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Colloquium Paper

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This paper serves as an introduction to the following papers, which were presented at a colloquium entitled "Industrial Ecology," organized by C. Kumar N. Patel, held May 20 and 21, 1991, at the National Academy of Sciences, Washington, DC.

Industrial ecology: Concepts and approaches

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ABSTRACT **Industrial ecology is a new approach to the industrial design of products and processes and the implementation of sustainable manufacturing strategies. It is a concept in which an industrial system is viewed not in isolation from its surrounding systems but in concert with them. Industrial ecology seeks to optimize the total materials cycle from virgin material to finished material, to component, to product, to waste product, and to ultimate disposal. To better characterize the topic, the National Academy of Sciences convened a colloquium from which were derived a number of salient contributions. This paper sets the stage for the contributions that follow and discusses how each fits into the framework of industrial ecology.**

It is not difficult to find evidence that human activities are beginning to overrun the resources of the planet. The exhaustion of the oil that has fueled the industrial revolution appears to be less than a century away, waste disposal sites are in increasingly short supply, the atmosphere over Antarctica is being radically changed as a consequence of industrially synthesized halogenated gases, and so forth. In many of these cases, the industrial processes that have benefited society are also among the sources of the problems. It is clear that "business as usual" is not an option that industry can maintain for long. Nonetheless, the complexities involved in new approaches to industrial design and operation are many, and individuals who are adequately equipped to make decisions with the full spectrum of those complexities in mind are few.

Recognizing that new approaches are required for the industrial design of products and processes and the implementation of sustainable manufacturing strategies, the National Academy of Sciences, in cooperation with the AT&T Foundation, sponsored a colloquium in Washington, DC, on May 20–21, 1991. In this communication, we wish to frame the concept on which that discussion was based and to describe how the papers that follow fit into that overall concept.

Industrial Ecology: A Systems Description

Traditional biological ecology is defined as the *scientific study of the interactions that determine the distribution and abundance of organisms*. The relationship between this concept and that of industrial activities has been discussed by Frosch and Gallopoulos†:

> In a biological ecosystem, some of the organisms use sunlight, water, and minerals to grow, while others consume the first, alive or dead, along with minerals and gases, and produce wastes of their own. These wastes are in turn food for other organisms, some of which may convert the wastes into the minerals used by the primary producers, and some of which consume each other in a complex network of processes in which everything produced is used by some organism for its own metabolism. Similarly, in the industrial ecosystem, each process and network of processes must be viewed as a dependent and interrelated part of a larger whole. The analogy between the industrial ecosystem concept and the biological ecosystem is not perfect, but much could be gained if the industrial system were to mimic the best features of the biological analogue.

It is instructive to think of the materials cycles involved with the earliest of earth's life forms. At that time, the potentially usable resources were so large and the amount of life so small that the existence of life forms had essentially no impact on available resources. This individual component process might be described as *linear*—that is, as one in which the flow of material from one stage to the next is independent of all other flows. We term this pattern type I ecology; schematically, it takes the form of Fig. 1.

A contrasting picture is an ecosystem in which proximal resources are limited. In such a system, the resulting life forms become strongly interlinked and form the complex networks we know today as biological communities. In this system, the flows of material within the proximal domain may be quite large, but the flows into and out of that domain (i.e., from resources and to waste) are quite small. Schematically, such a type II system might be expressed as in Fig. 2.

The type II system is much more efficient than the previous one, but it clearly is not sustainable over the long term because the flows are all in one direction, that is, the system is "running down." To be ultimately sustainable, biological ecosystems have evolved over the long term to be almost completely cyclical in nature, with "resources" and "waste" being undefined, since waste to one component of the system represents resources to another. [The exception to the cyclicity of the overall system is that energy (in the form of solar radiation) is available as an external resource.] This type III system may be pictured as in Fig. 3. It is important to

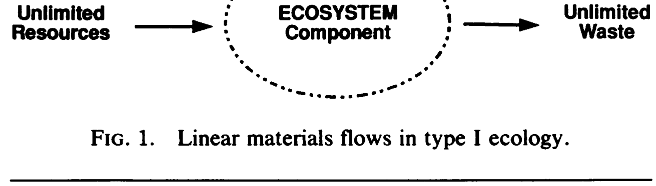

FIG. 1. Linear materials flows in type I ecology.

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†Frosch, R. A. & Gallopoulos, N., paper presented to the Royal Society, London, February 21, 1990.

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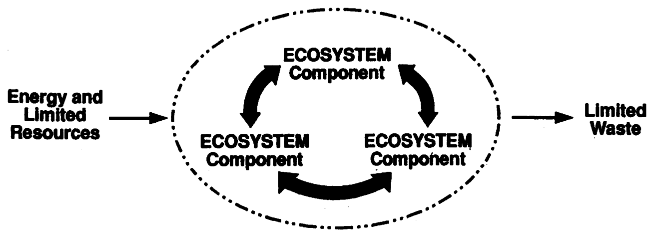

FIG. 2. Quasi-cyclic materials flows in type II ecology.

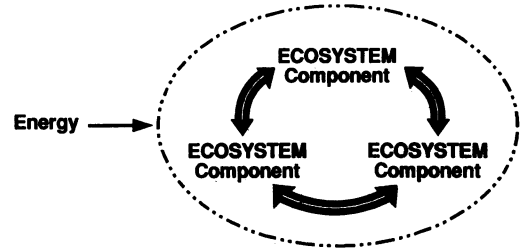

FIG. 3. Cyclic materials flows in type III ecology.

recognize that the cycles within the system tend to function on widely differing temporal and spatial scales, a behavior that greatly complicates analysis and understanding of the system.

The ideal anthropogenic use of the materials and resources available for industrial processes (broadly defined to include agriculture, the urban infrastructure, etc.) would be one that is similar to the ensemble biological model. Many uses of materials have been and continue to be essentially dissipative, however. That is, the materials are degraded, dispersed, and lost in the course of a single normal use, mimicking the type I unconstrained resource diagram. This trend can be associated with the maturation of the Industrial Revolution of the 18th century, which, together with exponential increases in human population and agricultural production, took place essentially in a context of global plenty in which copious quantities of energy and raw materials were available. Many present day industrial processes and products still remain largely dissipative. Examples include lubricants, paints, pesticides, and automobile tires.

Not all present day technological processes are completely dissipative, however. Where specific materials are sufficiently precious, some demonstrate ecological type II behavior, at least in part. An example is precious metals recovery.

On the broadest of product and time scales, there are many demonstrations today that the flows in the ensemble of industrial ecosystems are so large that resource limitations are setting in: the rapid changes in atmospheric ozone, increases in atmospheric carbon dioxide, and the filling of available waste disposal sites being examples. Accordingly, industrial systems (and other anthropogenic systems) are and will increasingly be under selective pressure to evolve so as to move from linear (type I) to semicyclic (type II) modes of operation.

The central domain of industrial ecology is conveniently pictured with four central nodes: the materials extractor or grower, the materials processor or manufacturer, the consumer, and the waste processor. To the extent that they perform operations within the nodes in a cyclic manner or organize to encourage cyclic flow of materials within the entire industrial ecosystem, they evolve into modes of operation that are more efficient, have less disruptive impact on external support systems, and are more like type III ecological behavior. Examples range from the recycling of iron scrap by the heavy metals industry to the popularity of garage sales for the reuse of products within the consumer domain. The schematic model of such an industrial ecosystem is shown in Fig. 4. Note that the flows within the nodes and within the industrial ecological system as a whole are much larger than the external resource and waste flows.

Characterization of Industrial Ecology

The first of the contributed papers in this issue is that of Patel (1). His presentation emphasizes the basic characteristics of industrial ecology and points out the many perceptions that inhibit such a system from functioning properly. He calls for enhanced communication among specialists, a restraint on the use of jargon, and a willingness to develop new concepts to deal with new approaches to understanding the functioning of industrial processes.

For many of the papers from the colloquium, it is helpful to use the schematic model of Fig. 4 to place them into the framework of the industrial ecosystem. From this perspective, the paper by Frosch (2) treats the ensemble of constituents within the broken line. Perhaps the most striking of Frosch's many points is that natural ecosystems, evolving over millions or billions of years, have produced every entity needed for a type III ecosystem. The industrial ecosystem, in contrast, is a system moving from type I to type II behavior. If we wish it to approach a type III system, we may need to artificially create some of the missing entities. Frosch regards a healthy recycling and remanufacturing entity as an example

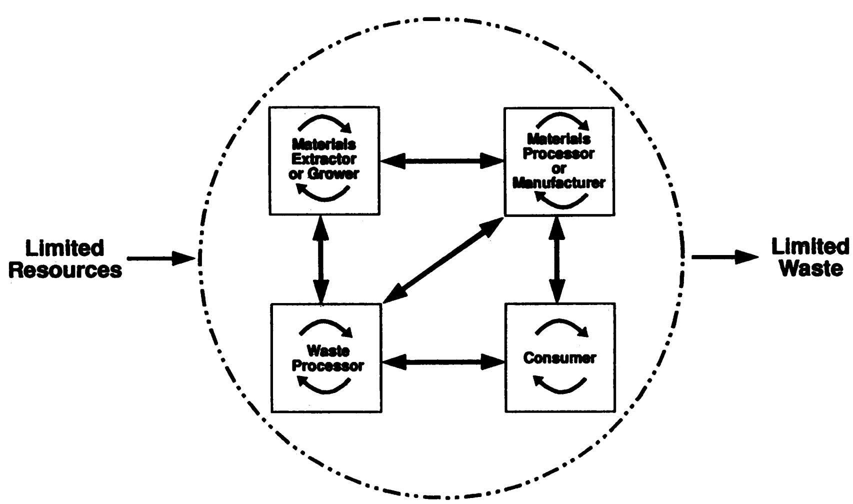

FIG. 4. Type III model of the industrial ecosystem.

of an entity that is missing, or nearly so, and may need to be created by fiat if we wish industrial ecology to proceed at a rapid pace.

Smart's essay (3) asks why an individual entity in the industrial ecology system is motivated to act in ways that benefit the system. He finds the metabolism of this entity to be responsive to economic forcing and shows how price signals to that entity for such factors as the true value of natural resources can alter the metabolism of a corporation. His approach can be taken to refer to either the "Raw Materials Extractor" or "Materials Processor" boxes in Fig. 4 and to the factors that control the flows to and from those boxes.

Examples of Industrial Ecology in Manufacturing

Industrial ecology may be approached in either of two ways. The first is material-specific; that is, it selects a particular material or group of materials and analyzes the ways in which it flows through the industrial ecosystem. Such an analysis in manufacturing operations is generally made while products are in their manufacturing cycle, and any modifications to materials or processes tend to be costly and difficult.

The second type of industrial ecology analysis is one which is product-specific; that is, it selects a particular product and analyzes the ways in which its different component materials flows may be modified or redirected in order to optimize product–environment interaction. Such an analysis is particularly appropriate at the initial design stage of a product, when decisions on alternative materials or processes can often be made at a stage preceding the investment of large amounts of capital for equipment or process development, an action that often locks in a particular material or process for the long term.

Several of the papers that follow present examples of situations in which one or more aspects of industrial ecology were used in actual industrial situations. These are activities that fall largely within the "Materials Processor or Manufacturer" box in Fig. 4 or in the flows to and from that box. An example of a material-specific analysis is that presented by Boyhan (4), in which he describes the ways in which AT&T has revised its approach to cleaning electronic circuits while eliminating the use of chlorofluorocarbons (CFCs). An important message from this paper is that modern manufacturing processes often use materials and processes at the forefront of technology and that it may be difficult in the short run to sustain that technology while implementing major changes in the processes on which it is based.

A broader material-specific analysis is that of Ayres (5), in which the materials flows of a number of toxic heavy metals are presented. Among the results of that study is the realization that very large amounts of material must be processed to extract the metals from their ores and that many uses of the metals are dissipative. The sustainability of the biosphere over time is probably incompatible with these current practices.

A product-specific analysis is that of McFarland (6), who discusses DuPont's analyses of possible replacements for CFCs by more environmentally benign substances. An important result of this paper is that it is often difficult to determine which of several possible choices is most desirable from an environmental standpoint. In other words, the environmental forcing function can sometimes be rather ambiguous.

Mitchell (7) discusses a technique for eliminating the hazards involved in the transportation and storage of potentially harmful chemicals by synthesizing them as a part of the industrial process. Here the forcing function, both from an industrial hygiene standpoint and a regulatory standpoint, is very clear. Success was possible only by bringing new and insightful scientific and technological approaches to bear on a problem with a long history.

Influencing Industrial Ecology Flows

The Fig. 4 diagram includes not only inputs of energy and materials (from the left) and outputs (to the right), but also the quasi-cyclic flows within and between individual entities. Two of the papers that follow deal specifically with energy use. Ross (8) points out that much of the energy used in industry is concentrated in very few sectors: aluminum smelting and cement production, for example. Major reductions in energy will follow from the trend to declining quantities of materials use, since modern technologies are much less energy-intensive than the processes they replace. Hoffman (9) presents a simple and more universal goal: to reduce the energy used in lighting. Many of the technologies needed for this process are already in hand; the challenge appears to lie rather in achieving satisfactory economic incentives.

Stein (10) discusses the level of recycling of polymers today and the prospects for the future. He envisions today's 30% recycling rate increasing to about 60% but sees difficulty in progressing much further so long as plastics are designed into products in such a way that their extraction after use is unfeasible or causes excessive degradation of the basic polymeric material. Thoughtful initial design of products, utilizing industrial ecology principles, will be needed. Ways around this problem may come from innovative work like that of Luzier (11), whose use of biotechnology and materials science as part of the manufacturing cycle has resulted in a family of plastic materials that are produced from renewable resources while being completely biodegradable.

Constraints and Incentives for Industrial Ecology

Industrial ecology cannot be studied and optimized in isolation from the human institutions of various kinds that promote or constrain the materials or energy flows indicated in Fig. 4. Consider the following:

(*i*) Engineering excellence can often promote cyclic behavior within the manufacturing node by designing processes to promote materials reuse.

(*ii*) The desire to avoid toxic wastes may promote process changes to reduce the quantity of wastes or (better) to substitute materials or components that result in less toxic or nontoxic wastes.

(*iii*) The economic system may make it difficult to raise capital to alter a process and render it more efficient, that is, to improve its cyclic nature.

(*iv*) Taxation may promote raw materials flows or import-export flows that are contrary to cyclization of the industrial ecosystem.

(*v*) Government regulations may make reuse of materials so difficult that enhanced waste flow is *de facto* encouraged.

(*vi*) The price system, by failing to include relevant externalities in prices and costs, may preclude adoption of industrial ecology by manufacturers and producers.

(*vii*) The standard of living of the consumer may encourage long product use or, alternatively, may promote early product disposal.

(*viii*) The rapid rate of technological evolution and obsolescence contributes to an enhanced waste stream.

Several of the issues mentioned above are discussed in more depth in papers by Nordhaus (12), Duchin (13), Henrichs (14), and Pariza (15). Nordhaus (12) discusses industrial ecology in the context of today's intricate web of economic activity. He points out that one could force the economy into

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the economic equivalent of a closed ecosystem by ensuring that all environmental costs and benefits are priced at their full social value.

Duchin's paper (13) concentrates on the ways in which economic factors may be assessed in the industrial ecology perspective. Appropriate methodologies are vital, since environmental tradeoffs are certain to arise, just as do economic and technological tradeoffs. Duchin describes how economic input–output analysis is particularly suitable to industrial ecology.

Legal constraints to industrial ecology are discussed by Henrichs (14). She points out that regulations that are based on incentives rather than on sanctions are those that have proven to be the most effective. In addition, such legal approaches are far easier to change as knowledge changes than are those that dictate every detail of the industrial process they seek to regulate.

Pariza (15) looks at regulatory matters from the point of view of risk assessment and public perceptions. This perspective is important for industrial ecology in that processes and products can be designed to avoid the use of materials with known ecological consequences but cannot be designed to avoid the use of materials whose use might be constrained by irrational legislation. In this connection, a good case can be made for close cooperation among industry, government, and the public if real environmental progress is to be achieved.

Educating Industrial Ecologists

No matter how clearly industrial ecology is defined, it cannot be implemented without a sufficiently numerous cadre of trained personnel. For the most part, such individuals do not now exist, and the process of creating them from the potential reservoirs of industrial hygienists, process engineers, and students is a challenging one. Troxell (16) argues that in the short term most of the people will come from industry itself. Universities and professional societies will initially train these people through short courses, industry visits, and the like. Industry itself will then need to expand its expertise by extensive in-house training.

For the longer term, Hutchinson and Lynch (17) present a possible syllabus for a master's degree program in industrial ecology. They model this syllabus after that of a two-year professional school, and structure it around three primary academic core topics: environmental science and engineering, management science, and public policy. Starr (18) directs his comments chiefly to the latter topic and argues that the crucial item in educating industrial ecologists is bridging the traditional separation between the study of technology and of society.

Looking to the Future

To be broadly implemented, industrial ecology will require the setting of broad goals and of effective ways of reaching those goals. Speth speaks to that topic in his paper (19), in which he points out that the solutions to today's environmental problems lie mostly outside the established "environmental sector." He calls on the business and technological communities to move beyond compliance to leadership and cites the colloquium as a promising step in that direction.

A similar perspective but a somewhat more directed focus is taken by Piasecki (20), who makes the point that industrial ecology requires not only fresh approaches to technology but also institutional innovations in management. He then discusses several "popular fallacies" to demonstrate the many natural alliances that have been discovered and that will occur in the future among economic considerations, government, industry, and the environment.

Finally, Brown (21) contributes a plan of action from the perspective of one whose career is within the political system. He calls for a roundtable organization to bring together appropriate personnel from the industrial, scientific, engineering, and economic sectors in order to promote activities in industrial ecology and to minimize constraints to it, intended or accidental.

Summary

The colloquium whose discussions are reported in this issue of the PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA demonstrated that industrial ecology is a concept that is relevant to the modern industrial community and that is already being implemented in various ways, at least on a partial and preliminary basis. In his conference summary, Ausubel (22) reflects that one important accomplishment is the obvious awareness that many in industry, academia, and government are now bringing to the field. He cites the potential advantages to be gained through industrial ecology and notes the great disadvantages to all of us if the tenets of industrial ecology are not followed.

A simple and useful synopsis of the colloquium is to cite several characteristics of industrial ecology that, in one way or another, permeate the papers that follow:

(*i*) Industrial ecology is *proactive* not *reactive*. That is, it is initiated and promoted by industrial concerns because it is in their own interest and in the interest of those surrounding systems with which they interact, not because it is imposed by one or more external factors.

(*ii*) Industrial ecology is *designed-in* not *added-on*. This characteristic recognizes that many aspects of materials flows are defined by decisions taken very early in the design process and that optimization of industrial ecology requires every product and process designer and every manufacturing engineer to view industrial ecology with the same intensity that is brought to bear on product quality or manufacturability.

(*iii*) Industrial ecology is *flexible* not *rigid*. Many aspects of the process may need to change as new manufacturing processes become possible, new limitations arise from scientific and ecological studies, new opportunities arise as markets evolve, and so on.

(*iv*) Industrial ecology is *encompassing* not *insular*. In the modern international industrial world, it calls for approaches that not only cross industrial sectors but cross national and cultural boundaries as well.

Two hundred years ago, industry changed from a small, labor-intensive, inobtrusive activity to one that has become large, obtrusive, and potentially destructive to the resources that support it. Industry now has the opportunity to take a step as great as was taken in the industrial revolution of the 18th century: to move from unconstrained use and disposal of materials to manufacturing approaches that take products and impacts into account in the same design and with the same degree of foresight. The twenty-two papers that follow show us all how to get started.

1. Patel, C. K. N. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 798–799.
2. Frosch, R. A. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 800–803.
3. Smart, B. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 804–806.
4. Boyhan, W. S. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 807–811.
5. Ayres, R. U. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 812–814.
6. McFarland, M. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 815–820.
7. Mitchell, J. W. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 821–826.
8. Ross, M. H. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 827–831.
9. Hoffman, J. S. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 832–834.
10. Stein, R. S. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 835–838.

11. Luzier, W. D. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 839–842.
12. Nordhaus, W. D. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 843–850.
13. Duchin, F. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 851–855.
14. Henrichs, R. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 856–859.
15. Pariza, M. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 860–861.
16. Troxell, D. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 862–863.
17. Hutchinson, C. E. & Lynch, D. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 864–867.
18. Starr, C. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 868–869.
19. Speth, G. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 870–872.
20. Piasecki, B. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 873–875.
21. Brown, G. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 876–878.
22. Ausubel, J. H. (1992) *Proc. Natl. Acad. Sci. USA* **89,** 879–884.

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