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This article defines the new field of industrial ecology and identifies the fundamental premises which make this approach to the information society a significant improvement over current practices. The article compares the environment as overhead paradigm with the industrial ecology paradigm and uses a conceptual framework to clarify the relationships between industrial ecology, sustainable development and technology. The hypothesis that the information revolution and sustainability are aligned, mutually dependent directions of societal evolution is supported by the analogy of the automotive sector. Over the past 25 years the automobile industry has undergone an almost revolutionary change and the modern automobile is now a profitable product which also offers much improved environmental and social performance and is altogether a more complex system with a far higher information content than its predecessors. However, the limitations of technological evolution in achieving economic, environmental and social sustainability show that simply relying on technology will not avoid the need for difficult and complex political decisions.

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Industrial ecology is the objective, multidisciplinary study of industrial and economic systems and their linkages with fundamental natural systems. Two fundamental premises of this new field are: reflecting the reality of the world within which human and environmental systems operate, industrial ecology always takes a systems view, and second, it is about technology and the evolution of human culture and economic systems. Both these principles sound simple, almost trivial, but when applied make industrial ecology a significant, almost radical, improvement over current practices. Taking an industrial ecology approach to the information society, one can hypothesize that the information revolution and sustainability are aligned, mutually dependent directions of societal evolution. The data to prove this broad hypothesis have not yet been developed, but it can be supported by analogy given an industrial ecology view of the automotive sector.

One must begin with the understanding that the usual and traditional approach to environmental issues treats them as if they are overhead, not strategic, for consumers, producers and society – overhead activities are ancillary to the primary activity of an individual, a firm or society, while strategic activities are integral to the primary activity. Thus, environmental problems have been widely perceived as local in space and time, and frequently associated with a single substance, such as the pesticide DDT. Reflecting this overhead approach, social responses are still ad hoc, reflecting a strong bias towards remediation of existing localized problems. Even pollution prevention programmes generally focus on relatively simple adjustments of existing production technologies. Moreover, virtually all environmental regulation and management also focus on manufacturing or, at best, manufactured artifacts, even though service sectors account for some 70 to 80% of most developed country economies and often offer the most potential for discontinuous improvements in environmental performance across the economy as a whole.

This overhead approach has in many cases demonstrably resulted in cleaner air and water, and less toxic loading of the environment. The question is, however, whether it is adequate to respond to the new information and data that have accumulated since it was first developed, or whether it must be subsumed into a broader approach. The answer to this latter question is clearly yes. The ad hoc focus on symptoms of economic activity – specific media impacts, or waste sites – is augmented and made more efficient, not replaced, by a far more comprehensive approach which focuses on production and consumption patterns throughout the economy.

Table 1 compares the prevailing overhead paradigm and the evolving industrial ecology paradigm. Importantly, the risks that each approach addresses are profoundly different in both scale and complexity. Remediation and compliance aim at the reduction of localized risks, often defined only in terms of human risk, while industrial ecology addresses not only those, but also the environmental perturbations threatening sustainability – such as loss of biodiversity, global climate change, stratospheric ozone depletion, and global degradation of water, soil and air resources. Mitigating the latter requires fundamental changes in technology, and in economic and cultural behaviour, not just the establishment of a fund to support clean-ups. The industrial ecology approach is integrative, not reductionist, reflecting the basic premise that technology – which is, after all, the means by which humans interact with the environment – is a critical theme of industrial ecology. More subtly, remediation and compliance programs generally assume a complete understanding of the systems involved, so that a specific regulation can be targeted to have the desirable effects without causing any unanticipated side effects elsewhere. If properly implemented, this is an appropriate approach to specific, well-defined, localized hazards. For the kinds of complex natural and human systems with which industrial ecology deals, however, it is inappropriate, the more so because it is often unconscious.

It is in fact the highly multidisciplinary, integrative nature of industrial ecology, and its focus on complexity, which allows us to pose the question: what is the relationship between the information society, sustainability and technology, and argue from analogy that the relationship, properly understood and managed, is not only positive, but synergistic. But first, it might be useful to provide the reader with an industrial ecology conceptual framework that clarifies the relationships between industrial ecology, sustainable development and technology.

Table 1 Technology and environment: characteristics of principle approaches

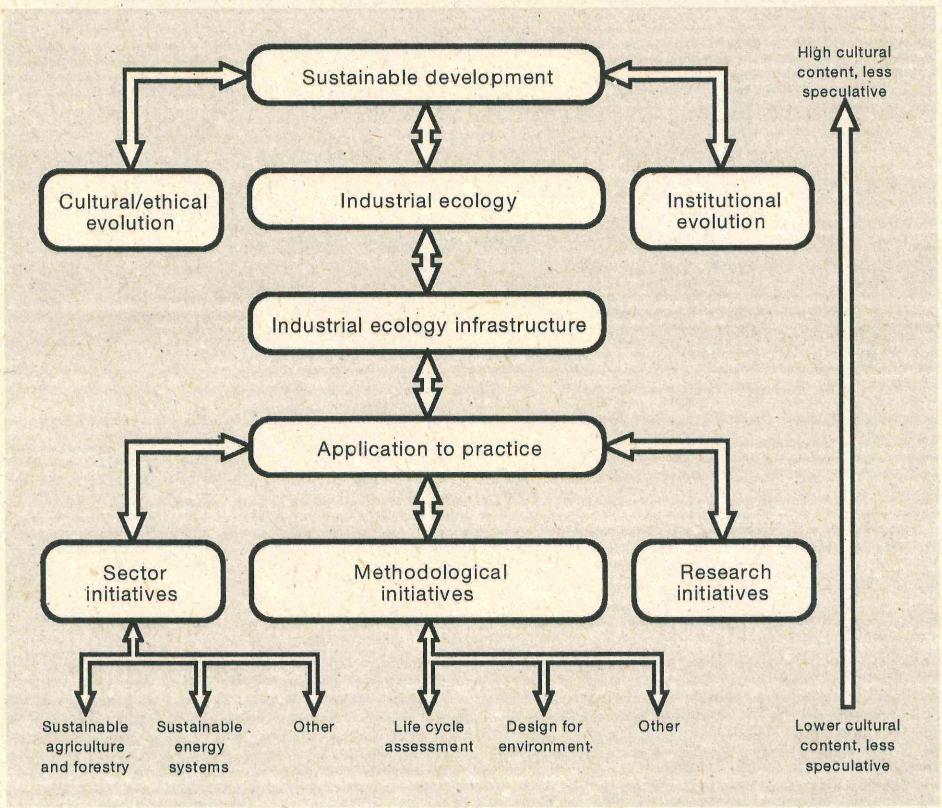
Primary activity	***Timeframe***	***Primary risks addressed***	***Focus of activity***	***Relation of environment to economic activity***	***Disciplinary approach***	***Assumptions***
Remediation and compliance	Past/ present	Local and visible environmental and human risk	Individual site, media or substance	Overhead	Toxicology and environmental science; reductionist	Known system, simple dynamics
Industrial ecology	Present/ future focus	Global climate change; loss of biodiversity and habitat; degradation of air, water and soil resources	Materials, products, services and operations over life cycle	Strategic and integral	Engineering; physical sciences; biological sciences; social sciences; law and economics; highly integrative	High degree of uncertainty; system and its dynamics complex and not well understood

An industrial ecology conceptual framework

Figure 1 presents an industrial ecology conceptual framework which should be taken as only illustrative at this point. The highest level is the vision of sustainable development. In this, one can adopt the Brundtland Commission definition of 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs', although this definition is both ambiguous and inclusive of a number of values such as redistribution of wealth within and among human generations, a need to aggressively restrict population growth, and equal rights for women, which are contentious for some people. More importantly, perhaps, there are many possible global systems that would be sustainable over some finite time period. For example, an alternative sustainable world might be one where elites barricade themselves and continue to enjoy a materials and energy intensive, high quality of life, while sustainability over time is maintained by low levels of biodiversity and mortality rates among the poor. Indeed, sustainable development is just one of many futures – it may not be the most probable and, cynics would argue that modern trends, such as increasing income disparity within and among nation states, are moving us further away from it. Even so, some countries are setting a good example, the Netherlands, for instance, where sustainable development is a general goal towards which environmentally preferable activities are being directed.

The second level is industrial ecology, the multidisciplinary study of industrial systems and economic activities, and their linkages with fundamental natural systems. It provides the theoretical basis, and objective understanding, upon which reasoned improvement of current practices can be based. Even given this broad scope, however, it is important to note that the study of industrial ecology alone is not sufficient to support the achievement of the vision of sustainable development, which is heavily normative. Rather, progress towards any desirable sustainable world requires concurrent evolution in ethics and institutions. In part, this is because any global sustainable state relies on political, cultural and religious systems for its definition and achievement. Industrial ecology, on the other hand, is an objective field of study, relying on traditional scientific, engineering, and other disciplinary research – standing alone, it cannot define what is at bottom a values decision about what kind of world we as humans desire.

Figure 1 An industrial ecology conceptual framework



The third level, the industrial ecology infrastructure, contains society's response to the question: 'Assuming that private and public firms and consumers can be encouraged to behave in environmentally appropriate ways, what must the state and society in general provide so that they may do so?' It thus includes developing and implementing the legal, economic and other incentive systems by which desirable behaviour can be promoted, as well as the methodologies, tools, data and information resources necessary to define and support such behaviour. An example might be removal of environmentally and economically inefficient subsidies for virgin, as opposed to recycled, materials, as well as those encouraging over-investment in agricultural, fishery and forestry sectors. Another important example is providing an integrative prioritizations of risks – including economic, environmental and social risks - so that private decision makers can be guided in their choices.

Unlike the first three levels, the fourth level, application to practice, is primarily concerned with implementation. While the specific activities undertaken will be different for different firms, different consumers, different economic sectors, and different elements of the public, it will for all of them represent the level of immediate action, based on industrial ecology principles as currently understood and translated into policy. Examples at the firm level include development and implementation of Design for Environment (DFE) practices in electronics manufacturing and Life Cycle Assessment (LCA) methodologies for chemical or personal product firms. While still nascent, such implementation efforts represent important experimentation activities, and there is a dialogue between this level, which plays with industrial ecology principles and theories, and the more theoretical higher levels of the industrial ecology framework.

This then, is the framework. Our knowledge becomes more specific and less speculative as we move from sustainable development down the scale to implementation, but it also becomes less systemic. Thus, for example, we can assert that e-commerce is an important area of study for industrial ecology, but we are not yet able to say anything definitive about its systemic impacts on the environment. At a lower level of the scale, however, we can say that an important variable for e-commerce is the transportation modalities involved – air freight is many times more energy intensive than rail or water per unit of product shipped. At the implementation stage, we can say that a critical environmental technology for package delivery services – albeit completely overlooked by traditional environmental organizations – is efficient routing algorithms, which greatly reduce energy consumption in a delivery network. Given this reality, but faced with the need to understand these complex social, technological and environmental systems now, let us turn to analogy. More specifically, let us turn to the automotive sector.

Case study: the automotive technology system

Examples often make a difficult concept easier to understand. Accordingly, it is useful to use a common object, the automobile, and explore both the artifact and the sector behind it from an industrial ecology perspective. In particular, the evolution of the automobile into an information system, which was a necessary adjunct to significant improvements in environmental and social (eg safety) performance, offers an interesting illustration of what might be a much wider dynamic. Data and examples are drawn from the US experience; other countries have followed different trajectories, but the general evolutionary trend towards much higher information content and structure in automobiles is still robust. Thus, for example, no other country had quite the infatuation with large displacement muscle cars that the USA did, but countries such as Japan and Singapore are ahead of the USA in implementing some kinds of automotive information systems.

An appropriate place to begin is to consider the apex of the initial stage of evolution of the post-World War II automobile technology. In the USA this arguably occurred in the late 1960s, when the most desirable automobiles were powered by what aficionados fondly called 'Detroit iron' – big V-8 engines which were relatively crude but effective. These so-called 'muscle cars' consumed enormous amounts of fuel, frequently getting less than ten miles per gallon, and the untreated exhaust was high in hydrocarbon and NOx (nitrogen oxides) concentrations. But they were fast, at least in a straight line, and popular with customers – ever-larger engines became a significant competitive dimension in automobile marketing. Then came Earth Day in 1970, and the energy crises of the early 1970s. Pollution control equipment was superimposed on existing engine designs. Demand for improved gas mileage increased, culminating in the establishment of corporate average fuel economy requirements in the Energy Policy and Conservation Act in 1975. Predictably, average engine size, efficiency and power dropped as a consequence.

Yet the drop in automotive performance, measured along almost any parameter, was temporary, and a second post-war generation of car began its evolution under these significant, apparently mutually exclusive, pressures for improvement in both environmental and energy efficiency. The average size of the engine in passenger cars did, indeed, drop and stay smaller, but engine horsepower began to rise as the engineering of the drive and engine systems became more sophisticated. Accordingly, the ratio of horsepower to engine displacement increased significantly, indicating more efficient operation. Indeed, between 1975 and 1991, the fuel economy of the average new car in the USA improved significantly, from 15.8 to 27.8 miles per gallon. At the same time, absolute performance of the product was increasing, as measured by acceleration times. In fact, a 1992 National Research

Council report noted that the average passenger car horsepower-to-weight ratio, an important indicator of performance capability, was greater in 1992 than at any time since 1975. The modern automobile unquestionably provides more performance per unit resource, in this case, petrol.

Moreover, the automobile of today is considerably safer, handles better, lasts longer, and offers far more amenities – such as advanced sound systems, on-board diagnostics and climate control systems – than two decades earlier. Impressively, these gains have been matched by similar increases in environmental efficiency: since controls were introduced in 1968, volatile organic carbon (VOC) and carbon monoxide emissions per vehicle have been reduced by some 96%, and, since imposition of NOx controls in 1972, emissions of those species have been reduced by over 75%.

In short, over the last two and a half decades, one of the principle, and defining, artefacts of the modern industrial economy has undergone an almost revolutionary change. It has improved its environmental performance on a per unit basis substantially, it is a far safer and more desirable product, and it has significantly enhanced not only its performance, but the efficiency with which it generates that performance. The modern automobile is, in short, a much overlooked example of the triple bottom line – a profitable product, which also offers much improved environmental and social performance.

This evolution provides an interesting, if not perfect, analogy to the stages society must go through in its overall effort to integrate science, technology and environmental considerations in all economic activity. The first stage of this integration process treats environmental impacts as completely ancillary to the primary economic activity – fast cars or industrial production. The second stage begins to recognize that emissions must be controlled, but the underlying technological systems are not altered - this is the early 1970s car and the compliance stage of environmental regulation. In either case, the blend of naive end-of-pipe control and pre-existing technology is an uncomfortable one, and produces performance that is neither environmentally nor economically efficient. These are classic environment as overhead approaches. The next and more desirable stage involves the re-engineering of the underlying technology to reintegrate economic, engineering and environmental efficiency from initial design through use and end-of-life resource recovery. Note that only the last stage has the potential to produce significant integrated environmental and economic gains.

In this sense, then, the evolution of the automobile is somewhat analogous to the evolution of the environmentally efficient economy. The first stage is a linear economy which, just like a muscle car engine, takes in resources, uses them inefficiently, and pumps out substantial waste streams. The second stage is one where first generation end-of-pipe controls are placed on existing technologies – scrubbers on factories, or emission controls on cars - which leads to a situation where neither environmental nor economic efficiency are optimized. This is, roughly speaking, the stage developed country economies are in now. The third stage is the fundamental systems redesign stage, which has been achieved for the automobile but not for any economies as a whole (although the product regulation focus in Europe, and much of the DFE and LCA work to date, is suggestive of such a systemic redesign).

What is somewhat ironic, of course, is that the automobile remains the most significant source of environmental impact in many areas of the globe. This results from non-technological factors: in many places, the benefits achieved by re-engineering the automobile as an artifact have been more than outweighed by population increases tied to higher per capita automobile ownership, combined with increased annual mileage per vehicle, and a shift from fuel efficient sedans to four-wheel drive sports utility vehicles. What technology has gained, changes in customer demand and vehicle use patterns, combined with population increases, have negated.

The automobile as an artifact, then, illustrates both the promise, and the limitations, of technological evolution in achieving sustainability. Its evolution is optimistic in suggesting that, if the technology systems handed down as a result of the previous stages of the Industrial Revolution are, indeed, re-engineered, substantial improvement in not just environmental performance, but also engineering and economic efficiency, might result. The viability of at least the weak sustainable development model – better quality of life with less environmental degradation – is supported by the automobile analogy. It suggests – although no persuasive data exist that come anywhere near proving – that substantial environmental improvement, at acceptable cost and offering increased quality of life, is possible with good engineering. At the same time, the evident limits to technological fixes are instructive: consumers and society as a whole must not be left with the impression that simply relying on technology will avoid the need for difficult and complex political decisions. Better technology can buy time, it cannot by itself buy sustainability.

Information and the automobile

The record thus demonstrates that, over the past 25 years or so, one of the principal artefacts of the modern industrial economy has undergone an almost revolutionary change. It has improved its environmental performance on a per unit basis substantially, and it is a far safer and more desirable product. How? And more to the point, what has that to do with the information economy and sustainability?

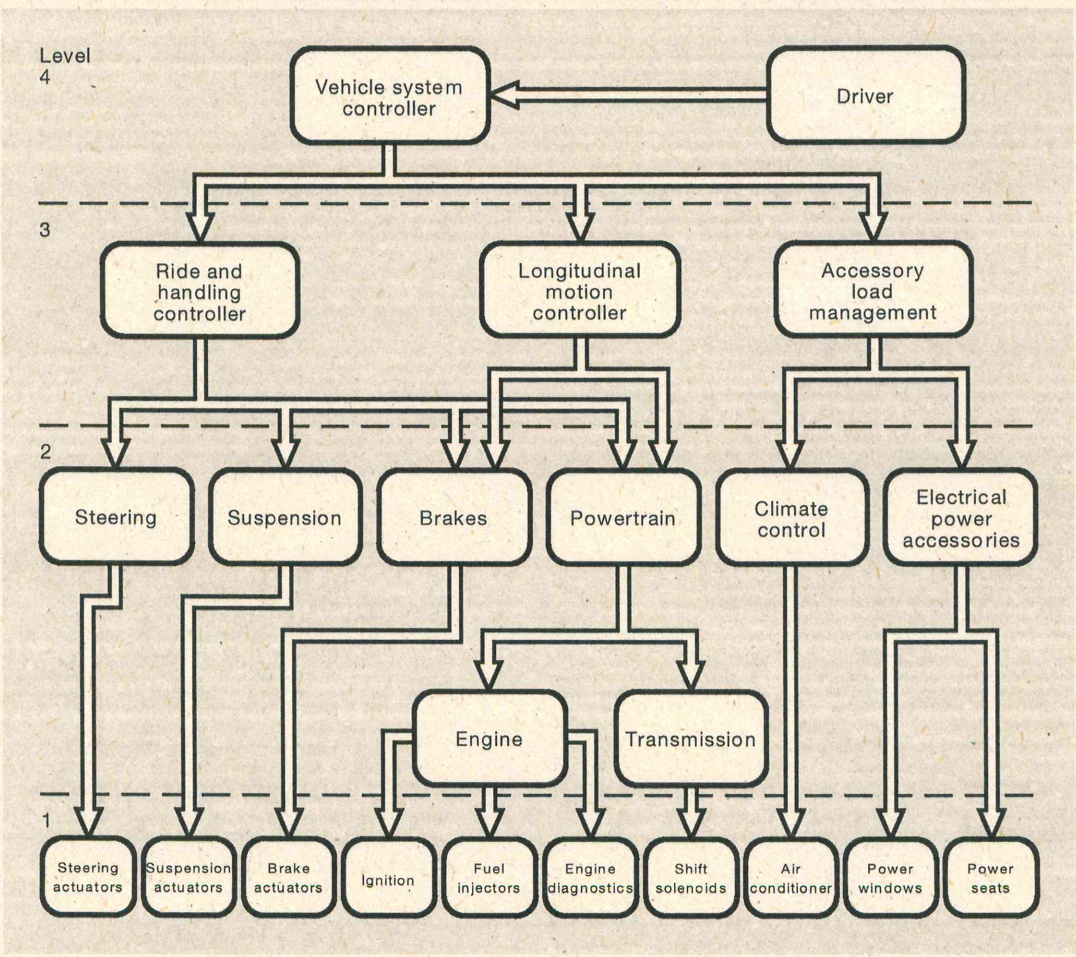
The performance of the modern automobile reflects a number of incremental improvements: reductions in vehicle weight, better aerodynamic design, reductions in tyre rolling resistance, reduction in friction losses, new catalytic systems, more efficient engines and drivetrains. But there is one common theme underlying the evolution of the modern automobile – it has become a much more complex system, with a far higher information content than its predecessors. Moreover, it is increasingly linked to its external environment, becoming a subsystem in a yet more complex automotive transportation system. The parable of the modern automobile is increasingly one of systems integration through information generation and linkages, of increased information density in the technology system, of computer and electronic, rather than mechanical, engineering.

Internally, mechanical subsystems in older cars were linked mechanically whereas new car systems are linked by sensor networks feeding into multiple computers. Whereas older cars had minimal electronics, newer ones have substantial systems that need to be integrated both physically and functionally. In fact, the numbers of cables and wiring harnesses required by the modern automobile have increased to such an extent that routing them through the vehicle becomes a design problem in itself. Automobile manufacturers now produce complete advanced engine management systems to balance performance, emissions, fuel consumption, operating conditions (eg cold starts, stop-and-go conditions). Such systems typically include control units, different sensor systems, and actuators, and utilize complex information topologies to maintain optimal system operation. Reflecting a greatly more complex engineered system, sophisticated multiplexed microcontrollers thus become a necessary component of the modern automobile. In fact, the modern automobile is such an information rich artifact that a complex information hierarchy is required (Figure 2).

Producing a more complex system requires, in turn, more sophisticated design tools and manufacturing technologies. For example, lightweighting – reducing the weight of vehicles through better design and material substitution – has been a major contributor to enhanced environmental performance; such designs require precision manufacturing, and the design process becomes a much more information intensive activity. Germany's Audi, for example, believes that only the advent of supercomputing technologies provided the necessary processing power to design the complicated lighter components that have permitted them to lightweight their product. Moreover, difficult design problems are resolved by virtual reality design processes – Boeing, for example, never built a physical model of its latest aircraft, the 777; rather, it was created entirely within a distributed computational system.

As with the artifact, so with the built infrastructure system within which it functions. In older cars, virtually the only information link between the automobile and the external environment was the driver. Today, sensor systems monitor exhaust systems, the oxygen content of air flows, and road conditions, and newer systems map the car's geographical position, provide up-to-date road conditions and optimal real-time routing options, and pay tolls electronically without the need to stop. The technologies that will permit ongoing communication between road networks and automobiles – in essence integrating the automotive built infrastructure, the automobile, and the driver into one automotive transportation system, which can then be optimized for real-time efficiency by, for example, use sensitive automatic roadway pricing – already exist. Cars linked to the internet with speech recognition capabilities, voice-controlled browsers, GPS (Global Positioning System) capabilities, email capability, and their own internal local area networks are on the road. The car is not only an information artifact, it has become an information appliance.

Figure 2 Vehicular information system control technology architecture



*Source:*Based on M.B. Barron and W.F. Powers, The role of Electronic Controls for Future Automotive Mechatronic Systems, IEEE/ASME Transactions on Mechatronics, Vol 1, No 1, March 1996, pp 80–88.

This, then, is the lesson of the automobile. Substantial improvements in the three relevant dimensions of sustainability – economic, environmental, and social – are possible in a complex technology system if it is redesigned for that purpose – and if information and intellectual capital are employed as substitutes for less preferable material and energy inputs. The automobile has mutated from a materially and energetically inefficient system to a far more sustainable system by a reconceptualization that viewed previously disparate mechanical subsystems as dynamic elements of an information hierarchy, then viewed the automobile itself as only a node in a larger information system. While this certainly does not prove that the information society will be more sustainable, it offers some support that it may well be if properly developed. Further research is necessary to determine what policy mechanisms and initiatives can best contribute to such a desirable outcome.

Conclusion

In sum, the evolution of a more environmentally and economically efficient automobile provides an analogy for at least some of the characteristics of a more sustainable economy. To the extent the analogy is valid, it suggests that such an economy will be more, not less, complex, and, concomitantly, far more information dense. Information generation through, eg appropriate systems of sensors, the evolution of more complex feedback systems; and tighter linking of previously disconnected subsystems through more information links – think of intelligent cars on intelligent roadway systems – will support a fundamental pattern: the substitution of data, knowledge, and systems development for other, less environmentally appropriate, inputs into economic activity.

The information revolution intersects the global drive towards sustainability through reconfiguration of systems; generation of more information, and translation of that information into knowledge, about systems performance; increased linkages among systems, mostly information rather than mechanically driven; redefinition of optimal system scale; increased complexity; increased information density and greater environmental and economic efficiency.

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