Multi-Agent Simulations and Ecosystem Management

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Abstract: This paper proposes a short and subjective review of the development and use of Multi-Agent Systems (MAS) for ecosystem management. The use of these tools go with the shifts in various paradigms on the study of ecological complexity, the introduction of behavior and interactions as the key issues to understand the organization, and the use of models in a constructivist way. Multi-Agent Systems are introduced in a conceptual way and some computer tools are presented. Then a discussion is proposed on the use of MAS for problems integrating social and spatial aspects. MAS may be used for several purposes from theorization to collective decision-making support.

Keywords: MAS; INRM; Organization; Interactions

1. INTRODUCTION

If a history of Multi-Agent Systems (MAS) were to be written over the coming years, the author would certainly situate the birth of this approach and its formative years in the rich breeding ground of the interdisciplinary movement. In the USA, Distributed Artificial Intelligence developed in computer science, separately from the world of physics where the concept of Artificial Life was first initiated. In Europe on the other hand the emergence of the MAS community arose from the coming together of researchers from different disciplines. In the general context of the sciences of complexity, which re-examine scientific questions by studying the interactions between elementary entities and their mode of organization, MAS provide a method to reformulate certain questions in the social and natural sciences. MAS were first used to study the question of decision making among agents by applying cognitive psychology and game theory - to rationalize the strategies used in establishing relations with other agents - before moving on to the question of interaction between agents to build artificial societies. This task involved both sociologists - to define the modes of interaction between individuals and society - and linguists to provide the agents with language and to organize communication protocols. A current question is that of the agents' environment. Among the scientific disciplines mobilized to address this problem, ecology, for which the environment is a fundamental notion, could play a key role in specifying concepts and developing appropriate tools.

Fruitful relations have already been established in the past. References to ecology, in its broadest sense, appear in the very first work on MAS. The anthill metaphor provides a much-used illustration to represent the notions of reactive agents and emergence and was the subject of the first applications [Drogoul, 1993]. Craig Reynolds' "Boids" [Reynolds, 1987] which imitate the behavior of groups of migrating birds even appear to precede the notions of MAS or Artificial Life. They were followed by a range of studies on animal behaviors and animal societies. Today, MAS are also used for so-called environmental applications, i.e., applications involving interactions between natural and social dynamics.

In this paper we propose a short review of the development and use of MAS for research on ecosystem management. For more than ten years, we have been developing MAS models for renewable resource management, using the simulation methodology. We have also developed a specific approach for the use of bottom-up approaches in decision-making processes. Firstly, we present how the use of a bottom-up approach leads to paradigms shifts. Secondly, we present MAS systems and their use in ecological and social research. Then we propose a classification of various uses of MAS.

2. MAS AND INRM: THE PARADIGM SHIFTS

2.1 From "Dynamics under Constraints" to Interactions

In the field of INRM, the problems of access and use of natural and renewable resources are key issues. Scientists working in this area need to examine the interaction between ecological dynamics and social dynamics. Indeed, for many years, this question was examined either exclusively from the angle of "an ecological system subject to anthropic disturbance" or, alternatively, from the angle of "a social system subject to natural constraints".

In the first case, scientists make a careful description of the dynamics of the resource, with management constituting a definition of the various forms of anthropic exploitation, which can be sustained over the long term by this resource. Social dynamics are summarized in terms of the type of resource exploitation they entail.

In the second case, researchers generally concentrate on the problem of resource usage, placing themselves in the position of an isolated economic agent who wishes to maximize the benefits obtained from a restricted resource and placing the collective use of common resources within a framework of competitive exploitation. Assuming the same decision-making model for every agent (the optimizing rationality), aggregation of behaviors is possible and the same model can be applied from micro to macro levels.

For ten years now the challenge has been to develop a new approach focusing more on the interactions between ecological and social components and taking into account the heterogeneity of these components.

2.2 From a Systemic to an Organizational Point of View

In his paper on ecosystem complexity Holling [Holling, 1987] defines three concepts that have dominated causality in ecological systems and that defines the principles for the management of ecosystems. The first one is based on the notion of equilibrium (balance of nature), the second one defines several states of stability (nature engineered or nature resilient). This second perception is interested in dynamics caused by variability, by events that occur at small scales. The third point of view is the one of organizational change (nature evolving). The system changes: external events lead to perturbation on the systems, but also, especially when human being are part of the system, the actors of the system may, by themselves, change the organization of the system. This point of view focuses on the connectivity of the ecosystem's elements and their organization across various scales. One important reference for that last point of view is the theory of hierarchy presented by Allen and Starr as a theory of observation of complex systems [Allen and Starr, 1982]. Complex systems are presented as intermediate between large number systems for which a statistical approach is adapted and small number systems for which mathematical approaches such as differential equations are suitable. Intermediate systems are opaque unless they are modeled as hierarchical organizations. In their book, Allen and Hoekstra [Allen and Hokstra, 1992]. explain that understanding of a complex system in ecology implies the understanding of interactions between various levels: organisms, populations, communities, ecosystems landscapes, biome and biosphere.

2.3 Modelling Tools: From Stocks and Flows to Behavior and Interactions

To take into account the links between the natural system and the socioeconomic system, the researchers have integrated the two sub-systems as modules of models [Costanza, et al., 1993]. This systemic research uses the tools and methods of the mathematicians who developed that methodology: system dynamics. A system is described as a set of modules or compartments interlinked by flows and controls. User-friendly software such as Stella, Vensim, Simulink or others are available. Practically, with these tools, the compartments are used to represent the stocks, aggregated variables and flows represent flows of matter, energy or information. It is thus possible to model linked ecological and economic components in an integrated model. Each subsystem dynamics is controlled by other subsystems. For instance stocks of resource are controled by harvest, which in turn is controlled by capital. Researchers who have tried to standardize the flows of both systems by means of energetic transformation have proposed a stronger link. The theoretical assumptions and the tools used by this approach lead to study the equilibrium properties of a system. For Uchmanski [Uchmanski and Grimm, 1996] this systemic point of view represent ecological systems as stable states. System dynamics is a method to identify the set of attractors and the properties of the system near the attractors.

While the systemic approach has been proposed as an alternative to a reductionist approach, a new point of view is emerging. The individual is the central object of that ecology which focuses on problems of behavior and interactions. For several researchers, the representation of individuals introduces inter-individual variability and thus heterogeneity is not aggregated. This does not challenge the principles of a systemic point of view and its major themes: equilibrium and resilience. For other researchers the introduction of the individual in the organization corresponds to an alternative to the systemic approach. The individual is given unique characteristics [Judson, 1994] and holds a specific history [Gross, 1998]. Furthermore, taking account the social aspects, the actors may perceive the system and decide to change the organization.

This new approach has developed its own tools and methods: the individual based models and agent-based models. According to researchers and applications these models fit in with the second or the third approach presented by Holling. Villa refers to the use of new computer tools and architecture to enhance the development of this new ecological point of view [Villa, 1992].

Table 1. Two systems of interpretation leading to two concepts of complexity

	Dynamic view	Organizational view
System conceptualisation	State variables	Lower level processes/entities
Suitable metaphors	Cybernetic systems	Parallel computers
Specification of mechanism	Centralized	Distributed
Means of analysis	Differential equations	Computer simulations
Key behaviours	Equilibrium, dynamic complexity	Self organization; structural complexity
System organization	Fixed, single level	Variable, multilevel

New computer models have been developed over the last fifteen years. These methods, developed by different researchers have various names. In ecology these models are called individual based models (IBM). In computer science this kind of model is called multi-agent system, also called agent based modelling.

2.4 The use of Models: From Positivism to Constructionism

Beyond the problem of sustainability the questions of how people interact with their environment and how they interact together about their environment are becoming increasingly important.

Under the paradigm of natural sciences, the role of researchers is to discover the truth and to unravel natural laws that drive the system [Castella, et al., 1999]. Definitions of sustainability emphasize bio-physical attributes of ecosystems and often focus on calculable thresholds below which land becomes unsustainable. Hard sciences can show that an ecosystem is endangered but the sustainable land use is defined as the outcome of human interaction and agreement, learning, conflict resolution and collective action. Soft systems are based on the assumption that people construct their own realities through learning in social processes. The role of interdisciplinary teams including natural and social scientists is to understand and strengthen the collective decision making process through platforms of interactions. The different stakeholders, including scientists, should work out in an interactive fashion a common vision on resource management that would lead to new indicators, shared monitoring procedures, information systems and concrete alternatives for action. The scientist's role is partly to feed this platform with "objectively true" knowledge on the bio-physical sub-system, and the ways to compare, assess and realize the concrete alternatives collectively decided. Thus adaptive management not only consists in the objective of increasing the adaptiveness of the ecosystem but also deals with the social process, which leads to this ecological state.

In other words, what is important are solutions which emerge from interaction. And with them comes a different portfolio of interventions including mediation to resolve conflicts, facilitation of learning, and participatory approaches that involve people in negotiating collective action. Computer enhanced modelling become tool for interactive learning [Röling, 1997], instead of tools for piloting the system.

3. MULTI-AGENT SYSTEMS: CONCEPTS, TOOLS

3.1 Concepts

3.1.1 MAS

The aim of multi-agent systems [Ferber, 1999] is to understand how independent processes in direct competition are coordinated. An agent is thus a computerized process, something that comes between a computer program and a robot. An agent can be described as autonomous because it has the capacity to adapt when its environment changes. A multi-agent system is made up of a set of computer processes that occur at the same time, i.e., several agents that exist at the same time, share common resources and communicate with each other.

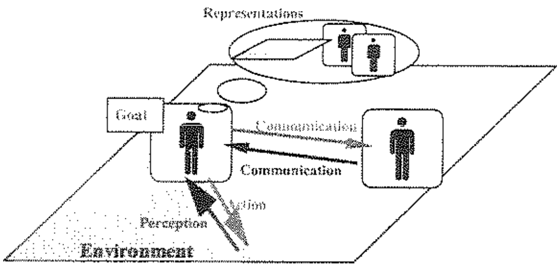

Figure 1. A Multi-Agent System [Ferber, 1999].

The key issue in the theory of multi-agent systems is formalizing the necessary coordination between agents. The theory of agents is therefore a theory of:

- Decision-making: what decision-making mechanisms are available to the agent? What are the links between their perceptions, representations and actions ?
- Control: what are the hierarchical relationships between agents? How are they synchronized?
- Communication: what kinds of message do they send each other? What syntax do these messages obey?

for which elaborate formulas are put forward.

Multi-agent systems simplify problem-solving by dividing the necessary knowledge into subunits, by associating an intelligent independent agent to each subunit, and by coordinating the agents' activity. Thus, it refer to distributed artificial intelligence. This theory can be applied to monitoring an industrial process, for example, where it adopts the sensible solution which consists of coordinating several specialized monitors rather than a single omniscient one. Fundamental research is being conducted on the problems associated with the representation of agents' decisions and protocols for communication. The main applications for MAS are in telecommunications, internet and physical agents, such as robots [Weiss, 1999]. There is a group of scientists that specializes in the simulations of agents' societies in ecology and social sciences.

3.1.2 MAS and IBM

In ecology, the distributed approaches, known as individual-based models (IBM) were developed at the end of the 1980s. The article written by Huston [Huston, et al., 1988] is the most frequently quoted. The authors argue that there are two reasons for developing this approach: first, the needs to take into account the individual because of his genetic uniqueness and, secondly, the fact that each individual is situated and his interactions are local.

Recently, a special issue of Ecological Modelling journal [Grimm, 1999, Grimm, et al., 1999] presented a discussion on what conclusions can be drawn after ten years of development and use of IBM. Mainly two ideas are expressed on the need of a consolidation phase. The biologists–computer scientists have to address classical modelers questions: how to describe the structure of a model, how to present the results? The consolidation is also theoretical. Too many applications were presented without any concern on the genericity of the results. It is proposed to favour models more close to theoretical issues, usually represented in mathematical terms.

There are some differences between MAS models and IBM. IBM were developed by ecologists who tried to introduce the notion of individual to understand the role of heterogeneity. MAS models are more influenced by the computer science field and social sciences also. It gives more emphasis on the decision making process of the agents and to the social organization in which these individuals are embedded. Furthermore, an agent is not compulsorily an individual. An agent can represent any level of organization (a herd, a cohort, a village, etc.). In a MAS, agents representing different levels may interact. This is consistent with the "layer cake" metaphor for ecosystem scales presented by Allen [Allen and Hokstra, 1992].

3.1.3 MAS, artificial societies and computational economics

MAS are developing rapidly in the field of social sciences. Society simulation is the subject of numerous conferences, for example, Multi Agent systems and Agent Based Simulation (MABS) [Sichman, 1998] among others. Research on the subject is published in the electronic journal Jasss (Journal of artificial societies and simulation). In addition, a group called Agent-based Computational Economics (ACE) [Tefstation, 1997] has been set up.

In social sciences, the application of multi agent to simulate social phenomena is generally associated with the methodological individualism in which the singular individual is considered as the elementary unit or the atom of society [Weber, 1971]. The overlap is, in fact, in the bottom-up approach that characterizes MAS. However, the assimilation between individuals from a society and agents from a multi-agent can be misleading: it is quite possible for social groups and institutions to be considered as agents with their own standards and rules for functioning [Livet, 1987]. The agents are directed by constraints or rules that are expressed on a group level, i.e., they are no more than entities that act and are placed in a dynamic environment.

This straightforward comment—which is natural when MAS are used for modelling—shows how the simple duality that exists between individualism and holism can be called into question, which is a major preoccupation for researchers working on renewable ecosystem management and MAS:

(i) individuals, products of history are driven by collective values and rules,
(ii) collective values and rules evolve because of the interaction between individuals and between groups,
(iii) the individuals are neither similar nor equal but have their own specific roles and social status.

How do individuals make up a group? How is an institution created? The individual cannot be considered as an autonomous entity that is independent of its social environment. How are individuals constrained by collective structures that they themselves have set up and how do they make these structures evolve [Gilbert, 1995]? What degrees of freedom are given to the definition of individual practices? Here are just some of the questions that can be explored using MAS and which can be expressed as follows: "how are collective structures set up and how do they function when they are based on agents with different capacities of representation, that exchange information, goods or services, etc., draw up contracts and are thrust into a dynamic environment which responds to their actions?"

3.2 Tools

The applications presented are generally developed with an object-oriented language. Some of them use platforms. They can be divided into three types:

- Generic platforms, some of which are regularly cited in environmental applications. Swarm [Minar, et al., 1996] is the favored tool of many researchers, especially in the US. StarLogo is also one refered tool: it is much more friendly-user but have less potential that Swarm. These tools are based on a principle which is not necessarily resource management. Many applications have been developed from Swarm, which now exists in several languages (Java, Objective-C). Generic tools have even been created from Swarm (see below).
- Ecosystem-oriented platforms. This type of platform, which includes Ecosim (Figure 2) [Lorek and Sonnenschein, 1999], mentioned above, and the Ascape or Cormas [Bousquet, et al., 1998] platforms, provides utility programs to simulate ecosystems or resource management problems. These tools, which include spatial representation, simulation utilities for Monte-Carlo type methods and links to other software (GIS, databases), are complete workshops for the implementation of different ecological systems. Algorithms or structures are provided to implement the link between agents and their environment and elements are provided to organize societies of agents (markets, auctions, predation mechanisms, etc.). Swarm is also evolving partly in this direction.
- Dedicated platforms. These tools concern more specific applications. For example, Manta [Drogoul, 1994] focuses on problems of foraging or task allocation in a society of insects, Arborscape [Savage and Bell,] models forest dynamics with emphasis on diversity while BacSim [Kreft, et al., 1998] models microbiological dynamics. Mobydic models the dynamics of fish populations [Ginot and Le Page, 1998]. Users gain valuable insight into dimensionality, relations of predation or competition and standard biological functions (mortality, growth, etc.).

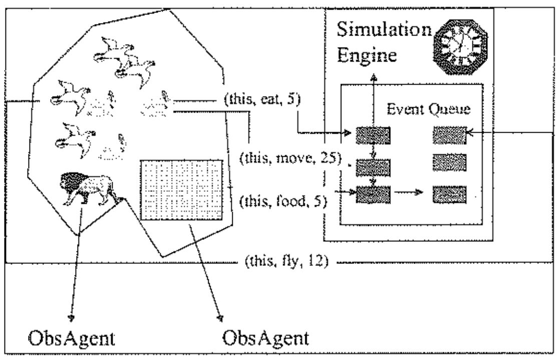

Figure 2. Simplified Ecosim architecture comprising a simulation engine based on discrete event simulations, domain agent and observation agents providing indicators on the dynamics of agents or sets of agents.

4. THE USE OF MAS

4.1 Coupling Spatial and Social Dimensions

As presented briefly in previous chapter the purpose of MAS is to study the interaction between autonomous agents and the organization. Is organization constitutive of the MAS or is it the result of the MAS? The emergence debate is less simplistic today and is based on a study of micro-macro circularity. Though organization is simultaneously a product, a context and a constraint for the agents, its characterization is nevertheless very limited. Though agent structures and interactions are categorized and described, organizations are less clearly formalized. In MAS dedicated to ecosystems, two elements of organization can be found: spatial organization and networks.

The spatial dimension is the most frequently mentioned, with descriptions of the organization of agents spread over space. Most problems associated with the search for food involve the organization of agents and their environment. Studies also focus on a very important question in ecology, that of regulation. In the context of agents' relations with their environment, the question of the number of animals capable of surviving and reproducing is often raised. It directly affects the calculations of how many of these animals can be harvested by the society and how the environment should best be adapted to this requirement. In an integrative cybernetic vision and taking inspiration from demography, numerous studies have been performed on the theme of density dependence. The concept of a maximum carrying capacity K use to be the cornerstone of ecosystem management. MAS have been used to test organization hypotheses other than density dependence. For example, Le Page [Le Page and Cury, 1997] test the theory of "Obstinate nature", according to which agents tend to reproduce under environmental conditions equivalent to those in which they were born. By combining the movement behavior linked to this theory with the structuring of space, the authors describe a population dynamic regulated without density dependence. Several researchers are now turning towards the characterization of spaces in which the agents move and coordinate their actions [Pepper and Smuts, 1999]. The landscape itself can be a MAS comprising different areas of space interacting on several levels [Le Page, et al., 1999]. The spatial representation of the agents is also of importance [Dumont and Hill, 2001]. The organization of the agents' space and of the resources within it can also be the driven force of a dynamic which leads to task allocation mechanisms. Drogoul, [Drogoul, 1993] thus shows how agents (ants) are able to specialize in different tasks to ensure that the anthill functions successfully.

The second type of organization that can be studied with MAS is that of interaction network structure. Many studies have been conducted in the field of food webs and species diversity. The relations of causality between the stability of an ecosystem and its degree of connectivity have been tested in this way [May, 1973]. This question was theoretically treated by Lindgren [Lindgren and Nordahl, 1994]. A similar question has been raised, in a very applied manner, with regard to fishing. Two experiments conducted at IRD are seeking to determine the link between predation and competition dynamics and ecosystem indicators. In the first experiment, a food web comprising three fish species whose behaviors are assumed to represent the diversity of strategies encountered in the Niger River was simulated [Bousquet, 1994]. The environment is a river-flood plain system represented by several habitats offering quantities of food that vary over time. The implemented agents present behaviors that express different adaptation mechanisms (adaptative strategies): different types of reproduction, movements in space and time. One species eats the plankton brought in by high waters. The second is heterotrophic: it consumes plankton or small fish. The third is a pure predator. The agents in this system are not models of individuals but rather models of groups. Starting with this food web, increasing exploitation pressure (fishing intensity) is simulated. It is thus possible to observe the impact of this pressure on the food web, notably the decline of species populations and the overall response in terms of catches. It is shown that this response takes the form of a plateau, illustrating the ecosystem's resistance to the stress of intensive fishing. This type of plateau is well known in resource ecology [Welcomme, 1989], indeed reflecting the response pattern of all organisms subjected to a stress. We thus move on from knowledge of species behaviors to the characteristics of the system's dynamics. A similar experiment was conducted by Shin [Shin, 2000]. Agents modeled on the basis of fish species database information and positioned on a spatial grid, interact through predatory behavior. The result of these numerous interactions is observed via a global indicator, the size spectrum, widely used by managers to analyze the biological situation. In the case of these two experiments, the aim is to establish a link between data at different levels: behaviors and interactions at micro level and patterns observed at ecosystem level.

If we include the human dimension in the ecosystem, social scientists model and simulate interaction networks between agents to analyze the effects of different rationalities and exchanges. For example, Rouchier shows how various hypotheses of relations between transhumant and sedentary agents in the Sahel produce very different resource dynamics [Rouchier, et al., 2001].

The most productive option is to combine the structure of a network and its position in space. Networks of interaction between species take on more importance if they are structured in space. In one of the original models, Hogeweg [Hogeweg, 1988] simulates agents based on social insects. Through interactions between TODO agents (behavior: do whatever activities come along) and DODOM agents (behavior: establish relations of dominance), social groups are formed and a rhythm is created. The influence of space structuring on the creation of hierarchies is demonstrated. In the same type of simulation, Doran studies the social networks that form to capture resources located in space [Doran and Palmer, 1993]. This work is based on a classic BDI (belief-desire-intention) approach with recruitment of agents to accomplish a task. Hierarchies appear and their functionality is studied. Epstein and Axtell present a set of simulation based on the theme of spatialized exchanges [Epstein and Axtell, 1996].

MAS are already used to study food webs, hierarchies, commodity sub-sectors, economic regulation tools, auctions, etc. New forms of MAS organization are still being explored, though we can already imagine the formalizations that will be confirmed in coming years to complete the structure of a MAS by adding to agents architectures, to the types of environments and interactions. The general institutional domain offers a general framework for studying the management of common property and social regulation mechanisms [Janssen and Ostrom, 2001]. It should also provide inspiration for MAS.

4.2 From Theorization to Collective Decision Making

MAS simulations are developed for several purposes.

The first type of possible utilization of these simulations complies with the principles of artificial life: "life as it might be rather than life as it is" [Langton, 1988]. The modeler sets up mechanisms and observes the emerging responses. These forms may actually exist. This research is founded on the results and approach adopted in physics [Weisbuch, 1991]: it is the transitions between phases of a system that we want to study. The aim is thus to build very simple interaction models and to find the critical coefficients which characterize the transitions. One assumes that the model and system under study belong to the same class of universality whose qualitative properties have thus been described. Although they do not explicitly refer to phsyics many publications use MAS for theoretical purposes [Doran and Palmer, 1993, Hales, 1997, Pepper and Smuts, 1999, Rouchier, et al., 2001, Thébaud and Locatelli, 2001]

Another more empirical use comes from the community of modelers working in life sciences and social sciences and either directly or indirectly involved in resource management problems. The underlying idea, which is to produce a system which behaves like reality, is always present, with the aim of using the simulator to ask the question "and what if...?". By adapting the model to reality the aim is not to make the model into a prediction tool, but rather to understand dynamics which exist or have existed. The authors examine behavior and identify parameters not to provide an explanation but to simulate observations of reality: the hypothesis tested can be used to simulate these observations, but other hypotheses could also simulate this reality. This method is used, for example, in archaeology [Kohler, et al., 2000] and history. One example of an application is that of Dean [Dean, et al., 2000] who reconstitutes the history of the Anasazi indians and simulates scenarios which examine population movements in response to environmental crises. Another famous example is the work of Lansing and Kremer on the coordination for water management in Bali [Lansing and Kremer, 1994]. It is also used to explore scenarios of renewable resource management [Bousquet, et al., 2001] or agricultural practices [Balmann, 1997].

The action. The vocation of a model is generally to serve as a decision support tool. It is likely that the domain of distributed problem solving will be applied widely to propose solutions for configuring an area of space for example [Le Ber, et al., 1999]. But simulation can also be used and contribute to decision making processes. Take the work of Gimblett for example [Gimblett, 1998], who suggested that a natural park be redesigned to prevent competing users (mountain bikes, walkers, jeeps) from crossing each other's paths by simulating the movement and field of vision of agents. Other methods are proposed, such as accompaniment modelling [Bousquet, et al., 1999].

This method proposes to use MAS to deal with problems of common property management as part of a constructivist approach with the players of the system. The model becomes a shared representation and can become, as the social process moves forward, a tool for dynamic co-adaptation between one or more social groups and their environment. A circular approach of model presentation and model construction with the players involved has been proposed and tested in several different field situations. The role playing method is used [Barreteau, et al., 2001]. Role playing can be used to present a MAS or to construct it with the players: bottom-up modelling for bottom-up decision making [Lynam, et al., in press].

5. CONCLUSIONS

Since the mid 1980's, various research communities have been working on distributed models and ecosystems. Ecologists have introduced the notion of the individual in their models of dynamics to gain a clearer understanding of how ecosystems work. Computer scientists have developed ecosystem models both to find new conceptual models of behavior and interaction and to test the architectures they have imagined. After a number of exciting years many applications are under progress. However, some researchers involved for several years feel less enthusiastic. Some question the real value of taking the individual into account, while others wonder how to avoid becoming bogged down in the application. These two worlds have probably covered less common ground than they first believed and a new step forward should be achieved in coming years. Ecologists can use multi-agent systems to go beyond the role of the individual and to study more deeply and more effectively the different forms of organization (spatial, networks, hierarchies) and interactions between different levels. Computer scientists can exploit the knowledge of the ecologists, not only on the behavior of individuals but above all on the systems of interaction between agents and their environment (relations between organizations and properties of stability, resilience, resistance). Though each community can benefit from the other, it is together that real progress will be achieved in methodologies and in the use of these models: methods for observing an artificial world, experimentation, problem solving, forms of participation in the decision-making process.

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