Industrial Ecology and Ecological Engineering

Opportunities for Symbiosis

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Keywords

biological analogy
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Summary

Ecological engineering (EE) and industrial ecology (IE) strive to balance humanity's activities with nature. The disciplines have emerged separately but share theoretical foundations and philosophies on how to address today's complex environmental issues. Although EE and IE share motive, goals, theories, and philosophies, there are many differences. These similarities and differences may make for a strong symbiotic relationship between the two fields. The goals of this article are (1) to compare and contrast the two fields to identify opportunities for collaboration and integration and (2) to suggest three cross-disciplinary focal areas that bridge EE and IE.

The first symbiotic area, ecosystem engineering for by-product recovery, is defined as the design, creation, and management of living ecosystems (e.g., forests, wetlands) that utilize the by-products of industrial systems. Examples of this exist, including constructed wetlands for lead recovery and phyto-mining of nickel tailings. The second symbiotic focus is entitled "ecosystem analogues for industrial ecology," which fits with a founding principle of IE to strive to have industry emulate the energy efficiencies and material cycles of natural ecosystems. This focal area quantifies the ecological analogy and exploits the tremendous library of design alternatives that nature has developed over thousands of years to deal with varied resource situations. The third focal area is termed "ecosystem information engineering." The means by which living ecosystems have created robust knowledge systems and information cycles should be understood in terms useful for managing current society's information explosion. As industrial society evolves toward the information society, holistic models are needed that account for the available energy and material resources required to operate effective information ecosystems, such as service industries.

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Introduction

Over the past decade, the two new fields of industrial ecology (IE) and ecological engineering (EE) have witnessed growing interest from researchers and practitioners in industry, academia, government, and nongovernmental organizations (Richards 1997; Schulze 1996). This interest is likely the result of the new emphasis in environmental management to recognize and deal with complex systems. The disciplines share the same ultimate goal of balancing humanity's activities with nature, although their means to that end differ significantly. Similarities exist regarding their theoretical foundations and philosophical outlook on how to solve today's environmental issues. The most significant difference lies in how core functions are envisioned and acted upon. Among the core organizing ideas in IE is the evolution of industry through the creation of models of symbiotic production systems that use energy and materials efficiently. The core function of EE has been to design ecosystems, broadly defined to include humans, that balance the needs of nature with those of humanity. At this stage in their development, both fields are actively evolving, so opportunities exist to create bridges between the two.

IE and EE, which coincidentally both formed new professional societies in 2001 (ISIE 2002; AEES 2002), are still undergoing early evolution that includes rapid change. Prior to the formation of the American Ecological Engineering Society, the International Ecological Engineering Society was formed in 1993. (Formation of the the former was necessary as a critical step in a long-term strategy to accredit EE curricula in U.S. universities.) Because EE and IE share a common goal and exhibit philosophical similarities, the probability of their mutual success could be increased if areas of cooperation were determined. At a minimum, participants in each field should be aware of activities in the other. Therefore, the goal of this article is to initiate an intellectual conversation between the societies so that future collaborative efforts can be realized. Specific objectives of the article are to provide a brief overview of each field in an effort to compare goals, philosophies, analytical tools, problem sets, and means of solving complex environmental problems and to propose three focal areas in which a great deal of common interest exist and which require the expertise of each field to achieve success.

The three focal areas that are discussed stress the hardware (physio-mechanical) and software (information processing and knowledge storage) role that natural ecosystems can play in improving the economic and environmental performance of industrial and service enterprises. The aim here is to highlight occasions whereby a living ecosystem is either a physical component of an industrial ecosystem or provides the knowledge for creating, designing, and operating an industrial organization. The first symbiotic area, ecosystem engineering for by-product recovery, defined as the design, creation, and management of living ecosystems (e.g., forests, wetlands) that utilize the by-products of industrial systems, represents the hardware role of living ecosystems in industrial systems. The second symbiotic focus, ecosystem analogues for IE, fits with a founding principle of IE to strive to have industry emulate the energy efficiencies and material cycles of natural ecosystems. It requires developing a quantitative understanding of the resource basis that ecosystems use to develop organization and operate their systems. The third focus area is termed "ecosystem information engineering," which concentrates on understanding the resource basis of how living ecosystems create and maintain information cycles.

An overview of each field's goals, philosophies, analytical tools, problem sets, and means of solving complex environmental problems is given. Energy systems diagrams of each field and a cross-comparison table are presented to highlight similarities and differences. Analyses of the systems diagrams and table, which help identify those areas where the two fields have common attributes, may indicate areas of direct synergism. Characteristics that are not common may indicate opportunities for collaboration, which can strengthen the core knowledge of each. To make the case that there are distinct application areas that could benefit from having both EE and IE involved, the three focal areas are introduced. Definitions and examples are given for each specialty area. Emergy synthesis is demonstrated as an analytical systems tool capable of quantifying the resource base of ecosystem structure, which can lead us beyond the ecological metaphor[1] toward the use of ecosystem knowledge for decision making and strategic planning. Energy systems diagrams are developed to demonstrate how the resource basis of ecological information cycles can be evaluated. Examples of information cycles given include one from a living ecosystem and one from a human system.

Overview of IE

The impetus for developing IE stems from the need to incorporate a multidisciplinary, holistic approach, which considers sustainable development and multiple objectives spanning several levels of system organization, into the strategic and operational decision-making processes of industry. Frosch and Gallopoulos (1989) popularized the idea that ecological systems could be an analog for industrial systems, suggesting that manufacturers who take in raw materials, generate products, and emit wastes could optimize their energy and materials consumption, minimize waste generation, and be more responsive to total environmental concerns by acting more like a living ecosystem. Graedel and Allenby (1995, 9) defined IE as "the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution". Early in its formation several definitions were offered for IE, which demonstrates the dynamic evolutionary development of the perceived scope and definition of IE, one that continues to the present. This expansive evolution in scope and definition of IE is similar to what occurred in EE, as is shown later.

1. "Designing industrial infrastructures as if they were a series of interlocking systems" (Tibbs 1991, 3)
2. "A new approach to the industrial design of products and processes and the implementation of sustainable manufacturing strategies" (Jelinski et al. 1992, 793)
3. "The totality or the pattern of relationships between various industrial activities, their products, and the environment" (Patel 1992, 798)
4. "The network of all industrial processes as they may interact with each other and live off each other, not only in the economic sense but also in the sense of the direct use of each others energy and material wastes" (Ausubel 1992, 879)
5. "The study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flows, use and transformation of resources" (White 1994, v)

Topics in IE

Although IE is a young field, it consists of several focal areas, including industrial by-product exchange and resource sharing facilitated by colocation (eco-industrial parks), product design for lessened environment impact (design for environment), product stewardship (extended producer responsibility [EPR]), reduced material intensity of products and services (dematerialization and eco-efficiency), and integrated systems analysis tools (e.g., life-cycle assessment, materials flow analysis) (Lifset and Graedel, 2003). Eco-industrial parks, which are industrial parks that facilitate material by-product exchange, recycling, cogeneration of energy from waste, and preservation of natural habitat, represent the physical space that emulates the energy flow and material cycles of an ecosystem. Ayres and Ayres (1996) gave an overview description of the now classic eco-industrial park located at Kalundborg, Denmark. Design for environment incorporates environmental objectives into product and process design while considering the entire product life cycle. Examples of this include designing automobiles for easy disassembly, uncomplicated reuse of components, and economically beneficial recycling of spent parts. Eco-efficiency focuses on lowering the environmental impact of a product over its life cycle. Dematerialization is conceptualized as the more efficient use of a given material for a particular function. The miniaturization of the integrated circuit, which has revolutionized how society and its economic system operates, appears to be a classic example of dematerialization; Williams and colleagues

(2002), however, poignantly demonstrated that 1.7 kg of materials are ultimately used to produce one microchip. This may point to the broader difficulties inherent in dematerialization efforts. EPR seeks to improve the environmental performance of products by making producers responsible for their management at the end of their life. Driedger (2002), for example, described the British Columbia case of implementing EPR for household hazardous wastes management.

Industrial ecologists are working to improve integrated systems evaluation tools that assess the relationship between nature and humanity for more informed environmental decision making. Tools under development include materials flow analysis, environmental cost accounting, and life-cycle planning, design, and assessment. Industrial metabolism is the study of the total energy and material flow of an industry, city, watershed, or nation. It accounts for all the energy and material resources used in systems of various scales, including industrial facilities (Reiskin et al. 1999), cities (Bjorklund et al. 1999), and watersheds (Stigliani et al. 1994).

In environmental cost accounting, the corporate costs of ensuring environmental compliance are allocated directly to products and processes similarly to how activity-based costing is used in managerial accounting to distribute indirect costs directly to product costs (Stuart et al. 1999). It allows companies to make more informed decisions about product mix, manufacturing, and processing techniques because they have more detailed information about the individual environmental impacts of their line of products. Life-cycle assessment (LCA) quantifies the inputs used and outputs generated throughout the network of processes needed during the life of a product, service, activity, or facility. Life-cycle impact assessment (LCIA) is defined by the International Standards Organization (ISO) as the evaluation of the potential environmental impacts of a product system throughout its life cycle. It is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system (ISO 1997). Thus, the methodology takes a systems viewpoint of the potential impact associated with a product's life cycle. Guinée and colleagues (2002) and Curran (1996) provide comprehensive reviews on the state of the art in LCA.

Overview of EE

The concept of EE was first proposed by Odum and colleagues (1963) as a branch of engineering and a field of science in which solutions to environmental problems would be grounded in the technology available from natural systems so that the human engineering required would only be supplementary. More recently, Mitsch and Jorgensen (2003, 1989) defined EE as the development of sustainable ecosystems that integrate human society with its natural environment for the benefit of both. Kangas (2003), in an introductory text on EE, stated simply that "ecological engineers design, build and operate new ecosystems for human purposes." EE is maturing as the practiced engineering discipline that combines natural and applied sciences, especially systems ecology, with the discipline of engineering to design, construct, analyze, and manage ecosystems and to develop ecotechnologies. The emphasis in EE, therefore, is on the design of man-nature systems in which living ecosystems are the major component.

Beginning in the late 1960s, the applications of EE were demonstrated with the initial research on the ability of wetland ecosystems to effectively treat municipal wastewater (Ewel and Odum, 1984; Kadlec et al. 1979). Since that time, the use of constructed wetlands for treating wastewaters of all types has flourished (Kadlec and Knight 1996) and is normally considered a prototypical example of EE. The field has branched out, however, from its emphasis on environmental pollution control using natural systems to include such new applications as restoration ecology, phyto-remediation, eco-toxicology, agro-ecosystem management, soil bioengineering, stream restoration, environmental landscape planning, and sustainable development (Kangas 2003). It is hoped that in the near future EE will incorporate elements of IE in its approach to problem solving.

Restoration ecology is a research-oriented discipline that enhances understanding of ecosystem functioning for improved repair of damaged ecosystems (Whisenant 1999). From an EE perspective, restoration of ecosystems should emphasize the recovery of the main energy and material inputs (sunlight, water, nutrients), rather than the reestablishment of specific species or historic ecosystems. One of the largest examples of restoration ecology is the restoration of the Florida Everglades in the southeastern United States, which calls for the reestablishment of vast areas of Everglades wetlands. It is an effort to restore the original water quality and quantity that existed prior to channelization by the U.S. Army Corps of Engineers (Schrope 2001).

In agro-ecosystem management, the desire is to develop farming systems that maintain high yields while relying less on chemical pesticides and processed fertilizers and more on natural systems for nutrient recycling and pest control (Mader et al. 2002). Tilley and colleagues (2002) demonstrated how a constructed saltwater marsh can be integrated into a shrimp aquaculture facility for complete recirculation of process water, while creating a large ecological habitat for resident and migratory birds.

Soil bioengineering uses ecosystems and biological materials for their structural and functional properties to reduce soil erosion. Stream restoration is a popular example of soil bioengineering that is commonly practiced in urban environments (FISRWG 1998). More and more municipalities are deciding to rip out concrete ditches that were installed to expedite storm runoff and minimize local flooding prior to the era of ecological awareness, opting for more natural stream systems. Stabilization of coastal shorelines with soil bioengineering techniques, also referred to as "soft" engineering, is increasing in popularity as the need increases to identify sustainable measures for preventing shoreline erosion (Jones et al. 2003).

National and regional agencies, with important input from the ecological scientific community (Christensen et al. 1996), are embracing ecosystem management as their philosophy for managing large tracts of public land. Ecosystem management strives to balance the needs of the ecosystem, the desires of society, and the demands of the economy by managing ecosystems from a holistic standpoint. For example, application of ecosystem management principles to the management of public forests requires that the needs of the living ecosystem be given equal weight with the demands of nature recreationists (e.g., hikers and kayakers) and logging interests. Meyer and Swank (1996) proposed how managers and scientists can collaborate to achieve the U.S. Forest Service's mandate to practice ecosystem management. As engineers, ecological engineers are trained to be systems managers. As the field grows, the combined knowledge of systems assessment tools and ecosystem science will prepare graduates to practice ecosystem management.[2]

As more and more organizations decide to implement EE projects of all kinds, there arises the need to justify them in a manner that accounts for nonmonetary benefits. Similar to the reticence of many researchers in the IE community to rely solely on money as a metric of analysis, ecological engineers turn toward energy and material flows to supplement financial accounting with assessment of nonmonetary benefits. EE economy analysis needs to be further developed to apply new methods to justify EE projects. Emergy synthesis, embodied energy analysis, and exergy analysis are examples of analytical systems for assessing the advantages and disadvantages of projects that do not rely solely on money flows.

A systems analysis tool popular among ecological engineers, but not universally applied, is emergy synthesis (Brown et al. 2000). Emergy is defined as the total direct and indirect energy of one source type (e.g., solar) required to produce a product (e.g., biomass, coal) or provide a service (e.g., waste treatment). Thus, it accounts for the total energy and material flows required to support a systems network. It shares with LCA the intent to quantify the environmental impacts of multilayered systems, but differs in its theoretical foundations and decision-making philosophy. A more in-depth explanation of emergy synthesis is given later, during the discussion of a proposed symbiotic area.

The question often arises of how EE differs from other engineering disciplines, especially well-established environmental engineering. EE and environmental engineering share a common concern for solving environmental problems. Leaders in each field have openly debated this topic (McCutcheon and Mitsch 1994; Mitsch 1994). Kangas (2003) made the distinction by saying, "There is a commitment to using ecological complexity and living ecosystems *with* technology to solve environmental problems in ecological engineering, whereas environmental engineering relies on new chemical, mechanical or materials technologies in problem solving" (emphasis added). Many environmental engineers appear to view EE as a subfield of their own. Personally, I question whether an engineer can be sufficiently educated and trained to appreciate and deal with all the multifaceted aspects of environmental problems (e.g., wastewater treatment, air pollution control, solid waste management, radiological health, ecological risks, and industrial hygiene). The expectations of an environmental engineer are already so broad it is likely unreasonable to add the subject matter required to create a skilled ecological engineer. In the United States, the Accreditation Board for Engineering and Technology has seven professional engineering societies that define the curricular standards and content for undergraduate degrees in environmental engineering, whereas most other engineering disciplines have one or two. Tacking on the tasks of EE to an environmental engineer's responsibilities would weaken the expertise that environmental engineers must have to maintain their engineering ethics. EE also has some synergism with the older discipline of agricultural engineering, which is developing into a fruitful relationship, as evidenced by the growing popularity of EE specialties in agricultural/biological engineering departments in U.S. universities.

Comparison

Table 1 provides an initial comparison of IE and EE. Above all, they share the ultimate goal of balancing nature and humanity.[3] Their scientific philosophies are both grounded in systems science, taking the view that reductionist thinking does not suffice in today's complex world (Allenby 1998; Odum 1996). On a nature-human spectrum, the technological solutions of IE tend more toward human-designed solutions, whereas EE, because of its subject of design (i.e., ecosystems), stresses incorporating the self-design capabilities of living ecosystems into a solution. Some of the best examples of incorporating self-design in ecological engineering projects include wetland creations where engineers design the geomorphic and hydrologic character (i.e., shape, depth, and flooding regime) of the wetland, but natural processes, such as species seed dispersal, are encouraged to colonize the wetland with plants and animals (Mitsch et al. 1998; Odum 1989). These researchers found that multiple seeding of plant and animal species resulted in early dynamic oscillations in wetland metabolism, species diversity, and biomass accumulation but progressed toward dynamically stable patterns. The engineering philosophy behind each field emphasizes coupled systems of human and natural design. Both fields recognize the difficulty of managing complex systems. EE has stressed understanding self-organization as a means for dealing with complexity. As for the scales of operation, IE is multiscalar, analyzing industrial processes, firms, interfirm networks, geographic regions, national economies, and supranational groups (Lifset and Graedel, 2003). EE is multiscalar as well but defines its boundaries to always include the natural environment and extends out from there to include the portion of the human-built environment appropriate for the question considered. The two fields appear to be in agreement that neoclassical economics is insufficient for evaluating impact and proving benefit. Each field incorporates energy and material resource consumption as key indicators of successful design (Rejeski 1997; Brown and Ulgiati 1999).

Figure 1 presents preliminary diagrams that employ H. T. Odum's energy systems language (Odum and Odum 2000) to outline the network components of most concern to IE (figure 1A) and EE (figure 1B). The energy systems language, with its energetically defined symbols (see figure 1 caption for explanation of symbols), offers a means for clarifying system organization in a formal manner and brings forth the importance that the entire network plays in system success. Both IE and EE take the view that the whole system should be considered for proper problem solution. In the energy systems diagram, the network of production, transformation, and consumption units, of which industry is one, is organized to utilize a multitude of factors to operate. Effective organization includes information feedback loops from downstream processes (to the right in the

Table 1 Similarities and differences between industrial ecology and ecological engineering

Attribute	*Industrial ecology*	*Ecological engineering*
Goal	Balance humanity with nature	Balance humanity with nature
Social responsibility	High, but normative aspects debated	High
Science	Integrative, holistic	Integrative, holistic, systems ecology, general systems
Technological solutions	Human designs analogous to living ecosystems	Integrate living ecosystems
Engineering philosophy	Coupled human-natural systems	Integrate ecosystem self-design into final design
Management psychology	Manage complexity	Self-organization as guide to manage complexity
Scale	Intrafirm processes to supranational organizations	Living ecosystems through human-designed systems
Economic model	Neoclassical economics insufficient; energy and material basis helps decision making	Neoclassical economics insufficient; energy and material basis more priority in decision making
Role of living ecosystems	Analogy, marginal	Core basis for system development
Industrial relationship	High	Occasional

diagram) to upstream units (to the left) and multiple levels of material cycles. The philosophy behind the layout of the diagram when read from left to right is that each unit of the system transforms less finished materials into more finished products. Pathways represent flows of energy, materials, and information. Energy availability lost during irreversible transformations (e.g., visible radiation transformed to sensible heat and long-wave radiation during photosynthesis) is accounted for through the heat sink at the bottom of the diagram. Energy dissipated through the heat sink is no longer available for doing further work in the system diagrammed. The heat sink accounts for the balance of system energy flows according to the first law of thermodynamics (conservation of energy). The second law of thermodynamics is taken into account for each energy transformation and storage of energy. In addition to requiring that the first and second laws be included in systems diagrams, the energy systems language has precise mathematical definitions for each symbol that are used to develop dynamic systems models for computer simulation (Odum and Odum 2000).

Figure 1A is used to explain, in general, the issues of concern to the industrial ecologist. Of course, IE is focused on the interaction of an industry with its contributing and consuming units, paying particular attention to energy and material efficiency. In addition, IE desires to minimize industry's generation of wastes by engineering new pathways for recycling, which in turn minimizes the stress that wastes place upon humans and the environment. In figure 1A, a distinction has been made between the two contributing environmental units. The directly contributing unit represents those environments that provide material or energy directly to an industry, such as a forest providing wood to a pulp mill. The indirectly contributing environment represents all other services of nature, such as the oxidation of the combustion by-product carbon monoxide by soil microorganisms or the sequestration of carbon dioxide by forests. In the former case, minimizing consumption reduces stress on the environment. In the latter, environmental stress is minimized by reducing waste emissions.

Whereas the emphasis in IE radiates from industry, the central theme in EE is the design of

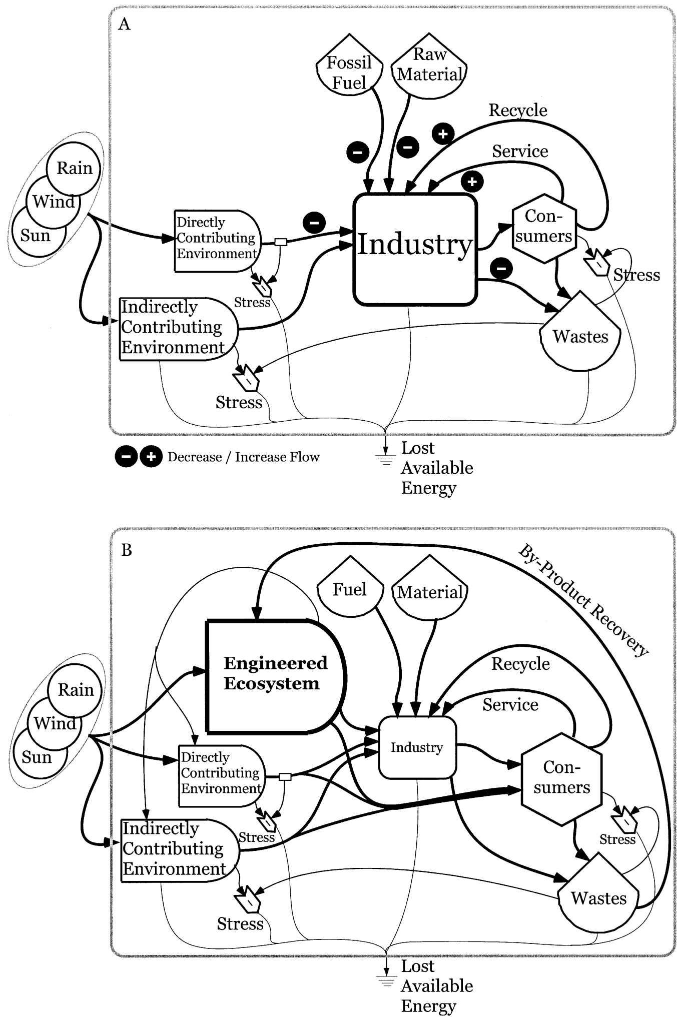

Figure 1 Energy systems diagrams outlining the roles and interests of (A) industrial ecology and (B) ecological engineering. Circles outside main box = forcing function sources; elongated Ds = green producers; capped semicircles = stocks; boxes = miscellaneous subsystems; hexagons = consumer subsystems; small directional "boxes" = interactions; bottom symbol = heat sink (see Odum and Odum [2000] for more detail on energetic, mathematical, and hierarchical properties of the energy systems symbols).

interface ecosystems. Figure 1B contains an overview systems diagram of the role EE would play in creating the symbiotic relationship between industry and its surrounding landscape. A main goal is to create engineered ecosystems that provide an interface between industry and the environment that is to be protected. EE recognizes that not all wastes emitted from industry can be recycled with energy-intensive, industrial processes. This notion has similarities to Ayres' (1994) classification of materials into three categories of recyclability: (1) economically recyclable, (2) technically feasible but not economically recyclable, and (3) inherently infeasible, which he labels "dissipative materials." He places most structural metals in the first class and most chemical products in the third. The wastes that are too dilute to recycle with a technological process (i.e., Ayres' dissipative materials), but too toxic to release to the environment, can be effectively recycled via engineered ecosystems. This offers another level to the multitude of material recycling options needed to operate efficient material cycles. In addition to designing engineered ecosystems for by-product recovery, EE also strives to manage the interaction of industry with its directly contributing environments.

Another important characteristic of EE is its philosophy that many of the systems that ecological engineers design and manage have the innate ability to self-design (i.e., to develop a complex network of energy flows and feedback mechanisms) to promote survival (Mitsch et al. 1998). Thus, practitioners of EE are expected to develop the ability to deal with complexity. Through simulation modeling, EEs are trained to simplify complexity so that it is manageable but at the same time appreciate the fact that it will most likely dominate the system they are designing.

Opportunities for Symbiosis

Three cross-disciplinary endeavors, EE for by-product recovery, ecosystem analogues for IE, and ecosystem information engineering, are presented as possible bridges between IE and EE. In addition to these specific instances of overlapping interest and skill, there are a number of analytical tools and conceptual models from each field that could prove useful to the other. Briefly, the "big-picture" mentality inherent in IE's use of LCA and other analytical tools is a mind-set that needs to pervade EE thinking. From a general systems perspective, the ecological analogy should work in both directions. That is, IE has borrowed some underlying principles of ecological theory (e.g., energy flow and material cycling), but there should also be feedback from IE to EE and the larger field of ecology concerning the applicability and robustness of ecological theories. An obvious advantage of studying industrial systems as ecosystems is the tremendous amount of data collected and maintained. Historically, ecologists have borrowed ideas from social systems to seed their own theories of ecosystems. This form of feedback from IE to ecology may be best achieved by making use of IE's strong interest in material cycling. Are there general principles of material cycles that apply across natural ecosystems and industrial systems?

Ecosystem Engineering for By-Product Recovery

The first cross-disciplinary endeavor is EE for by-product recovery, which is envisioned as the design, creation, and management of living ecosystems (e.g., forests, wetlands) that utilize the by-products of industrial systems. Under the IE philosophy, to close material loops, it must be recognized that there is a range in the "quality" of by-product materials, so there should exist a range of recycling technologies to match their quality. For example, aluminum cans are efficiently recycled via industrial processing, but dilute concentrations of lead may be best recycled by engineered ecosystems, such as constructed wetlands (Odum 2000). Other examples are phyto-mining (Anderson et al. 1998), whereby specific species of plants have been found to hyperaccumulate metals from contaminated soil to concentrations economically attractive for recovery. Soil-bed reactors and biofilters, which remove volatile organic and inorganic compounds from air emissions (DeVinny et al. 1999), are other natural-systems-based technologies that currently are used for treatment, but they need to be developed as recycling agents. Using ecosystems to close the material cycles of dilute waste substances may be the area of investigation that initially offers the highest degree of symbiosis between EE and IE.

Ecosystem Analogues for IE

A second cross-disciplinary endeavor is termed "ecosystem analogues for industrial ecology." This focus area quantifies the ecological analogy and exploits the tremendous library of design alternatives that nature has developed. It is not clear how far IE is willing to carry the ecosystem analogy (Côté 1998). Hesitancy may stem from the belief that human systems are managed through human intentions, whereas some believe that living ecosystems without humans are incapable of having goals or purpose. In fact, the maximum power principle (Lotka 1925, 1945; Odum 1996) expresses the view that all systems, whether operated by humans or honeybees, develop organization for the purpose of using energy and materials most effectively. Indeed, humans possess a great intellectual capacity that allows them to operate a trial-and-error scheme of learning, but living ecosystems have had the advantage of operating their method of "learning" over a much longer time. In IE, Benyus (1997) promoted biomimicry as inspiration for innovative design. Thus, ecosystems represent a tremendous library of organizational design alternatives that have proven to endure thousands of years of variability in resource availability.

EE, well grounded in the field of systems ecology, maintains a rich academic and professional history that seeks to understand the basis for these ecological designs and embraces this complexity as an asset. Obviously, IE is also intrigued by the wealth of information contained in ecosystem networks. To make full use of the ecological metaphor, a better quantitative understanding of ecosystem organization and resource utilization is needed. This type of effort has been a realm of research within EE (e.g., Tilley 1999; Kangas and Adey 1996). If IE is not to miss an important opportunity, it must not fall short of integrating the ecosystem model as its "software" for operating industrial systems. Researchers should accelerate their quantitative understanding of how ecosystems are organized to process energy, material, and information. The task at hand, as demonstrated in figure 2, for ecological engineers and industrial ecologists is to collaborate to transfer that knowledge so that it is of use to industrial engineers, government regulators, business managers, and others to design, construct, develop, and manage technological society. Technology transfer of ecological process and system configuration knowledge is easier and more effective with systems assessment tools that integrate natural and human systems. One such tool, popular in EE, is emergy synthesis (Rydberg and Jensen 2002; Brown and McClanahan 1996).

Emergy synthesis (Brown et al. 2000; Odum 1996) is an integrative systems tool that allows for seemingly disparate systems to be compared quantitatively on an equal basis. From its beginning in the 1970s, emergy synthesis has evolved into a tool for analyzing ecological-economic systems, incorporating, equally, the importance of the natural environment and the human environment. Emergy synthesis combines thermodynamics, systems ecology, and principles from the science of general systems (Odum 1988) to ac-

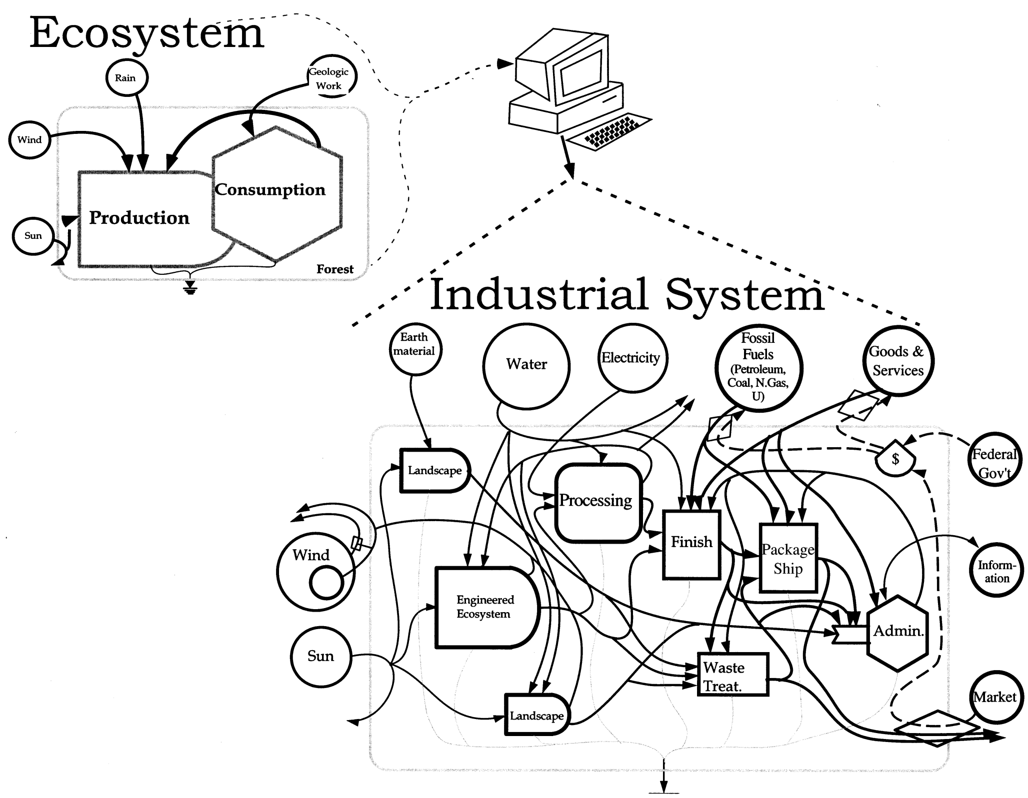

Figure 2 The study of the network structure and processing in natural ecosystems can lead to new ideas on how to organize and operate industrial ecosystems.

count for the total amount of earthly resources dedicated to the generation of a product or service, including ecological sequestration of wastes. Emergy synthesis inventories not only the energy and material used throughout the life of a product but places this usage in a contextual framework that includes both the natural and human environment. It does this by converting all input and output flows, whether they are money, material, energy, or information, into a single system of measure, emergy. This system normalization is accomplished by calculating the total solar energy (plus the equivalent solar emergy of tidal energy and Earth deep heat) required both directly and indirectly through networked processes to produce flows of energy, material, or information.

Emergy, then, is a measure of the global processes (natural and human influenced) required to produce something expressed in units of the same form of energy. By energy "form" I am distinguishing among the different "carriers" of energy. Energy occurs in such forms as visible radiation, near-infrared radiation, high-temperature heat, organic molecules, the chemical potential of freshwater, electricity, and the weight of elevated objects. From a systems ecology perspective, different energy forms have unique characteristics that are critical to operating ecosystems. Most commonly the equivalency is expressed in units of solar emergy, because solar radiation is the primary source for most forms of energy on Earth and responsible for driving many material cycles, including those of the geosphere (Odum 1988).

In emergy accounting, the contribution of the Earth's deep heat, which plays a direct role in many biogeochemical cycles (especially metals), is included as an independent source of emergy to the biogeosphere. This is accomplished by assuming that the half of the total deep heat budget (13.21×10^{20} J/yr) unaccounted for by either radioactive decay or residual heat (Sclater et al. 1980) is contributed by sunlight through various pathways that start with surface processes (e.g., biologically driven chemical weathering of bedrock assists in the transport of material from land to sea as part of the sedimentary cycle [Odum 1988; McGrane 1998]). Although this is likely a controversial assumption, it provides a means for assessing the solar emergy of geologic heat.

The production of energy forms or concentration of materials (e.g., refining ores to high-purity metals) requires that energy be transformed and degraded, which increases the solar emergy of that which is produced or concentrated. For example, the solar emergy of refined lead (10×10^9 solar emjoules [sej]/g) is greater than the solar emergy of lead ores (1×10^9 sej/g) because of the solar emergy used for mining and refining (Odum 2000). By evaluating complex systems using emergy methods, the major inputs from the human economy and those coming "free" from the environment can be integrated to holistically analyze questions of public policy, environmental management, and product stewardship.

The factor for signifying the spatiotemporal scale and importance of system inputs and components to system performance in emergy synthesis is known as the "solar transformity" (ST) (figure 3), which is defined as the total indirect and direct solar energy used throughout an entire network to create a unit of available energy of another form. Solar transformity has been proposed as a "quality" factor of energy forms (Odum 1988). For example, electricity, which is a higher "quality" form of energy than the coal burned to create it, has a solar transformity of about 150,000 sej/J, whereas coal has a solar transformity of 40,000 sej/J. (Solar transformity is reserved for energy forms, but a similar metric, solar emergy per mass, is used to account for the solar emergy of material items.) In emergy accounting, the solar transformity and solar emergy per mass are used to convert energy and material flows, respectively, to solar emergy.

Examples of solar transformities given in table 2 demonstrate how the solar transformity is greater for items that require more solar emergy for their creation and existence. For example, solar energy was transformed within the network of the bio-geosphere through many pathways and processes to create rainfall. On average, this network processing used 18,000 sej for each joule of chemical potential energy contained within the freshwater of precipitation. Thus, the mean global solar transformity of the chemical potential of rain is 18,000 sej/J. Wood in a temperate

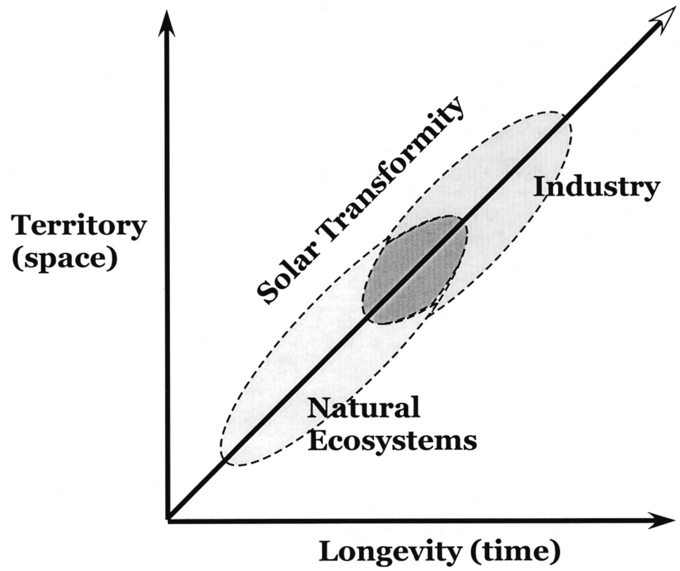

Figure 3 Solar transformity (Odum 1988) is a systems scaling factor that allows inputs and components of nature and industry to be compared on an equal basis.

Table 2 The solar transformity of items increases as the scale of their support increases and their realm of system influence increases

Energy form	*Solar transformity* (sej/J)*	*Reference*
Solar insolation at Earth's surface	1	Definition
Rain, global mean	18,000	Odum 1996
Wood, temperate U.S. forest	21,000	Tilley 1999
Electricity (coal-steam plant)	160,000	Odum 1996
White writing paper (U.S. industry average)	241,000	Tilley 1999
Published, scholarly journal article	3,500,000,000,000	Tilley and Swank (in press)

* The units of solar transformity used throughout the article are solar emergy-joules per joule.

mixed forest, which required rainfall as a main input, has an ST of 21,000 sej/J (table 2). As the wood is processed for paper production, other resources, such as water, fuel, electricity, and chemicals with unique solar emergy value, are used, increasing the solar transformity of the wood-based paper (in the United States in 1995) to 241,000 sej/J (table 2). From a systems science view, the paper is further from thermodynamic equilibrium, is more rare than wood (i.e., less physically abundant in terms of mass and energy), occupies a higher level in the energy hierarchy of ecological-economic systems, and affects system performance more with a smaller unit of energy than wood. Paper provides a major means for information processing in modern society, which is a large-scale, enduring phenomenon, whereas wood is most often used for its structural, chemical, or heat values.[4] In other words, paper serves a higher purpose (in the system) than wood, which is evident from its higher solar transformity. Going one step further, we see that unused writing paper has a lower solar transformity than paper used to publish scientific writing (ST $= 3.5 \times 10^{12}$ sej/J) (table 2). Thus, as the solar transformity of an item increases, its utility increases through the hierarchical levels of a system. Energy forms with low solar transformity perform work more effectively at the lower end of the space-time continuum, whereas energy forms with high solar transformity perform work more effectively at the higher end (figure 3).

What is the utility of emergy synthesis to IE? This is a topic worthy of greater consideration than can be adequately covered in this article; however, two examples demonstrate the thinking behind emergy synthesis. From an environmental assessment perspective, emergy synthesis is a complimentary systems evaluation tool to LCIA that brings a different perspective for assessing environmental concerns. A strength of emergy synthesis lies with its ability to assess the direct and indirect contribution of natural systems to economic production and waste amelioration, which appears to be the weaker component of LCIA (Bakshi 2002). A focus of emergy synthesis has been to quantify the work that nature contributes to the human economy.

This affirmative view of the nature-human relationship leads to conclusions difficult to conceive through a framework focused mainly on "protecting" the environment from man. For example, eutrophication of the environment is one of the main impact categories of LCIA (i.e., eutrophication is undesirable). Few doubt that humans, through their industrial and technological revolution and utilization of the Haber-Bosch process for fossil-fueled ammonia fertilizer production, have eutrophied many of the planet's ecosystems, changing their ecological balance. But is eutrophication necessarily "bad"? From an emergy-based EE viewpoint, the excess nutrients should be considered valuable resources that have useful ecological roles in specific ecosystems when properly managed. This is the impetus for initiating research on wastewater wetland treatment systems (Kangas 2003), which make eutrophic waters oligotrophic (i.e., low nutrient) while providing critical ecological habitat and protecting downstream water bodies from nutrient contamination. Nelson and colleagues (2001) used emergy synthesis to compare conventional sewage treatment with wastewater wetland systems as alternatives for developing countries. They concluded that wetland systems were more sustainable based on their much greater use of renewable solar emergy (60% for wetlands compared to 1% for sewage systems) and much lower use of purchased solar emergy (e.g., electricity, cement, steel, technical services).

In IE, recycling of by-product materials is strongly encouraged, which intuitively appears to be "good" for the environment and the economy. As I assume many industrial ecologists question, however, what level of resource consumption is appropriate for recycling particular materials? For example, how much fuel, human labor, and other resources should be expended to recycle newspaper? Obviously there is an upper limit, but what is the best investment in this recycling activity? Buranakarn (1998) proposed that recycling should occur as long as the solar emergy of the newspaper is greater than the solar emergy of the sum total resources required to perform the recycling. If more solar emergy is used to recycle the newspaper than the newspaper contained, then recycling is a wasteful activity. Alternatively, if the newspaper solar emergy is significantly greater than the solar emergy of invested resources, then recycling is environmentally beneficial. With emergy synthesis, the difference between the solar emergy of the recycled material and the required recycling resources is a quantitative measure of environmental benefit. This type of approach could assess whether proposed process improvements in an industry are environmentally beneficial and worth the investment. Ulgiati (2001) applied emergy synthesis to evaluate the role of ethanol in contributing to the power supply of developed and undeveloped countries, concluding that the net emergy yield was too small in developing countries and that the supply was insufficient to make ethanol competitive in developed countries.

Ecosystem Information Engineering

Ecosystem information engineering is the third proposed area for cross-disciplinary collaboration. As industrial society evolves toward the information society, holistic models are needed that account for the available energy and material resources required to operate effective information ecosystems, such as service industries. Such models could prove especially useful in fostering decision making in the "new economy," which relies heavily upon effectively creating, managing, and disseminating information. Models of information ecosystems that include the full resource requirements for their creation and continued operation are also needed so environmental consequences can be inventoried and assessed (Rejeski 2003; Graedel 1997).

IE has employed the ecosystem model to demonstrate how holistic systems thinking can improve the environmental performance of corporations and related entities. Early success has generally been in the arena of physical resource management (e.g., energy efficiency, dematerialization, design for environment, and product stewardship). In *General Systems Theory*, von Bertalanffy (1973) recognized not only the commonality of energy flow and material cycles in systems, but also how all systems required information feedback to operate the system components that transform the energy and material. Living ecosystems not only provide powerful models to achieve energy and material efficiency, they also offer strategies for creating robust knowledge systems and maintaining them effectively for long periods. Indeed, living ecosystems have self-organized over Earth's history, utilizing available resources to operate dynamic, resilient information ecosystems. The means by which living ecosystems have created powerful, long-lasting knowledge systems and information cycles should be understood in terms useful for managing current society's information explosion. That is, the resource requirements of information systems needs to be understood and assessed to decide whether, for example, the transition to a service-based economy is truly less energy intensive (Laitner 2003).

Ecosystem information engineering could have two immediate impacts. First, the industrial world can learn some valuable lessons from the strategies of living ecosystems to create and manage information as they adjust to a dynamic resource base (Odum 1988). This topic has some overlap with the portion of artificial intelligence community interested in learning from social insects (e.g., swarm intelligence) (Bonabeau and colleagues 1999) to develop simple algorithms for control and optimization. A question in EE is how biodiversity relates to system performance and resource requirements. One thought in systems ecology is that the importance of information processing and communication grows as a system transitions from simple organization in its beginning stages toward more complexity in later stages (Odum 1969). The second area of importance is to develop a holistic, life-cycle-type assessment approach that incorporates the special properties of information (e.g., copying, error generation) to comprehensively evaluate the environmental impacts and benefits of large-scale information systems.

Diagram of an Information Cycle

Figure 4 is an energy systems diagram of the cycle necessary to create, maintain, and use information for operating physical systems, such as industrial and commercial enterprises, based upon a diagram proposed by Odum (1996). The entire information cycle requires energy, money, services and labor, and material resources to operate each stage of the cycle. IE has been conceptualized in terms of the physical systems that process raw resources into finished goods and services and generate waste. Stages 1 and 2 in figure 4 depict this aspect of IE. Stage 1 represents the raw resources that drive the activities of the various types of operating systems shown in stage 2. "Operating system" in this context is the system of physical, chemical, and biological processes that use energy and material to provide products and services. For example, a single-family home is an operating system that provides shelter and related functions for living. The architects, developers, contractors, and trade schools operate the information cycle for housing by drawing blueprints, laying out neighborhood developments, building homes, and training workers.

Figure 4 shows the sequence of stages of an information cycle that are required to create and maintain the knowledge necessary to operate and improve the performance of the operating systems. As a first step in the information cycle (stage 3), the contribution of the products, services, and knowledge (i.e., outputs) provided by the operating systems to its end users is sensed. In stage 4, based on the contribution that each operating system makes, information is selected from among the operating systems. Upon selection, information is extracted, interpreted, and assembled into a more condensed form (stage 5), which can then be copied and dispersed (stage 6). Next, the newly condensed information is communicated (stage 7) so that it becomes part of the stock of shared information (stage 8) available for the functioning of existing and new operating systems.

Like other structures, information is thermodynamically distant from equilibrium and thus is

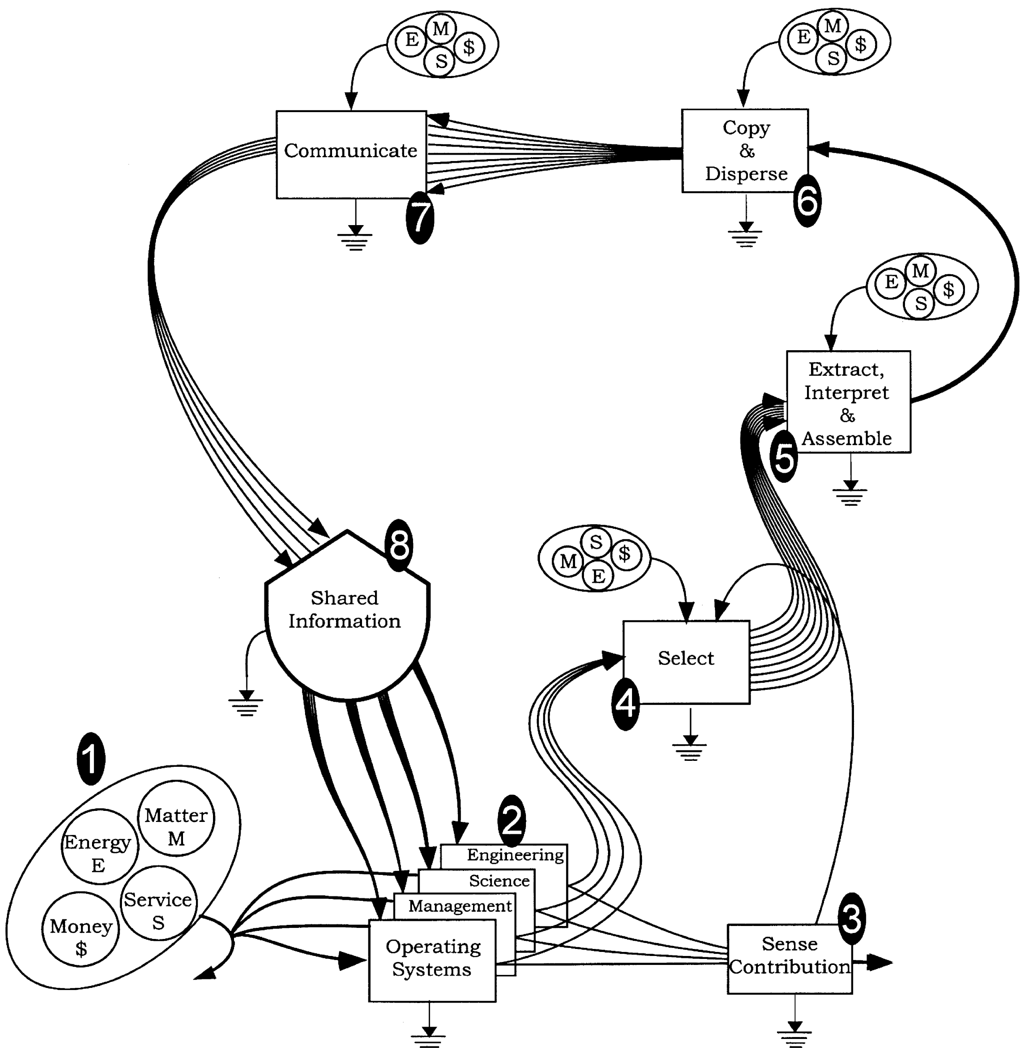

Figure 4 Energy systems diagram of a generic information cycle highlighting the resource consumption (e.g., energy [E], material [M], services [S], and money [$]) required to operate each stage of the cycle. *Source:* Modified from Odum 1996.

continuously lost by error generation, dispersal, depreciation,[5] and destruction. This feature of the second law is depicted in the diagram in figure 4 as heat sinks connected to each stage of the cycle. Work that consumes resources irreversibly is required not only to make the operating systems function, but also at each stage of the information cycle. If information is not cycled through the multistage loop, the shared information is degraded, lost, or forgotten. New knowledge must also go through a similar cycle.

An Example of a Human-Controlled Information Cycle

An example of an information cycle is the creation of an EE textbook. To share the knowledge of EE with a greater audience, a textbook is written, published, distributed, and used to teach principles and applications to students, who become practitioners. Operating systems needed to create such a text include, but are not limited to, fields of science such as ecology and environmental science; fields of engineering such as civil, environmental, agricultural, and biological engineering; experimental and demonstration ecosystems; research publications; and university libraries. The first step toward creating the text is to sense the contribution that these fields make to nature, society, and economy. The sensing is a combination of social perspective, author recognition, publisher acceptance, and academic and professional demand. Once the demand for EE knowledge is sensed, the next step is for the author to select which operating systems can best contribute to the creation of the text. Knowledge is extracted from the various operating systems, interpreted by the author, and assembled into a draft manuscript, which is then sent to peers for review and suggested corrections. The publisher's editor may also contribute to the assembly and manner of presentation of the information. Once the text is proofed and typeset, it is published, creating copies for distribution. At this stage, the dispersed knowledge has been concentrated into a format that allows for easier communication and sharing of the knowledge. Processes for communication and sharing include classroom lectures, video broadcasts, interactive Webcasts, and independent study. As the newly condensed information is shared, it becomes available for improving the workings of existing operating systems or creating new ones.

It is important to understand the cycle in its entirety so the energy and resource intensity of information generation and maintenance can be fairly assessed. A suite of environmental and human-controlled energies not only power each operating system, but also power each stage of the information cycle. For example, the authors of the text are fueled by high-quality food, drive energy-intensive automobiles, fly around the world in jet airplanes, and rely on sophisticated communication devices. The university system, which allows the coalesced knowledge to be effectively transferred to students, is a large consumer of energy and materials. The resource intensity of information generation and maintenance may be poorly understood at present.

An Example of an Ecological Information Cycle

Figure 5 shows a systems diagram of the information cycle required to maintain a forest. Beginning with the operating systems (i.e., plants, animals, soil system) labeled as "stage 2," various energies and material resources are required to operate each as well as maintain the overall organizational structure (stage 1). Those components of the operating system that are most successful in terms of longevity or dominance contribute significantly to surrounding ecosystems (stage 3). A multitude of selection mechanisms (e.g., predation, human-forced land clearing, floods, disease, fire, and insect infestation) determine which components of each operating system become a part of the information cycle. Those components that survive the selection process then go through a reproduction stage (stage 5), which has unique mechanisms for action. Those individuals that survive selection and produce progeny have created unique copies of their genes, which are then dispersed across the landscape by various processes (e.g., wind, animals, rivers), as shown in stage 6. By stage 7 the new carriers of the new genetic material are embedded in the original or new ecosystems, increasing the amount of shared genetic information (stage 8) available for future operating systems and information cycles to use.

Lessons Learned from Ecological Information Cycling

Like the example of the textbook information cycle in figure 4, each stage of the forest information cycle requires energy and material inputs and obeys the laws of material conservation and thermodynamics. The stock of shared information depreciates and is occasionally destroyed in natural systems. Despite these ecological constraints, the forest ecosystem continues to evolve and maintain vast quantities of information. From an IE and EE perspective, one task is to understand the energy and material basis of ecosystem information processing so that knowledge can be applied to design effective information cycles for industrial and service systems.

Information requires fewer resources to save and copy than to make anew. This is likely why systems store useful information once it is developed. The creation of new information may be quite resource intensive, however, as demonstrated in our example of creating an EE text. Therefore, a basic question is how much total

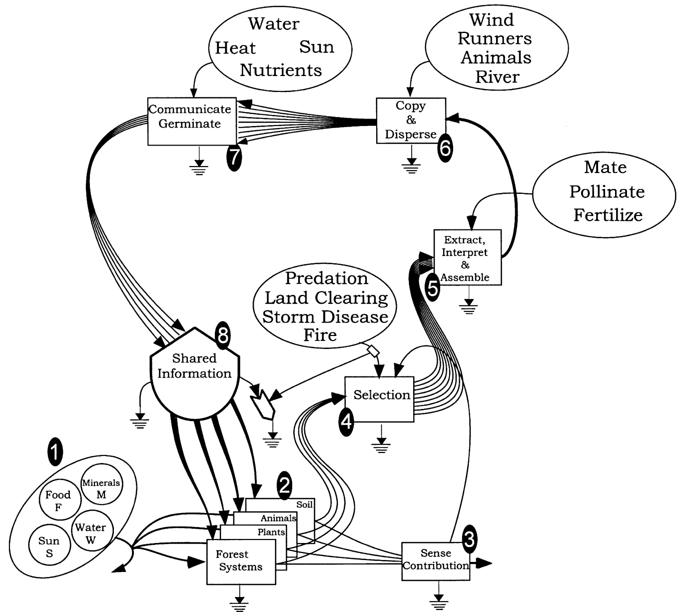

Figure 5 The information cycle of a forest ecosystem.

resource (i.e., energy and material) is needed to create or maintain various types of information. Creating information is not environmentally benign, nor is it free, but do we know how resource intensive it is? The argument here is that we need to quantify the resource intensity of nature's information cycles using a metric such as emergy so that we quantitatively understand nature's optimization process. Once we assess the resource intensity of a natural systems information cycle with emergy, we could scale this knowledge up to our own human-controlled information cycles.

For instance, assuming that the information cycle of a natural ecosystem is sustainable, then knowing how much solar emergy is allocated to each stage could be an indication of how resources (measured with solar emergy) of a human-controlled information cycle should be distributed to achieve sustainability. Forest trees devote a fraction (F_i) of their solar emergy budget to operate each stage of the information cycle, which varies according to resource availability and other factors. If human and natural information cycles behave similarly as demonstrated here, then knowing the distribution of the F_i's in natural ecosystems could be a valuable guide for organizing human information cycles. The distribution of the F_i's is an open question that needs to be addressed by researchers in EE and IE alike.

The information cycle diagrams presented here represent a general view of the stages required to operate ecological information cycles and do not represent a consensus among ecological engineers. Accounting for the resource requirements of information cycles is a fresh area of investigation that needs further development. This is one approach to a problem that needs to be addressed.

Future Collaborative Efforts between IE and EE

As can be seen from this preliminary comparison, IE and EE have a great deal in common and many opportunities for cross-pollination and future integration. Each field maintains a unique set of analytical and problem-solving methods suited to its focus area. Their common purpose and shared systems view of the world indicates that there is potentially a strong symbiotic relationship to foster if the fields were to understand and appreciate the purposes, problems, and solution techniques of the other.

Realization of the cross-fertilization and integration can begin with a jointly convened conference, whereby industrial ecologists and ecological engineers are forced to listen to one another. From this meeting, research teams could form to solve problems of mutual interest. This research would then lead to joint publication of papers and possibly a textbook on ecological industrial engineering.

Notes

1. Editor's note: For discussions of the role of metaphor and analogy in the *Journal of Industrial Ecology*, see articles by Isenmann (2003), Ehrenfeld (2003), and Spiegelman (2003).
2. Like other applications mentioned in this article (such as restoration ecology), ecological engineers are not the only professionals working in ecosystem management. It is nonetheless an area in which ecological engineers are making an important contribution.
3. There is debate within the IE community as to whether the field is positive, normative, or both. See, for example, the exchanges between Allenby (1999) and Boons and Roome (2000).
4. In this example, I give point estimates of ST for wood, paper, and information. Obviously, in real systems there are distributions of ST for items. Thus, some wood will have an ST greater than some paper and some information. However, high-quality information (e.g., principles of math, science, and democracy) has endured through millennia to provide modern society with a powerful ability to organize society, develop economies, build public works, and so on.
5. By "depreciation," I mean the natural irreversible process of losing the quality of the information. One example would be books in a library: Loss of whole books is dispersal, degradation of the quality of one book due to physical deterioration is depreciation, a fire would be destruction, and error generation often comes from photocopying.

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