hierarchy of different sized units superimposed as in Figure 2 produces bare patcher words, there are frequencey

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es and patches of complex content intermixed as different spots are in different stages. A false controversy in ecology has concerned whether disturbance increases or decreases complexity. In a bare spot following a pulse the complexity is reduced, but on the larger scale the pulse has increased the variety of stages and thus of total diversity and complexity. The unnecessary argument was really over boundaries and scales of interest.

Pulsing Spatial Models

Whereas the model and simulation in Figure 12 have the dispersed producers and the concentrated consumers aggregated, the spatial performance of these relationship may be simulated, as recently done extensively by John Richardson (17). With different means for the timing and sequence of consumer feedbacks (representing material recycle, behavior control actions, patterns of consumption, etc), different spatial patterns emerge, which are most suggestive of spatial patterns and patches in ecosystems that are often attributed to indeterminate species randomness. See one example in Figure 14.

Higher Level Pulse Controls

Producer-consumer models like that in Figures 12 and 14 represent only two stages in the energy hierarchy. Pulsing is also going on at higher levels of the hierarchy with longer periods than those of the system that may be of interest. When the pulses 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 zooplankton consumers, whereas oscillations in populations of fishes cause every level to pulse including the nutrients and phytoplankton. See for example the simulation of an estuarine lagoon ecocystem in Figure 15, running on constant inputs but with consumer oscillations at the top of the chain pulse all levels, cascading the effect of the larger animals downward. For units like phytoplankton with short turnover time the long sustained pulses from higher level appear as catastrophes.

Ecosystems as Energy Maximizing Filters

For self organization to maximize power where there are pulses coming into the system from higher levels in the hierarchy, there must be adaptations to absorb and utilize energy. Examples are floodplain plants that are adapted to various hydroperiods and desert organisms adapted to rainfall events. Extensive theory in electrical engineering has concerned filters usually for removing pulses as unwanted energy, whereas the theory which is relevant for self-organizing systems concerns the designs for maximum energy utilization. In a sense, an adapted ecocystem is like an FM (frequency modulated) radio, self organized to receive whatever channels are incoming from the environmental resources.

Daniel Campbell (18) simulated the response of basic ecosystem configurations and producer-consumer hierarchies to pulsing inputs of various power and frequency. He studied the response of a salt marsh ecosystem model calibrated with time constants from observed data. A version of the Bode graph was used to relate the power of the input oscillations to that absorbed (used) by the system. Over a wide range of frequencies of inputs, the ecosystem model maintained an ability to filter and use available inputs.

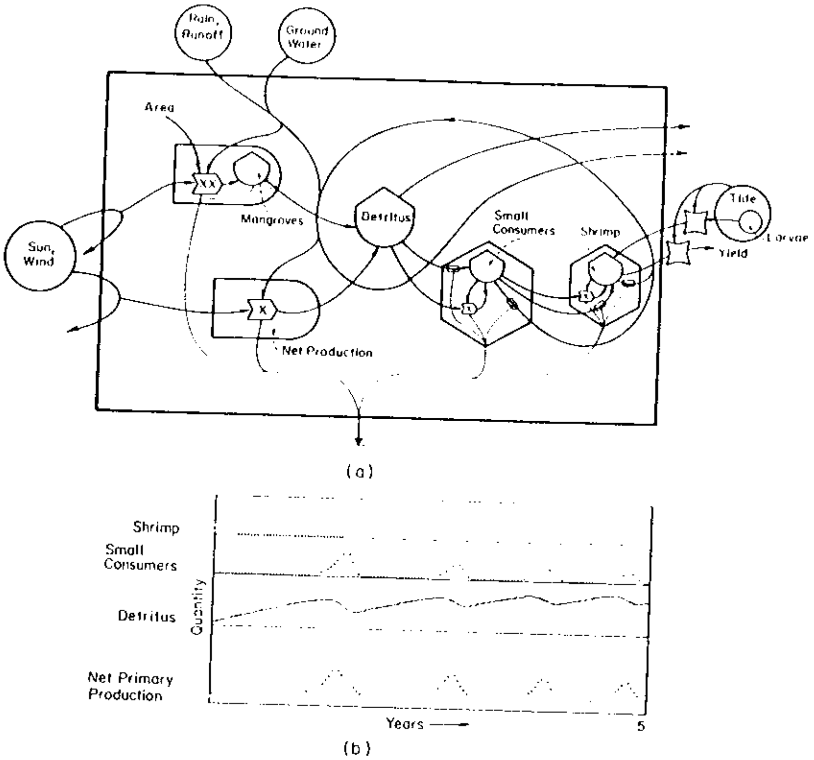
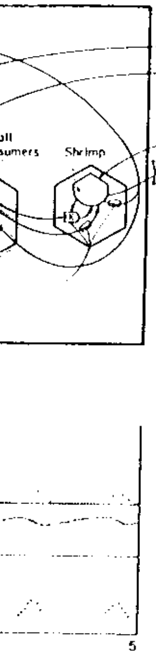


Figure 15. Microcomputer simulation of an estuarine lagoon ecosystem in which internal oscillations of higher, long period consumers cause the whole system to pulse including nutrients and phytoplankton components. (a) Energy systems diagram; (b) simulation graph with external sources constant.

Inertial Pathways and Oscillators

Ecosystems and especially human systems have behaviors that respond to an impetus with a negative acceleration. Such pathways have the same mathematics as inertial forces in mechanics and inductive impedance in electronics. In other words, ecosystems have stubborn pathways and units. In electronics such units are used to give systems desired design properties for timing of oscillations and filters to control oscillations. The stubborn properties in ecosystems may have similar roles.

Paul Zwick (19) developed simulation models involving inertial acceleration and oscillators, considering how basic ecosystems with such properties respond. By adjusting timing characteristics of internal oscillator configurations, optimum values for maximum input energy were found. A survey of some of the extensive literature on physiological time clocks suggest that internal oscillators are widespread and are a species characteristic. For sources with different frequency characteristics of available energy different species may be adapted. Thus, ecosystems may develop those species capable of using these sources.



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Complexity of Causality

In Part II, basic patterns of hierarchy, production, and consumption when simulated with computer models, using turnover times and energy constraints of the real world, generated patterns in space and time that most people would regard as complex. The designs that emulate self organization generate many observed features of complex systems (20). The models used are of dynamic, causal, mechanistic type, not empirical, statistical or indeterminate. In Part III next we consider complexity, information and its measures, and questions of randomness, before considering the human in the economic system.

PART III. COMPLEXITY AND INFORMATION

A system is complex if it has many parts and connections. I seems complex to humans because so much is hard for the mind to grasp. In Part III, consider measures of this complexity and its relation to information and energy. Ecosystem examples help us clarify measures of information and their relationship to energy, EMERGY and transformity.

If there are many parts, there are many possible arrangements and possible connections. The situation is complex, whether arrangements and connections are specified or not. If parts and connections are arranged in a particular way, it is regarded as complex whether the arrangement has use to the system or not. Complexity is a neutral word so far as implications of organization or utility. First we need to review some old and new measures of complexity in the ecosystem.

Possibilities for Measuring Complexity

One way of measuring complexity of a system is to enumerate the possibilities inherent in the available parts.

Possibilities: One measure of complexity is the number of parts, the number of possible arrangements of the parts, and the number of possible connections between parts. The number of possibilities is a measure of the complexity, whether things are organized or unorganized, whether the organization is known or unknown. These numbers measure complexity of a situation whether there is an operating system or not. The complexity in a working radio is measured by the possibilities for that set of parts and wires, whether they are connected and operating or disconnected loose in a box.

Logarithm of the possibilities: Another long-used measure of complexity is the logarithm of the possibilities. This is a mathematical formula which calculates units in "bits" (21). One bit is a single choice. A coin has a complexity of 1 bit because there is a choice between heads and tails. If a road has 3 successive forks, it requires 3 choices to reach a destination. The road has a complexity of 3 bits. If a system has no choices, there are zero bits.

"Information" Content as in Information Theory

Some of the measures of complexity are part of a branch of mathematics called "information theory". As used in that field, the word "information" has much narrower meaning than it has in general English usage. The word refers to the logarithm of the possibilities as already defined. It measures uncertainty or certainty. It measures complexity but not necessarily useful knowledge.

Separation of Functional Information from Its User System

A network of species relationships in an ecosystem or a network of components in a radio have measurable complexity. The complexity of their arrangements may be measured with bits. This is a property of the system.

The plan of their arrangements can be extracted and written on paper, on a computer disk, or in coded genes. This information, now separated from the real operating system, can still be measured in bits. The information about relationships may be in a dormant, unused form, stored in a book. Or if the relationships are in operation, the information is in applied form in the configurations of the real user system.

Utility of Functional Information

Information is the essence of relationships stored in compact form which may be used to configure much larger components. When functional information is extracted, it has utility when it is fed back to control and organize a systems of parts again. The relationship of information to its supporting system is given in Figure 16, showing the process of generating the information and its role in feeding back to reinforce its own maintenance and replacement. The arrangements which are useful have been through a process of testing and selection. Operations that used energy were required before the best functioning arrangements were found.

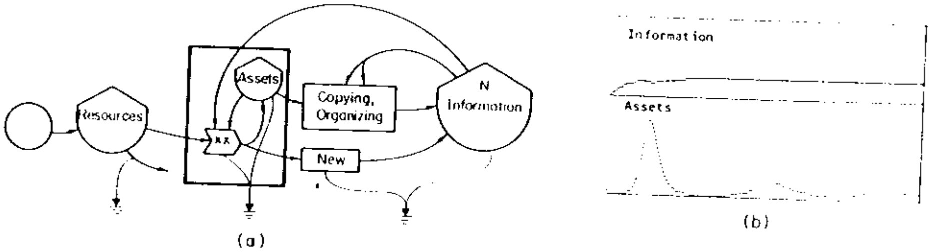

Figure 16. Diagram of information storage and its relation to copying, depreciation, and feedback for use and amplification of production. Equations:

Resources: $dR/dt = I0 - k0*R*A*N - k5*R$

Assets: $dA/dt = k1*R*A*N* - k2*A - k7*A*N*N$

Information: $dN/dt = k6*A*N*N - k4*N - k9*R*A*N + k3*R*A*N$

(a) Systems diagram; (b) simulation of the system with information time constant ten times that of system assets.

Miniaturization of Abstracred Information

When a functional plan is abstracted from its using system as isolated information, it may be miniaturized. Thus we represent the plans for networks or the switching controls of networks in small spaces in brains, computer chips, memory disks, etc.

The extracted information has less energy than the parts it arranges. The information emerges as a product supplied by the parts usually using their energies. Since the information must control parts over larger areas (to justify resources required) and since information has less energy, it must be miniaturized or otherwise economical in spreading function over a larger area.

Energy Accompanying all Information

Information requires a carrier and the carrier has energy. It is not possible to separate information from a tiny bit of energy. The configurations of letters in books, messages on telephone, computer memories are all dependent on what is used to carry or store them.

Information is Pattern Which is Cheap to Copy

Another defining characteristic of information is that it is easier to copy than to generate a new (22). Notice the copying loop in Figure 16. Whereas large flows of energy are required in the trial and error development and selection process for the first time, little energy is required for copying. Once the functional information is copied, the whole system can be built or repaired from the plan with little resources.

Information Storage and Depreciation

Information cannot be stored without some carrier, paper, computer disks, human minds, geologic materials, etc. Since anything that can store information has to be different from its surroundings, the carrier of information possesses some concentration difference and may depreciate, especially when their carrier depreciates. Some information is also depreciated by its uses. Since material arrangements tend to disperse, there is a depreciation of information that goes according to the dispersal rate of the information carrier. To maintain information one has to copy it to keep up with the depreciation.

Wherever there is a storage, the processes at smaller scale cause dispersal of information because the material carrying the information is being dispersed. In other words, information is highly subject to depreciation caused by the second law and by uses.

EMERGY as a Measure of Information

Much work is required to develop and maintain functional information (Figure 16). Information is the essence of relationships stored in compact form, which may be used to configure much larger components. After a self-organized system works, its plan may be saved, stored, and reapplied to develop another such system. Work was used to develop the operating system. The process of abstracting and storing the information in the plan also requires work.

The solar EMERGY used up in the self-organizational process of trial and error is a measure of that information. EMERGY of new information is that of making the choices, of making the selections based on tested use. The solar EMERGY of the development operation is a property of the resulting useful information. The more work required, the higher is the EMERGY of the product. EMERGY is a measure of the functional information of systems.

EMERGY to Maintain Information

EMERGY flow required to maintain information in storage is the EMERGY required for new information inflowing plus EMERGY of copying to maintain it. See Figure 16. An example is the EMERGY contributed when a library receives new books and also has to repair and replace (recopy) old books.

Resource Limitations on Complexity

If information depreciates and has to be continually recopied and readapted to changing circumstances, there is a substantial EMERGY requirement for its maintenance and use. Thus, there is not an unlimited capacity for systems with limited resources to develop or sustain information.

Complexity (the possible arrangements and connections) increases rapidly with number of units. If EMERGY of maintaining, copying, adapting, retrieving, applying information goes up proportionately, then a limit to information use is reached before complexity gets very high.

Solar Transformity of Functional Information

When the functional information of a system is isolated and placed in memory storage, its solar EMERGY is raised, but the actual energy associated with its storage is reduced. Hence, the ratio of solar EMERGY to energy, the solar transformity, is very large. The information is of higher quality with higher transformity than the operation systems it can organize.

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. Since the energy in one copy is small, the solar transformity is high.

Small Solar EMERGY of One Copy Among Many

Since little efforts is required to make a copy, the solar EMERGY of a copy that is not the last copy is small, that of a small amount of energy, materials, and service in making the copy.

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. Thus, the shared information has higher EMERGY for maintaining the same information in the shared status.

For example, if one is protecting the last members of a species, the solar EMERGY is what is required to regenerate a species (evolution or other means) like that from its nearest available stock of a related species, if any. If there are plenty of individuals remaining, then the solar EMERGY value is less, only that required to reproduce it from other individuals of the species.

Information Territory

Shared information may achieve larger territories and influence when it is smaller and cheaper to copy. The shared genetic information in the popula-

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tions of birds and plants has broad territories due to bird movements and seed dispersals. Information shared by a species has a larger territory than the individual organisms.

Two Transformities for Shared Information

One transformity of shared information 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 tranformity is the total solar EMERGY supporting the shared information divided by the energy flow for ONE copy. This measures what is required to maintain the shared status per unit of the information shared. This is the *transformity of a shared original*.

Information and Hierarchy

As already described, information is high quality and high in the hierarchy of a system. Solar transformities are given for the military hierarchy in Figure 3 (23). An example of information in a system hierarchy is given in Figure 17, which contains data on the Texas Highway system (23). The bars represent quantity as a function of the solar transformity. The highway system is on the left; maps and booklets of highway specifications are the abstracted information. Road maps in the hands of millions of Texans are shared information, an even higher transformity and influence. Information is higher in hierarchical position than the system where it is used. Its position in the energy diagram of Figure 16 is appropriate on the high transformity side of the diagram (on the right).

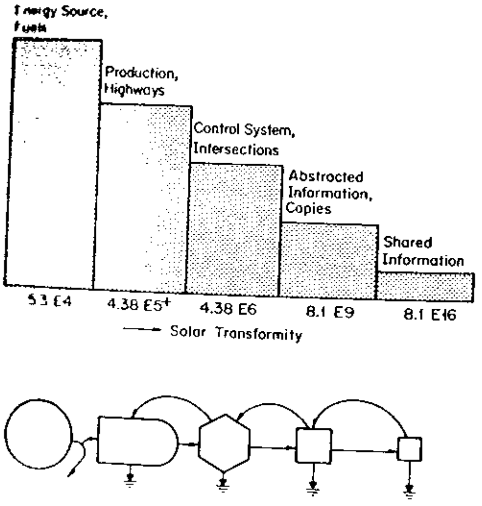

Figure 17. Information on a generalized spectral diagram of energy and transformity using example of the highway system of Texas studied by Wernhuar Lyu (23).

Higher Quality and Hierarchical Position of Shared Information

Shared information covers larger areas and has larger areas of influence. In the aggregate, it lasts longer (turnover time of shared information is longer), has larger territory, and greater influence.

An item of information that is shared, held by many units, has the greater EMERGY that copied and established it in may units, but its territory is now much bigger than any one carrier and its effect is larger, its time constant longer, and its depreciation less than any one carrier.

Because systems are made up of populations of units of similar type and function, information has additional utilities to unify and cause common functions. If each member of a functional group has the same information, they operate in unison with much greater power and effect. Thus, members of the same species with shared information have similar effect over the whole landscape. Humans with similar language and culture can pull together with enormous control effect on their landscape. When information is shared, it has a much larger territory, sometimes worldwide. It also has much longer turnover and lifetime.

Converting information into shared information involves considerable energy of copying, selecting, and generating loops that reinforce and reward those that become part of the group with common information. This process takes place when the sharing is producing effect. The members of a self-organizing system adopt that information that is proving useful, in other words, feeding back as an amplifier.

Information as an Emergent Property of Higher Quality

In a hierarchy there may be one level that generates information at the next and also is causing some loss of that information due to use (Figure 16). Movements of people in a city are controlled by information that the people developed. The pattern of an arrangement may be abstracted to another higher level where it is regarded as information to the level below, for it is that level where the pattern has functional use. As information it has less energy than in its application, but higher EMERGY and transformity. See example of highways in Figure 17 and the extraction of the information in the plans and specifications.

Plan information is at a higher level in the energy hierarchy of the universe. For every sized system the information of that system is smaller, higher in the energy hierarchy, and with a larger territory of influence.

Information Transformity and the Spectrum of Information

The development of useful complexity, the abstraction of the pattern into easily copyable information, and then the upgrading of useful information to shared information, are stages in a hierarchy of energy transformations readily measured with transformity. Figure 17 suggest that information has spectral characteristics like that of other aspects of hierarchy, with more quantity and energy flow on the left, higher quality but less quantity on the right. Tribus and McIrvine (24) suggested that the higher the sophistication of electronics the lower energy there was per bit.

Transformity and the Flexibility of Information

Consistent with the role of controlling larger area with less energy, items of higher transformity (which have been through self-organization processes) have more flexibility. Electricity is a more flexible energy form than coal, and information is more flexible than electricity.

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Transformity and the Ability to Transmit Information

The plans of ecosystems, businesses, and cultures are generally transmitted as information, which then interacts with resources and environment to regenerate a system. The high transformity of information correlates with its role in transmitting the essence of systems.

Similar Complexity on Different Scales

Arrangements on one scale of size may look like those on another when magnified. The complexity is mathematically similar and the complexity in bits may be the same, but the functional roles of different sized systems are different. More resources are required for a network of roads, than for a network of molecules even if the complexities in bits are the same. If one changes scale and both levels have the same design in proportion to their scale, the solar EMERGY is higher at the larger size.

Transformity and Value

Since transformity measures the resource at one level required for a unit of energy at the next, it measures the EMERGY required to maintain the information when it is used. If prior self organization has retained only information with an effect (when fed back to lower level for use) that is commensurate with resources required, then solar EMERGY measures its value in the sense of its effect.

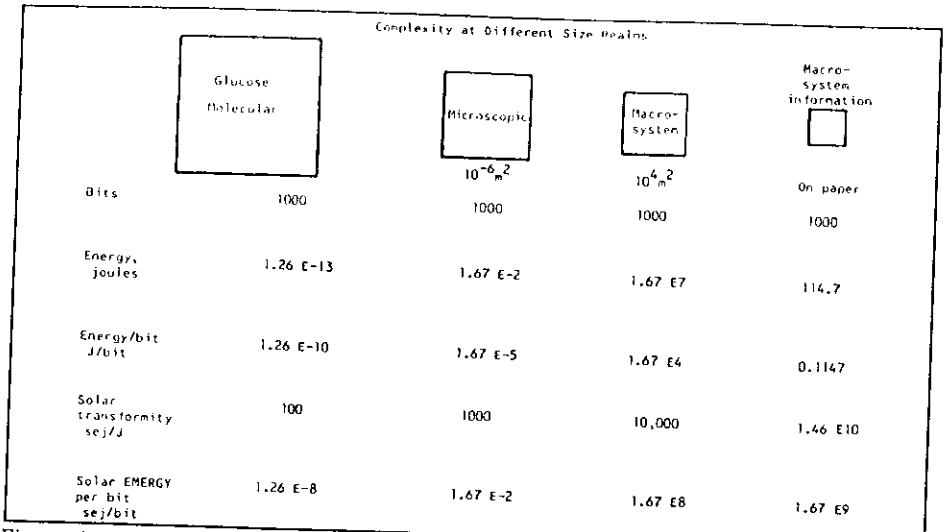
Transformity as a Scale Factor of Information

Transformity (EMERGY per unit energy) is a scale factor for distinguishing information between levels. The arrangements at one level of size are the means for organizing the processes at another lower level. The higher the level, the less energy is flowing, but the more influence is exerted per unit energy. Information on a large scale has higher transformity than that on a smaller scale.

In Figure 18 comparisons are made of the same number of information bits at three size levels: glucose molecules, micro-organisms under a microscope, and large units seen in the ecosystem and landscape from a low flying plane, and finally the information about the landscape extracted to paper. After energy content of the information was determined, it was multiplied by solar transformities to obtain the solar EMERGY, thus putting the bits calculated from different scales on a comparable basis.

Solar EMERGY per Bit

Another measure of information is the solar EMERGY per bit. The higher the level in hierarchy, the higher is this measure. See examples in Figure 18. The energy per bit changes, but the solar EMERGY required per bit gets larger. Miniaturization which reduces the energy per bit may be accompanied by increased solar EMERGY per bit. Smaller realms with the same complexity per unit have lower solar EMERGY per unit but more units. Thus, the ratio of bits at one level to those at another is an index that tends to be larger for smaller items. EMERGY per bit rises as one goes from an item of uncertainty to functionally selected information, to widely shared information.



	Glucose Molecular	Microscopic $10^{-6} m^2$	Macro-system $10^4 m^2$	Macro-system information On paper
Bits	1000	1000	1000	1000
Energy, joules	1.26 E-13	1.67 E-2	1.67 E7	114.7
Energy/bit J/bit	1.26 E-10	1.67 E-5	1.67 E4	0.1147
Solar transformity sej/J	100	1000	10,000	1.46 E10
Solar EMERGY per bit sej/bit	1.26 E-8	1.67 E-2	1.67 E8	1.67 E9

Figure 18. Comparison of energy, EMERGY, and transformities for the same number of bits of information on several scales of size (24).

As ecosystems and humans have evolved higher levels with greater roles and influences of information, the values of solar emjoules per bit have increased. However, the lifetime of a unit of information of higher value remains small if its storage is small. However, by sharing the information with more copies, the effect is reversed. Copying cost is small and counteracts depreciation of the information carrier. Hence, a long time constant can emerge for shared information with high solar emjoules/bit.

Information and Species in Ecosystems

One essence of life is that it stores and copies information which is used to maintain its necessary ecological systems. An ecosystem has several levels of information storage, some in the inherited genes. When an ecosystem has developed a functioning set of species by self organization of available seeds and immigrants, the set of reproductives constitute a package of information that can restore disturbed areas much more rapidly than occurred the first time.

Some of the information in an ecosystem is in the diversity of species and their inheritance and reproduction. Observations of complexity in bits show that within a functional area there is a limit to the information in use. There seems to be a limit to the complexity which an ecosystem develops.

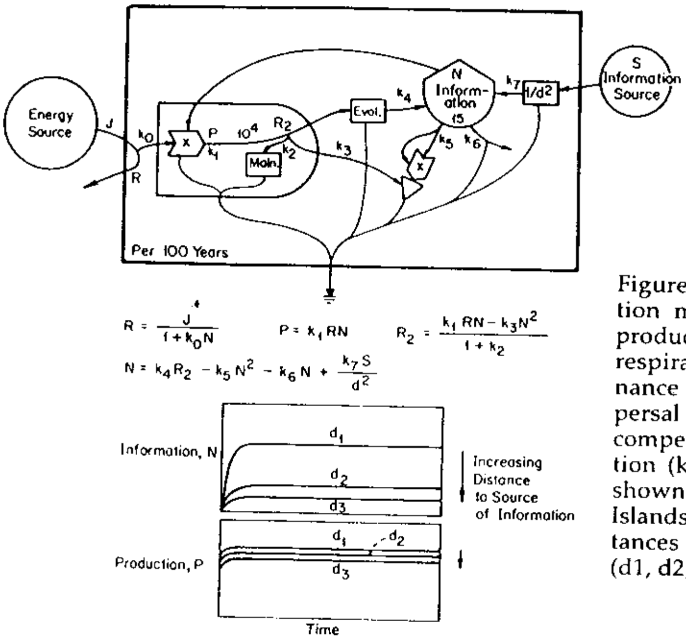
Information in a Gene

The gene in which biological information is stored and passed on to succeeding generations is a small piece of the DNA (deoxyribonucelic acid). If one relates the energy of a gene to the biological cells in which it is contained and then to the energy that is supporting those cells, a transformity may be calculated for the gene. For example, if an aquatic plant cell is running entirely on solar energy, the solar transformity of the gene structure is about 4.0 E5 sej/J. If the gene is shared by a whole species, then the territory of the one gene is much larger. For a species which has a territory 100 kilometers across, the solar energy requirement is much larger and the solar transformity becomes 4 E13 sej/J. See Endnote (25).

A Model of Diversity and Productivity

Increased diversity of species allows improved division of labor and increased productivity. A back-up of contingent species can become more important and improve processes as conditions vary. A simulation model is given in Figure 19 for the number of species and calibrated for the isolated Galapagos islands. The diagram shows productive products P being used to maintain the biomass (Main.), drained in support of the species interactions, and some evolving new species. New species are also being dispersed to the island in proportion to the inverse square of the distance. As Figure 19 shows, there is depreciation of information in species extinction. Two extinction pathways are included in the model, one linear and one proportional to the quadratic self interaction of the number of species in potential competition.

Successive simulation runs are graphed in Figure 19 for different distances from the mainland. The further from the mainland, the fewer species develop and the lower the ecosystem production. As calibrated new information from external immigration and that from speciation and adaptive radiation are of similar magnitude. This model may apply to other kinds of information such as human knowledge on islands.



$$R = \frac{J}{1 + k_0 N} \qquad P = k_1 RN \qquad R_2 = \frac{k_1 RN - k_3 N^2}{1 + k_2}$$

$$N = k_4 R_2 - k_5 N^2 - k_6 N + \frac{k_7 S}{d^2}$$

Figure 19. Computer simulation mini-model that links production P, community respiration and maintenance (main.), species dispersal S, speciation (evol.), competition k5, and extinction (k5 & k6). Simulations shown are for the Galapagos Islands at increasing distances from the mainland (d1, d2, d3).

Taxonomic Categories and Transformity

The distribution of species as classified by biologists according to natural similarities and differences and some knowledge of separation of gene flow forms a hierarchy. Many species are in fewer genera and these are in fewer families and these in fewer orders, etc. This taxonomic hierarchy is the result of evolution that develops small changes in forming different species, and accumulation of these changes develops larger differences in generating higher categories. The solar EMERGY required to operate the species during its development of changes is the resource use necessary to operate a fewer number of genera, etc. The solar EMERGY required to develop each category can be calculated in an aggregate as done in Figure 16.

Simulation of a Minimodel of Information

The general model of information, its sustenance, and its role in Figure 16 was simulated to gain insights on the abstract role of information as a control-member of a system web. Its pathways of copying and retrieval make information autocatalytic with mathematical similarities to carnivore populations and pulsing consumption. However, because of its long time constant, shared information may have long periods between pulses.

As we move further into an information age, the autocatalytic nature of information begins to behave like storms in meteorological models. Oscillations depend on high energy levels. The depreciation rate may be the most critical coefficient. At this stage the simulation model helps us identify the general systems characteristics and identify the measurement data needed to develop these concepts towards an emulation of system information behavior.

The Biosphere's Information Processor, the Human

The ability to be reprogrammed and reorganized (among other reasons) causes humans to become dominant in self organizing a culture and economy in harmony with nature, a process of development very much in progress still. With a wide range of education and roles in social hierarchies, human beings and their services have a wide range of solar EMERGY support in their background. Countries prosper when educated humans immigrate, for example.

Figure 20 has a spectral graph showing a wide range of solar transformity for human training and roles. In a rough way the graph begins to evaluate the human being by evaluating eduction. Included on the right is shared information of public leaders and writers with a high transformity, representing the large solar EMERGY of a large territory of support, development and identification (22).

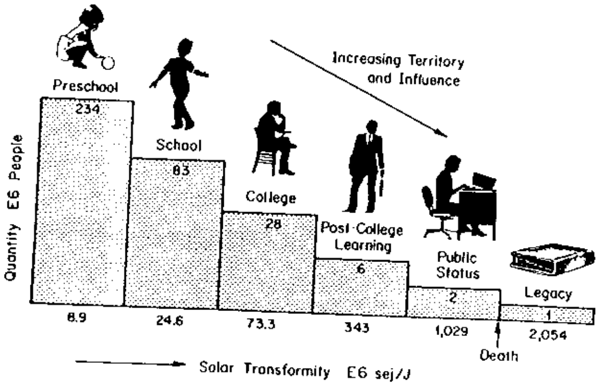


Figure 20. Hierarchical levels of education attained in human growth and development. Population of the United States in each category is graphed as a function of solar transformity. Transformities were calculated by dividing the total annual solar EMERGY use of the United States by the number of people in the category and the annual metabolic energy per person.

PART IV. COMPLEXITY IN PHYSICAL SCIENCE

In this Part IV the functional concepts of energy hierarchy used to consider ecosystem complexity are extended to the molecular realms of physical science, where the traditional view has been almost opposite. Molecular complexity, energy distributions, and entropy have been viewd as random, indeterminate, non-functional, disorganized, and non adaptive. The ecosystem concepts of complexity allow physical systems to be viewed with the same principles as living systems without changing any of the facts or mathematics of thermodynamics and statistical mechanics.

Second Law and Building of Useful Structure

In the sense of ecosystems the term "structure" implies a storage and a pattern, usually functional. The second Law (of thermodynamics), by stating that energy storages tend to be degrated (measured by entropy increase), characterizes structure as something that can be spontaneously degraded. In other words, structure is something away from energy equilibrium.

In open-system thermodynamics there has been argument about whether rates of energy flow and dispersal tended to decrease or whether they tended to increase. The first point of view was called an "entropy minimum principle;" the rate of dissipation of potential energy (with entropy increase) was said to decrease (minimum power principle). The opposite point of view was the maximum power principle that said that the rate of dissipation of available energy (with entropy increase) tended to increase (27).

Open systems are shown in Figure 10 where potential energy is flowing in, being transformed, and dispersing out in degraded form. If the available potential energy is small, the flow simply degrades without building a structural storage. If there is an initial storage it cannot be maintained and it disperses, generating entropy increase along with that of the inflowing energy. Thus, the rate of entropy increase tends to decrease as all the storages away from equilibrium are discharged.

With more available energy, storages can be maintained. The system in Figure 10 transforms the energy to a higher quality in a storage which acts autocatalytically to accelerate energy use. Energy flow is maximized by transforming energy and developing the structure away from equilibrium. At higher levels energy is degraded most rapidly by building useful structure which feeds back to accelerate the process. In other words, by building structure, self organization and evolution maximize useful power (the transformation and feedback of high quality controls and amplifiers) and the dissipation of available (potential) energy. It degrades faster by upgrading.

Among chemists the structure and complexity developed by open systems has been called dissipative structure. For this audience the maximum power principle might be stated: self organization generates whatever structure and complexity that is necessary to maximize the rate of entropy increase.

In other words, both principles, minimum power and maximum power, are correct, one applies to low rates of inflow of available energy, the other applies to higher rates of inflow of available energy. The old controversy about whether flows of energy evolve so as to generate structure or disperse structure is thus resolved.

Comparison of Evolutionary and Dissipative Perceptions

Where energy inflows are adequate, the same behavior can be stated in two ways, one (A) that pleases the evolution-oriented, biological-backgrounded person who thinks in terms of the maximum power principle succession-evolution and the other (B) that pleases the physically grounded person who thinks in terms of the second law dissipation. The difference in expression comes from the different training as to what constitutes scientific causality:

(A) The process of building autocatalytic (useful) structure disperses available energy faster and prevails because power (energy use) is maximized.

or

(B) The pattern with most rapid second law dissipation prevails by developing autocatalytic structure to accelerate dispersal.

Chaos

We started this essay with the views of vegetation in Figure 1, showing how what looked simple and was easily understood and managed was not necessarily as usefully structured as a more complex pattern. With higher levels of available energy, more complexity and hierarchy develops, so that in the aggregate it is not easy to visualize and comprehend the efficient, maximum performing system. At this point the human mind calls a pattern chaos, implying the lack of undestanding and sometimes implying lack of useful function.

The alternate point of view is that systems said to be chaotic have higher order structure generated by self organization at higher energy levels. The pulsing in time corresponds to pattern i space. Learning to live with chaos is learning to use higher energy systems (28). Chaos at one hierarchical level becomes subordinate to the control of longer time constant structures at higher levels.

The adoption of the word chaos for scientific phenomena is unfortunate because the word implies the lack of functional structure, whereas much of the research is showing the opposite, that very complex structure does develop what is functional (26).

A Reversal of Perception of Complexity in Physics

Using insights from ecological systems, this essay suggests that the generalizations from physical science about complexity, randomness and indeterminacy are incorrectly reversed. A statistical concept of complexity has interfered with a unified theory of the macroscopic world of ecological and economic systems and the microscopic worlds of physics and chemistry. What is regarded as random, disorderly, indeterminate, and disorganized is really structured, orderly, causally explained, and organized. See below:

Entropy as a Measure of Useful Structure

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absolute zero), by definition the entropy increases (29). Entropy is a measure of molecular complexity, and the molecular complexity increases as heat is added, and motions and patterns begin to develop beyond a simple initial state of molecules in rows in a crystal. This increase in complexity has been regarded as increased disorder and randomness. Entropy has even been used as a synonym for the lack of structure by people outside of science.

Yet mathematically entropy has the same formula as information discussed in Part II (21). Traditionally the same measure has been used to measure the lack of structure in molecules that is used to measure the useful structure in ecosystems.

When energy availability is added to ecosystems or economic systems, the complexity and information (macroscopic entropy) also increase, but here we can see the increase in useful structure that is self-organizing increased power and EMERGY use. In Figure 18 transformity was used to relate information (entropy) between different scales so that the molecular and macroscopic worlds were viewed as part of the same continuum.

The revised view proposed here is that molecular systems, when they increase their entropy of state, are also increasing useful structure which facilitates their energy flows, whether it is passing through in open systems or recirculating between energy levels in closed reversible systems (30).

Ambiguity of Order

The word order has two opposite meanings that make the word almost useless. On the one hand order refers to simplicity as with molecules in a crystal in neat rows. This is low entropy order. This is simple order.

On the other hand, order is used to refer to arrangements in useful, complex configuration. This is high entropy order. This is complex order.

The conclusion is that one cannot use entropy as a synonym for order or disorder (26).

Ambiguity of Entropy as Structure

Similarly, useful structures and complexities may be high entropy or low entropy. Most structures of society and of the ecosystem are an organized mixture of both (31).

Hierarchy Diagrams of Microscopic and Macroscopic Systems

It is well established that it takes many molecules of low energy to support fewer at higher quality states, such as travelling at greater velocity. The distribution of energy in physical-chemical realms is often represented with graphs of Maxwell-Boltzmann distribution which can be generalized with energy-transformity diagrams like that in Figure 6c (32).

The generalized hierarchy diagram of quantity plotted against transformity (Figure 6c) works for any scale of system. That the graphs are the same shape for all systems is evidence that they follow similar principles. Thus, self organization generates hierarchical energy distribution patterns of quantity and transformity. In other words, it is proposed that high entropy molecular states are highly functional structures like high complexity configurations of our own society.

Deriving Gaussian Velocities from Energy Hierarchy

The assumption that the molecular world was disordered, random, and without useful structure came partly from the fact that the distribution of molecular velocities fit the Gaussian "normal" curve that is generated when there are small variations around a mean. If molecular velocities are Gaussian, and molecular energies a square of velocities, then the energy distribution has a curve like the general hierarchy graphs in Figure 6c. The main problem with this classical concept is that there is no reason why the velocities should be Gaussian.

Revised Interpretation of Gaussian Molecular Velocities

What makes much more sense and makes all levels of the universe similar is to explain the energy distribution curves like those in Figure 6c as an energy hierarchy emerging with self organization of many small low quality energies supporting a few higher quality ones. then, since molecular velocity is the square root of the energy of the molecular movements, the Gaussian velocity distribution is explained as a consequence of self-organizing energy hierarchy.

Continuing the comparison between energy hierarchies suggests that Brownian motion is pulsing by longer time constant members at the upper part of the energy web. In other words, Brownian motions are the carnivores of molecular hierarchies (30).

Energy Hierarchy and Statistical Inference

Most of the macroscopic world does not have Gaussian distributions because the states of ecosystems and economic systems are not related to energy as the square root. Statistics based on Gaussian distributions of variation are rarely valid in the macroscopic world and statistical practice goes through contortions and transformations to make their inferences about significant differences valid. What is generally universal are the energy hierarchy patterns (30).

Many scientists have strong beliefs in the inherent randomness and indeterminacy of phenomena. Perhaps some of these beliefs may change as hierarchical energy structure is found to be general.

Superposition of Pulsing of Hierarchical Levels

In Figure 2 spatial views of several hierarchical levels were superposed, showing how hierarchical complexity results from simple components. Next, consider what this superposition produced in time. In Figure 21 three pulsing models of the type simulated in Figure 12 were combined in a computer program, each with a different time scale appropriate for a different level in hierarchy. Since units at different hierarchical position have multiplicative relationships (Figure 8b), the three amplitudes shown separately in Figure 22b were multiplied together in Figure 21c. The pattern that results seems complex, although it is composed of simple temporal components. The resulting distribution of amplitudes was a skewed graph of quantity and magnitude like those often found in nature.

In Figure 21d the pulses are added; the result is not like nature. One is reminded that time series analysis removes components by Fourier subtraction, which is inappropriate for hierarchical systems. Perhaps a factoring decomposition should be used.

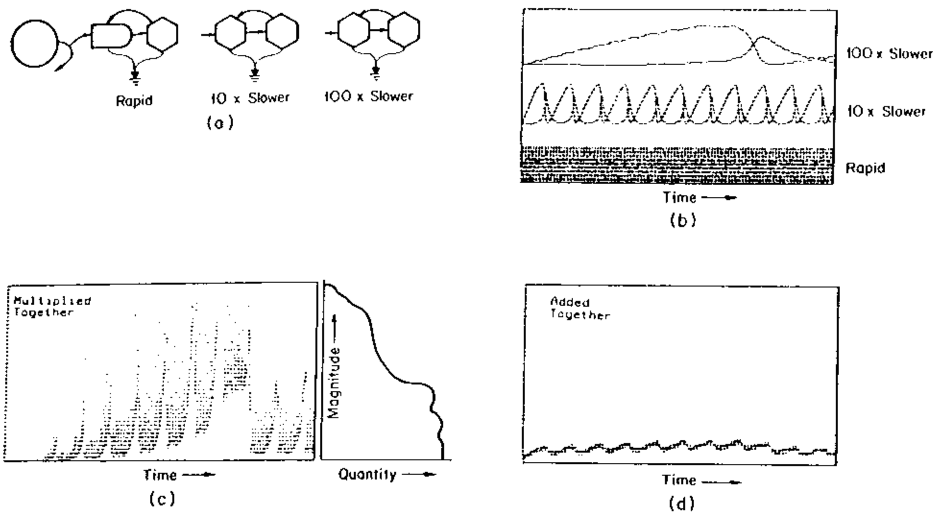

Figure 21. Patterns produced by combining pulsing oscillations each on a different time scale. (a) Energy diagrams and time scales of three levels; (b) computer pulses showed separately; (c) computer simulation with amplitudes multiplied together. Shown on the right side is the distribution of magnitudes; (d) computer simulation with amplitudes added.

Degree of Control for Self-organized Maximum Power

Referring once again to the hierarchy of a food chain, the pulses and fluctuations at smaller levels of size are not important to the next larger level that is being supported, because larger size, territory, time constants, and unit size filter out energy variation. Therefore, it is not essential that the feedback system of the larger, amplifying and stimulating the smaller, should regulate the small fluctuations. In other words, self-organizational processes may not extend control below a small percent of flow.

Time's Speed Regulator

Many papers have now verified our earlier demonstration that there is an optimum efficiency for maximum power (33) so that self organization for maximum power sets controls so as to operate at much lower efficiency that maximizes power (not efficiency). We called the maximum power criterion "time's speed regulator" because this is the criterion for self-organized systems. When humans engineer systems to meet economic survival criteria they are the means by which self organization is working.

Energy Quality and Temperature Differences

Basic to thermodynamics and heat engineering is the principle determining the amout of mechanical work that can be derived from a heat engine using a difference in temperature. As loading approaches a stalling condition, the efficiency, approaches the Carnot ratio (the fraction that the temperature difference is of the Kelvin temperature; Kelvin temperature scale is that measured from absolute zero). In other words, the highest possible conversion of heat energy into mechanical work (pressure-volume work) is the percent of the available heat that is a higher temperature than that of the environment. As discussed above as "time's speed regulator", operations at maximum power are at lower efficiency, often around 50% of the Carnot fraction.

Transformities of Temperature Differences

Sometimes the Carnot temperature ratio is described as an energy quality measure, the higher the temperature gradient, the higher quality. More work is done. In Figure 22 solar transformity of mechanical energy was used to make a graph of solar transformity as a function of half of the Carnot Ratio, which is the maximum power operational efficiency. Thus, we relate the EMERGY concepts to classical thermodynamics (33).

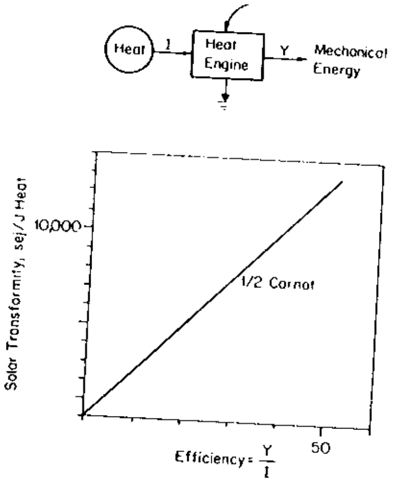

Figure 22. Solar transformity of heat sources as a function of the operational efficiency of a heat engine Y/I, where efficiency is half the Carnot ratio [0.5*delta T/T]. The solar transformity of source heat in solar emjoules per heat joule was obtained by multiplying the 25,000 solar emjoules per mechanical joule observed in some earth processes by the efficiency in mechanical joules per joule heat.

Transformity Antecedents in Electrical Generation

One aspect of standard thermodynamic practice utilizes a transformity-related concept as special case. In engineering, the conversion of fuel-generated heat energy into electric energy, after 50 years of trial, error, and research, reached a plateau of no further increase in efficiency. If one includes as an input the fuel EMERGY of the goods and services involved, the electric generation efficiency is about 25%. In other words, the fuel transformity of electricity is 4 coal emjoules per joule. Although this is a generally accepted practice in comparing electrical and fuel energy capabilities, the more general principle needs to be adopted that all energy flows are of different quality and need to be multiplied by transformities to evaluate work potentials.

Work Redefined as an Increase in Transformity

A corollary of the maximum power theory of self organization is that no en-

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ergy tranformation will be retained unless it has feedback amplifier role commensurate with the energy required for its generation. This means that work in real self-organized systems usually produces higher quality energy outputs.

What is usually discussed as the efficiency of a work process in relation to the second law is really an expression of the thermodynamic transformity. The language descriving work by early scientists such as Maxwell using the phrase "energy transformation" is closer to the correct one than the modern textbooks that define one kind of work, mechanical work, as if it were a general definition of all work.

Transformity and Reality in Science (34)

Use of the thermodynamic transformity concept helps disperse pipe dreaming in science that it it possible to increase efficiencies of processes that have had a billion years of self-organizational fine tuning. Examples where efficiencies are inherently low because transformities are inherently high are the unsubsidized conversion of solar insolation into organic matter and electricity, not likely to be increased over efficiencies of plants.

Another example is the mechanical efficiency of the atmosphere in converting solar energy heating into wind energy, which is around 4% in the real self-organizing atmospheric-oceanic system. Some people think of this as a poor efficiency that humans can improve. The reason the efficiency is lower than a single heat engine conversion is that the global transformation involves concentrating solar energy spatially, increasing its quality into kinetic energy, and further transformations into higher quality storm structures (30).

The Generality of Eco-energetic Paradigm

If the hierarchies and processes of nature are constrained to follow self-organizational reinforcement principles and if these are described in the aggregate by the equations and energy characteristics of these models, then these concepts may apply to all systems. The eco-energetics theory may change viewpoints in physical science about randomness, molecular patterns, and entropy. In other words, the overview models of ecosystems seem to have applicability to physical, chemical, economic, astronomical, and other self-organizing systems.

Top Down Modelling in Physical Science

Even more than in biology and economics, physical-chemical and meteorological models are often constructed with mechanisms from the parts up, overlooking and sometimes denying that there are mechanisms at larger scale, self organizing the smaller performances, and reinforcing those that contribute most. For example, global weather models costing a million dollars a run lose their accuracy after simulating seven days. This approach is comparable to simulating the phytoplankton cell by cell in order to understand the fisheries. To understand the larger scale, longer time-constant phenomena of the atmosphere, the models need the equations for the large units, the storms, the global sized units, and the main categories of storage, not the equations of motion of little bits of atmosphere. The hierarchical energy diagram in Figure 23b may help explain the comparison (30).

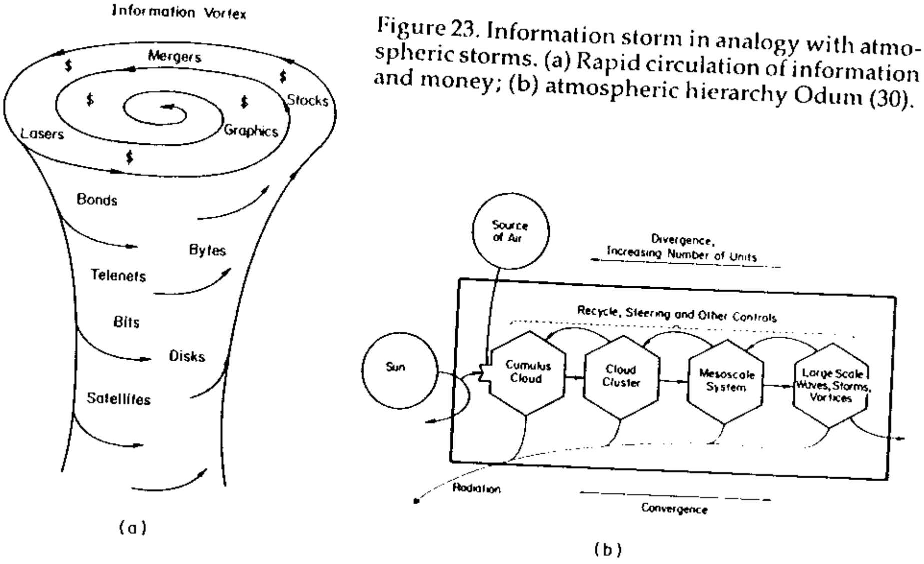

Figure 23. Information storm in analogy with atmospheric storms. (a) Rapid circulation of information and money; (b) atmospheric hierarchy Odum (30).

PART V. STORMS OF HUMAN COMPLEXITY

Finally, we come to human complexity where the simpler view from the ecosystem may help us understand human society and the public policies that can be successful.

Information Storms

Facilitated by human flexibility and self-organizational skills, the biosphere is now swirling with "information storms". Like storms in the atmosphere, which occupy the hierarchical center of atmospheric process (Figure 23b), the earth is being reorganized about the turbulent centers of information. Aided by economic mechanisms and computers, centers are receiving their resource basis from the landscape and feeding back their materials and controls very rapidly.

The super consuming information storms at the centers of our economy and culture are so new that we don't yet know much about their structure, except that they are accompanied by lights and music. An abstract sketch is provided in Figure 23a. Table 3 has the concentration of EMERGY flow per area in several countries, showing a wide range. High values indicate the locations of hierarchical centers where the convergence of EMERGY may generate information storms, especially centered in the great cities.

Whereas meteorological storms have high energy concentration, information storms have low energy concentration, but both have high EMERGY concentration. Both have high transformity; both are hierarchical centers; both organize the circulation of materials converging inward and the recycle them diverging outward; both feed back their control actions to improve performance (Maximum EMERGY); and both have long periods (long turnover times) pulsing surges that are imposed on the surrounding, low transformity

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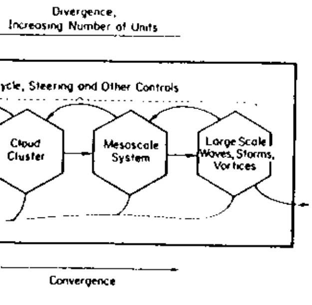

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part of the hierarchy. Figure 23b shows four levels in the atmospheric hierarchy, the general circulation being the largest.

Insertion of the Human Complexity

Throughout their biological and later cultural evolution, the humans have moved toward higher transformities as more and more solar EMERGY has gone into shared information of society. This historical passage is represented by the arrow in Figure 20. Just as meteorological storms are on the high transformity end of the fluid turbulence spectrum, so the storms of information occupy the high transformity end of the human participation.

EMERGY Ontogeny Recapitulating Evolution

The individual human starting as a small baby with only half of its information complement, is part of the world of rapid turnovers, low in the hierarchy. As life proceeds, the individual gets a larger and larger size, territory, and turnover time, especially of his or her informational processing. A healthy psychological life may require a stepwise increase in scale of operation and contributory roles in the whole system. Those who find widening rols as they age are part of the means by which the social system generates useful feedback service.

Table 3. Concentration of EMERGY Use

Nation	Area E10 m^2	Population* density people/km^2	Empower density# E11 sej/m^2/yr
Netherlands	3.7	378.	100.0
West Germany	24.9	247.	70.4
Switzerland	4.1	154.	17.7
Poland	31.2	111.	10.6
Dominica	0.075	107.	8.8
USA	940.	24.2	7.0
Liberia	11.1	16.1	4.18
Spain	50.5	68.5	3.12
New Zealand	26.9	11.5	2.94
Brazil	918.	13.2	2.08
India	329.	192.	2.05
Soviet Union	2240.	11.6	1.71
Australia	768.	1.9	1.42

* Population from Table 4 divided by national area.
# Rate of EMERGY use (Table 4) divided by national area.

Individual Human's Own Hierarchy

As long perceived in human systems biology, the body is itself a hierarchy, ranging from the fast turnover physical and chemical levels to the long-term information storing and processing levels of the mind. A healthy person needs reinforcement at all these levels. Not infrequently, cerebral people try to be above it all, doing damage to their physical basis by not feeding reinforcement back to the low tranformity components. The struggle to give adequate support to food processing, exercise, and sex while striving for as high level of mental transformity as possible is the self-organizational struggle of daily living.

Human Complexity on the Energy-Transformity Spectrum

Some preliminary efforts to estimate the transformities of human information are represented in Figure 20. The methods used were those of Part 3. Two transformities go with information, one the solar EMERGY required to copy and maintain, the other the higher solar EMERGY required to generate the first copy of that information from the environmental state of reference.

Inherited Information in Humans

The capture of a self-organizing system by insertion of information at the top is like the role of virus in taking over living cells. Those working with such a system sometimes speak of the key information as the "selfish gene", recognizing the role that the hierarchical center has in the larger system. Since the genes are shared among a population, the shared gene has even larger managerial (and dependency) role and higher transformity. When that population is 5 billion humans worldwide, then the shared complement of genes is a very high transformity part of the total human information storm.

Learned Information

With information in great excess there is rapid self-organizationl evolution of means for information selection, storage, and recopying. The central question is which information is worth duplicating to become shared information and what are its limits.

In the process of trial and error with new information technologies the waste can be rationalized as the necessary requirements for finding what is essential. For example, television has the ability to generate enormous concentrating of shared information and increasing the size of territory influenced. It would be natural in light of the correlation of size, time, and resource required, if the information dealt with was commensurate in importance with the cost and items that would be long stored. Yet much of the television is entertainment, of short time significance, and possibly not remembered. Presumably self organization will work to increase the scale of the television role. Cultures that forego the potential of the media to generate large scale power and efficiency are likely to be displaced.

Educational EMERGY in High Technology

As states and nations compete for the role of being in the center of information storms, public policies are being directed at encouraging high technology industries (i.e. those with high transformities). By summing the solar EMERGY inputs to technology, some insight is obtained on questions of national competitiveness and the possibilities of sustaining an information society on declining resource availabilities. See analysis of a high Technology company in

Austin Texas by A. Brown revised somewhat in Figure 24 (35). Part of high technology is new research and development, which runs as high as 50% of the expenditures in some defense industries. The rest is involved in manufacturing, which is essentially copying of information and coupling information to hardware, not a very high EMERGY process.

The input of EMERGY from professionally trained people was generated from family education and public education sources, not directly paid for by the company. The diagram shows further that the basis for high technology industry comes only partly from the purchased inputs of the industry using money from sales of products. About a fourth of the EMERGY basis of the company, especially in its research and development division was based on prior public and private education and a high level of information in the society. Presumably ability to compete in industries that are based on information innovations will depend on availability of high EMERGY flows of high quality (high transformity).

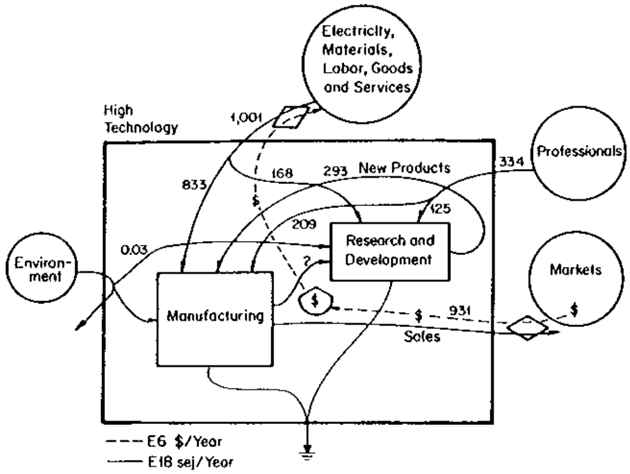

Figure 24. Solar EMERGY flows supporting a high technology electronics industry in Austin, Texas modified from A. Brown, (35).

Complexity in Aesthetics

Although it remains for more empirical testing, a case can be made that aesthetic values go with high EMERGY and transformity. The EMERGY of aesthetic subjects includes what was required to generate the item plus the EMERGY used to develop the information about the subject into shared status.

For example, natural areas which attract humans include beaches, mountains, streams, and areas with large unusual fauna. Such areas have high transformity from environmental work often augmented by high EMERGY in cultural sensitization and advertising.

Art develops high EMERGY as its products are moved up the transformity hierarchy from isolated items of information to a shared status with public recognition and with large territory of appreciation and influence.

Economic Complexity

Facilitating the accelerating, higher exponent autocatalysis is the complexity in the economic system, part of the shared information that accelerates commerce. Centered hierarchically in financial centers, money management designs resulting from self organization are superior in pumping resources. Economic complexities, like the information in the species of the ecosystem, has high transformities from self organization for maximum performance.

Organized Economic System or Indeterminate Free Randomness

That self organization brings useful purpose is close to traditional economic dogma about the invisible hand from the free economy being competitive. Yet the majority believes this complexity is indeterminate, not organized, and not predictable from universal design principles. The hierarchical perspective rationalizes the individualism with the system determinism as compared next.

Humanistic Tradition of Individual Freedom and Creativity

The strongly held beliefs that there are no scientific principles to the design of the human society is a form of humanism out of which modern economics has evolved. It is part of the faith in progress and the capabilities of man that there be no constraints on what can be done, no resource limits, no design restrictions, no obligations to higher levels of performance (34).

Hierarchical Structure of the Economy

Studies in human geography have shown economic society to be hierarchically organized like the ecosystems with converging spatial patterns, steep graphs of the quantities and sizes of cities, and in the income curves that have the shape of the generalized energy-transformity diagram (Figure 6). Individuals may think they are an unfettered multitude of free agents, but the facts show the same kind of organization as in the ecosystem.

The Individualistic Doctrine of Value

The atomistic faith that the whole is what individual humans do takes its extreme view in current economic dogma that value is what people are willing to pay. This is tantamount to saying that only one level of organization, that of buying or selling of individual services is important. In its extreme form, questionaires are mailed to people to find out their wishes as the means to the future. As a result, the system becomes warped with excesses in non-functional individual consumer waste, and failures develop in the resource production and in the higher levels of organization.

EMERGY-based System Value

According to the opposing scientific energy concepts of value, trial and error by creative people acting freely and individually generates the tests by which public policy can make choices. The system as a whole may be predicted to organize differently from the individual-only concepts of value. Ultimately there will be a rejection of the individual value dogma.

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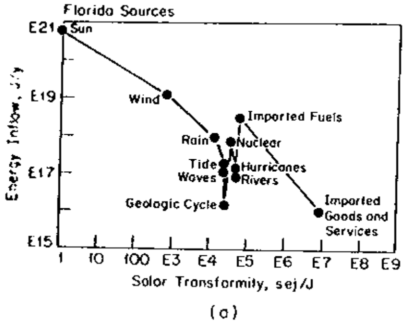
In Part I, we derived a theory of value for any real system that the self-organizational process generates the designs that maximize EMERGY use. Thus, continuation and survival of patterns goes with maximum EMERGY and come to be regarded as the correct, lasting values after the trial and error processes of self organization. Since EMERGY use may be predictable from resource availabilities, some prediction of the designs of society may be possible from scientific principles.

Individual free initiatives and creativity are necessary and important to both concepts, but in the multi-level EMERGY value system, freedom, variation, and choice at one level is the means for system design and control at the next level.

Geopolitics of EMERGY

With different resources in different parts of the earth, the self organization of economic systems maximizes performance by developing specialties around special resources that provde the highest EMERGY. Figure 25 shows the EMERGY inputs for Florida plotted on the scale of solar transformity with low quality sources on the left. In developed countries there is the large hump in the middle of the spectrum representing the input of fuels and minerals from non-renewable resources.



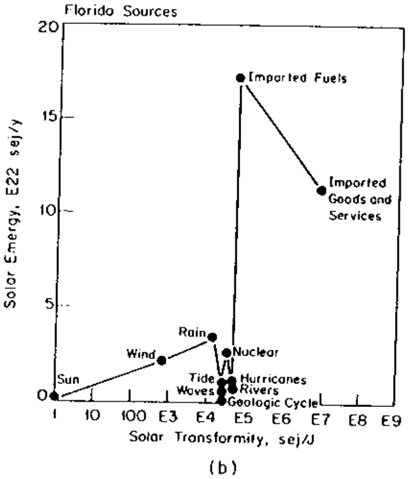


Figure 25. EMERGY inputs to the economy of humanity and nature in Florida (39). (a) Energy as a function of solar transformity; (b) solar EMERGY as a function of solar transformity.

Figure 26 shows the national system of the United States and its uses of resources from inside and outside expressed in solar EMERGY so they may be compared for their contribution to the economy.

The EMERGY signature of several countries is given in Figure 27. The developed countries have very much higher resource uses, but each country has a different set of special resource availabilities.

EMERGY Use of Nations

We have applied EMERGY analysis to a number of other countries, 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 (Table 4) and on an area basis to get a measure of concentration and thus hierarchical position (Table 3).

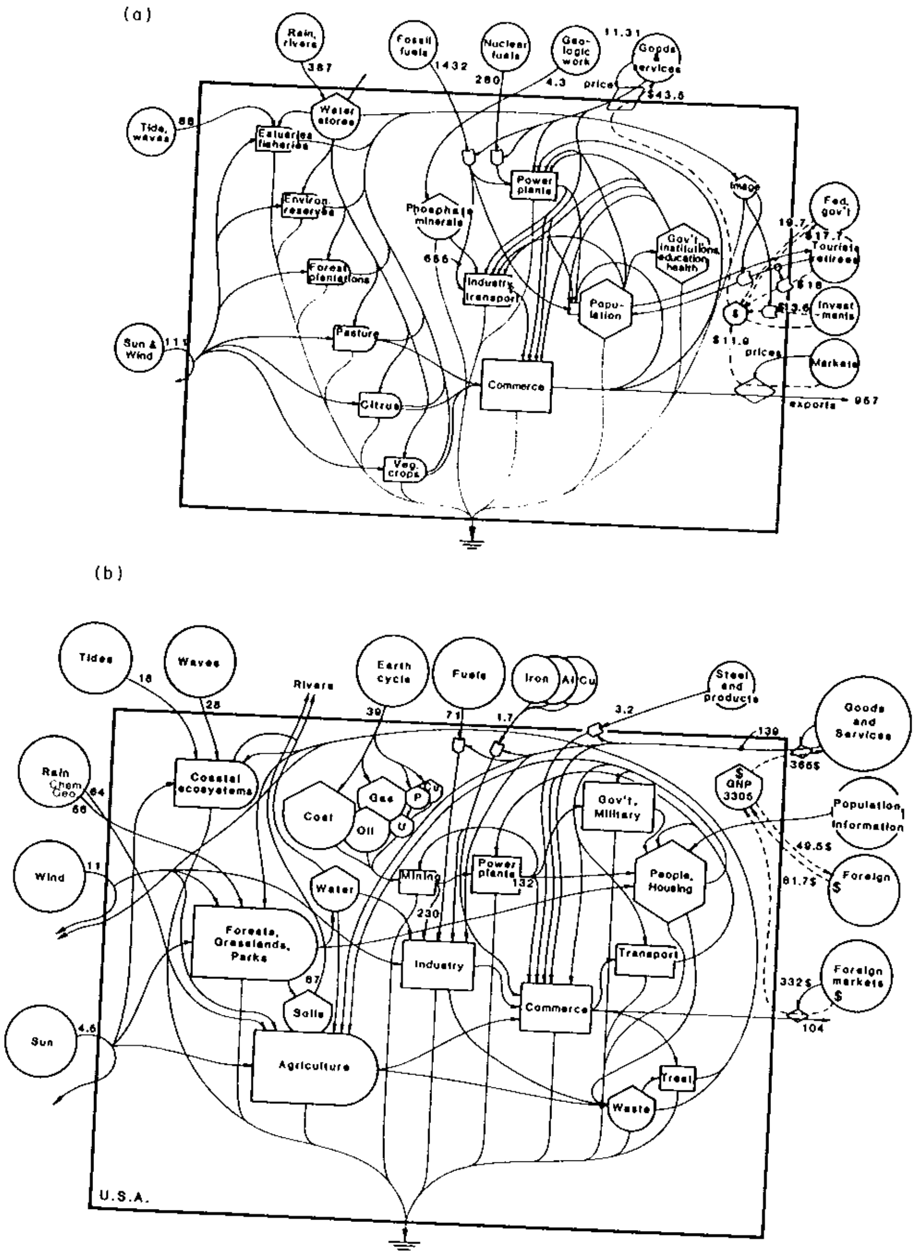


Figure 26. Solar EMERGY basis for (a) the state of Florida; (b) the United States of America in 1983 (36).

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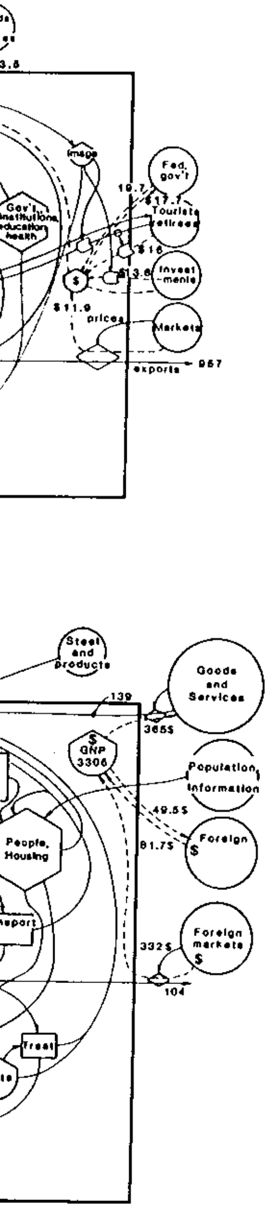
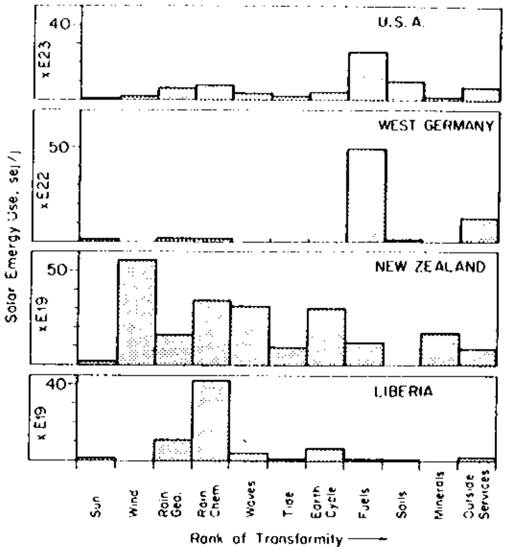


(b) the United States of

Figure 27. EMERGY signatures of several nations, annual solar EMERGY inputs arranged in order of solar transformity (11).



Macroeconomic Value

An economy circulates money that is paid to people for their services, not to the environmental resources which are the real value. By evaluating the total SOLAR EMERGY per year used by a country from all sources, (with care to avoid double counting), a measure of total macroeconomic value is obtained, one that is readily compared among countries. The Solar EMERGY contribution of each resource such as rain or coal can be calculated as a fraction of the total. Although it sometimes leads to confusion, the proportion of the total solar EMERGY can be used to evaluate the proportion of the dollars that derive their buying power from the resource.

Table 4. EMERGY Use and Population

Nation	EMERGY used E20 sej/yr	Population E6	EMERGY use per person E15 sej/person/yr
Australia	8850	15	59
USA	66400	227	29
West Germany	17500	62	28
Netherlands	3702	14	26
New Zealand	791	3.1	26
Liberia	465	1.3	26
Soviet Union	43150	260	16
Brazil	17820	121.	15
Dominica	7	0.08	13
Switzerland	733	6.37	12
Poland	3305	34.5	10
Spain	2090	134.	6
India	6750	630.	1

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.

EMERGY/Currency Ratio and Macroeconomic Value

Any nation has a circulation of money measured by gross national product, which facilitates the total EMERGY use that we believe is the measure of "real value", buying power, useful work, etc. If total annual EMERGY use is the real value, then it is the basis for the gross national product that circulated in the process. The dollars of gross economic product per unit of EMERGY use measures the value of the currency. Table 5 has EMERGY/$ ratios 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.

Any process or storage can be assigned a part of the gross economic product based on its EMERGY fraction of the total EMERGY use. We already defined macroeconomic value. Expressed in currency units, it can be compared with market values (values to individuals) in determining what is good for public policy.

Table 5. National Activity and EMERGY/$

Nation	U, EMERGY used/yr E20 sej/yr	GNP E9 $/yr	EMERGY/$ E12
Liberia	465.	1.34	34.5
Dominica	7.	.075	14.9
Brazil	17820.	214.	8.4
India	6750.	106.	6.4
Australia	8850.	139.	6.4
Poland	3305.	54.9	6.0
World	188000.	5000.	3.8
Soviet Union	43150.	1300.	3.4
New Zealand	791.	26.	3.0
USA	66400.	2600.	2.6
West Germany	17500.	715.	2.5
Netherlands	3702.	16.6	2.2
Spain	2090.	139.	1.6
Switzerland	733.	102.	0.7

International EMERGY Exchange

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. See, for example, the EMERGY advantages to the purchaser in Table 6. Thus, international trade is often uneven in its contributions to the trading economies. For example, U.S. received twice as much as it returned to Mexico in various exchanges (36). Table 7 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 the international cooperation, enriching the world economy and foster peaceful relationships.

Table 6. EMERGY Advantages to Buyers of Commodities (36)

Item	Unit	1983 Price Dollars	Emergy Ratio*
Water	Acre-foot	50	1.9
Fuel	Gallon	1.00	3.3
Fertilizer	Ton	164	11.8
Beef	100 pounds	55	6.5
Cotton	Pound	0.59	3.9
Wheat	Bushel	3.55	3.5
Wool	Pound	0.83	16.7
Potatoes	100 pounds	8.50	2.0

* Ratio of EMERGY in commodity to EMERGY of money paid.

Limitations to an Information Society

Often there is a faith that human brilliance developing technology will always eliminate limits to growth and progress of the type that requires expansion of resource use rates. We see from the nature of useful complexity that it has en EMERGY requirement and thus the total amount that is possible is limited. See Figure 16. More complexity and information is not possible and the amounts that are used and supported will have to become less during the period of decreased availabilities of resources.

We see that an exclusively information society makes no more sense than an exclusively information ecosystem. However, there are hierarchical centers of information concentration in both. Part of the question of economic futures of nations is which ones will be the hierarchical centers of information processing. Will the present centers of information processing continue in ascendancy, or will there be a reorganization with other centers and perhaps more centers, representing greater equity around the world.

Possibilities in Space

Space exploration and travel is very high EMERGY, and its units have very high transformity. In the self-organizational process, many space operations such as communication and earth watch satellites have very large territories and high amplifier actions in their feedbacks to their supporting society.

Other aspects such as setting up space colonies and extended travel are being misrepresented in public policies in regard to their abilities to be self supporting on resources from space. The analysis by G. Noyes (37) provided some preliminary evaluations of what is required for space shuttles as vastly larger than any available resources in space to support human activity. The idea that space is an overflow frontier for earth's people has no basis at present.

On a more abstract basis there may be some long range basis for greater roles in space. The higher is the transformity of information, the lower the actual energy, the greater may be the ease and flexibility of transmission. Perhaps the transmitting of high transformity information into space can be connected in some way to control and amplify astronimical systems already in space.

Table 7. EMERGY Self Sufficiency and Exchange

Nation	EMERGY from within %	EMERGY received / EMERGY exported
Netherlands	23	4.3
West Germany	10	4.2
Switzerland	19	3.2
Spain	24	2.3
USA	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

Pulsing Paradigm on the Earth Scale

In Part 3, the pulsing paradigm (Figures 12 and 13) was suggested as the general self-organizing pattern in time for maximum long range performance. Now the entire biospheric system has been drawn into a large scale pulse of the human economic consumption of one cycle of earth accumulation of available EMERGY.

Figure 28 is a simulation which was calibrated with the geologic production of earth resources being consumed by autocatalytic surge of consumption by the information-guided storm of consumer society. The result is King Hubbert's blip, the famous pulse of our fuel-based economy when viewed on a longer scale of time.

A Christmas Tree Model of Human History

The lights at night are a symptom of information processing. Viewed from satellite the centers of population show patterns of hierarchy like those in Figure 1a, including the small and the large. Over historical time the rise and fall of cities and states as viewed from satellite has been marked by the flashing of lights like a Christmas tree.

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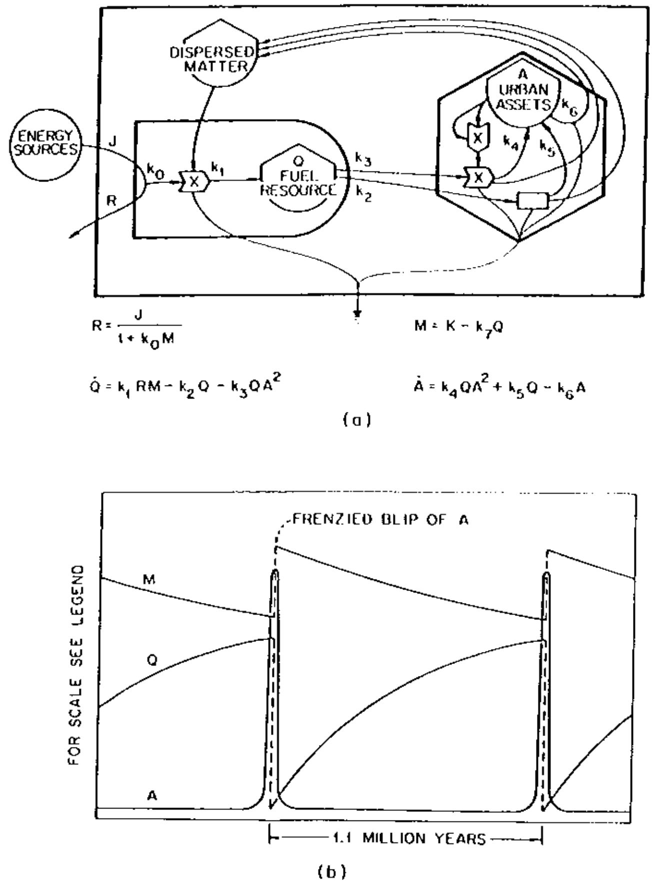

Figure 28. Pulsing model of earth biogeochemical production and frenzied human economic consumption. Simulation generates King Hubbert's Blip. (a) Energy systems diagram of the model; (b) Simulation graph with coordinates: M, dispersed matter, 3 E18 g carbon; Q, Fuel resource, 4.2 E22 coal Joules; A, urban assets, 5.3 E26 solar emjoules.

Complexity for the Prosperous Way Down

As the surge of a larger scale representing the human society graduation to the high transformity of global geochemistry, the phenomena are quite outside the experience of human society and its economic management. In the abstraction, however, as the rest of the world becomes entrained in the phase of decreasing consumerism shifting to a period of excess production again, there has to follow a reorganization of our social system's information programming, which even now may be underway.

Where ecosystems go through the pulsing pattern of ups and downs, the information is not discarded, but is carefully processed into storages of essentials available for the next round of pulsing. We see from this the task ahead for human creativity and selection, the preparation of designs for the downward trend.

For the way down money can still circulate, and the human use will still be coupled to the availabilities of resources. The self-organization process, learning rapidly from local failures, can generate a prosperous way down, providing we have the sense to direct our research effort towards it.

Long Persistence of Cultural-information Effects

We see that the anthropologists' insistence on the important role of culture can be given numerical values with solar EMERGY and transformity. If shared information of culture has long time constants as well as wide influence, then systems that have been dominating hierarchical centers of the world because of their information and culture, will not have this decay away rapidly even though their ability to sustain this role disappears.

This is not to say that cultural information is not rapidly changed in one generation or less when there is strong availability of resources to drive the changes. See the transformations in this century in Puerto Rico and Iceland for examples.

Information Time Constant in Simulations

One of the uncertainties in macroscopic-minimodels that we generate to represent the self-organizational process is the time constant (turnover time) of the shared information at the top of the hierarchy of our society. Whereas infrastructure has a time constant of the order of 50 years (example: Texas Highway study by Will Lyu (23), the information essence of our culture must be longer. Since we don't have a good estimate of the depreciation rate of information and culture, we don't know what time constant to give them in the simulation models like that in Figure 16. How much delayed will be the decline of our current pulse due to long-lasting, shared information?

General Systems View of Stabilize World Participation

If people of the world understand the way hierarchies operate, about pulses, and flashing Christmas trees, then they can adapt to the rise and decline of their own subsystems without losing a faith in the overall benevolence of it all.

Faith in the Self-organizing Process

Many humans have a faith that the human is free to do what each likes and have (God given) duty to be different.

Other humans have faith that the human has a duty (God given) to play a fixed role according to guideline information from the past.

The EMERGY based ethics seem to reconcile these and in so doing draw the best out of religions and science. Faith is justified in individual rights *and* in information from the past because together they insure continuation of maximum performance if neither becomes a limiting factor. In other words, there may be an EMERGY-measurable symbiosis between the politics of the left and those of the right for maximum performance (38).

The Quest for High Complexity for the Way Down

We summarize our essay on living with complexity, which shows the universal comparability of systems of the large and the small, the transformity and EMERGY scale factor for the universe, and the new frontiers of science to look more for the general systems designs where most scientists and citizens raised in our economic society have been taught not to look. If the future is controlled by the pulsing of the larger scale units of the earth and information, the most important priorities concern the current information storm and its likely prognosis as its sources are used up. We need to dedicate more resources to research for the down phase of our resource oscillation. In the schools we need to unify environment, economics, energetics, systems, and public policy as one introductory course, a new way to introduce science and mathematics (39). The most important problem of our time, not yet perceived by most, is the preparation to manage our information reserves for appropriate complexity and a prosperous way down (40).

ACKNOWLEDGEMENT

The author recognizes a shared lifetime mission with his associates and students the world over and rededicates our purposes with all due recognition and thanks. I deeply regret any threats to the careers of others I may have caused by advancing theory faster than is customarily credible in science.

Post Script

The financial oscillations starting with the stock market crash of October 19, 1987, came after the presentation of this essay in Stockholm, September 23, 1987, and seem to be a dramatic demonstration of the emerging importance of the information storm.

ENDNOTES

(1) A General Systems Model from Ecosystems. Measurements of similar quantities in ecosystems of widely varying type showed a commonality among systems. When these were generalized in terms of energy, information, mathematical performances, and hierarchical structures, a set of theories resulted that appears to apply to the human economic system as well as to other realms of nature. The emerging concepts and computer models relate energy, entropy, populations, evolution, and biogeochemistry. The ecosystem provides us a model with which to better understand the whole economic-ecologic, noospheric, system of humanity and nature.

(2) Mathematics are inventions of human mind, often useful in explaining nature. Since all phenomena of nature are accompanied by flows of energy, applied mathematics have the constraints of the real world, and therefore are consistent with energetics. Sometimes the mathematics applied in ecology has been unrealistic because energy constraints were omitted.

Fractals are formulas for designs that result when something is divided into fractions and then divided again and again and again. (Mandelbrot, B. 1977. Fractals. Freeman, London). Beautiful designs result that resemble natural patterns such as flowers, clouds, rivers, etc. Fractals are a way of describing hierarchies like those in Figure 2.

The reason that fractals work is that energy organization of the universe is hierarchical. Because of the maximum power principle, energy in systems is converged while being transformed into smaller but more valuable forms. At the same time valuable controls are diverging as they feed back to stimulate the more numerous lower units. The fraction by which one level of hierarchy is related to the next is determined by the amount of energy of one dilute form such as sunlight required to generate more concentrated forms at another level such as plant production. See discussion of *transformity*.

(3) Ecological microcosms have been an important means of simplifying nature for the purpose of study and understanding. We first studied metabolism and the self-organizational process in closed aquarium and closed circulating stream microcosms at Duke starting in 1955 with National Science Foundation support (Odum, H.T. and J.R. Johnson, Jr. 1955. Silver Springs and the Balanced Aquarium Controversy. Science Counselor, Duquesne Univ., 4 pp.; Odum, H.T. and C.M. Hoskin 1957. Metabolism of a Laboratory Stream Microcosm. Publ. Institute of Marine Science, Univ. Texas, 4 (2):115–133).

Silver Springs plants with periphyton were added, but an entirely different ecosystem developed with species that had been added unintentionally. We learned early that what emerges in an ecosystem is rarely the species you try to grow, but instead is a better tuned set of species that can generate performance with maximum total metabolism.

Self organization takes place when some species through their behavior reinforce other species, thus contributing to maximum power of the whole system, insuring their continuation. A hierarchy is part of resulting organization because it couples the small to the large so that each contributes what the other cannot. Big animals chop-up things, move, manage, and stir. Smaller organisms have the numbers and means to do the necessary chemistry.

(4) Lotka gives general explanations of the maximum power principle (Lotka, A.J. 1922. Contributions to the energetics of evolution. Proc. Natl. Acad. Sci. 8, 147–155; 1925. Elements of Mathematical Biology. Reprinted by Dover, New York). Lotka cited Boltzmann's lecture in an address to the Imperial Academy of Science in 1886 (Reprinted in English in Theoretical Physics and Philosophical Problems, selected writings of L. Boltzmann. 1905. The second Law of Thermodynamics. Populare Schriften. Essay No. 3 D. Reidel, Dordrecht, Holland).

Juan Martinez-Alier has recently reviewed the roots of "ecological energetics" in many rarely quoted contributors in the nineteenth century (Martinez-Alier, J. 1987. Ecological Economics. Basil Blackwell, N.Y.). He quotes S. Podalinsky as giving an early statement of the role of energy use in increasing availability of energy.

(5) The author acknowledges collaboration on general system theoritical concepts with Dr. David Scienceman of Bathurst, Australia who has been three times visiting research associate in our Ecological Economics Program in Gainesville 1983–86. Dr. Scienceman suggested the name EMERGY and the unit emjoule for the embodied energy concept we have been using since 1967. The name "EMERGY" was suggested by Dr. Scienceman as appropriate for a

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concept of "energy memory" and "emergent property of energy use". This should eliminate the confusion of our measure with different ones from input-output analysis that have been called embodied energy by several authors. In his role as editor, Nicholas Polunin suggested putting an "n" in the name to further distinguish the word from energy, calling it "enmergy", which was done in one paper (Odum, H.T. 1986. Enmergy in Ecosystems. pp. 337–369 in Ecosystem Theory and Application, ed. by N. Polunin, John Wiley, N.Y.

David Scienceman has now given his thinking on nomenclature and definitions of these and other concepts (Scienceman, D. 1987. Energy and EMERGY. pp. 257–276 in Environmental Economics, ed. by G. Pillet and T. Murota. Roland Leimgruber, Geneva). His suggestion to develop an EMERGY-defined "emdollar" basis for foreign trade may be of great practical importance.

(6) Most ecosystems and economic systems are dependent on their resource inputs, which may include fuels, matter, and information, all of which are accompanied by energy. However, different kinds of energy are of different importance and should not be considered equal. A joule of sunlight cannot do the same work as a joule of fuel, a joule of electricity, or a joule of human service.

The term TRANSFORMITY was substituted in 1984 to replace "energy transformation ratio", introduced in the response of the award of the prize of the Institute de La Vie, Paris, in 1975. (Published version: Odum, H.T. 1976. Energy quality and carrying capacity of the earth. Tropical Ecolocy, 16 (1):1–8). Transformity is the quotient of EMERGY of one type and energy of another, and strictly speaking is not a ratio. The word is appropriate to measure energy quality of production processes, where work is defined as an energy transformation, a usage that goes back to Maxwell in the last century. Solar transformity of a flow or storage is the solar emjoules per joule, abbreviated: sej/J (5).

Physics and engineering courses often confuse their beginning students by teaching that energy is a "measure of the ability to do work". Degraded energy from a transformation cannot do any work. It is only when available energies of the same type are compared that energy measures work. For example, where engineering deals with one kind of energy, mechanical energy, works are in proportion to energy since they are of one class. Exergy includes mechanical energy and Gibbs free energy defined as pressure-volume work, but not the wide range of energy qualities involved in the universe. Much of the confusion about national energy policies comes from erroneous beliefs that dilute solar energy can be substituted for higher quality fuels without most of it going into the work of concentration. Plants use up much of the availability in the solar energy they collect in the process of maintaining the necessary structure to catch and concentrate the dilute photons.

(7) Adapted from Diamond, C. 1984. Energy Basis for the Regional Organization of the Mississippi Basin. M.S. Thesis, Dept. of Environmental Engineering Sciences, University of Florida, Gainesville, Florida, U.S.A., 250 pp.

(8) The result of each transformation is an increase in energy quality in the sense that the work at the higher level convers greater territory, has a longer

time span, controls more energy as it feeds its controls to the lower level, and is able to support the next higher level.

Transformity calculated from data in joules is numerically equal to that calculated from data in Calories or other energy units; the value of transformity is independent of the units. Yet the number is not a dimensionless ratio since the numerator is EMERGY and the denominator is energy. In short, transformity is tne EMERGY per unit energy, but the type of EMERGY has to be specified. The abbreviations for this are:

sej/J = sec/C

(9) The earth is a unified system, as one would expect, with self organization for maximum power, which causes all processes to be intercoupled. The cycles of the earth movements under the sea (sea floor spreading cycle) are coupled to the sedimentary and other cycles on land driven by the sun's action in pumping the rains and rivers. For a coupled system, all of the main kinds of process require all the others. As shown in Figure 9, part of the deep heat is from deep residual heat and radioactivity and part from compression and chemical potential energy moving down with the sediments from the sun-driven hydrologic cycle (Sclater, J.G., G. Taupart, and I.D. Galson, 1980. The heat flow through the oceanic and continental crust and the heat loss of the earth. Rev. of Geophysics and Space Physics 18:269–311). The solar transformity of the deep heat is inferred from Figure 9 as the total global solar energy absorbed per year divided by the deep heat it contributes. Therefore, the solar EMERGY of all these pathways is the same, the sum of the two main sources, 8.0 E24 solar emjoules per year.

If one adds the solar EMERGY of current use of previously stored world fuels (1985 UN statitics: 2.78 E20 terajoules coal equivalents/year ★ 4 kE4 solar emjoules/joule = 11 E24 solar emjoules per year), the world's energy budget expressed in solar EMERGY is temporarily higher (19 E24 emjoules per year). The tidal energy is another independent but smaller source.

(10) Solar EMERGY accounting in energy webs: Whereas solar EMERGY and transformity are simple enough concepts, they can be confusing when considered in an energy web such as that in Figure 4. Self organization causes products and byproducts to feed back to interact and aid the production processes from which they were generated. Thus, system webs usually have closed, autocatalytic loops, many nested within others. The solar EMERGY of any pathway is the total solar EMERGY required. The EMERGY flow of a return feedback loop is not added into the production process that it stimulates since that would be double counting. See Figure 9b for example. Before adding the solar EMERGY of inputs, it is necessary to examine a larger system than the one of interest in order to determine if the sources are really independent inputs of different solar EMERGY and not byproducts of one common flow. See inputs to production in Figure 4 for example.

There are other systems measures such as input-output techniques that divide the incoming energies among the pathways of a web to obtain a measure of "embodied energy". However solar EMERGY is defined differently, requiring different rules and mathematics.

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(11) Odum H.T. and E.C. Odum, ed. 1983. Energy Analysis Overview of Nations. International Institute of Applied Systems Analysis, Laxenburg, Austria. Working paper WP-83-82, pp. 1–467.

(12) The substitutions of species that take place are part of the fine-tuning by which the trial and error of self organization finds the pathway for maximum performance. Many scientists with primary interest in species are disturbed to have the models that simulate the main features of maximum system performance, i.e., production, consumption, diversity, etc., omit the species. They see overall functions as an unconstrained sum of what the species do rather than the potential limits into which species are constrained by self organization to fit.

(13) Differences between population and systems ecologists is one of scale and the degree of control of population by larger scale organizational mechanisms. All this is curious historically, since most of the roots of ecology, energetics, and biogeochemistry are in writings of Alfred Lotka and many others before (4). Lotka and later my major professor, George Evelyn Hutchinson, presented a unified story of population and systems ecology. Systems ecology models often include population ecology models nested within. Some population ecologists deny there is any larger model that determines the population performance. The only time this is true is when they are isolated in the laboratory or in early stages of colonization before self organization has proceeded very far.

(14) When pathways are provided which are linear, autocatalytic, and quadratic-autocatalytic, the growing system uses the linear one until energy levels are higher and then is predominated by the autocatalytic pathway; later at even higher energy levels the quadratic process becomes predominant.

In other words, the power of the exponent which becomes predominant is determined by the energy levels. Power in the mathematical sense is dependent on power in the energetic sense (Richardson, J.R. and H.T. Odum, 1981. Power and a pulsing production model. pp. 641–648 in Energy and Ecological Modelling, ed. by W.J. Mitsch, R.W. Bosserman, and J.M. Klopatek. Elsevier, N.Y.; Odum, H.T. 1982. Pulsing, power and hierarchy. pp. 33–59 in Energetics and Systems, ed. by W.J. Mitsch, R.K. Ragade, R.W. Bosserman, and J.A. Dillon, Jr., Ann Arbor Science, Ann Arbor, Mich).

W.C. Allee devoted much of his life to documenting the cooperation among organisms, which is a quadratic autocatalytic relationship (Odum, H.T. and W.C. Allee. 1953. A note on the stable point of populations with both intraspecific cooperation and disoperation. Ecology 33:45–97; quadratic model pp. 151 in Odum, H.T. 1983. Systems Ecology, Wiley, N.Y. 644 pp.). Development of intraspecific cooperation in this sense may be an example of the mechanisms that self organize with higher level energy availabilities whose mathematical role may be predictable with emulation modelling. In simulations of sprucebudworms and other autocatalytic consumer oscillations, ecologists at British Columbia have included quadratic effect of the producers output on consumption, and invoking this pathway may also be a general property of higher energy (Ludwig, E., D.D. Jones and C.S. Holling. 1978. Quantitative analysis of insect outbreak systems: The Spruce Budworm and Forest. J. Animal Ecol. 47:315–332).

(15) Successional curves in microcosms, see note (3); basic simulation model of ecosystem homeostasis: Odum, H.T., R.J. Beyers, and N.E. Armstrong 1963. Consequences of small storage capacity in nannoplankton pertinent to measurement of primary production in Tropical Waters. J. Marine Research, 21:191–198; pp. 262–272 in Odum, H.T. 1971. Environment, Power and Society. Wiley, N.Y. 331 pp.; generalization of successional-climax paradigm with overshoot: Odum, E.P. 1969. The strategy of ecosystem development. Science 164:262–269.

(16) Alexander, J.F. 1978. Energy Basis of Disasters and Cycles of Order and Disorder. Ph.D. Dissertation, Environmental Engineering Sciences, University of Florida, Gainesville, Fl., 323 pp.

(17) Richardson, J. 1987. Spatial Patterns from Pulsing Simulation. Ph.D. Dissertation, Environmental Engineering Sciences, University of Florida, Gainesville.

(18) Campbell, D.E. 1984. Energy Filter Properties of Ecosystems. Ph.D. Dissertation, Environmental Engineering Sciences, University of Florida, Gainesville, Fl., 478 pp.

(19) Zwick, P. 1986. Impedance in Ecosystems. Ph.D. Dissertation, Environmental Engineering Sciences, University of Florida, Gainesville, Fl.

(20) Essentials in Ecosystem Models

The following need to be in models capable of emulating ecosystems and other systems:

1. Conservation of energy.
2. Conservation of essential materials.
3. Constraint of each proces of interaction and production by a realistic transformity. In other words, coefficients must not be allowed for work transformations that output more energy of higher quality than is possible for the change in hierarchical position involved.
4. Autocatalytic designs, including the material recycle and amplifier feedbacks to production.
5. Hierarchical turnover properties with an increase in turnover time of units in going from lower levels of hierarchy to the higher centers.
6. Linear, autocatalytic and higher order pathways should be included in parallel so they are available as in nature for reinforcement in the simulation of self organization.

Other characteristics of self-organizatinal design are given in Odum, H.T. 1983. Systems Ecology. John Wiley, N.Y. 644 pp. This was originally entitled "Ecological and General Systems", but changed to Systems Ecology at the suggestion of the publisher.

(21) The formula for bits of complexity (often called bits of information I) is the logarithm of the possibilities (n):

I = Log2 n, where n is the number of possibilities.

The logarithm of possibilities increases more slowly than the possibilities. Bits increase slowly as possibilities are increased. When the base number is 2 as in this example, the logarithm is said to be in bits (bits of Information).

The logarithm of the possibilities measure has been called "information" in the sense of "information theory" and widely used in many fields. However, everyone agrees that the word information, as generally used in society, is not appropriate for this bits measure, because the word information usually implies a useful role whereas many collections of parts with high information (bits) values have little value to systems. The bits of information in the association of animals in a zoo may be large and indicate a complex set of units, without indicating any organization or function of the group. Furthermore, the bits measure does not distinguish between items of molecular size and those at the level of human relationships.

(22) Solar EMERGY of Copying

An important question arises when one tries to evaluate the solar EMERGY in the human transfer of information in a lecture or a book. If the transformity of his education and experience is known, what is the rate of delivery of stored information per hour? When a human teaches, he is copying knowledge out to a receiver, without draining his knowledge. The copying process reinforces his own knowledge. Does it make sense to multiply the transformity of his education by the rate of energy processing by him as a carrier? This procedure is suggested here very tentatively, with sample calculations presented.

Figure 20: Evaluation of the increasing transformity of human information during ontogeny, education, and life experience is a calculation of the convergence of more inputs which move the person to a higher status, transformity, influence, territory and period. A tentative estimate was made using the territory of the people at each stage to estimate the proportion of the whole system's input on which their role is based. As individuals move up the hierarchy their numbers decrease and, thus, the EMERGY input is divided among smaller and smaller numbers as they take larger roles.

Solar transformities for human educational levels in Figure 20:

Attainment	Individuals# E6 ind.	EMERGY share/ind.* E16 sej/ind/yr	Transformity! E6 sej/J
Total (pre school) +	234	3.4	8.9
School +	83	9.4	24.6
College grad +	28	28.	73.3
Post college ed +	6	131.	343.
Public status +	2?	393.	1029.
Legacies	1?	785.	2054.

\# U.S. Statistical Abstract

* Annual U.S. EMERGY use, 785 E22 sej/yr (19) divided by number of individuals in the category

! Annual EMERGY share/ind./yr divided by the energy per individual (2500 kcal/day) (365 days/yr) (4186 J/Cal) = 3.82 E9 J/ind/yr

(23) *Military Hierarchy.* Using a military example, a preliminary sample calculation suggests how EMERGY-transformity evaluations may be made for a

hierarchy. Suppose there are 130 soldiers, corporals, sergeants, and a lieutenant organized as in Figure 3 and each individual has an individual energy flow of 2500 kilocalories per day. Suppose the main support of the system is from goods and services on a budget of $10,000/day when the solar EMERGY/DOLLAR ratio is 2.0 E12 solar emjoules per $ (1987 US $). The transformities are the quotient of rate of solar EMERGY support and the rate of personal energy use per category.

Solar EMERGY support for the whole hierarchy and thus for each level is:
($10,000/day) (2.0 E12 solar emjoules/$) = 2 E16 solar emjoules/day solar transformities for ranks:

Soldiers:

(2 E16 solar emjoules/day)/[(117 soldiers) (2500 Cal/day) (4186 J/Cal)] = 1.63 E7 solar emjoules/joule

Corporals:

(2 E16 solar emjoules/day)/[(9 corporals) (2500 Cal/day) (4186 J/Cal)] = 2.12 E8 solar emjoules/joule

Sergeants:

(2 E16 solar emjoules/day)/[(3 sergeants) (2500 Cal/day) (4186 J/Cal)] = 6.37 E8 solar emjoules/joule

Lieutenant:

(2 E16 solar emjoules/day)/[(1 Lieutenant) (2500 Cal/day) (4186 J/Cal)] = 1.91 E9 solar emjoules/joule

Texas Highways. Data for illustrating the EMERGY measures of highway information, an example of energy transformation chain leading to shared information in Figure 17 were obtained from: Lyu, Wernhuar 1986. EMERGY analysis of highway transportation in Texas. Unpublished class report, pp. 130–157 in The Texas System, ed. by H.T. Odum, E.C. Odum, and M. Blissett. Lyndon Baines Johnson School of Public Affairs, Policy Research Project course, Public Administration 882a–882b, The University of Texas, Austin. See details in published report (36).

The EMERGY in shared information is EMERGY of the whole larger area system that supports and receives controls from that information. For Texas highways in 1986 at a time when gains and losses were believed to be about equal (steady state), 3.97 E22 solar emjoules per year are required in the production processes that maintained the highway system in 1986. The EMERGY used in this process included that of fuels, asphalt, cement, steel, and labor. The energy used was 9.07 E16 J/yr. The information in the Texas highway system can be abstracted from the system in the form of highway maps, and books of construction specifications. Suppose these can be stored in printed form in about 1000 kilograms of books, updated each year, the energy content of which is:

(1 E6 g/yr) (4 kilocalories per g) (4186 J/kilocalorie) = 1.67 E10 J/yr

The most important essence of the information on Texas highways that is shared information is printed in maps distributed to the public who use the maps in driving their cars. EMERGY involved in the use of the highways is

porals, sergeants, and a lieuten-
idual has an individual energy
e main support of the system is
0/day when the solar EMERGY/
(1987 US $). The transformities
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on Texas highways that is
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the use of the highways is

15.1 E22 sej/yr being controlled by the maps produced each year with an energy content of each map:

(300 g map) (4 kilocalories/g) (4186 J/kilocalorie) = 5.0 E6 J/map.

If maps are replaced every three years, the energy flow through maps is:

(5.0 E6 J/map) (0.33 maps/year) = 1.83 E6 J/yr.

The population of Texas was 15 million people and the numger of maps in service was assumed to be 5 million.

Transformities
There are three transformities. One is of the highways themselves; the second is the copy of information that is in functional use; the last is of the information itself, which is an only copy.

Solar transformity of highway construction and replacement:
(3.97 E22 sej/yr)/(9.07 E16 + J/yr) = 4.38 E6 + sej/J

Solar transformity of the highway specification books:
(3.97 E22 sej/yr)/(1.67 E10 J/yr) = 2.37 E12 sej/J

Solar transformity of highway use maps calculated as EMERGY of highway use and energy of 5 million copies of maps:
(15.1 E22 sej/yr)/[(5 E6 copies) (5 E6 J/copy)] = 6.04 E9 sej/J

Solar transformation of the shared original:
(15.1 E22 sej/yr)/(1.83 E6 J/copy) = 8.11 E16 sej/J

(24) That energies associated with information decrease with more sophisticated information processing was suggested by Tribus, M. and E.D. McIrvine. 1971. Energy and Information. Scientific American 225:179–188.

Figure 18 compares the same complexity on different scales. The energy content is estimated for the same number of bits (1000 bits) at each of three levels. Then the solar EMERGY per bit is calculated:

Molecular Energy in Glucose
Following Augenstine (in Quastler, H. 1953. Information Theory in Biology, University of Illinois Press, Urbana, Ill.), the molecular information in bits per molecule I is obtained from the Entropy S in kilocalories per degree per mole as follows:

$$I = 0.73^{*} S$$

Consider glucose with entropy, 50.7 kcal/mole/degree:

$$\frac{(1000 \text{ bits})}{(0.73^{*}.0507) \text{ bits/molecule}} = 27018 \text{ molecules/1000 bits}$$

$$\frac{2.7 \text{ E4 molecules/1000 bits}}{6.02 \text{ E23 molecules/mole}} = 4.48 \text{ E-20 moles/1000 bits}$$

Energy content is:
(673 Cal/mole) (4186 J/Cal) (4.48 E-20 moles/1000 bits) = 1.26 E-13J/1000 bits
Solar transformity of glucose dispersed where it is produced in aquatic plant tissues as part of gross production is about 1% of 4000 kcal/m^2/day = 40 kcal/m^2/day, a transformity of 4000/40 = 100 sej/J

Microscopic Realm. For a scale with 1000 bits of structure in an area one millimeter across under microscope (1E-3 m), square area E-6 m^2, assume the energy of an ecosystem:

For the net production that generates observed structure in algae under the microscope, efficiency may be:

0.1% of 4000 kcal/m^2/day = 4 kcal/m^2/day

(4 kcal/m^2/day) (4186 J/kcal) (1 E-6 m^2) = 1.67 E-2 J/day

Assume a solar transformity of 1000 sej/J (0.1% efficiency) (Figure 4).

Macroscopic Realm. For the individual units in a landscape viewed from the air, the 1000 bits occupy a hectare, which is running on environmental inputs of sun, rain, wind, etc., with input EMERGY:

(1 E4 m^2) (40,000 solar emcalories/m^2/day) (4186 J/Cal) = 1.67 E12 sej/day

Since the 1000 bits are larger objects such as tree trunks, large animals, human structures, then the transformities are higher – use 10,000 sej/J (0.01% efficiency)

The energy flow through larger items of the ecosystem is:

(4000 kilocalories/m^2/day) (0.01%) (10 E4 m^2) (4186 J/kilocalorie) = 1.67 E7 sej/day

Information Abstracted to Paper

For the fourth column of Figure 18, the information of the macro-system is abstracted to paper and still contains 1000 bits. However its energy content is now that of the paper carrying the information, 100 kilocalories which is renewed every 10 years. The energy flow through this information is:

(100 kilocalories) (4186 J/kcal)/[(10 yrs) (365 days/yr)] = 114.7 J/day

The solar EMERGY generating the information is that of the macrosystem (1.67 E12 sej/day)

Solar Transformity of Abstracted Information:

(1.67 E12 sej/day)/(114.7 J/day) = 1.46 E10 sej/J

(25) Solar Transformities of a Gene:

The following very tentative calculations of solar transformities in genes is made to suggest the principles involved and attract the interest of genetic specialists with the detailed knowledge to make more accurate determinations.

From an earlier calculation in Systems Ecology (20), p. 273, solar energy of an algal cell (without other EMERGY inputs) was related to energy flow in the DNA of that cell. Thus, 4000 kcal/m^2/day sunlight supported 0.1 kcal/m^2/day DNA. The solar transformity of DNA is

4000/0.1 = 40,000 sej/J.

In the outdoor world of land vegetation in Florida, the EMERGY input in rains is about 10 times the direct solar energy input. Thus, the solar EMERGY is: (10) (4000 solar calories/m^2/day) = 40,000 solar emcalories/m^2/day.

Assume one billion paired bases in a cell, and about 1000 nucleotides in a gene. Genes per cell then are about: 1 E9 bases per cell/1000 nucleotides per gene = 1 E6 genes per cell.

The solar EMERGY of a single gene is that gene's share of the EMERGY support (solar EMERGY divided by the number of genes, where this is calculated as the number of genes per cell times the cells per square meter). If cells are 20 E-6 m in diameter and individual area about 4.0 E-10 m^2/cell, the number of cells per square meter in one cell layer is the reciprocal, 2.5 E9 cells/m^2. If there are 30 cells vertically in each leaf and a leaf area index of 5 leaf layers per area of ground underneath, then the total number of cells is: (2.5 E9 cells/m^2) (30 cell layers/leaf) (5 leaves per area) = 3.75 E11 cells/m^2.

One gene's share of the energy flow:
(0.1 calories/m^2/day)/(3.75 E17 genes/m^2) = 2.66 E-19 Calories/gene/day

The number of genes per square meter of vegetation may be:
(3.75 E11 cells/m^2) (1 E6 genes per cell) = 3.75 E17 genes/m^2

The solar EMERGY flow share of one gene is:
(40,000 solar emcalories/m^2/day)/(3.75 E17 genes/m^2)
= 1.066 E-13 solar emcalories/gene/day

The energy flow through the DNA of one type of gene in a square meter is:
(0.1 kilocalorie/m^2/day)/(1 E6 gene types)
= 1 E-7 kilocalories/type/m^2/day

Solar transformity of a gene structure is:
1.066 E-13 solar emcalories/gene/day/2.66 E-19 kilocalories/gene/day
= 4.0 E5 sej/J

Solar transformity of one type of gene:
(40,000 solar emcalories/m^2/day)/(1 E-7 Calories/m^2/day) = 4 E11 sej/J

Suppose a gene is shared by members of a dominant species which has an area of 10,000 square kilometers and that species constitutes 10% of the area of vegetation. Suppose the whole input of the species is required to generate and operate that gene. Then the EMERGY input in support of the one shared gene is: (1E4 km^2) (1E6 m^2/km^2) (0.1 of area) (40,000 solar emcalories/m^2/day)
= 4 E13 solar emcalories per day per shared gene.

The energy flow through one copy of a shared gene is that through one gene, estimated above as 2.66 E-19 kilocalories/day.

The solar transformity of the shared information is the solar EMERGY of the support area of the shared gene divided by the energy through a single copy
(4 E13 solar emcalories/shared gene)/(2.66 E-19 kilocalories/day) = 1.50 E32 sej/J.

(26) After there is excitement in some area of science, efforts are made to explain the significance of the new things to generally educated people using regular verbal language. Often there is communication failure because the words in the general vocabulary have broad general meanings quite different from the quantitative, restricted uses of the words in the science. The more scientists narrow the meaning of words in common use for their purposes, the more the confusion – for example, energy, entropy, order, stability, chaos, random, causality, force, information, progress, value, etc.

(27) Entropy minimum principle for open systems: Prigogine, I. and J.M. Wiaume. 1946. Biology et thermodynamique des phenomenes irreversibles. Experimentia 2:451–453. Entropy maximum principle (maximum power principle) for self organization of autocatalytic systems: Odum, H.T. and R.C. Pinkerton. 1955. Time's Speed Regulator, the Optimum Efficiency for Maximum

Power. American Scientist, 43:321–343; Odum, H.T. 1975. Combining energy laws and corollaries of the maximum power principle with visual systems mathematics. pp. 239–263 in Ecosystem Analysis and Prediction. Proc. Conf Ecosystems, SIAM institute for Mathematics and Society.

(28) In the last decade the research in chemical reaction systems and study of physical fluid structures operating at higher energy levels find increasing complexity in time and space that are being referred to as chaos because of inability to predict precisely. For example, where energy flows in pulsing systems (like Figure 7b) are of the same order of magnitude as the turnover times of the stored elements, there is an alternating between empty and full. Such variation may not be important to higher levels of hierarchical organization which adequately filter and use the variation for adaptive purpose as already discussed.

(29) Entropy is proportional to the logarithm of the molecular possibilities. It is a measure of molecular complexity, the same measure used in the macroscopic world to measure complexity under the name "information".

(30) Discussions of energy and entropy are often made simpler by postulating a closed equilibrium through which there is no energy flowing. However, the hierarchical pattern of closed and somewhat open systems do not differ much, and only open systems are real. Flow of potential energy being degraded and dispersed is the only real world pattern and these are similar for molecular systems and for macroscopic ecological ones. The similarities were shown by the author with energy systems diagramming and spectral graphs in Chapter 15 of Systems Ecology (20); meteorological and geological hierarchies are diagrammed in Chapter 26 (20). For hierarchical role of storms see page 558 (20).

(31) The influential book by Schrodinger in 1947 (What is Life) explained life as the process of consuming low entropy food as a means of keeping structures at lower entropy than the surroundings. This turns out to be half right. Life consists of some structures lower in entropy (that is, of lower complexity as with bone crystals or bodies maintained at lower temperature) than surroundings and many more that are of higher complexity than surroundings (such as configurations of system relationships and bodies maintained at higher temperature than surroundings). The food is used to maintain structures both higher and lower entropy than surroundings. For diagrams of these relationships see Systems Ecology pp. 314–315 (20).

wrong,

We would add that the structures maintained in self organization must have useful (feedback and amplifying) contribution to maximum EMERGY use. Further,. comparisons between molecular and higher levels should be made only after the transformity (universal energy quality scale factor) is used to express in common terms of EMERGY required. See Figure 18.

(32) When the set of inflowing energies are of more than one type and transformity, other energy distribution shapes result as given in Systems Ecology, pp. 274–275 (20). There is often a hump where there is high EMERGY input from a second source. For example, the fossil fuel inputs to the world economy generate such humps in income distribution curves.

um, H.T. 1975. Combining energy
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(33) A derivation by Odum and Pinkerton (27) showed the optimum efficiency for maximum power in transforming energy is about half of the reversible efficiency, a property of open systems found independently by many authors, as discussed elsewhere (Odum, H.T. 1983. Maximum power and efficiency: a rebuttal. Ecological Modelling, 20:71–82). However, most transformations also involve a step up in hierarchy which reduces efficiency as available energy goes into concentrating or otherwise upgrading energy quality.

(34) Science is not without its emotional attitudes to progress. Sometimes editorial and article selection policies have rejected papers that imply that there are any limitations on the human brilliance in achieving anything. The emotional rejection of realities shows up in energy analysis controversies in which faulty public policies have been encouraged by researchers who see any possibility as a means of research support and really believe information can overcome any efficiency limitations.

(35) Figure 24 was modified from a study by Allard Brown working with H.T. Odum in course work at the Unversity of Texas in 1986. Data were assembled on a high technology company in Austin, Texas, one with manufacturing and research-development divisions. The figure has the solar EMERGY values written on the pathways using solar transformities suggested by Figure 20: professionals, 500 E6 sej/J; for labor inputs, 100 E6 sej/J.

(36) Odum, H.T. and E.C. Odum. 1987. Ecology and Economics: EMERGY Analysis of the Texas System. Special Report of the LBJ School of Public Affairs and the Texas State Department of Agriculture, 184 pp. EMERGY analysis of other commodities (Table 7) are given in Odum, H.T. 1984. Energy Analysis of the environmental role in agriculture. pp. 24–52 in G. Stanhill, ed., Energy and Agriculture. Springer-Verlag, Berlin.

(37) Noyes, G. 1977. Energy analysis of space operations in Energy analysis of models of the United States, ed. by H.T. Odum and J. Alexander. Report to U.S. Department of Energy, Contract EY-76-S-05-4398, Energy Analysis Program, Center for Wetlands, University of Florida, Gainesville, FL.

(38) A model of the necessary symbiosis of the political left and the right, analogous to the phytoplankton and the larger consumers of the ecosystem, was simulated, thus comparing the control systems of the ecosystem and the human system. (Odum, H.T. and D.M. Scienceman, 1986. Commonalities between hierarchies of ecosystems and political institutions. Yearbook of General Systems, XXIX:23–32).

(39) Odum, H.T., E.C. Odum, M.T. Brown, D. LaHart, C. Bersok, J. Sendzimir, G.B. Scott, D. Scienceman, and N. Meith. 1987. Environmental Systems and Public Policy, Ecological Economics Program, Phelps Lab, University of Florida, Gainesville, FL. 227 pp. This generic introduction is intended to have supplements for each state or nation. The one available for Florida: (Florida Systems and Environment, 83 pp., 1986) includes the EMERGY analysis of the state.

(40) Part of this essay is a condensation of theory given in Systems Ecology (20).

Crafoord Prizes Awarded

1982 in **mathematics** within the field of nonlinear differential equations
Vladimir I. Arnold, Moscow State University, USSR and **Louis Nirenberg,** New York University, USA for their outstanding achievements in the theory of nonlinear differential equations.

1983 in **geosciences** within the field of large-scale movements of the atmosphere and the sea
Edward N. Lorenz, Massachusetts Institute of Technology, USA and **Henry Stommel,** Woods Hole Oceanographic Institution, USA for their fundamental contributions in the field of geophysical hydrodynamics that in a unique way contributed to our understanding of the large-scale circulation of the atmosphere and the sea.

1984 in **biosciences** within the field of coevolution – the mutual adaption of organism populations in the natural environment
Daniel H. Janzen, University of Pennsylvania, USA for his imaginative and stimulating studies on coevolution, which has inspired many researchers to continued work in this field.

1985 in **astronomy** within the field of the interstellar medium including star formation and interaction with stars
Lyman Spitzer, Jr., Princeton University Observatory, USA for his fundamental pioneering studies of practically every aspect of the interstellar medium, culminating in the results obtained using the Copernicus satellite.

1986 in the **geosciences** within the field of isotope geology
Claude J. Allègre, L'Institut de Physique du Globe, France and **Gerald J. Wasserburg,** California Institute of Technology, USA for their pioneering work in isotope geology.

1987 in the **biosciences** within the field of ecosystem ecology
Eugene P. Odum, University of Georgia, USA and **Howard T. Odum,** University of Florida, USA for their pioneering contributions within the field of ecosystem ecology.

Crafoord Lectures

1982 **Vladimir I. Arnold:** On some nonlinear problems.
Louis Nirenberg: Mathematical methods in nonlinear problems.

1983 **Edward N. Lorenz:** Irregularity: a fundamental property of the atmosphere.
Henry Stommel: The delicate interplay between wind-stress and buoyancy input in ocean circulation: the Goldsbrough variations.

1984 **Daniel H. Janzen:** The most coevolutionary animal of them all.

1985 **Lyman Spitzer, Jr.:** Clouds between the Stars.

1986 **Claude J. Allègre:** Isotope geodynamic.
Gerald J. Wasserburg: Isotopic abundances:inferences on solar system and planetary evolution.

1987 **Eugene P. Odum:** Global stress on life-support ecosystems mandates input management of production systems.
Howard T. Odum: Living with complexity.