COMMENTARY

Achieving Sustainable Development through Industrial Ecology

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Introduction

It has become apparent to thoughtful observers that current economic, population, and associated cultural patterns are not sustainable; that is, they cannot be continued indefinitely as they are. Abundant data support this point.[1] The logical question is then obvious: what now?

The concept of "sustainable development," first developed in a study by the World Commission on Environment and Development (the Brundtland Report), is the response.[2] The concept, however, remains somewhat vague and ill-defined. In part, of course, this is simply a reflection of the nascent state of the dialogue on sustainable development. In part it is because the concept of sustainable development is, to several established disciplines and political authorities, somewhat revolutionary and thus subject to misunderstanding.

In large part, however, it results from the human desire to define an end state—"sustainable development"—and then to determine how to get there. Sustainable development, however, is not an end state; indeed, complex systems such as the global economic system and human cultures don't reach static end states (although they may indeed end). Rather, sustainable development will be a dynamic, continuous process; a verb, not a noun. It cannot, therefore, be defined absolutely as a thing in itself, but must be defined in terms of the process by which it is achieved and promulgated, and the principles that inform that process.

Those principles and that process constitute industrial ecology.

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What is Industrial Ecology?[3]

Somewhat teleologically, "industrial ecology" may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of establishing and maintaining the human species at levels that can be sustained indefinitely—given continued economic, cultural, and technological evolution.[4]

It is perhaps useful in clarifying this somewhat oxymoronic term to resort to a biological analogy. Use of biological analogies is always tricky; nonetheless in this case I believe they advance understanding (at the inevitable cost of oversimplifying the biology).

Classic ecology has been defined as "the study of the relation of organisms or groups of organisms to their environment . . . the science of the interrelations between living organisms and their environment . . . the study of the structure and function of nature."[5] It is a discipline that studies quintessentially complex biological systems. It is the focus on interrelationships and complex systems, in particular, that makes this biological analogy so suggestive, since it is the failure to focus on the interrelationships between human activity and fundamental global support systems that creates many of the current environmental perturbations.

In developing this idea further, consider a postulated primitive biological system, where the biological component is a small subsystem compared to its supporting environmental systems.[6] Under such circumstances, a quasi-linear biology might well be appropriate, perhaps even more efficient from the organisms' perspective. In such a protosystem, which I will term a "Type I" system, resources and sinks are for all practical purposes unlimited.[7] Accordingly, the flows of materials from "resource" through "organism" to "waste" are essentially independent, and there is no need for an organism or groups of organisms to expend the energy to create mechanisms for economizing or cycling any input or output (see figure 1).

As external constraints on unlimited resources and unlimited sinks begin to develop—that is, as the biomass of the organic subsystem begins to reach a scale where its activities affect the functioning of the supporting environmental systems—a Type II system evolves, where the flows within the biological domain may be large, but the flows into and out of the domain are limited (see figure 2). The biomass is now evolving as a system in its own right; it is no longer simply a disconnected set of linear flows. Driven by competition for scarce resources, feedback loops begin to develop; with scarcity comes more rapid evolution.

While the Type II system is more efficient in its use of now-scarce resources, it is not yet sustainable in an absolute sense, given continued reliance on lim-

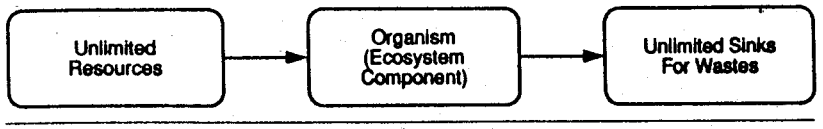

Fig. 1. Type I system

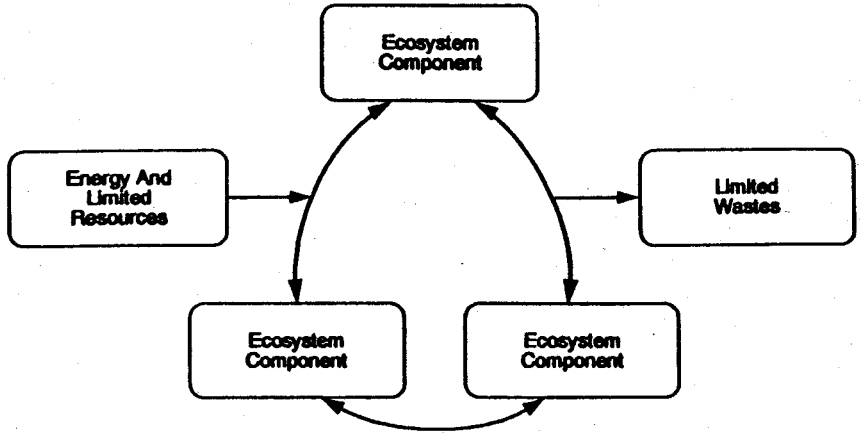

Fig. 2. Type II system

ited resources and limited sinks. To the extent growth continues and biomass accumulates, a Type III system exhibiting complete cyclicity will have to evolve for strict sustainability, as shown in figure 3.[8]

Type III systems are characterized by complete cycling of all materials, with no demand for inputs and no waste. Such systems are, however, energetically open, in that they depend on a continuous flow of solar radiation to maintain energy flows throughout the system. Obviously, these three systems are simplifications of a complex reality—and highly idealized at that. Nonetheless, these simplified biological paradigms illustrating complex systems can be applied to human economic activity as well. Like a biological community or ecosystem, human economic activity is a complex system embedded in supporting physical, chemical, and biological systems, which are also absolute constraints on the behavior of the embedded system. Materials flow through both systems in complex temporal and spatial patterns, and the structure of these patterns can have significant implications for the relationship between the embedded biological or economic system, and its supporting environmental systems. While individual parts of a biological or economic system—a species, a firm, or a national economy—can be studied in isolation, it is obvious

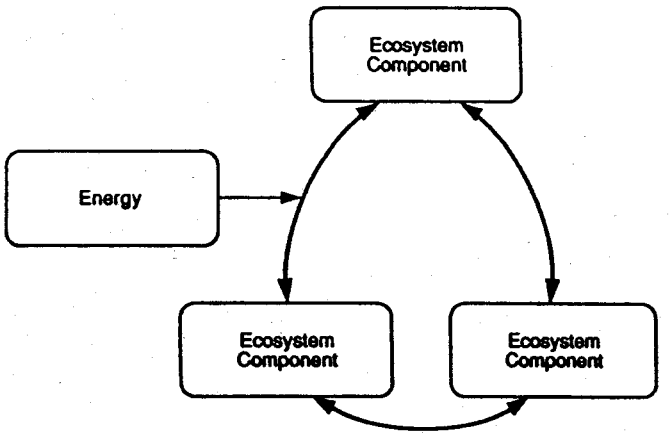

Fig. 3. Type III system

that each system must also be understood on its own terms, as a complex system. This is especially true where impacts of the embedded system on its support structure are involved.[9]

Let us explore in a little more depth some of the interesting implications of the proposed analogy. Consider, for example, the fundamental principle that the evolution of more complex systems—moving from a Type I to a Type III model—was necessary if continued growth in biomass was to occur, given the limited resources of the earth. In other words, the magnitude of the biomass subsystem that can be supported at a given level of resources is directly dependent on the efficiency with which that subsystem can maximize internal cycling and reduce resource and sink consumption.

Now consider the human condition. We unquestionably have a large and growing population that demands to be supported at a certain minimal economic level, thereby implying a certain minimal level of capital stock, given current technology. However, the human economy today is predominantly a Type I system. Many raw materials and resources do not cycle through the economy, but are simply mined or manufactured, put into a consumer article, and disposed of at the end of their useful life. This phenomenon of dissipation of materials in the modern consumer economy obviously is not compatible with a sustainable, cyclical pattern of resource use.[10] Although public and industrial recycling is increasing,[11] basic resources—especially inputs of air and water—and sinks—especially the atmosphere and receiving waters—are still treated as if they were essentially limitless.[12]

From a systems perspective, this is clearly unsustainable. What we are doing is attempting to support a biomass appropriate for Type III conditions with a linear Type I economy and culture. This is not a new insight,[13] but the indus-

trial ecology approach helps frame the alternatives: we can simply continue as we are, and let the inevitable global constraints reduce the human biomass to a level appropriate to Type I economic and cultural practices, or we can evolve towards a Type III structure.

There is another important insight to be gleaned from the biological analogy, one with serious implications for the size of the task facing us. It is well known that a biological population with no constraints will display essentially a sigmoid growth curve characterized by exponential growth until limiting conditions are met, then level off at a carrying capacity.[14] The leveling-off process may be more or less graceful; but in our model system, it amounts to a transition from the Type I system (exponential growth) to the Type III system (carrying capacity).

Not only human population, but human consumption of many important inputs (energy, fresh water, and raw materials) have displayed exponential-like growth curves since the Industrial Revolution (and the associated agricultural and population revolutions).

Fundamentally, the Industrial Revolution created a Type I, essentially unlimited, growth environment for our species. There is no question that localized environmental degradation could be severe, but the effect on global support systems was not perceived as a problem, in part due to temporal lags exhibited by these complex systems.[15] Now, of course, it is apparent that we have begun to degrade our global support systems badly, particularly the critical sinks of the atmosphere and the oceans. The exponential free ride is over as far as the earth is concerned. Unfortunately, our institutions have not yet responded to those signals. Thus, in many ways, current human economic activity is still shaped by the implicit model of continuing exponential growth, not the reality of encroaching fundamental biological, chemical, and physical limits. The shift from this growth phase to a state of sustainable development culture will be profound, affecting most human institutions.

Current trends in the evolution of technology, for example, tend to be unsustainable precisely because they fuel, and are fueled by, an increasingly dissipative economy. Telephones in the United States, for instance, used to be recycled by the Bell System for years. Now, telephones exhibit more functionality, but have much shorter lifetimes and tend to end up in landfills instead of being recycled back into the economy. In part, such examples also illustrate our failure to develop, and to apply, a systems understanding of the interrelationship between our economy and the underlying global support systems.[16]

Virtually all critical academic and intellectual disciplines today are still predicated on assumptions appropriate to an exponential growth phase, not a sustained development phase. The intoxication of mainstream economics with growth at any cost, and the virtually universal use of discount rates for resource consumption decisions, are examples. The failure of law to recognize any rights of future generations is another example. The strongly pronatalist policies of many faiths and governments, frequently grounded in the belief

that a larger population of believers or citizens makes for increased strength, are yet another example. The simple fact is that, as a species, we are in a Type III world with Type I institutions. The many indications that resource and sink limitations are becoming more critical, however, indicate that the current economic system and cultural institutions will be under increasing pressure to evolve toward a more cyclical stage or, alternatively, human activity will be forced back to a system size where the impacts on fundamental environmental support systems are reduced to sustainable forms and magnitudes. As it is evident that this latter course could include substantial economic and social disruption, as well as a significant collapse in human population, it is desirable to encourage evolution of the human economy on a relatively stable path toward a Type III system. Industrial ecology is the discipline that will inform this effort.

At the outset, it is necessary to emphasize that industrial ecology must subsume *all* human economic activity, including forestry, agriculture, extractive industries, energy production and use, manufacturing, service operations and processes, and sustenance activities. In doing so, it will also have to address significant cultural, technological, and political institutional issues. In fact, part of the reason we find ourselves in our current dilemma is that our systems thinking has, to date, been too limited in both the spatial and temporal dimensions.

Developing the ability to conceptualize and define the industrial ecology metasystem on this level is, however, currently beyond the state of the art. Thus it may be useful to provide a subsystem example of the kind of cyclical activity towards which we should be moving. For example, the modern manufacturing system is relatively well understood, so we can begin to understand in broad terms the appropriate model to work towards. Schematically, a Type III industrial subsystem of the industrial ecology metasystem might look something like that in figure 4. While this appears simplistic, it is not: for example, in some nations, hazardous waste laws are written in such a way as to actively discourage the kind of cyclical material flows one would wish, in fact, to encourage.[17]

More broadly, a failure to apply the kind of systems approach inherent in figure 5 lies behind much of the apparently inappropriate behavior of modern institutions. Any study of industrial ecology must recognize its metasystem attributes in comparison to the subsystem scale of current institutions. Indeed, many of the dysfunctional aspects of current institutions—political, legal, economic, scientific, or otherwise—arise not from inherent fallacies within the institution, but the application of the principles of the institution beyond the scale to which they are valid.[18] Schematically, these institutions properly are seen as subsystems of the industrial ecology metasystem (see figure 5).

Human beings are, of course, familiar with the institutions with which they interact. At this point, much less can be said for the industrial ecology metasystem. Some things are, however, apparent. For example, it is clear that the

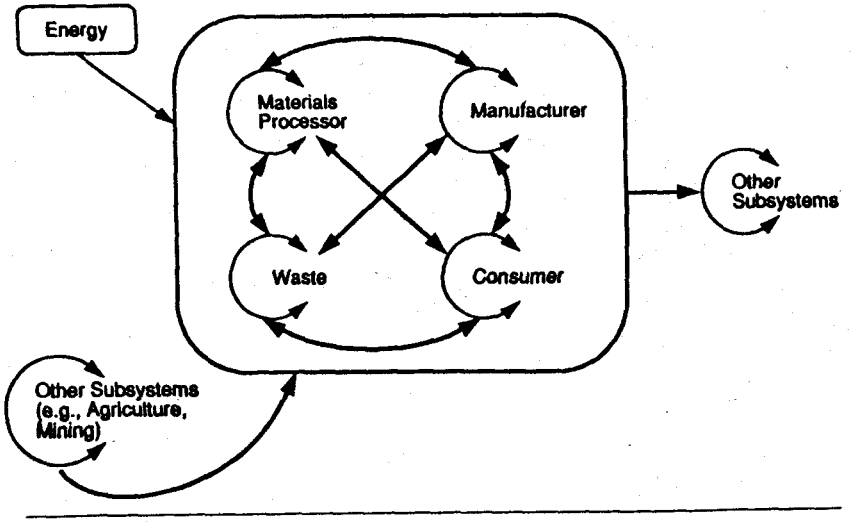

Fig. 4. Type III global economy

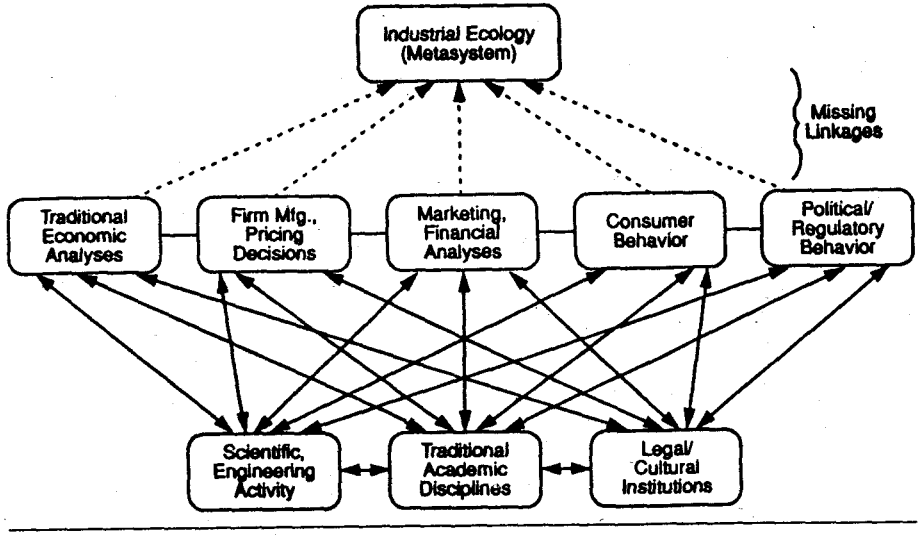

Fig. 5. Industrial ecology as a metasystem

scale of the industrial ecology metasystem must be global, so as to include all economies, developed and undeveloped—in the closed system. This does not mean that local traditions, cultures, and economies are precluded. To the contrary, they should be encouraged, as local responses to environmental constraints will be a valuable source for adaptive cultural mutations. Equally as important, different local and regional patterns may well constitute an important element of the quality of life in a sustainably developed world.[19]

Given these preliminary thoughts on the nature and scope of the industrial ecology metasystem, it is apparent that understanding this system, much less attempting to manipulate it, is a daunting task. Where should one begin?

Developing the Study of Industrial Ecology

There are several immediate and practical steps that can be taken by individual nations to initiate the study and practice of industrial ecology. Some of these steps are already being taken, albeit often without a full recognition of the scope of the metasystem involved. The most obvious need is to raise the visibility of industrial ecology as a legitimate area of study, and to begin to define the parameters of the metasystem more accurately. In the United States, the National Academy of Engineering has already done some work in this area. The work has resulted in a book on the interrelationship between technology and the environment.[20] The concept of life-cycle analysis, which is currently being developed by several groups, contains elements of an industrial ecology approach,[21] as does the nascent practice of integrating environmental considerations and constraints into product and process design, called Design for Environment, or DFE.[22] Similar efforts using different terminology, and focusing on what we would call "subsystems of the industrial ecology metasystem," are becoming increasingly common around the world.

There are other, more specific, efforts that must be undertaken, however, if industrial ecology is to flourish as a new international field of study. This suggests not only the need to establish an international society for industrial ecology, but international institutes for industrial ecology as well.

An international society for industrial ecology is a logical longer-term result of preliminary workshops and meetings. Such a society would serve as a critical information and networking resource for practitioners of industrial ecology, as well as a supportive peer group. Input from existing international organizations, such as the United Nations Environment Programme or the UN Center for Transnational Corporations, would be useful in ensuring that the necessary international scope is maintained.

The institutes for industrial ecology would also be pivotal in initiating the study of industrial ecology. In particular, they could be given several tasks:

1. The institutes should develop graduate and undergraduate curricula in facets of industrial ecology. This function could be performed independently, or in partnership with interested academic institutions. The institutes could also serve as an information clearinghouse for academic institutions experimenting with such curricula.
2. The institutes could identify and maintain data bases regarding existing organizations and data resources which are performing complementary work. This information would be available to academic institutions, industry, and others. The institutes would also integrate this material—much of which deals only with certain aspects of industrial ecology, such as pollution prevention, waste minimization, recycling, and energy conservation—in light of industrial ecology principles.

   As a corollary, the institutes should define the data necessary to perform industrial ecology-type analyses of industrial issues, and collect or fund the collection of such data. While there are several sources of raw data on production, sales import, and export activities involving the industrial, forestry, agricultural, mining, and other sectors in various countries, the data tend to be of uneven quality. Moreover, there are also significant data gaps which could impede understanding and analyses of industrial ecology issues.
3. The institutes should sponsor or participate in multidisciplinary, multinational conferences, seminars, and workshops on industrial ecology, with industrial, academic, government, and other appropriate partners.
4. The institutes should encourage, support, and fund research in industrial ecology. As the field grows, this activity should be coordinated with other private, industrial, academic, and national and international official funding sources to ensure efficient use of scarce research dollars.
5. The institutes should develop, manage, and (if appropriate and possible) fund an internship program involving academic and industrial participants. Internships should be offered at both academic and industrial locations.

   More broadly, the institutes must encourage the development of new forms of organizations linking multinational organizations, governments, and private and academic institutions. Because part of the cause of regional and global environmental perturbations is dysfunctional economic and cultural subsystems, part of the solution must be to evolve new organizations of the appropriate scope and scale. There are a few initial efforts in this direction, such as the Industry Cooperative for Ozone Layer Protection, but much more is necessary.[23] Determining how to encourage and implement such efforts, and how they may be made effective, would appear to be an important mission for the institutes.

If they are to be effective, the institutes should have some fundamental characteristics. Perhaps most important, they must be objective, and be perceived as being objective. This will not be trivial for organizations that, to carry out their mission, will have to work closely with industry and government entities having significant financial and bureaucratic interest in the way industrial ecology principles are implemented. The institutes may also be partially funded by industry or industry-related sources, raising additional potential for biases. Nonetheless, they will have to be *in* the world of industry, but not *of* it.

It also is absolutely essential that the institutes be multidisciplinary. Each discipline or profession carries with it an implicit and explicit set of biases, methodologies and assumptions that, taken alone, are inadequate to address the problem. Addressing metasystem issues will require contributions from numerous fields, including anthropology, economics, law, engineering, systems ecology, biology, and the physical sciences. Specialized institutes will obviously have additional expertise requirements. Moreover, the institutes will require people with industrial experience, whose areas of expertise may be impossible to categorize.

Additionally, the institute must insist on the highest professional and academic standards, without falling into the trap of disregarding new or multidisciplinary work because it does not conform to existing preconceptions or dogmas. This may prove difficult: there is a lot of unreviewed, second-rate material in the environmental field; yet traditional, narrow, discipline-based academic standards will frequently not be appropriate. Indeed, to some extent they are part of the problem, not part of the solution.[24]

Why institutes instead of just one institute? Simply put, it will probably be necessary as a practical matter to limit each institute to certain subsystems of industrial ecology, at least initially, to achieve any meaningful benefits. The industrial ecology metasystem is simply too big to tackle head-on. Thus, there will be a need for a linked series of regional—or perhaps—national institutes, each focusing on a specific subsystem within the industrial ecology metasystem, while recognizing the need to interact and integrate activities among fellow institutes to the extent possible.

A more subtle reason to begin with regional or, if necessary, national institutes is to reinforce the need for a unified global approach to industrial ecology, while demonstrating a concern for indigenous cultures and practices. Moreover, it is presumptuous in the extreme, particularly at this point, to assume that any specific culture will hold the key to industrial ecology. Indeed, some of the countries moving most rapidly toward certain elements of industrial ecology, such as waste minimization, are precisely those countries where one would expect psychological loyalty to the Industrial Revolution and the exponential-growth mindset to be greatest.

Conclusions

Current economic patterns and supporting cultural and political structures have, by and large, evolved during the exponential growth phase of human

history, generally termed the Industrial Revolution. It is now apparent that the levels of human population and economic activity traditionally associated with that phase are not sustainable. A primary reason is that existing cultural, economic, and technical systems are only subsystems of a metasystem I have defined as "industrial ecology." Optimizing or satisficing behavior at the subsystem level has clearly failed to create conditions under which the industrial ecology metasystem functions to support sustainable development. Our species will reach sustainable levels, of course. It is our choice as to whether this occurs through natural population control mechanisms (starvation, epidemics) and social collapse, or planned evolution toward sustainable development. If we choose the latter course, we must begin now to explore and understand the industrial ecology metasystem.

Notes

1. While there are excellent general sources on global environmental perturbations, the two *Scientific American* special issues, *Managing Planet Earth,* 261, no. 3, September, 1989, and *Energy for Planet Earth,* 263, no. 3, September 1990, are noteworthy.
2. The World Commission on Environment and Development, *Our Common Future* (the Brundtland Report), (Oxford: Oxford University Press, 1987).
3. Portions of the discussion in this section are based on background papers prepared by the author alone and in conjunction with T. E. Graedel and P. B. Linhart of AT&T Bell Laboratories, in support of a joint AT&T–National Academy of Sciences workshop on industrial ecology, held in Washington, D.C., in May, 1991.
4. Some readers will detect the concept of "carrying capacity"—a biological term denoting the maximum population a given environment can sustain for an extended time—latent in this broad formulation. While the carrying capacity concept has some descriptive power regarding what may constitute a state of sustainable development, it is difficult to apply this idea to a species such as ours that exhibits significant cultural and technological evolution. Indeed, it is our capacity for such evolution that offers a modicum of hope for the future.
5. E. P. Odum, *Fundamentals of Ecology,* (Philadelphia: W. B. Saunders Company, 1959), p. 4.
6. Whether the postulated quasi-linear community structure characterized the early stages of the actual evolution of life is as yet undetermined; there is much controversy about how life originally evolved. See J. Horgan, "Trends in Evolution: In The Beginning." *Scientific American* (February 1991): 116–125.
7. This structure is analogous to the energy models developed by H. T. Odum. In studying those systems, he found that, at low energy, the linear pathway in the models carried the most energy flow, while at higher energies, the energy competition was dominated by autocatalytic, higher exponent, pathways. See H. T. Odum, "Self-Organization, Transformity, and Information," *Science* 242 (November 25, 1988): 1132–1139.
8. By "strict sustainability" I mean sustainability that can be maintained indefinitely over time in the absence of significant exogenous shocks in the external environment, such as a meteor impact. The concept of sustainability must, of course, allow for evolution, be it biological or, in the case of humanity, cultural and technical.
9. A similar approach is taken by R. A. Frosch and N. E. Gallopoulos in "Toward an Industrial Ecology," a paper presented to the Royal Society, London, February 21, 1990.
10. See R. U. Ayres, "Industrial Metabolism," in *Technology and Environment,* J. H. Ausubel and H. E. Sladovich, eds. (Washington, D.C.: National Academy Press, 1989), pp. 23–49.
11. Both mandated and voluntary recycling initiatives have sprung up in Europe and the United States. In many cases, these are tied to the price of the recovered product. It is no surprise, for example, to find that precious metals are relatively highly conserved in the economy. See R. A. Frosch and N. E. Gallopoulos, "Strategies for Manufacturing," *Scientific American* 261, no. 3 (September 1989): 144–152. Recently, however, more attention is being paid to recycling of articles: in Germany, BMW has developed a "recyclable car," while in the United States the Office of Technology Assessment is investigating the degree to which companies factor environmental considerations into their design processes.
12. See Garrett Hardin, "The Tragedy of the Commons," *Science* 162 (December 13, 1968): 1243–1248; and the differentiation between "common property" (private property used by a group with attendant duties which tend to preserve the property) and "open access regimes" (where the tragedy of the commons may occur) drawn by D. W. Bromley and M. M. Cernea, "The Management of Common Property Natural Resources," World Bank Discussion Paper No. 57, 1989.
13. See, for example, Donella H. Meadows, Dennis L. Meadows, Jrgen Randers,and William W. Behrens, III, *The Limits to Growth* (New York: Universe Books, 1972).
14. There are obviously variations on this basic theme in the somewhat-messy real world. See for example Odum, note 5, p. 184.
15. The most obvious example is the increase in carbon dioxide with associated forcing of global climate change, albeit on a temporal scale. Humans find this hard to intuit. See R. A. Joughton and G. M. Woodwell, "Global Climate Change," *Scientific American* 260, no. 4, (April 1989): 36–43.
16. This example also illustrates the importance of appropriate scale for economic and political organizations if environmentally desirable behavior is to be encouraged. Because the Bell System in the United States controlled much of the physical plant it used from creation to destruction, economic savings effected by substantial recycling of cable, switches, public telephones, and other materials could be captured by one entity. With divestiture, however, the existing system was broken into subsystems, none of which could capture sufficient benefits to maintain the same level of recycling. This scale dysfunction factor, which is generally characteristic of industrial organization throughout the world, has contributed to the increasingly dissipative materials trends characteristic of modern economies.
17. The Resource Conservation and Recovery Act (RCRA), 42 U.S.C. Sec. 6901 et seq., is an example in the United States. While proper handling of hazardous materials, including wastes, is obviously necessary, this statute assumes a linear manufacturing paradigm by defining anything that falls from a manufacturing line as waste, and imposing burdensome paperwork and regulatory requirements on such materials, thereby discouraging recycling and reuse of such materials. It

thus becomes a self-fulfilling process: materials become hazardous waste because RCRA defines them so.

18. See Daly and Cobb, ***For the Common Good*** (Boston: Beacon Press, 1989), for an application of this principle to the discipline of economics.
19. See note 18; the book contains a stimulating discussion of this point.
20. ***Technology and Environment***, J. H. Ausubel and H. E. Sladovich, eds., (Washington, D.C.: National Academy Press, 1989).
21. See, for example, The Society of Environmental Toxicology and Chemistry, "A Technical Framework for Life-Cycle Analysis," (Washington, D.C.: SETAC Foundation, 1991).
22. See Braden R. Allenby, "Design for Environment: A Tool Whose Time Has Come," ***55A Journal*** (September 1991).
23. The Industry Cooperative for Ozone Layer Protection, or ICOLP, was planned by AT&T, the U. S. Environmental Protection Agency, and Northern Telecom as an organization which would provide information to facilitate the implementation of alternatives to chlorofluorocarbon use by electronics firms around the world. ICOLP has been spectacularly successful: it has already sponsored international conferences on CFC elimination, published six technical manuals on CFC alternatives, and implemented a worldwide data base, called "Ozonet," on CFC alternatives. The unique nature of the organization is demonstrated by the fact that it was conceptualized by a troika consisting of two bitter commercial rivals—AT&T and Northern Telecom—and a government agency, the U.S. Environmental Protection Agency, which is frequently in an adversarial legal posture against private industry. Moreover, ICOLP's current membership, which includes not only major companies from around the world but such organizations as the Japan Electrical Manufacturers Association, the State Institute of Applied Chemistry (the former USSR), and the U. S. Air Force, illustrates the eclecticism which will be required to meet the challenges of regional and global environmental constraints.
24. See note 18, especially their discussions of "misplaced concreteness" and "disciplinolatry."