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Colloquium Paper

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Industrial ecology: Reflections on a colloquium

(environmental technologies/dematerialization/decarbonization)

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ABSTRACT **Industrial ecology is 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 direct use of each other's material and energy wastes and products. This paper, which reflects upon the papers and discussions at the National Academy of Sciences Colloquium on Industrial Ecology on May 20–21, 1991, is structured around 10 questions. Do sociotechnical systems have long-range environmental goals? How is the concept of industrial ecology useful and timely? What are environmental technologies? Is there a systematic way to choose among alternatives for improving the ecology of technologies? What are ways to measure performance with respect to industrial ecology? What are the sources and rates of innovation in environmental technologies? How is the market economy performing with respect to industrial ecology? What will be the effect of the ecological modernization of the developed nations of the North on the developing countries of the South? How can creative interaction on environmental issues be fostered among diverse social groups? How must research and education change?**

Frosch (1) has defined industrial ecology as 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 direct use of each other's material and energy wastes. As the field has rapidly taken form over the last few years (2, 3), we can ask what are the provocative and fundamental questions that should frame its progress over the next few. Such questions should reflect the full span of relevant thought and practice, ranging from philosophy of nature and history of technology through science and engineering to economics and management. Drawing on this Colloquium on Industrial Ecology, I believe 10 questions come to the fore.

1. Do sociotechnical systems have long-range environmental goals?
2. How is the concept of industrial ecology useful and timely?
3. What are environmental technologies?
4. Is there a systematic way to choose among alternatives for improving the ecology of technologies?
5. What are ways to measure performance with respect to industrial ecology?
6. What are the sources and rates of innovation in environmental technologies?
7. How is the market economy performing with respect to industrial ecology?
8. What will be the effect of the ecological modernization of the developed nations of the North on the developing countries of the South?
9. How can creative interaction on environmental issues be fostered among diverse social groups?
10. How must research and education change?

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1. Do Sociotechnical Systems Have Long-Range Environmental Goals?

Societies assert broad goals such as reduction of poverty, universal education and health care, population stabilization, and enhancement of environmental quality. Concrete long-term technical projects, such as the building of highway and water supply systems, are periodically conceived and carried out. But what are the general long-range goals of such systems as agriculture, transport, energy, and production? There was never a goal to become reliant on fossil fuels; this reliance was reached through dynamic optimization of the energy system with respect to transport and storage of energy and other factors.

Society has directions in which it is driven, but is it driven by intent? It is unclear to what extent sociotechnical systems are directed toward an end or shaped by purposes (4). There may be purpose at the micro level, but the evolutionary track is the summation of ongoing processes whose interactions are not well understood. For example, the transportation system appears to be coded to seek low-cost speed to enable individuals to maximize range. It seems societal development is fundamentally evolutionary and thus to a large degree without purpose though with strict rules of choice at every stage. In some cases these rules of choice have been environmentally favorable.

The teleological question has several aspects for industrial ecology. One is the capacity for coordinated, creative design in the economy. On the one hand, there is the recognition of a need for some kind of larger-scale optimization of industry that takes better account of environment. On the other hand, there is the appreciation of myopia in economic systems. Blindness to consequences provides freedom to explore and experiment, and heterogeneity of preferences and expectations is required for evolution. Moreover, how far into the future can social radar look? How far into the future can societies effectively and sensibly plan?

The question "To what end?" also forces reflection on the basic question about products and services. What products and services do people need according to various criteria? Would it be preferable to have a particular system or get along without it? This question is hard for both private and public enterprises to ask. Most organizations want to sell more of any particular product they make and have more products. The issue of long-term public good is rarely asked in fundamental ways in technological or environmental impact assessment.

The issue may be interpreted as the traditional one in living systems of the difference between growth and development. Growth implies an increase in size that is a quantitative phenomenon, while development implies additionally a realization and enhancement of potential. It is a qualitative phenomenon. There is a widespread sense that the ad libitum feeding of the industrial economies cannot be sustained except at great environmental cost (5). The beneficiaries of economic development wonder whether they are becoming obese, complacent, unhealthy, and vulnerable like a bunch of fat laboratory rats. The rise of industrial ecology may indicate the maturity of industrial society to ask questions seriously about not only growth but also development and its consequences.

Industrial ecology also implies concern with equity, not only over time but also as the current network of production and consumption distributes goods and bads. Societies are accustomed to discussing and struggling over distribution of material wealth, wealth that industrialization has been astonishingly successful in generating over the last 200 years. The transformations of the economy have also generated new possibilities of loss and injury. They have reduced many hazards and dangers. We now meet mad hatters and wheezing chimney sweeps only in literature. But clearing away old risks allows latent ones to surface, and new ones also arise (6). How is the industrial web now affecting and distributing the risks people face and where may risk reduction be most effective? Who is going to shift what burden to whom?

In the end, industrial ecology suggests both some broad goals for sociotechnical systems, such as waste reduction and dematerialization, and revised rules of selection for the technologies, products, and enterprises that should survive. The goal in general terms for technologists should be to offer the possibility of superior efficiency and productivity in serving human needs such as food, clothing, shelter, health, transportation, and communication with reduced environmental impact, reduced consumption of raw materials, and substitution of more- for less-abundant raw materials, as well as inclusion of wastes and products at the end of their lives in the industrial food web as both material and energy (3).

2. How Is the Concept of Industrial Ecology Useful and Timely?

Traditionally concerned with landscapes and animals, ecology is the branch of science that considers how organisms are embedded in their environment and how they interact with it. Ecosystems are defined from the inner surface of their environment, or their ecological niche. The key is that the parts are conceived with respect to the whole (itself often poorly understood) and not the other way around. Ecology recognizes connectedness as the condition of existence. At the same time existence itself is constantly evolving. Nature is very much unfinished, quite provisional (7).

Of course, ecology is not the only discipline to make claims for a sound model of flows of energy, resources, and information. Its nemesis, economics, does as well. The field of chemical engineering also stresses dynamical systems. The value of industrial ecology will depend on the extent to which it can provide the grounds for synthesis and interrelation of the variables normally incorporated or ignored in each of these and other relevant fields. It is about deepening appreciation of technology and extending what is valued in economics, broadening the domain of what must be considered in engineering design and practice, and ending the isolation of ecology from the man-made world.

The concept appears now not only because of the accumulation of problems that already exist but also because of prospective multiplication of needs. The current anxiety can be illustrated with numerous examples. One powerful fact is that in 1991 the United States had about 185 million motor vehicles, whereas in 1970, when the first Clean Air Act was passed, there were only about 100 million. Simply keeping pace requires getting better. Projecting needs into the future, individuals will give their own preferred numbers. A conventional guess is that there will be a doubling of the world population in the next century. To meet the needs of a world of 10 billion people will likely entail at least a 4-fold increase in agriculture, energy use, and industrial production if the majority of people are to have better housing, diet, transport, and other services than today.

This multiplication of needs means that we need a science and industry for a small planet. Industrial ecology can contribute both understanding and solutions. If the current ratios of emissions, pollution, and waste creation to production and consumption are maintained, the environmental problems are certainly going to become worse.

Fortunately, there is reason for confidence that we can increase and probably double efficiency in many systems over 30 years or so (8). The question is whether the introduction and diffusion of technologies, including social technologies, will proceed in directions and at rates such that there is net improvement or deterioration.

The question of the scale of application and use of technologies, products, and services is fundamental to the emergence of anxiety. Many of the most serious impacts relate to scale. Can societies accurately anticipate the scale of application and use of processes and products? Few people, certainly not inventor Thomas Midgely in 1931, would have guessed the extent of the markets for chlorofluorocarbons that would exist 60 years later (9). Even in optimistic moments about the car market Henry Ford probably would have failed to predict the quantity of auto emissions. The same is probably true of fertilizers and chemical pesticides. Alfred Lotka, who understood exponential growth, nevertheless wrote in 1924 that it would take 500 years for the atmospheric carbon dioxide concentration to reach the level it is likely to attain in another 50 (10). Lotka drastically underestimated the rate of expansion of fossil fuel use.

Humans continue to be a rapidly growing species, and we are attempting to be aware of our impacts on the other organisms with which we share the planet. New techniques and their interactions will nevertheless have undesirable and unforeseen impacts, even if our "radar," technology, and technology assessment improve. Of course, not everything that is unforeseen in the web of industrial connections will be undesirable.

There are numerous wonderful examples from the history of technology where clusters of inventions turn out advantageously. The late Lynn White, Jr., illustrated industrial ecology vividly in an essay on technology assessment from the point of view of a medieval historian (11). White sketched a sequence that started with textiles and ramified unexpectedly. The arrival of the spinning wheel in Europe in the 13th century sped yarn production, lowered the price of cloth, and increased its consumption. Because it was unpatterned, seldom dyed, and bleached only by sunlight, linen was particularly affected. By the 14th century there was an immense increase in linen shirts, underwear, bedding, towels, and headwear. Increased use meant more and cheaper rags, and linen rags were the best material for making paper. The burgeoning paper industry could expand production, lower prices, and seek new markets. Formerly it had taken the skins of between 200 and 300 sheep or calves to produce a Bible. With the advent of cheap paper, the wages of the scribe became by far the greatest cost of manufacturing a book. Thus, it was the wastes created by the spinning wheel that created the conditions for success for Gutenberg's venture in mechanical writing.

We live inevitably in such a web of connections. As described by Frosch (1), we live off each other and sometimes off one another's wastes. We must now try more consciously to evolve to make use of waste products.

3. What Are Environmental Technologies?

There appear to be several definitions or categories of environmental technologies. Some remedy; some conserve;

some prevent pollution. Some people speak of the gardening or improvement of the planet. Some define environmentally sound technologies by their quality or performance relative to present practices. Examples are as diverse as compact, efficient lighting devices (12) and completely biodegradable plastic materials produced by bacteria from agricultural raw materials rather than petrochemicals (13). There are environmentally friendly technologies that relate to manufacturing and operations, such as just-in-time-inventory and on-demand generation of toxic chemicals to obviate mass storage and transport (14). Stein (15) points out the potential importance of design-for-disassembly, which would facilitate recycling of basic constituents of a product. The Volkswagen Passat can be disassembled for recycling in 20 min.

There has yet to be careful thinking about categories or criteria for environmental technologies. A successful taxonomy of environmental technologies ought to clarify opportunities for fast, generic progress. For example, large streams of contaminated water from various processes are a problem that arises repeatedly, as do problems associated with oxidation in regular air. Chemical engineering and other professions ought to be able to make rapid advances in a number of such areas. Design principles could change quickly with regard to use of pure oxygen for oxidation and processes involving excessive formation of salts or use of water.

4. Is There a Systematic Way to Choose Among Alternatives for Improving the Ecology of Technologies?

Patel (16) suggests there are six strategic elements in industrial ecology: selection of materials with desired properties at the outset; use of just-in-time materials philosophy; substitution of processes to eliminate toxic feedstocks; modification of processes to contain, remove, and treat toxics in waste streams; engineering of robust and reliable processes; and consideration of end-of-life recyclability. Are there systematic ways to decompose existing designs so that alternative processes to eliminate existing pollution sources can be identified? Boyhan (17) offers a case study of eliminating chlorofluorocarbon use in manufacturing by substitute cleaning agents, by processes that require no cleaning because precise amounts of materials are used, and by other alternatives, such as conductive epoxies, which would obviate the entire soldering process.

There is also the prospective question. Are there systematic ways to foresee pollution problems early and simply during development of techniques (18)? The question and responses should be central in the curriculum of industrial ecology. The need is to note all the decisions required to complete a design and their consequences in a context that encourages imaginative generation of alternatives processes. This is more than a requirement of good design software, although many key queries and outcomes could be captured in programs. Ultimately, as Duchin recognizes (19), it would be desirable to have coherent frameworks for examining potential long-term advantages of each web of industrial changes and identifying short-term bottlenecks that may emerge.

5. What Are Ways to Measure Performance with Respect to Industrial Ecology?

There are hundreds of familiar indicators of environmental quality and of economic performance (20). There are specific, promising reports of change. For example, according to one inventory of releases of toxic pollutants, major U.S. manufacturers may have reduced their emissions about 20% between 1988 and 1989 (21). However, few such indicators represent effectively the networks of industrial processes and how they are changing (19). All such measures require goals and rules to be meaningful.

William Clark suggested at this colloquium that one way to measure performance might be to identify major transitions that would take place in industrial ecology and assess standing in relation to these transitions. Such transitions are familiar reference points in other fields. For example, there is the demographic transition, at which fertility rates begin to fall, and labor force transitions, signaled by declines in agricultural workers and increased participation of women in the labor force. What would be the transitions expected or sought in industrial ecology?

The transition from materialization to dematerialization could be one (22). "Dematerialization" is the decline over time in weight of materials or "embedded energy" in industrial products (23). Dematerialization could translate into less waste from both production and consumption. Although statements about dematerialization of industrialized societies have been made casually, only a few short series of data are available as evidence. Time series extending back 30 years and more need to be assembled and kept current for a broad sampling of system levels (firms, industries, individuals, municipalities) in different countries.

The shift from increasing reliance on carbon fuels to "decarbonization" of the energy system might be another key transition in industrial ecology (Fig. 1). Carbon matters because it is the main element used to spin the industrial web and is also associated with greenhouse warming, smog, oil spills, and deforestation. Decarbonization might be defined in several ways. It could indicate the evolving mix of fossil fuels used. Coal, the most environmentally damaging fossil fuel, is heavy in carbon and would weight the measure; natural gas, which is mostly hydrogen, would lighten it. It could refer to the ratio of carbon used to total energy consumed or to economic activity. Between 1973 and 1986 Canada, the United States, Sweden, and France, in absolute terms large polluters, nonetheless moved on what might be labeled a green trajectory toward high energy efficiency and low carbon intensity. Meanwhile, Mexico and India moved in the reverse direction. Data for this measure for the former U.S.S.R. and China suggest these areas continue to function with a Victorian industrial ecology (Fig. 1*A*). An alternative formulation of decarbonization includes biomass (fuelwood and hay) in addition to fossil fuels. By this measure all nations are on favorable trajectories, though proceeding at different rates and by different routes (Fig. 1*B*). Viewed as one system, the globe is decarbonizing steadily (Fig. 1*C*).

Analysts might enjoy fun and profit over the next few years improving these measures and developing others, providing aggregate and disaggregate measures for performance with regard to industrial ecology. The discussion of transitions may be generalized. At what point after materializing or carbonizing does an economy bend around and move back down? Is this an "eco-transition" as discussed by Ayres (26)? Can the arrival of transitions be hastened?

It is important to include moral and aesthetic criteria in the evaluation of system performance. We each have a diffuse but deep sense that there exists a world of artifacts, of clay pots and plastic water bottles, and some of these artifacts correspond to what might be called peace with nature, while others seem to violate peace with nature (27). We know how to distinguish between gardens and garbage dumps, although bacteria might like both. Our measures must ultimately relate to concepts of what is right and beautiful, difficult and contentious though this may be.

6. What Are the Sources and Rates of Innovation in Environmental Technologies?

In contrast to sectors such as health and national security, there have been few studies of patterns of innovation and barriers to diffusion in the environmental area. Many ques-

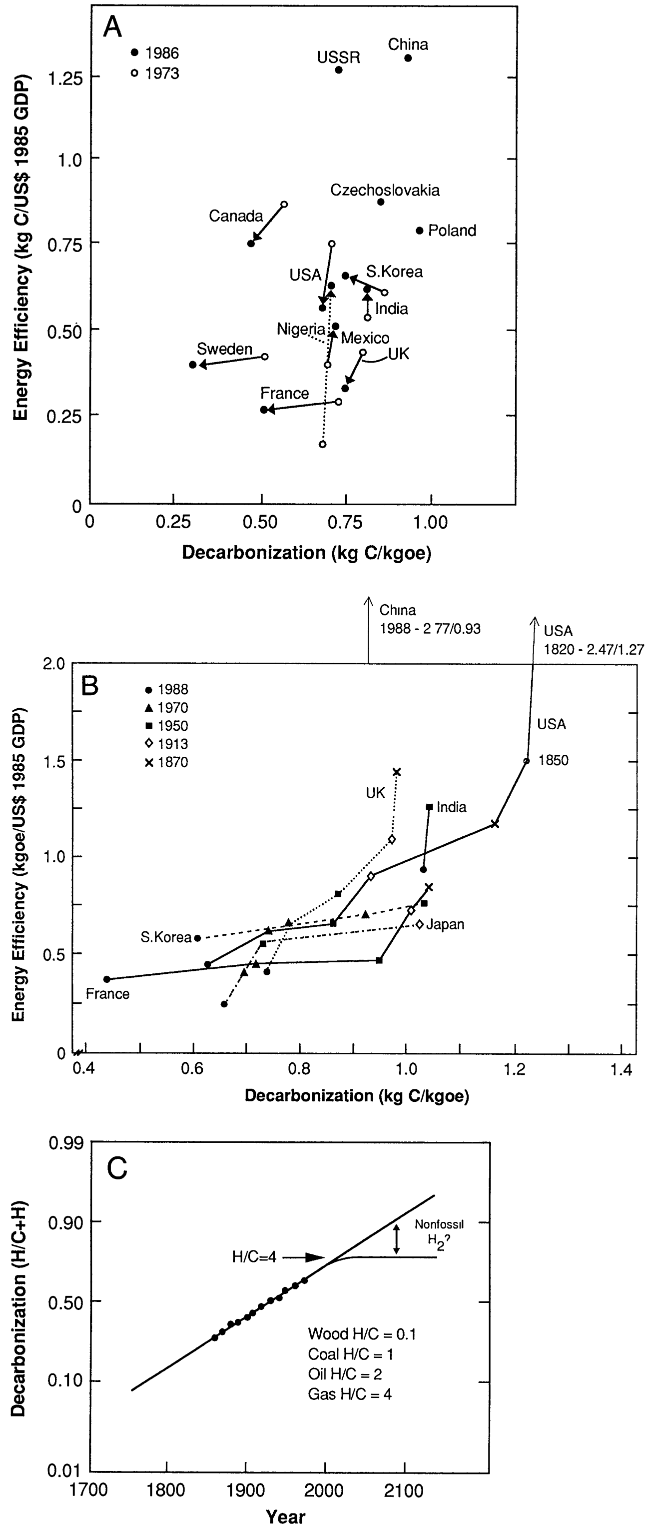

FIG. 1. Three views of decarbonization. (*A*) Decarbonization refers only to fossil fuel carbon used in energy supply, in units of kg of carbon per kg of oil equivalent. Energy efficiency is expressed as kg of carbon per 1985 gross domestic product in U.S. dollars (24). (*B*) Decarbonization indicates total amount of carbon, including carbon in noncommercial wood and hay used in energy supply (data courtesy of A. Gruebler, International Institute for Applied Systems Analysis, Laxenburg, Austria). (*C*) Decarbonization refers to evolution of the atomic ratio of hydrogen to carbon in the world fuel mix, where gas (methane), for example, is CH_4 (25).

tions remain little explored (28). Will environmental innovations be adopted on their own merit? How are unglamorous areas supported? It is easy to worry about the ozone hole and not so easy to worry about tribology. How fast can environmental technologies diffuse and conditions improve (9)? Is it necessarily a matter of many, many decades? Where do environmentally significant innovations tend to come from? Do they come mostly with urgency from the very dense areas where problems are most manifest, such as Tokyo and Southern California? Has the economic system generated enough opportunities for environmental innovation through explicit research and development programs and less targeted means? What balance is appropriate between conscious and planned processes of institutional experimentation and more decentralized processes of learning by, and also selection among, agents who try their best, often make mistakes, and learn from their own errors and from the errors of others?

7. How Is the Market Economy Performing with Respect to Industrial Ecology?

A set of environmental questions revolves around the market economy. There is an unease at the level of the overall system. The higher-level environmental effects that the invisible hands of the market have produced from the multitude of decentralized decisions have included both successes and tragedies. Also, a visible foot can undo the work of many invisible hands.

The main response to this anxiety is that the economic system needs more or fuller internalization of social costs (29). Modern societies have become accustomed to the idea of social overhead. For example, disability insurance and pensions have been internalized in the course of the twentieth century. Comparable adjustment is just now starting on the environmental front. But care is required. Nordhaus raises the question of how accurately it is possible to measure the relevant environmental costs and benefits. There is also the issue of how direct and explicit the effort to correct the economic signals needs to be. The challenge is to bring into compatibility the possibly conflicting decentralized decisions, ideally without the necessity for the individual or even institutions to bear in mind the logic of the whole system.

More generally, in thinking about the web of industrial processes and the economy there would appear to be five facets that need to be discussed (30). The first is performance of the economy with regard to *information structures*, among both economic and other agents. There is a view that the signals in the economy may be inadequate in this regard (12). Even where the economy is trying to transmit signals, or the environment is trying to transmit signals about itself, the economic and other agents are not always receiving them. The second area is *incentive structures*, including economic and social rewards and penalties for individuals and organizations (31). The third aspect of economies to be considered are the *learning mechanisms*. These should function within and between technologies and in markets. The bottom line is how rapidly we can exploit opportunities. The fourth facet is *selection processes*, among both individuals and organizations. How can consumers and firms make better choices, whether for products or technologies or performance in the market place? The final facet of the economy is *control and power structures*. These monitor performance and of course limit the range of acceptable behaviors. There is unending debate about whether increased centralization of authorities is desirable for environmental ends. At present, the pendulum has swung toward harnessing market forces for environmental goals, partly because of recognition of lags and weaknesses in the mechanisms of explicit governance of economic interactions (4).

8. What Will Be the Effect of the Ecological Modernization of the Developed Nations of the North on the Developing Countries of the South?

This is important to consider for both the short and long term. It is plausible to argue that ecological improvements in the North, increasing energy efficiency, for example, will in fact weaken the bargaining position of the South, at least in the near term. The South is for the most part an exporter of energy and of nature, in the sense of wood, minerals, and other primary products. In fact, carbon (embodied in fossil fuels) is by far the largest export of the South to the North. Carbon is also the largest export of the former U.S.S.R. If energy demand is substantially reduced in Europe and America, if the demand diminishes for resource inputs, if the North need not buy oil from Nigeria or Mexico or Venezuela, if the market is reduced for tropical woods, at least the near-term outcome could be impoverishment of the South. Although it may be highly desirable for the entire planet to move in the direction of accelerated efficiency, the short-term effects of a quick and effective move by the North could be a widening economic gap with the South.

The linkages between environment and development need to be explored in a second area. There has been little analysis of the effects of the integration of world markets on environment. There has been speculation but not much insight yet about how mobility of capital, for example, may influence environmental standards. There is enthusiasm for market strategies, but at the national level many environmental problems reflect market failures. Attentiveness is in order, as new international experiments begin that expand the web of connections.

9. How Can Creative Interaction on Environmental Issues Be Fostered Among Diverse Social Groups?

Different social groups have different rationalities, myths of nature, views of resources, scope of knowledge and expertise, learning styles, ideal scales of activity, aesthetics for engineering, ideals of fairness, perceptions of time, preferred economic theories, preferred forms of governance, models of consent, styles for handling risk, and extent of commitment to institutions (32). Brown (33) has made a proposal for a roundtable on industrial ecology bringing together advocates from diverse orientations to share experiences, articulate collective needs, and help build consensus on environment. If the institutional experiment proceeds, its design must take into account the extent of cultural differences that exist.

10. How Must Research and Education Change?

An issue that cuts across many of the questions discussed above is how scientific research and education must change to address the subject of industrial ecology. There is a general sense that science and education, to help solve these problems in technology, must be different from the science and education that have been involved in bringing about the problems in the first place (34–36). The direction is set by the ecological perspective. The interface between the part and the whole is what has to be given special attention. The mainstream of science so far has not been holistic in this way. In fact, many would argue that science has tended in a reductionist direction through much of the 20th century (37).

Leading disciplinary influences and points of departure should also be considered. This colloquium included exchanges between biologists and metallurgists. Contemporary technology is based mainly on the paradigms of physics and chemistry. One might ask the question, is biology a better place for industry to begin the 21st century? Are biological processes a better model for much of what needs to be done? Most biological processes proceed at ambient temperatures, for example.

Conclusion

To conclude, what are we talking about when we talk about industrial ecology? In a way it is encouraging our relationship with nature and production to follow the lines of the history of human society itself (27). In politics, absolutism has given way to a constitutional state and a more inclusive approach to participation and greater pluralism. Industrial ecology suggests that the community of nature, of which humanity is a part, has to be expanded to a broader definition, including both other living things and technology in a more sensitive manner. So, in a way, what we are talking about are more respectful, less obtrusive, forms of exercising productive power.

In the end the environmental crisis is as much an intellectual crisis as a technical one. Criteria have to be developed and considered according to which justice, waste, efficiency, elegance, and insensitivity in nature (including human industry) can be distinguished. The basis of life in nature is the basis also of human life, so when human industry damages the environment it emerges as a painful failure. But, our environmental predicament is not at all hopeless. The change over the last two centuries in human ability to create and move goods and information, the web of industrial ecology, has been quite extraordinary. There are also hints that the economic system is evolving to reduce and recycle wastes as it proceeds to a higher degree of organization. As much as we have transformed land and materials, we may also have created the technical and cultural basis for a deeply green planet.

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