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Chapter 37

ENERGY SYSTEMS AND THE UNIFICATION OF SCIENCE

Howard T. Odum

From the Celebration at Chapel Hill where we looked forward and back, let's share our view of energy systems in the future of science.

General Systems Principles

My first priority interests have always been open system thermodynamics of ecosystems, general systems theory, and simulation. Because I have taught in Biology, Marine Science, and Engineering departments, I did not always emphasize these fields with students. It seemed better to add these theoretical concepts into the more down-to-earth teaching of environmental science, using the energy language for a bridge. Those I taught did not always realize how fundamental and new these concepts were. Now, the unification of science using systems approaches, including thermodynamics, hierarchies, fractals, and chaos is increasing. Perhaps more of our students should participate in groups that attempt to unify science, such as the Society for General Systems, now named the International Society for Systems Sciences. As a graduate student, I attended early organization meetings for this group at the American Association for the Advancement of Science in 1948 and was (1991–1992) president of this small society.

We had a 20 year head start on unifying science with energy concepts with the help of some physical scientists, such as Richard Pinkerton in Gainesville, and our thermodynamics seminars in 1958–1959 at Port Aransas, which reviewed the literature on open system thermodynamics. At this time, Prigogine and others were advocating the "minimum entropy generation" principle, in sharp contrast to our development of the "maximum power" principle. Luna Leopold invited me to Phoenix, Arizona, to discuss the differences between maximum power and minimum power principles (minimum entropy generation) as applied to earth systems and to share our interests in passive electrical analogs. It became obvious to me that classical thermodynamic equations chop up real systems into pieces too small to represent adequately the thermodynamic principles of real networks. We came to realize that *work* is a hierarchical transformation process in a closed loop system configuration that requires a systems perspective for proper expression.

Because the existing symbolic and mathematical languages were inadequate to represent the thermodynamics of real ecosystems, we invented the energy systems language as a generalization of electronic circuits. This allowed us to express the first and second laws of thermodynamics adequately, as well as positive feedbacks and maximum power reinforcement. I used an early version of this language on ecologists at the ecological society meeting in Seattle about 1962. Our first published use of the symbols was in a review (Odum 1964), and some examples were given in 1967 (Odum 1967). Our latest excitement is through the use of the versatile Macintosh program EXTEND to represent and simulate a system and to calculate the EMERGY and transformities automatically.

In the 1960s, the emerging field of systems ecology was riding the crest of new computer innovations. The first methodology of modeling connected known parts of an ecosystem to obtain the whole system performance. Most ecologists still think this way, from the parts up. They thought our energy systems language was only another way of writing equations, like Forrester's language, and thus, they generally thought they could do their thinking in differential equations one piece at a time. But this approach misses the systems concepts of the network configuration, the designs for maximum power, transformities, and emulation.

I tried the term *emulation modeling* for a different methodology, where one uses the mathematics common to all self-organization to simulate systems without detailed knowledge of the local mechanisms. If maximum empower generates certain designs represented by energy-constrained mathematics, then such models will represent any system, even though the mechanisms by which the successful kinetics are reached are different. For example, gravity in stars is a concentration force equivalent to food gathering by carnivores in ecosystems, autocatalytic chemistry, or Cobb–Douglas production in economics (Odum 1988). In other words, there are universal models of all systems because these are the designs that emerge in self-organization for maximum power. If one can know the energetics and kinetics of a system in advance, even before it exists, one has the principles of planning and management that will be successful. This is a conceptual breakthrough for all fields.

The energy systems language was the means for representing observed systems and comparing them with the configurations for maximum power. More and more concepts were discovered with this approach. Often we diagrammed according to subconscious feelings from our studies in the field and then later found out why the system had to be that way for kinetic, hierarchical, and energetic reasons.

Our diagrammatic language specifies mathematic-kinetic relationships of systems that include energy constraints, whereas ordinary differential equations do not. For example, there are eighteen different systems configurations already known that generate logistic mathematics. Most do not include even such simple energy realities as the fact that the growth of an organism or a population requires an energy source, a source that is not included in most of the equations for the logistics. As one learns from analysis and simulation what each mathematical configuration does when energy constraint equations are added, one's ability to understand and see in advance what particular systems of medium complexity will do is greatly increased over what can be done from studying only the parts. We found that what was obvious—even first principles—for those who think in energy language was often attacked as unsubstantiated fantasy by those who expect to observe first and theorize second. This process reinforced what I learned most from Evelyn Hutchinson, my major professor—that the theory must come first and then comes observational testing.

The power of the energy systems diagrams to encompass complex and, hence, real problems, to anticipate experimental results, and to set out important hypotheses is overlooked by the majority of ecologists. Is it because of different aptitudes in regard to network thinking? Is it due to different training? Is it because our university system has so often defined rigor only from the perspective of looking downward to the smaller mechanism? Is it the desire of most scientists to simplify by isolation? Traditional experiments in biology remove all complexity except the one mechanism under study. But good ecology must retain all the complexity, holding it as constant as possible while varying the factor(s) of interest. Well thought out and validated simulation models are a way of seeing whether the mind's ideas as to causes are consistent with observations or experimental results.

We recognized back in the 1960s that our approach was innovative, open-system thermodynamics, but it required the new energy systems language and new terminology for its full application. The concepts and history of the thermodynamics of our systems are given in Chapter 28 of this book.

I was always faced with a dilemma as to whether to require our students to take classical thermodynamics, because this field had not had any new principles in many years. Its proponents generally have lacked a systems view and rarely had enough biological background to understand network roles in self-organizing biological systems. What was required was a rejection of classical definitions of work and recognition of the maximum power principle. Those who took thermo tended to pick up a reductionist way of thinking and sometimes became closed to the revised concept of work and transformity; those who didn't take it were vulnerable to those who criticized them for not knowing the older field.

At a Gordon Research Conference in New England about 1984, King Hubbert, Georgescu-Roegen, and I gave the preliminary talks, and a full discussion followed among thermodynamics people. I felt that most of those present were mostly on the wrong track in making too much of EXERGY, a new word for the old concept of chemical and mechanical potential energy. Exergy includes only energy types with similar transformities and did not discriminate between energy flows of much lower transformity (sunlight) or much higher transformity (human labor).

Where process analysis is supposed to evaluate *all* the work required for a product, it actually is not rigorous, because in reality, all the inputs of chemicals, fuels, and so on are of different transformities. Energy of different forms cannot be added to obtain the total work unless each is multiplied by its transformities. It's like adding one and two and getting two (numbers) because the qualitative aspects of the two numbers are not considered. In other words, the definitions of work still used in physics and engineering are incorrect for most uses to which they are applied. It is hard for scientists to reject what was taught them in freshman courses before they have learned to think for themselves. What one learns early becomes hard to question without creating an intellectual crisis because you must reject your life's earlier assumptions.

"Truth" is a state of mind in which there is no contradiction. A person perceives his idea as true because he has heard no contradiction. The less one knows, the easier it is to be dogmatic and to be sure that what one knows is true. We tend to defend dogmatically as true the things we are taught, whereas the things we learn from experience and experiments tend to be properly couched in sometimes-contradictory reality. Those who have had only "revealed truth" teaching (for example, religious or scientific dogma) are the ones with the strongest feeling that they are right—because there is no contradiction in their heads. People who have had only revealed truth (that is, uncontradicted teachings) are the most zealous and potentially the most dangerous in the sense of taking actions that have unexpected results that can be destructive to themselves and their surroundings. "Scientific truth" requires that one place together in one's mind both the ideas and observational data from the real world, expanding concepts until there is no contradiction. The reality of the world rarely lets it happen that simply. Perhaps that is why it is often better to go from the general systems pattern to the particular, for then you do not focus on the parts that do not seem to work.

The Future of Systems Ecology

The organizers of the symposium in Chapel Hill asked me to speak on the topic "What Is the Future of Systems Ecology?" But what "Systems Ecology" are we talking about? Many who consider "Systems Ecology" as their field define it in two parts: (a) study of whole ecosystems (such as microcosms or lakes) and/or (b) the mathematics and simulation of ecosystem models relating parts and predicting performance.

We called our graduate program at Florida "Systems Ecology" in 1970 because the chairman, Dr. Edwin Pyatt, found it timely in an engineering college, although my teaching objectives were always to train general theorists with environmental science as the practical realm of application. Many here call themselves "systems ecologists" but do not embrace all the subject matter of the general systems, thermodynamics, systems designs, hierarchies, the revision of ecological economics, or the introduction of abstract ecological concepts into other fields such as earth science and cosmology.

Some outstanding scientists who are systems ecologists, who in the past evaluated chemical budget networks, for example, did not model their whole ecosystem (which is necessary to simulate any part of it) or require their students to learn simulation. A diagram of the carbon cycle without the driving interactions is not a functional model. To our way of thinking, measurements and experiments without the modeling–simulating of the whole system cannot provide understanding, accurate prediction, or the solving of problems. These scientists provided good science of the parts but not of the systems.

The Ecological Society of America some years ago voted not to form a Systems Ecology section, although sections were formed for many other aspects of ecology. Many in the Ecological Society have emotional difficulties with the ecosystem, criticizing its study as teleological. But as Hutchinson (1948) showed long ago, what are often pejoratively called "teleological mechanisms" are simply just real mechanisms operating at a larger scale. But too often they look like "mystic" purpose to those who see only a piece of the system. Many scientists, thoroughly trained at one scale, can't see that what they study is controlled by the phenomena at the next larger level. For example, plant physiology cannot be done only at the level of the cell because the energy that drives the processes comes from large scale ecosystem processes and is changed in many ways by the actions and interactions at the level of the entire plant. The shortsightedness of these scientists may be the result of their having defined their lifetime specialty to be one scale of size and time. The education of all scientists needs to adopt curricula that teach the larger as well as the smaller realms affecting the level of interest.

An international society for ecological modeling was formed, and many of you here are its leaders. The name "Systems Ecology" was recently added to the title because the present "modeling" name sounds like a technique rather than a realm of science.

The language that television journalists give the public in the current period of new environmental interest probably will be the names that we give to programs of teaching and research. In the surge of public attention during the first Earth Day, the word *ecology* was partially tarnished because most academic ecologists refused to scale up their thinking to the scale of the problems that journalists and the public correctly perceived as important. Also, ecoactivists grabbed the word for incorrect concepts, polarizing the public with false environment versus economy issues. My perspective is that maximizing jobs and the economy requires maximizing the symbiosis of the economy with the environment and its resources.

I did an article for the INTECOL Bulletin 15 years ago (Odum 1980) that tried to predict ten directions that ecological research might take. These were:

Ecological organization at the larger scale
Unification of energetics and kinetics
Unification of economics and ecology
Unification of statistical distributions and ecology
Development of "embodied energy theories of value and energy quality"
Adaptation of ecosystems to pulsing and oscillation
Role of behavior as system controls
Synthesis of succession and evolution
Models for a low-energy future for humanity and nature

Many of these areas have already become important areas of research. Other areas not on that list that require further development are research in microcosms and ecological engineering. But what is important in the future depends on the trends in our global system and who can provide an integrated science of public policy and environment. According to the maximum power concept, those intellectual fields that accelerate our self-organization for these new conditions will prevail because they reduce the waste that would occur if the inevitable adaptation has to be reached by trial and error. Systems ecology has paradigms that general systems theory says are applicable for understanding and managing larger scales of the earth.

There has been for many years a crisis in Philosophy. Philosophy once claimed to be the most general of intellectual fields but lost that intellectual leadership of pure ideas, perhaps because its practitioners did not become quantitative or test their concepts against quantitative evaluations of the real world. General systems theories are a way of reuniting the fields that seek to generalize knowledge. As the resources supporting human society decrease, the information bases that we can afford to sustain may decrease, and choices may be required as to which ideas are primary principles that should be saved and taught. General systems theory may be an efficient way to store the information of science that we have now that was so costly to derive.

Ecological Growth Paradigms

Knowledge of ecosystems provides general systems models for understanding the global trends for resources and human economy. Apparently, alternating net production and net consumption in pulses maximizes the performance of many ecosystems. According to this model, our current consumer economy, which exceeds nature's net production process, will be, and may already be, turning down to the alternate regime of environmental net restoration and declining consumption.

As part of this self-organizing cycle, our ways as a species and a culture are about to change dramatically with a reversal in concepts when the people who are becoming dedicated to environment become a majority. The realities of economic climax and subsequent downturn will generate a new global unity around the paradigm of seeking a harmonious and prosperous way down (and perhaps later, up again on different energy sources). The ethics of successional net growth of consumers based on net loss of resource products will be replaced by new ethics of fostering resource net production and declining consumption. This ecological model for what is appropriate at different times in the global oscillation is the basis for our unpublished manuscript "The Prosperous Way Down" (Odum and E. C. Odum).

In the autumn season, many ecosystems enter their own downturn at the end of a pulse of production and have explosions of high-quality, late season flowers and seeds. These are information storms, analogous to the informational storms predominating the current late stage of our own growth cycle. In Figure 37.1, note the way there is a wave of consumption that moves up the transformity hierarchy, creating maximum flowering of information even while the flow of resources at the base is declining.

Macroeconomists estimate that the turnover time of the U.S. economic assets in dollars is between 3 and 17 years. But this is only the turnover of the capital, not of the real infrastructure and informational structure, which is appropriately measured by total emergy storage, not dollars. Because money is paid only to people, it does not measure the contributions of environmental resources. Nor does money measure the emergy contributions of information, which travels around the world with lightning speeds, mostly uncontrolled by anything economic. Ultimately, it is the shared information—with higher transformity than economic goods and services—that can control and regulate the economic system, organizing it to serve the system of humanity and nature better. For the time of downturning, borrowing doesn't work, capitalism is mothballed, and a new economics will emerge.

One of the most important but neglected intellectual areas is the simulation of history. Ulf Sundberg, Jan Lindegren, H. T. Odum, and S. Doherty (1994) have a paper on emergy evaluation of Sweden in 1650 and wood as the basis of Sweden's overseas army. Robert Woithe's Ph.D. dissertation was on emergy evaluation of the U.S. Civil War (Woithe 1995).

We began predicting downturn at the end of this century based on our overview energy simulation models. Already the total world fuel consumption has begun to level. The output of these models is very sensitive to the turnover time of the assets of civilization; in other words, to the depreciation rate. For infrastructure, turnover times of 50 years seemed appropriate. Yet we know that civilizations do not decline so rapidly. Later we realized that the appropriate measure of civilization is its shared information, which has much slower depreciation rates and longer turnover times. When turnover times of 100 or 200 years are used, the process of cresting and downturning is gradual and often hidden by the oscillations of its smaller components. Determining the depreciation rate (forgetting rate) of our cultural information is a priority research need for making our global minimodels trustworthy.

The Closure of the Noosphere and Solid Wastes

The world human economic–population frenzy has now reached the dimensions where it can no longer be absorbed by the environmental life support system without a better integration of its material cycles. The solid waste crisis is already on us. The people trying to solve it are working at the wrong level, dealing with technologies for using *more* high-quality resources to change waste to something else. Waste recycling should be a systems ecology and ecological engineering problem requiring the fitting of the entire human economy into well-evolved biogeochemical cycles.

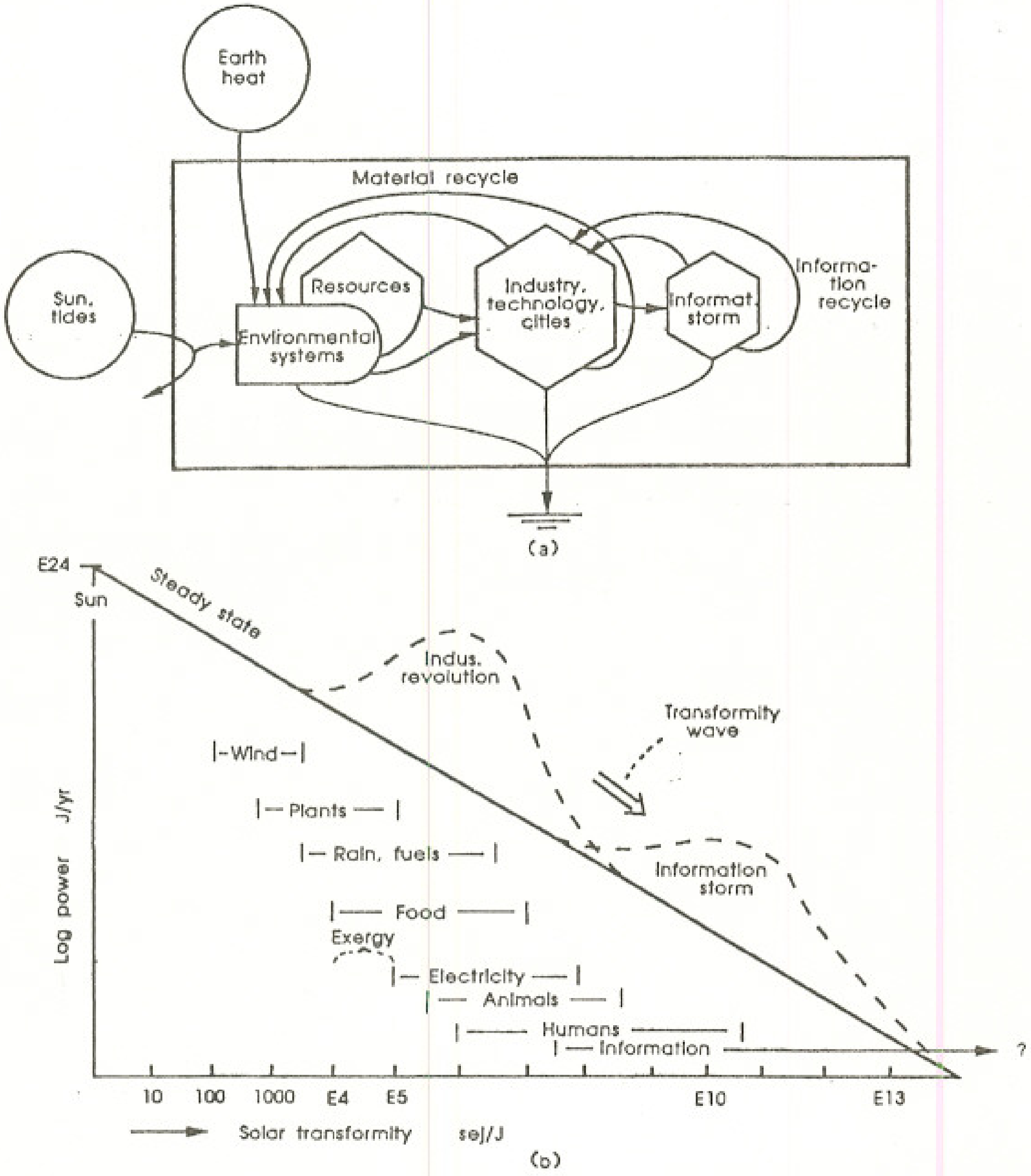

Figure 37.1 Hierarchical transformity wave generating information storm outlasting the disappearance of resource reserves: (a) energy systems diagram; (b) graph of power and solar transformity showing wave of development.

Starting with the marine sewage marsh pond experiments at Morehead City, North Carolina, in 1967 (Odum 1985; Odum 1989), followed by 20 years of work at our Center for Wetlands in Gainesville, we have developed the concepts and demonstrations of using self-design processes (ecological engineering) to recycle wastewaters to wetlands (see Section II of this volume). The principle is to use all wastes as useful by-products somewhere else in the system, or don't make the product.

Paper mills make ligneous wastes that are often regarded negatively. Yet an emergy evaluation by Keller (1992) shows the high transformities of the waste, which implies that a policy should be developed to use it. Preliminary evidence from the field and from microcosms was assembled to justify recycling paper wastes back to the forest lands from which the trees were obtained, with the overflow draining into wetlands where the paper lignin can be diluted and reconditioned by the natural peat before reaching streams and lakes. Thus its emergy content implies a potentially positive contribution to the landscape.

In an analogous way, the correct answer to solid waste, in addition to the obvious need for reuse and the prohibition of the manufacture of toxic items, is organized dispersal–recycling of appropriate materials to nature; in other words, the correct way may be to litter appropriately, with the right materials going to the right ecosystems but with dilute concentration per unit area. Wayne Smith, in an 18 year experiment, obtained rapid growth of slash pines planted in a soil of shredded solid waste on the Austin Carey Forest area of the University of Florida, Gainesville. Artificial marine reefs are another example still under study as to their ultimate role.

While on sabbatical at the University of Texas Lyndon B. Johnson School of Public Affairs (an interesting mix of new self-organizing initiatives of the large scale), I tried to explain the good ecology of light littering in the right place (solid recycling) to lovely Lady Bird Johnson at a social, where she was presiding graciously from her wheelchair. Many activists think her anti-littering campaigns are good ecology. High-emergy sparks were probably out of place at that time; I retreated, but the right time is coming soon. Neither she nor my wife, Betty, would accept a pro-litter stance, so deeply is our culture hung up on such wrong principles as Cleanliness is Godliness. Clean up nature? Civilize the bush? (Cleanliness usually means remove complex nature and replace with pavement or grass). Must we have neat lawns as evidence of prosperity whatever the cost? Should we poison the self-organizing ecosystem that tries to surround us and give ourselves cancer from the chemicals?

In Chapel Hill, in my boyhood, Stroud Lowgrounds wetland was the place that solid wastes were given a quick burn and then spread out in the swamp, which also had some sewage effluent. My elder brother, Eugene, rapidly developing as a leader in ornithology, took everyone there for the best wildlife in central North Carolina. The marvelous populations of rats brought hawks and owls in great numbers. The wetlands were full of rails, waterbirds, and high densities of wintering and summering flocks. If we had continued to appreciate the valuable role of that system for waste processing, it might not now be paved over as Eastgate Shopping Center.

I have seen this solution all over the world: the New Zealand tips with thousands of water birds, the Scarlet Ibis and Black Vulture in beautiful contrast in dumps in the Venezuelan llanos; thousands of varied birds in the dumps at Bariloche, Argentina. Our American mistake was covering them over instead of developing an ecological ecosystem that used these materials to support wildlife. Out of sight is out of mind, but newspapers are still readable from 50 year old landfills in California. The Japanese have a similar problem. Cleanliness there is washing everything down concrete channelized rivers into their local toxic seas and then bringing in their fish from everyone else's waters. Although microbes do the chemistry in decomposition situations, it also takes the animals to provide the large scale manipulating.

Microcosms for Theories and Pragmatic Purposes

Microcosms are now a mainstream. Our book reviewing self-organization in microcosms is published (Beyers and Odum 1993). It has a bibliography of 850 titles but is far from complete. Microcosms need to be better integrated with models that consider biogeochemical cycles, fundamentals of theory, and so forth. Already microcosms are used to study island biogeography, self-organization to stress conditions, and other topics.

Biosphere 2 finally did what we tried to get the National Aeronautics and Space Administration to do starting in 1958, namely, put people in a large microcosm of the biosphere with a full, complex ecosystem for life support. The first 2 year closure experiment showed why systems have to be studied with all their cycles and Gaia dynamics. The excess organic matter put in from desert soils was analogous to the fossil fuels in Biosphere 1, contributing more consumption than photosynthesis and making excess carbon dioxide, much of which was bound into carbonates. It pulled carbon dioxide into a calcareous sink away from green plants, causing gaseous oxygen to decline. This is a new insight on the links between cycles of the earth (see Chapter 19 in Beyers and Odum 1993). Biosphere 2 used enormous electric power and technology. We still need a closed system of humans and complex ecosystems that minimizes technology and electric power.

Systems Ecology and Evolution

The time is ripe for the synthesis of systems ecology and evolution. It ought to be happening in the several departments of "Evolution and Population Ecology," but the scales of these two fields don't match. The scale of systems ecology is required to bridge the gap between fast and small genetic processes and the long and large scales involved in information processing by evolution. See, for example, the model in Chapter 28 of this book, which includes micro- and macroevolution.

Ecological Economics

The new field of ecological economics has many new investigators and institutes. The field includes:

1. Comparing similar models and function in ecology with those in economics.
2. Study of the interface between ecosystems and economic systems.
3. Study of whole systems that include both ecosystems and economic systems.
4. Development of new measures of environmental value to replace market value.

As we studied the larger ecosystems that included the economy in 1967, we realized that the "willingness to pay" paradigm of neoclassical economics was the root of global destruction and a new value measure was needed for environment and resources. Energy analysis had been tried many times but failed because different kinds of energy were used interchangeably as a measure of what was required. Our emergy approach corrects this failing by multiplying energy flows by transformities, putting everything in units of one kind of available energy previously used up to make a product. The three unpublished classroom books used to teach energy analysis to many of you for 2 decades have now been condensed into a book manuscript on emergy accounting (Odum 1995).

Our approach was opposed massively by economists, process analysts, and small scale ecologists—each for different reasons. Many who attended the gathering in Chapel Hill have had their careers hurt by the war over energy concepts. Because journalists, so far, are trained only in economics, it is hard for the public to get any kind of substantive discussion of the basis of environmental value, but it is coming. As all things now go more rapidly with the information storms, the public's demand for this field may come before we have finished making it rigorous. This ought to be the top priority of foundations.

In earlier days, foundations supported our controversial work that is now accepted in textbooks, but funding is so difficult now for the radical proposals that it is hardly worth writing proposals. This leaves the universities with a special responsibility to do the new and long-range development that will ultimately take back from government the scientific leadership. In many cases, the duty of universities to do long-range, original science is hindered by chairpersons and deans pressuring the young to seek available money, any money, rather than striking out in original directions. From us, a special thanks goes to The Cousteau Society for their backing.

The most important need in ecological economics may be an international effort to prepare a compendium of transformities (including the emergy tables by which they were calculated). We have submitted several proposals for this without success. It is taking us a long time to do it as classwork.

A National Systems Ecology Diagramming Project

A major need for Systems Ecology is a national project to put as many models as possible into an atlas, representing each fully with energy systems diagrams, numbers used for calibration, differential equations, representative simulations, and some summary of conclusions obtained. The atlas can also include other kinds of diagrams that may have been used for these models. Twenty people diagramming for 6 weeks, with others dropping in to check or add their efforts, could produce a marvelous reference with systems perspective. Nobody's work should be represented without his or her final approval.

Expressing all of these analyses in the common language makes the models understandable and comparable, shows their comparative anatomy, comparative functionality, comparative energetics, and comparative hierarchical patterns. Most publications reporting model results don't show their equations, computer codes, or premises. Nobody can check, repeat, criticize, believe, or build on them. If a model is even moderately complex, readers cannot even visualize it without the energy language. There should not be diagrams with miscellaneous boxes and undefined pathways.

Perhaps we are all accustomed to people losing interest because a system thrown at them is too complex to encompass. Often there is the opposite, when the diagrams appear too simple for people to believe. Thus we have learned to show both—to show that details have been considered and appropriately aggregated for the scale of size and time of the window of interest.

Teaching Systems Ecology

Systems Ecology will increasingly be centered in Environmental Science centers and departments. It ought to refer to all scales of ecology but may be identified increasingly with larger scales. Because of the dominance of molecular biology, the ecology in biology departments in many places is being pulled down to molecular, genetic, and evolutionary considerations, not up to the larger scale. In the experience of many of us, ecology once included environmental science, but that is probably not the modern view. Good ecology at the larger scale can no longer be taught properly in most biology departments in normal time because the course emphasis is skewed to the small scale. Because biology departments teach many premedical students, they have an excess of medically oriented TAs and thus are overrepresented as their graduates seek environmental jobs with good training in molecular and organismal biology but not much environmental science. Many do not have hydrology, geology, meteorology, oceanography, limnology, soils, economics, remote sensing, environmental biogeochemistry, and systems ecology necessary to do those jobs. Those trained on the wrong scale require several years of experience to learn to think at the environmental scale, and some never learn. We should teach students how to think on several scales from the start.

But now there are several hundred of my former students and associates teaching a systems perspective to ecology, economics, engineering, and other disciplines and interdisciplines. As can be seen from the list of contributors to this book, they teach and do research at a great many of this nation's, and the world's, most important universities, and research and management institutions. Equally important are those who teach in high schools, junior colleges, and small colleges. Once a systems perspective is introduced, then most students can readily see its applications and the failures of approaches that are not systems oriented. This book captures the diversity of intellectual and practical applications of our systems approach. It is a tribute to the hard work and patience of my many former students and associates who have combined their great range of previous backgrounds and special abilities with these ideas to generate entire new fields of study and applications all over the world.

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