

## **Background: Agent Based Modeling of Industrial Ecosystems**

This proposal responds to the EPA research solicitation in the area of Corporate Environmental Behavior: Examining the Effectiveness of Government Interventions and Voluntary Initiatives. It directly addresses the research focus area on identification and analysis of the motivators of corporate environmental behavior.

### **Objectives**

Our main objective is to perform what Stokes (1997) calls use-inspired basic research, by asking a set of very practical questions about environmental protection in order to frame some fundamental research on the evolution of social processes. Practically, we want to investigate behavior change as a means of reducing environmental impacts. Fundamentally, we want extend the reach of computational social science as an approach for investigating such important social phenomena as firms, markets, governments, and social movements.

Thus we plan to create functioning agent-based computer simulation models that allow us to investigate some classic problems in business-environment relations. Examples include pollution-producing incentive incompatibilities within organizations, incentive incompatibilities between organizations and society as a whole, introduction of environmentally preferable products to the marketplace under conditions of imperfect information, supply chain relationships, and understanding the preconditions for radical innovations that reduce adverse environmental impacts.

We expect to be able to replicate familiar patterns of environment-economy interaction, and then to test the efficacy of alternative behavioral rules and information pathways on environmental and economic outcomes.

### **Expected Significance**

At a practical level, we expect that this work will create a low-risk, inexpensive

laboratory for prospective research on organizational and individual behavior. We hope that it will suggest new rules and procedures for reducing environmental impacts produced by large organizations and institutions.

For fundamental researchers, we expect to enhance the toolkit for computational social science by developing agent specifications that will yield new classes of emergent phenomena, e.g., intra-firm inefficiencies. We also expect to advance the state of the art in this field by investigating more complex phenomena than previous research has done.

The proposed project directly serves both practical and fundamental long-term goals. In the applied world of environmental management and policy, there is growing concern that policy fragmentation, inefficiency, and inequity are hindering environmental innovation and that solutions are failing to keep pace with the increasing scale of environmental problems. One response has been the adoption of a systems, or industrial ecology, perspective which emphasizes big-picture integration and the evolutionary potential of human institutions. Yet a realistic characterization of our institutions as evolving, self-organizing collections of autonomous individuals has been missing from this perspective. This project brings such a bottom-up perspective to the study of environmental decision-making.

As a field of fundamental research, computational social science is rapidly maturing into a mode of analysis that is broadly useful to economists, political scientists, sociologists, geographers, and many others. Yet in order to make progress, researchers need a rich library of empirically validated agent specifications that are robust building blocks with which later investigators can create cumulatively more sophisticated models. This project will extend substantially the range of multi-agent systems models that are available in the public domain.

## **Relation to Present State of Knowledge**

### **Industrial Ecology**

A good metaphor expresses complex ideas in neat shorthand. Descriptively, the phrase "industrial ecology" captures the Darwinian essence of both markets and ecosystems, including fierce competition among individuals for scarce resources, their dizzying array of survival strategies, and the development of structured communities. Prescriptively, it highlights the value of evolutionary forces and the innovations they engender. This metaphor, popularized by Frosch and Gallopoulos (1989), has evolved into a field of study with a peer-reviewed *Journal of Industrial Ecology* (MIT Press), a burgeoning literature, Gordon Research Conferences and innumerable other meetings around the globe, and a group of researchers and practitioners who claim that this is what they do.

It is above all a systems perspective, one that locates human activity in a larger, environmental context, and one that views the natural world as a model for organizing industrial activities. It has deep roots in engineering systems analysis (e.g., Forrester, 1969; California Energy Commission, 1977; Bennett and Chorley, 1978; Checkland, 1993) and systematic analysis by natural scientists (e.g., Carson, 1962; Commoner, 1971; Meadows et al, 1972; Ayres, 1989; Botkin, 1990). It overlaps with ecological economics (e.g., Boulding, 1966; Daly, 1968; Ayres and Kneese, 1969; Georgescu-Roegen, 1971/1995; Harris, 1995; Krishnan, 1995) and the subfield of organizational behavior known to its members as ONE—organizations and the natural environment (e.g., Ochsner, Chess, and Greenberg, 1996; Alexander, 1998; Franken, 1998; King and Baerwald, 1999). Industrial ecology is a next generation approach to environmental management that draws lessons from ecologists (Holling, 1978) and well as engineers (Ortolano, 1997) and planners (McAllister, 1980).

We will use industrial ecology as shorthand for the disparate strands of research and practice at this intersection between ecology, economics, and sociology. The strands could be better linked, and one way to do so is to build a micro foundation for the field that identifies actors and their motives. By micro foundation we mean a body of theory and evidence about the individuals—the smallest identifiable autonomous agents—in the industrial ecosystem. Individuals are elements of the system's larger structures or aggregations (such as firms, sectors, economies, advocacy groups, governments, and social movements); in a sense

they are its building blocks and foundation.

Why bother with this exercise? We think that a bottom-up approach will provide a better way to think about certain problems than we currently have. We think that it has explanatory and even predictive power in certain cases, and that it thus serves as a useful lens for identifying probable solutions to some tough problems. We think that it makes visible certain classes of problems that are invisible to top-down analysis. Many environmental researchers believe that the issues of greatest interest occur at the macro level of, say, the carbon cycle; our goal is to show that issues of equal importance occur at the micro level, because:

- First, motives matter. Jackson and Clift (1998) point out that a simplistic profit motive, operating within the narrow context of advanced capitalism, will not lead to a sustainable industrial society. Any associated eco-efficiency gains will be overwhelmed by expanded output. A better theory of agency may give reformers leverage on the economic system itself.
- Second, individual humans are fundamentally interesting units of analysis as well as being building blocks for aggregate agents such as firms and nations. Firms and governments employ individuals who may—or may not—make decisions that are in the best interests of their employers or of society at large (Panayotou and Zinnes, 1994).
- A third reason to build a micro foundation is that it may improve the value of more aggregate levels of analysis, as it has elsewhere in ecology and economics, fields which study complex, evolving systems made up of autonomous individuals. Structure and agency can be interlinked (Giddens, 1984).
- Fourth, in general it is very difficult to build accurate aggregate models of phenomena that are in fact highly distributed, localized and nonlinear. This difficulty is exacerbated when the domain is dynamic. In such cases macro models having properties that faithfully represent the underlying micro-dynamics will not generally exist (Axtell, 1992, Iwasa and Levin, 1987) and so the nature of the aggregate representation needed depends on the question being asked of the model.

- A final reason is to move the field beyond “what?” to “how?” questions. Many environmental analysts, with roots in the sciences, see their roles as providing “what?” guidance, as in “what problems should people worry about?” Researchers should be equally concerned with “how?” guidance, as in “how can people solve their problems?” Making the problem-solvers visible is a logical first step in implementing environmental improvements (Andrews, 2001).

There is value in re-visiting the parent field, ecology, to appreciate how it is organized. As it has developed a micro foundation, ecology has evolved away from popular notions of a harmonious natural world in perfect balance. The "new ecology" of recent decades denies the existence of stable states or a balance of nature, and instead describes a natural world that is at best meta-stable and often full of surprises (Botkin 1990). Ecology encompasses sub-fields focusing on phenomena operating at several distinct scales and levels of aggregation. Industrial ecology research and practice has a similar range. While there is always a danger in taking a metaphor too literally, the exercise suggests a useful typology and interesting new questions (Graedel 1996; Allenby and Cooper 1994).

Fields as diverse as applied ecology (Dyer and Shugart, 1992) and organizational behavior (Rousseau, 1985) investigate compositional phenomena such as isomorphism, cross-level phenomena where effects at one level have causes at another level, and multi-level phenomena where relations among independent and dependent variables generalize across two or more levels. To date, most work in industrial ecology has been at the macro level of material flows (Ayres, 1989; Ayres et al, 1994; Thomas and Spiro 1994; Wackernagle et al, 1995), the meso level of product chain relationships (Frosch and Gallopoulos, 1989; Lund, 1996; Sagar and Frosch, 1997; Socolow and Thomas, 1997; Andrews and Maurer, 2001;

NERC 1998), and at the intra-organismal level of product and process designs (Graedel and Allenby 1995). We argue that greater attention should be given to behavioral questions. In particular, a coherent theory of agency must clarify the distinction between individual humans and firms. To accomplish this it is necessary to leave biology behind and enter the realm of the social sciences.

## Beyond Biology

Although economics had a strictly macro focus during the latter half of the 18<sup>th</sup> century under the physiocrats, the micro-focused neoclassical tradition represented the core of the discipline throughout the last century. In recent decades, mainstream microeconomic research has begun to focus on information problems, real human behavior (as elicited, for example, through experiments with human subjects), and the structures and organizations within which individual decision-making takes place, and less on the frictionless neoclassical ideal. Some microeconomists have successfully connected micro-, organizational-, and meso-level topics in both theoretical and empirical research.

Contributors such as Miller (1956), Kahneman (1973), and Simon (1979) brought behavioral data to economics from other fields such as cognitive psychology. They convinced some economists to pay attention to evidence of bounded rationality, heuristics, biases, and other human divergences from the ideal of *homo economicus*. Innovators within the discipline have developed conceptual tools and performed experiments linking purposive agents, their external environments, social structures, and the evolution of economic systems (Schelling 1978; Nelson and Winter, 1982) and political systems (Axelrod 1984 and 1997). Today, experimental economics is an increasingly visible specialty (Kagel and Roth 1995).

The venerable neoclassical theory of the firm was crafted over centuries, with contributions continuing to the present (see, e.g., Samuelson and Nordhaus 1995). The neoclassical approach stresses technological and cost constraints, focuses on the producing unit, and uses scale economies as the rationale for the existence of firms. While these factors are important, they do not explain which economic

functions firms will perform, what forces, in addition to scale of production, determine the size of firms, what type of organizational form the firm will adopt, and how regulators will behave.

A modern theory of the firm has more recently evolved which places informational constraints on the maximizing activities of *homo economicus*, and adds friction to the economic system. Its wellspring is Coase's (1937) insight that "it is costly to rely exclusively on the price system to coordinate economic activity." This transaction cost paradigm (Williamson 1979) points out that there are at least two ways of coordinating economic activities--the market system and administrative command. Each has associated costs.

Both within and outside of the firm, there exists a complex web of contractual relationships, hence the development of a contracting literature in economics (e.g., Williamson 1987). Contractual relationships link employees to employers, suppliers to purchasers, producers to consumers, and firms to society as a whole. Characteristics of transactions affect the nature of these contractual relationships and their requisite governance structures, and they determine which institutional arrangements prevail: market governance, bilateral contracts, trilateral contracts (buyer, seller, arbitrator), or ownership integration.

Features of industrial structure, such as the size of firms and the degree of vertical integration, can be dictated by two types of cost-reducing opportunities. Technological opportunities associated with scale economies, the scheduling of production and inventory reduction play important roles (Blair and Kaserman 1985). Equally important are transaction cost reductions associated with measuring the output of intermediate production stages, or with the opportunistic bargaining that accompanies transaction-specific investments (Williamson 1987). Industrial ecologists concerned with managing products over their entire life cycle can usefully employ the transaction cost concept (Scharfman et al 1997).

Ownership integration creates administrative command structures that can be thought of as teams, peopled by self-interested individuals and leading to

incentive incompatibilities (Panayotou and Zinnes, 1994). Also, because corporations exist only at the pleasure of society, in the sense that they are licensed and regulated by governments, a social contract can be said to link firms (as agents) to society (as principal). Managers of firms face ethical dilemmas, as agents, when the interests of their two principals, owners and society as a whole, diverge.

The microeconomic, contracting approach has been extended into the public sector, so that government interventions justified using market failure arguments can alternatively be explained by an interest group theory. This application of economic concepts to politics "closes the behavioral system" by assuming that all actors, public and private, are self-interested (Buchanan 1972). As descriptive social science this approach is reasonably powerful (Stein 1990; Levy 1995; Hedstrom 1996; Monroe 1997), although not without controversy (Green and Shapiro 1994). Its normative aspects remain disputed. Society needs to rely on government as its agent and it is reasonable to expect that there are public sector principal-agent problems just as there are within firms. Researchers of very different political stripes plainly see this in the environmental policy arena (e.g., Greve 1992; Ringquist 1997).

In short, the "new" institutional microeconomics provides a more consistent way to link realistic individual behavior to the structures found in our self-organized economic and political systems (Shugart 1990). It provides a powerful analytical lens that looks a fair distance past the ecological metaphor and clarifies key issues in industrial ecology.

This approach engages one of the classic debates in the organizational behavior literature, between those adopting a deterministic, macro-level *natural selection* view, and those with a voluntaristic, micro-level *strategic choice* view (Astley and van de Ven 1983). We advocate a cross-level synthesis of these views that differentiates the concept of agency at two levels.

The micro foundations of ecology and economics are similar because the fields have exchanged many ideas over the centuries. They share terms such as

disequilibrium, cost-benefit analysis, optimization, niche creation, and enlightened self-interest. Industrial ecologists may fruitfully use many of these ideas, but first they must navigate a minefield laid between the natural and social sciences concerning the notion of individual agency.

Biologists often focus on *ultimate* drivers of behavior (Hamilton 1964; Dawkins 1976; Barash 1982, 138). Social scientists are uncomfortable with biological determinism, to put it gently. Thus they tend to focus more on the *proximate*, or situational, drivers of behavior (Goldsmith 1991). Behavioral evidence from both the biological and social sciences suggests that enlightened self-interest will be the dominant motivating force for individuals in industrial ecosystems (Marwell and Schmitt 1975; Batson 1991; Harcourt and de Waal 1993; Palfrey and Prisbrey 1997; Penner and Finkelstein 1998). However, while biologists are typically more interested in the links between behavior and the forces *within* the agent, social scientists prefer to focus on the forces *outside of* the agent. Epstein and Axtell (1996, 4-5) remind us that *both* types of links are needed to characterize any complex society with realism. Realistic behavior is a function of within-agent forces (decision rules, cognitive capabilities, and codes of behavior), agent-environment interactions (such as exploiting natural resources), agent-agent interactions (such as trade and war), and environment-environment interactions (such as geographic location influencing natural resource availability). The challenge to industrial ecologists is to pursue an empirically-grounded synthesis of the biological and social science approaches that acknowledges the ultimate and the proximal, the agent and the environment, our biological bounds and our human creative potential. In sum:

- Individuals act in a self-interested manner most of the time, and those seeking to establish a normative foundation for industrial ecology (e.g., Jackson and Clift 1998; Allenby 1999) should not let their aspirations obscure a realistic view of the empirical evidence. For example, committed environmental consumers who are willing to pay substantially more for green products made up only 7% to 15% of the U.S. buying population in 1996, depending on the survey instrument used (Frankel 1998). Prescriptions to change human behavior fundamentally are as naïve as they sound.

- Expect entities' actual behaviors to reveal varied preferences, with individual humans exhibiting a vastly greater range of goals than firms. While there is a central tendency, there is also a wide variance around the mean. This establishes a basis for viable niche markets, green consumerism, political advocacy, and systemic change—7% to 15% is a nice wedge for catalyzing market transformations that reduce environmental impacts.
- Humans are resourceful, evaluative maximizers who are also cognitively limited in important ways (Jensen 1994). Humans can be educated but they rarely have the luxury of making decisions with complete information, because information gathering and processing are costly activities. We should not assume away ignorance when developing a theory of agency.

There is a clear distinction between human individuals and firms as classes of autonomous agents. Unlike human individuals, firms have no real biological basis; they are social creations. Firms can be thought of as contractually-linked aggregations of individuals, and in following society's laws they exhibit a relatively narrow range of behaviors. Today's firms must pursue profits with zeal if they are to survive. Yet as human inventions their characteristics can be changed. This sounds more Lamarckian than Darwinian, and it shows the limits of the strict biological analogy (Hayes 1999). By transcending literal ecological analysis, industrial ecologists can find a much more hopeful vision of the future. Humans can tinker with both the ultimate and proximal drivers of corporate behavior. In sum:

- Firms are aggregations of individual humans, and the behavior of a firm is affected by the contractual links between, cognitive abilities of, and aspirations of its employees, owners, and external stakeholders. Humans make the choices, they are the agents. While organizational behavior is more than the sum of the individual actions, the agency responsibilities manifested in the transactions that individuals complete are the organization's defining core.
- When managers engage in transactions, they exercise agency responsibilities, which in turn have ethical dimensions framed by their social and political context. Contractual relationships in today's firms embody the historical consensus on a narrow interpretation of fiduciary duty. The small

fraction of today's firms that appear to be environmentally proactive do so mainly because managers perceive this as leading to long-run profitability (Andrews 1998; Reinhardt 1999). But the context can be changed. Those pursuing a vision of sustainability will actively engage all three of society's collective decision-making mechanisms (culture, politics, and markets) in concert.

- Biological systems are largely self-organizing, meaning that structures can develop from the bottom up and that they can adapt to changing conditions. The same is true for economic systems. The structures visible in industrial ecosystems were created largely by the decentralized decisions of many autonomous agents. Researchers have demonstrated that intricate, familiar structures can evolve even when autonomous agents follow very simple decision rules (Resnick 1994). There is still room for top-down influences, but the system's adaptability depends to a large extent on its decentralization.
- The sociological concept of structuration is also helpful here, because it argues that social institutions are enacted. Giddens (1979; see also Cohen, 1989) claims that individuals decide, upon waking up each morning, whether to continue reproducing current social practices. The thesis that human agency and structure cannot be understood apart from one another is now central to the organizational behavior literature (Karnoe and Nygaard, 1999; Drazin et al, 1999; Wicks, 1998).

In sum, there is a strong rationale for developing a bottom-up approach for investigating economy-environment linkages, termed here industrial ecology. The next section briefly reviews the state of the art of computational social science, our proposed approach.

## Computational Social Science

Agent-based computer modeling techniques have a history that is traceable to early computer science innovations including cybernetics (Wiener, 1961) and self-reproducing automata (von Neumann, 1966). Biologists, computer scientists, and cognitive scientists have put much effort into variations on this theme including

connectionist cognitive science (e.g., Rumelhart and McClelland, 1986), distributed artificial intelligence (e.g., Gasser and Huhns, 1989) and multi-agent systems (Weiss, 1999), cellular automata (e.g., Wolfram, 1994), genetic algorithms (e.g., Holland, 1992), genetic programming (e.g., Koza, 1994), artificial life (e.g., Langton, 1994), and individual-based modeling in ecology (e.g., Haefner and Crist, 1994).

Applications to social science research started later. Following important early work by Steinbruner (1974) and Schelling (1969, 1971a, 1971b, 1978), little was done until the last decade, when computing power became ubiquitous and cheap. An exception was in the related field of game theory, where contributions have been continuous since the days of von Neumann and Morgenstern. Since 1990, economists have begun to investigate market formation (Albin and Foley, 1990; Holland and Miller, 1991; Tesfatsion, 1995; Vriend, 1995), market dynamics (Arifovic, 1994; Arifovic and Eaton, 1995), oligopoly (Marks, 1992), bounded rationality (Arthur, 1991 & 1994), stock markets (Arthur et al, 1994), and the evolution of money (Marimon, McGrattan and Sargent, 1990). Political science investigations have included fiscal federalism (Kollman, Miller and Page, 1992 & 1994), and coalition-building and war (Axelrod, 1995). Sociologists have investigated group stability (Carley, 1991). Philosophers have investigated morality (Danielson, 1992 & 1996). Edited volumes on the computer simulations of social life now appear regularly (e.g., Gilbert and Doran, 1994; Gilbert and Conte, 1995) and they cover topics in anthropology, economics, geography, politics, psychology, and sociology in an integrative spirit.

A highly visible sign that the field is maturing is that standard programming systems are beginning to develop along with an infrastructure for sharing computer code. StarLogo is an entry-level program for educators and students that is freely available from the MIT Media Lab (Resnick, 1994). The Santa Fe Institute provides free access to the Swarm family of codes written in Objective C and Java that have been developed for use by professional researchers primarily in the natural sciences (SFI, 2000). The Brookings Institution makes available a family of pure Java routines for use by professional researchers primarily in the social sciences (Parker, 2000). This project will rely on the Brookings

framework.

The current state of the art in computational social science can be summarized as follows. Researchers have successfully demonstrated the emergence of a variety of primitive social behaviors, including mating, kinship, groups, alliances, wars, wealth accumulation, and urbanization. They have not yet succeeded in simulating the pure, bottom-up evolution of organizations with formal constitutions or charters. There are two schools of thought in this regard. Purists (typically economists and ecologists) insist that organizations and institutions should be endogenous to the computer models in order to ensure the validity and stability of these emergent structures; hence they prefer to wait until the simulations become complex enough to produce such forms. Others (typically sociologists and organization theorists) create structures exogenously in order to examine how agents and structures interact; they prefer to simulate structures already known to exist (e.g., firms, governments) in order to learn more about them. This project will take a hybrid approach, making initial structure exogenous but also allowing it to evolve.

There have been several investigations of agent-environment interactions that simulate economy-natural environment linkages so central to industrial ecology. Resnick (1994) creates a resource-constrained artificial world. Bousquet et al (1994) simulate fisheries. Epstein and Axtell (1996) include both pollution and resource extraction in their simulations of artificial societies. The proposed project will extend significantly beyond these efforts, by seeking to evolve both informal and formal regulatory mechanisms.

The multi-agent systems approach is beginning to find use in applied social science domains such as urban planning (e.g., Bernard, 1999; Batty and Jiang, 1999), economics (e.g., Luna and Steffanson, 2000), and environmental issues (e.g., Janssen and DeVries, 1998; Janssen et al, 2000) because it provides a systematic way to experiment with alternative policy formulations, and to explore structure-agency relationships.

In particular, Teitelbaum (1998) is one of the first attempts to use a multi-agent

system to explicitly model firm behavior in environmental regulatory contexts. His results strongly suggest that modeling with adaptive agents can yield results that are at variance with those of neoclassical economics. In particular, in perfectly competitive markets, regulation is either distorting and inefficient or irrelevant. However, when agents--firms in his model—are heterogeneous, boundedly rational, and interact directly with one another out of equilibrium, regulations can be demonstrated to have positive welfare effects. Furthermore, research on environmental management and policy is focussing increasingly on innovation as a policy lever, and on the efficacy of alternatives to government regulation, such as incentives and norms. Teitelbaum's model explicitly treats the process of improvements in abatement technologies and therefore provides an additional foundation from which to build on.