# Chapter 2
# Cognitively Rich Architectures for Agent-Based Models of Social Behaviors and Dynamics: A Multi-Scale Perspective

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## 2.1 Introduction

The field of modeling social behaviors and dynamics has a long and established tradition (from Trivers 1971; Axelrod and Hamilton 1981; to Sigmund et al. 2002; Hoffman et al. 2015). In this tradition, mathematical and analytical modeling approaches have played a major role since the field was established in early 1980s (Axelrod and Hamilton 1981), and they still play a central role at some of the best international research institutions (e.g., Prof. M. Nowak at Program for Evolutionary Dynamics, Harvard University; Prof. K. Sigmund at Faculty for Mathematics, University of Vienna; Prof. R. Boyd at School of Human Evolution and Social Change, ASU; Prof. J. Henrich at Department of Psychology and Vancouver School of Economics, University of British Columbia).

Starting from modeling simple (social) behaviors of human and nonhuman animals (e.g., "boids" flocking model, Reynolds 1987; cooperation, Axelrod 1984, primate fission-fusion dynamics, Boekhorst and Hogeweg 1994a, b; primate female dominance, Hemelrijk 1996), a new method and scientific approach to model social behaviors and dynamics has gained more and more attention and interest over the last decades, namely, agent-based modeling (ABM).

This approach (and more broadly speaking, this class of modeling techniques and tools) has proven to be very interesting and useful in many different applications.

ABM allows to deal with the heterogeneous individual units (i.e., agents) and emergent properties and dynamics.

The traditional analytical top-down perspective suggests modeling social dynamics at the population level, trying to individuate a possible equilibrium (i.e., a so-called steady state). Agent-based modeling, on the other hand, adopts the opposite perspective, i.e., the so-called bottom-up perspective, where the main effort of

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modeler is to design and develop properties and behaviors of agents and rules governing the whole system and environmental conditions (the "environment" being a physical or a social environment, or a simple idealized space where interactions may take place) to make the system behaviors and dynamics emerge at the global (or collective) level starting from the local/individual interactions (i.e., the micro–macro relationship: see Alexander and Giesen 1987).

Some of those models have shown that very simple and local rules facilitate the emergence of complex behaviors at the collective level. This is the case with the famous flocking model from Reynolds (1987). In this model the simple definition of three local rules—namely, (1) separation (i.e., steer to avoid crowding local flock-mates), (2) alignment (i.e., steer toward the average heading of local flock-mates), and (3) cohesion (i.e., steer to move toward the average position of local flock-mates) applied to each individual within a group of agents—allows the flocking/schooling collective behavior to emerge at the group level.

These three simple rules combined with a small set of individual properties, such as the perceptive ability to calculate the distance from another individual and the individual direction of moving, may produce a complex and fascinating behavior common in different social species in the animal realm. In this way, the flocking behavior of birds, the schooling behavior of fishes, and many other social behaviors of living organisms may be explained as the result of simple local interactions.

## 2.2 Agent-Based Modeling

A simulated world may be used for exploring adaptation and evolutionary processes. The use of agent-based models allows us to improve our understanding of the behavior of individuals and populations in social and evolutionary settings.

Our claim is to suggest the use of agent-based modeling as a general theoretical and methodological tool for analyzing, studying, and modeling social behaviors and dynamics in living organisms.

Agent-based modeling (ABM) is a style of computational modeling that focuses on modeling individuals, components of individuals, or heterogeneous parts of a complex system.

There are many resources available for those interested in developing or using ABM (for a list of available tools see https://www.openabm.org/page/modeling-platforms) and there are several fields of research where researchers have adopted this approach: social sciences and human behavior (Bonabeau 2002; Gilbert and Troitzsch 2005; Gilbert 2008; Epstein and Axtell 1996), ecology (DeAngelis et al. 1991), biology (Kreft et al. 1998; Campennì and Schino 2014), and animal behavior (Hemelrijk 2000; Bryson et al. 2007).

Agent-based models are simulations based on the global consequences (macro-level) of local interactions of members of a population (micro-level). These agents (or individuals) might represent plants and animals in an ecosystem, vehicles in traffic, orpeople in crowds.

Typically, ABMs consist of an environment or framework in which individuals interact and are defined in terms of their behaviors (by procedural rules) and characteristic parameters (i.e., individual properties).

In such models, the characteristics of each individual are monitored over the time; this differs from other modeling techniques where the characteristics of the population are "averaged" and the model attempts to simulate changes in these averaged characteristics at the whole population level.

Some agent-based models are also spatially explicit: this means that individuals are associated with a location (i.e., in a geometric space). Some spatially explicit individual-based models (which is an alternative way to refer to agent-based models, often preferred in ecological and biological scientific domains) also exhibit mobility, where individuals can move around, e.g., exploring the environment or looking for sources of food.

There are three main benefits of ABM over other modeling:

- ABM captures emergent phenomena;
- ABM provides a natural description of a system;
- ABM is flexible.

Emergent phenomena result from interactions of individuals. They cannot simply be reduced to the system's parts; the whole, in this case, is more than the sum of its single parts, and this is possible because the parts interact in a complex way.

A phenomenon that emerges can have its properties' values modified in a nonlinear way; this crucial factor makes emergent phenomena very difficult to understand and predict (e.g., they can be counterintuitive).

In ABM, the researcher models and simulates the behavior of the system's constituent units, namely, agents, and their interactions and behaviors, capturing emergence from the bottom-up.

ABM is implemented as a software: the formulation, design, and implementation of algorithms, procedures and data structures needed to run an ABM force the researcher to describe the natural phenomenon or system in a very natural way.

This description is also in itself new theory generation: as in other scientific domains theory formulation is made possible by means of natural language sentences or mathematical formula; in ABM, the programming language code itself "is" the new theory.

ABM is flexible in different ways. This means that the same model can be used to investigate different aspects of the same real phenomenon or system (e.g., by modifying some model parameters); but this also means that different ABMs can be used in investigating the same topic from different perspectives to explore its multiple dimensions (e.g., evolutionary, behavioral, or cognitive).

### *2.2.1 Social Behavior and Communication in Living Organisms*

Social behavior and cognition in living organisms are characterized by a certain number of different abilities, such as social learning, gaze following, and imitation; moreover, some living organisms exhibit a complex communication system which allows them to express a wide range of emotions, moods, social relationships, and mental representations.

Human language can be considered as a tangled web of syntax, semantics, phonology, and pragmatic processes. All of these components work together, allowing language to emerge; we can find most of them (perhaps in different forms) in other animals. We can make a rough classification of these mechanisms, identifying three different classes of processes: (1) signaling, (2) semantics, and (3) syntax.

Signaling includes all of perceptual and motor systems underlying speech and signing; semantics may be considered as the central cognitive mechanism that supports the formulation of concepts and their expression and interpretation; syntax represents the mechanism that allows animals to generate structures and to map between signals and concepts.

Signals and semantics have strong social components: the former are used in communication and must be learned and shared among community member and require sophisticated abilities in order to imitate complex signals; the latter require the ability to infer the signaler's intentions by more-or-less indirect cues.

Scientific research in comparative cognition aims at studying different species to reveal similarities and differences in each cognitive mechanism; the investigation includes the study at multiple levels of description, from the genetic to neural and then behavioral level. Hypotheses about the evolution of cognition can be generated and tested from found similarities, both in terms of homology and analogy.

Only recently, researchers working in the field of comparative social cognition have started to considerate non-primate mammals (e.g., dogs, rats, goats), many bird species (among corvids, jays, crows, ravens), reptiles, fish, and social insects to investigate cognitive abilities and skills needed for social interactions (for a detailed table of taxonomic information, see Table 2.1 [reproduced from Fitch et al. 2010]).

Results obtained with these species often revealed surprising cognitive abilities: dogs or ravens succeeded in tasks when our closer non-human primate relatives failed. These kind of results have to be taken with a grain of salt, as they reflect a view of evolutionary mechanisms in which cognitive capacities increase with a species' relatedness to humans (Striedter 2004). More modern Darwinian viewpoints postulate that a species' cognitive ability evolves to fit its cognitive niche. So we expect that the evolution of specific cognitive capacities derives from the physical and social environment: species living in environments where they have to perform complex navigation tasks will evolve sophisticated spatial memory, whereas species living in complex social communities will exhibit superior social cognition.

This perspective allows us to surmise that a convergent evolution of analogous cognitive mechanisms (analogs) will be detected in widely separated species that face similar cognitive problems.

**Tab. 2.1** Species and Clades Studied in Contemporary Social Cognition Research

| | Common Name | Genus | Species | Major Clade | Minor Clade |
|---|---|---|---|---|---|
| Vertebrates | Common Marmoset | *Callithrix* | *jacchus* | class Mammalia | order Primates |
| | Chimpanzee | *Pan* | *troglodytes* | ” ” | ” ” |
| | Orangutan | *Pongo* | *pygmaeus* | ” ” | ” ” |
| | Capuchin | *Cebus* | *apella* | ” ” | ” ” |
| | Rhesus Macaque | *Macaca* | *mulatta* | ” ” | ” ” |
| | Bottlenose Dolphins | *Tursiops* | *truncatus* | ” ” | order Cetacea |
| | Humpback Whale | *Megaptera* | *novaeangliae* | ” ” | ” ” |
| | Harbor Seal | *Phoca* | *vitulina* | ” ” | suborder Pinnipedia |
| | S. African Fur seal | *Arctocephalus* | *pusillus* | ” ” | ” ” |
| | Domestic Dog | *Canis* | *familiaris* | ” ” | order Carnivora |
| | Domestic Goat | *Capra* | *hircus* | ” ” | order Artiodactyla |
| | Greater Sac-Winged Bat | *Saccopteryx* | *bilineata* | ” ” | order Chiroptera |
| | Japanese Quail | *Cotumix* | *japonica* | class Aves | order Galliformes |
| | Pigeon | *Columba* | *livia* | ” ” | order Columbiformes |
| | Bald Ibis | *Geronticus* | *eremita* | ” ” | order Threskiornithidae |
| | Budgerigar | *Melopsittacus* | *undulatus* | ” ” | order Psittaciformes |
| | Kea | *Nestor* | *notabilis* | ” ” | ” ” |
| | African Gray Parrot | *Psittacus* | *erithacus* | ” ” | ” ” |
| | European Starling | *Sturnus* | *vulgaris* | ” ” | order Passeriformes |
| | Woodpecker Finch | *Cactospiza* | *pallida* | ” ” | ” ” |
| | Swamp Sparrow | *Melospiza* | *georgiana* | ” ” | ” ” |
| | Zebra Finch | *Taeniopygia* | *guttata* | ” ” | ” ” |
| | Bengalese Finch | *Lonchura* | *striata domestica* | ” ” | ” ” |
| | New Caledonian Crow | *Corvus* | *moneduloides* | ” ” | family Corvidae |
| | Raven | *Corvus* | *corax* | ” ” | ” ” |
| | Rook | *Corvus* | *frugilegus* | ” ” | ” ” |
| | Scrub Jay | *Aphelocoma* | *californica* | ” ” | ” ” |
| | Archerfish | *Toxotes* | *chatareus* | infraclass Teleostei | family Toxotidae |
| | Red-footed Tortoise | *Geochelone* | *carbonaria* | class Reptilia | family Testudinae |
| Nonvertebrates | Octopus | *Octopus* | *vulgaris* | phylum Mollusca | class Cephalopoda |
| | Honeybee | *Apis* | *mellifera* | class Insecta | order Hymenoptera |

This table provides taxonomic information regarding the species discussed in this review. Only the common name is used in the main text. The major and minor clades help to contextualize the phylogenetic position of these species utilizing traditional Linnaean classification, even when (as for class "Reptilia") this traditional grouping is polyphyletic.

### *2.2.2 Communication, Social Cognition and Theory of Mind (ToM)*

Can non-human animals have a theory of mind? The debate is still open, but since Premack and Woodruff asked, "Does the chimpanzee have a theory of mind?" in their seminal paper (Premack and Woodruff 1978), the interest of researchers has steadily increased (Povinelli and Vonk 2003; Tomasello et al. 2003).

Even if some earlier results obtained testing the cooperative behavior of primates in tasks where they must trustingly interact with human experimenters showed little evidence of ToM in chimpanzees (Povinelli and Eddy 1996; Povinelli et al. 1990), more recent competitive experiments showed unexpected strong results (Hare et al. 2000; Hare 2001). In these experiments subjects competed with other conspecifics and/or human experimenters for sources of food and results probably derive from the more ecological significance of the task for primates.

A large amount of data obtained from experiments using a wide range of different primates (Braeuer et al. 2007; Karin-D'Arcy and Povinelli 2002; Kaminski et al. 2008) suggests that in most cases primates can distinguish between conspecifics who know where some sources of food are hidden from "guessers," who know that food has been hidden, without knowing exactly where.

Corvids tested with similar tasks (Clayton et al. 2007) showed a strong use of sophisticated cognitive mechanisms. Both scrub jays and ravens can differentiate between competitors that have or have not seen food cached in particular locations, modifying their strategy or behavior in accordance with information retrieved using ToM (Bugnyar and Heinrich 2005, 2006; Emery and Clayton 2001; Dally et al. 2005, 2006).

We can assume that some primates and corvids can consider perceptions of others in using information derived by interaction with them and the environment to infer possible consequences of others' actions in food-related tasks.

Finally, some results seem to suggest that chimpanzees and corvids are capable of attributing certain mental states to others (Call and Tomasello 2008; Clayton et al. 2007), even if they are not able to deal with false beliefs like humans do. In this sense, scientific studies of avian cognition (and not only the study of primate cognitive abilities) can help us to better understand the evolution of advanced socio-cognitive skills.

Nevertheless, there are many different elements contributing to the success of such kinds of tasks; cooperative behaviors and complex interactions between individuals can emerge from simple individual aptitudes or motivations. So it is not clear at all wherein and when cognitive abilities (such as ToM) are strictly necessary to solve these kind of tasks; it may be sufficient to integrate perceived information with some simple heuristics to solve quite complex food-related tasks. Moreover, experience (both in terms of past interaction with others and familiarity with a specific task) plays a very important role in developing social intelligence.

### *2.2.3 "Animal Culture" and Imitation*

Evolutionary biologists study the evolution of cultural artifacts, related cognitive abilities, and processes because these kinds of phenomena represent a very good example of a system's operating by inheritance and adaptation. Moreover, cultural transmission processes are more rapid than genetic ones, and the study of "culture" in animals can allow us to better understand and identify evolutionary roots of cultural processes in humans, possibly the most cultural animals on the earth.

Cultural evolution works in a way that is very similar to biogenetic evolution (Mesoudi et al. 2004), following some principles and dynamics already identified by Darwin (Darwin 1964) more than 150 years ago. In this context, language is a very good example of this kind of historical change (Fitch 2008), and linguistic elements (words and grammatical rules) can be studied and analyzed using tools and instruments borrowed from molecular phylogenetics (Cavalli-Sforza et al. 1992; Lieberman et al. 2007; Pagel et al. 2007). A very distinctive mechanism of cultural phenomena is their cumulative nature: ideas, especially good ideas, can be accumulated within the same generation and transmitted to the next, following a principle of high-accuracy copying very similar to that adopted to explain genetic transmission. Accumulation of high-fidelity elements in animal species is a topic still open to debate in the study of cumulative change and evolution of culture (Heyes 2009; Huber et al. 2009; Tennie et al. 2009).

The relation between culture and social learning could be very interesting and stimulating for researchers studying social behavior in animals. Some results suggest that social learning is possible in group-living mammals (Heyes 1994), birds (Zentall 2004), fish (Schuster et al. 2006), and insects (Leadbeater and Chittka 2007); however, we don't have sufficient information about the evolutionary roots of these abilities, and even if some eminent researchers have hypothesized about the social origin of intelligence (see Dunbar and Shultz 2007), in some cases non-social species have also shown the same ability to learn to solve a task by observing actions performed by a conspecific (see Wilkinson et al. 2010, where solitary tortoises can solve a detour task after the observation of a conspecific completing the task).

In this view, imitation can be viewed as the non-genetic reply to the inheritance of phenotypic attributes in supporting cultural phenomena. However, it is less clear what types of imitation can play this role in cumulative culture. Surely, imitation has to be as accurate as possible in the copying process and it must involve certain forms of learning, i.e., the ability to acquire new skills and behaviors.

Moreover, observation of someone else's behavior has to be selective, as shown by theoretical models of adaptive advantages of social learning (Galef and Laland 2005). An individual who observes the behavior of others has to consider the specific relationship existing between the target individual and her- or himself (i.e., dominance, affiliation, tolerance) in order to perform the correct action; thus, the ability to correctly monitor the behavior of others is a crucial element of any social behavior (cooperation, communication, and competition). Environmental and physical conditions may limit the individual's capacity to observe every animal and actions performed within a specific social group; for this reason, selectivity is also very crucial for acquisition and spreading of social information.

### *2.2.4 Information Exchange*

Information is the vital component for the emergence of communication and communicative systems. It may be transmitted, processed, and used to make decisions and to coordinate actions or individuals.

The transmission of information may be related to the existence of a system that allows an individual to signal something to someone else: in this case, emitted signals have to be exchanged in a coordinated way, preserving the original content. Nevertheless, the transmission of information may also occur in an unintentional way: the individual behavior of performing a specific task (e.g., searching for food in a particular place) can be used as a behavioral cue by other observing individuals. In nature, we can find a wide range of possible signaling systems that have evolved over the time to permit the exchange of information at very different levels, from very micro entities to macro ones: e.g., from quorum signaling in bacteria (Schauder and Bassler 2001; Taga and Bassler 2003; Kaiser 2004) through the dance of the honeybees (Dyer and Seeley 1991), birdcalls (Hailman et al. 1985; Evans et al. 1993; Charrier and Sturdy 2005) and alarm calls in many different species (Cheney and Seyfarth 1990; Seyfarth and Cheney 1990; Green and Maegner 1998; Manser 2002) and, finally, to human language (Fitch 2010; Cangelosi 2001). The emergence of communicative systems facilitates the evolution of social structures and dynamics in animals.

### *2.2.5 Agent-Based Modeling of the Evolution of Communicative Systems*

Some researchers have proposed to study the evolution of signaling systems as sender–receiver games (Skyrms 2009), stressing the fact that such games are simple, tractable models of information transmission and that they provide a basic setting for studying the evolution of meaning. In these models it is easy to investigate not only the equilibrium structure, but also the dynamics of evolution and learning.

Some previous studies of the adaptive nature of communication for coordination found communication beneficial; others, not. Schermerhorn and Scheutz (2007) claim that this results from the lack of a systematic examination of important variables such as (i) communication range, (ii) sensory range, and (iii) environmental conditions. These authors presented an extensive series of simulative experiments where they explored how these parameters affect the utility of communication for coordination in a multi-agent territory-exploration task.

A very useful review of recent progress in computational studies investigating the emergence of communication among agents via learning or evolutionary mechanisms was published by Wagner et al. (2003). In this work, Wagner and colleagues presented a review of issues related to animal communication and the origins and evolution of language. The studies reviewed show how different elements (as population size, spatial constraints on agent interactions, and the specific tasks agents have to face) can all influence the nature of the communication systems and the ease with which they are learned and/or evolve. The authors identify some important areas for future research in the evolution of language, including the need for further computational investigation of key aspects of language such as open vocabulary and the more complex aspects of syntax.

Alarm-calling behavior in animals is one of the most intriguing behaviors exhibited by a wide range of animals, and the study of such behavior may allow us to better understand the evolutionary roots of human language. Noble and colleagues (Noble et al. 2010) proposed a model of alarm-calling behavior in putty-nosed monkeys, stressing the need for real data to determine whether a computational model is a good model of a real phenomenon (or behavior). They argued that computational modeling, and in particular the use of agent-based models, is an effective way to reduce the number possible explanations when competing theories exist. According to their approach, simulations may achieve this both by classifying evolutionary trajectories as either plausible or implausible and by putting lower bounds on the cognitive complexity required to perform particular behaviors. Of course, this last point has a lot of implications for many fields of investigation (e.g., the study of bounded rationality). The authors use the case-study method to understand whether the alarm calls of putty-nosed monkeys could be a good model for human language evolution.

In a previous article (Noble 1999), one of the same authors presents a general model that covers signaling with and without conflicts of interest between signalers and receivers. In this work, simple game-theoretic and evolutionary simulation models are used to suggest that signaling will evolve only if it is in the interests of both parties.

As we made clear above (see section 2.2.3 about animal culture), another critical issue concerns the relationship between gene and culture co-evolution. It has been argued that aspects of human language are both genetically and culturally transmitted. Nevertheless, how these processes might interact to determine the structure of language is not very clear yet. Agent-based modeling can be used to study gene-culture interactions in the evolution of communication. Smith (2002) presented a model showing that cultural selection resulting from learner biases can be crucial in determining the structure of communication systems transmitted through both genetic and cultural processes. Moreover, the learning bias that leads to the emergence of optimal communication systems in the model resembles the learning bias brought to the task of language acquisition by human infants. This result seems to suggest that the iterated application of such human-learning biases may explain much of the structure of human language.

Finally, a well-constructed presentation of different types of models implemented to study the evolution of communication and language was made in Cangelosi (2001). In this study, the distinction among signals, symbols, and words is used to analyze evolutionary models of language. In particular, the work shows how evolutionary computation techniques, such as the Artificial Life approach (artificial neural networks and evolutionary algorithms), can be used to study the emergence of syntax and symbols from simple communication signals. First of all, the author presents a computational model that evolves repertoires of isolated signals. In the model presented, the case study is the simulation of the emergence of signals for naming foods (good and bad sources of food) in a population of foragers. Then, another model is implemented to study communication systems based on simple signal–object associations. Finally, models designed to study the emergence of grounded symbols are discussed in general, including a detailed description of a work on the evolution of simple syntactic rules. In the paper, several important issues (such as symbol–symbol relationships in evolved languages and syntax acquisition and evolution) are discussed, and computational models are used to suggest an operational definition of the signal/symbol/word distinction and to better understand the role of symbols and symbol acquisition in the origin of language.

### *2.2.6 Agent-Based Modeling of Social Organization, Structures, and Dynamics in Living Organisms*

One of the most important aspects of all biological systems is the ability to cooperate. Complex cooperative interactions are required for many levels of biological organization, ranging from single cells to groups of animals (Hamilton 1964; Trivers 1971; Axelrod and Hamilton 1981; Wilson 1975).

How can natural selection lead to cooperation? This kind of question has fascinated evolutionary biologists since Darwin (Darwin 1964; Trivers 1971; Hammerstein 2003). Cooperation among relatives is usually explained by adopting the concept of kin selection: it represents the idea that selfish genes lead to unselfish phenotypes (Frank 1989; Hamilton 1963).

Concerning the evolution of cooperation among genetically unrelated individuals, various mechanisms have been proposed based on (evolutionary) game theory (Doebeli and Hauert 2005): cooperators form groups and thus they preferentially interact with other cooperators (Sober and Wilson 1998; Wilson and Sober 1994); cooperators occupy spatial positions in topological structures (e.g., lattices or networks) and interact with their neighbors—who are also cooperators (Hauert 2001; Killingback et al. 1999; Nowak and May 1992); reputation may facilitate the evolution of cooperation via indirect reciprocity (Alexander 1987; Nowak and Sigmund 1998) or punishment (Sigmund et al. 2001).

From insects to animals, the social behavior shows complex relationships between individuals and interesting effects at the population level of very local interactions.

Eusociality, i.e., the phenomenon by means of which some individuals reduce their own lifetime reproductive potential to raise the offspring of others, underlies the most advanced forms of social organization and the ecologically dominant role of social groups of individuals (from insects to humans). For more than 40 years kin selection theory, based on the concept of inclusive fitness (in evolutionary biology and evolutionary psychology, inclusive fitness is the sum of an organism's classical fitness—how many of its own offspring it produces and supports—and the number of equivalents of its own offspring it can add to the population by supporting others), has been the major theoretical explanation for the evolution of eusociality.

Nowak and colleagues (2010) showed the limitations of this approach, arguing that standard natural selection theory in the context of precise models of population structure could represent a simpler and better approach. This new perspective allowed the evaluation of multiple competing hypotheses and provided an exact framework for interpreting empirical observations.

In the animal kingdom, a well-known form of cooperative/altruistic behavior may be found in the social organization of vampire bats—more precisely, the blood-sharing activity among vampire bats.

In this pro-social behavior, of particular interest is the specific formation and maintenance of (new) social structures (i.e., roosts) from initial populations as a consequence of both (i) demographic growth and (ii) social organization. This specific example is especially interesting because of the flexible nature of roost-switching behavior shown by these animals in natural wild conditions.

A very interesting agent-based model of such natural phenomenon is described in Paolucci et al. (2006). In this work, the main hypothesis concerns the role of grooming networks in roost formation, and the investigations are performed by means of agent-based simulations based on ethological evidence (i.e., using real data to parametrize the model).

The use of simulation allows the authors to discuss generative hypotheses concerning the origin of roosts, which can emerge from individual behavior. Results obtained not only confirm the main expectations but also reveal the need for a natural ordering in grooming-partner selection. This specific ordering can be obtained not only through (i) kin-based groups but also through (ii) the maintenance of a non-kin–based precedence rule.

Individuals of most social species (even guppies) keep track of how their group-mates have treated them in the past, but only some of these social species are able to exhibit complex social behavior, complex relationships, and dynamics between individuals.

Primates, for instance, appear to also keep track of how their troop-mates treat each other. This takes much more memory, and possibly compositional reasoning; generally speaking, it requires more sophisticated cognitive abilities.

Many researchers have proposed agent-based models of social behavior and organization in different species. Several publications concern the social behavior and dynamics of non-human primates, both for the intrinsic complex nature of social behaviors in primates and for a wide range of similarities between human and non-human primates activities. Hemelrijk and Bryson (see Hemelrijk 2000; Bryson et al. 2007) presented very interesting agent-based models of social organization in non-human primates based on dominance-ranking dynamics and relationships and gender differences (e.g., in terms of aggressive behavior propensity).

## 2.3 Why Do We Need Cognitive Agents?

Group-living animals often exhibit complex (and/or complicated) social behaviors. Sometimes the pure observation of such behaviors is not sufficient to improve our understanding of reality and the best option may be to use modeling to capture essential elements of the real phenomenon or system and to better understand the dynamics governing the whole process (as shown in Campennì and Schino 2014—see also Figs. 2.1 and 2.2), the theoretical assumption about a possible simple cognitive mechanism of memory governing the reciprocal exchange of cooperative behavior and the mechanism of partner choice can represent an useful way to understand the origins of cooperation in living organisms both from a behavioral and an evolutionary perspective. The hypotheses that non-cognitive mechanisms and dynamics may allow the cooperation to emerge and spread in populations of group living animals has been shown to represent a valid alternative from the behavioral point of view (i.e., they can deal with cooperation “hic and nunc”), but not from the evolutionary perspective (i.e., they are not able to explain the related evolutionary process).

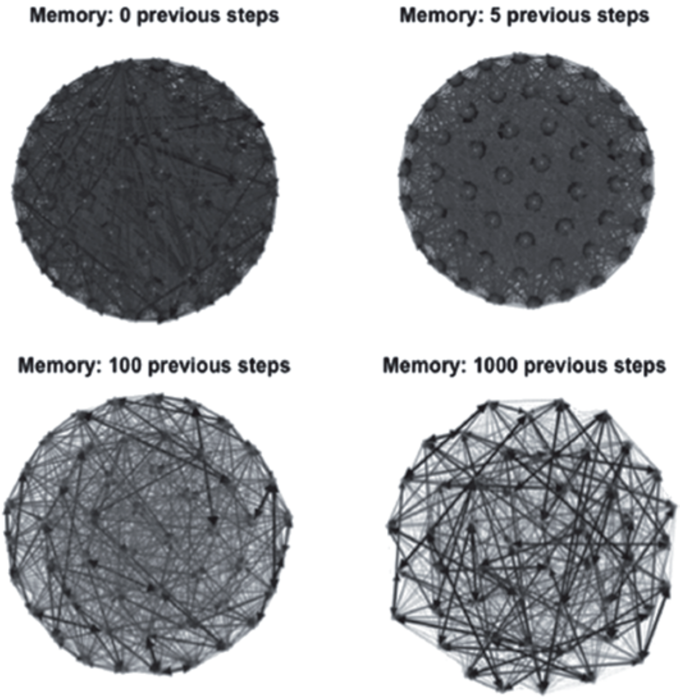


**Fig. 2.1** Social network analysis of sociometric matrices obtained as output of an ABM of cooperative behavior based on partner choice

### *2.3.1 Cooperation Theory and ABM*

The exchange of cooperative behaviors is a common feature of different animal societies. This is particularly true for those species that form stable social groups, where exchanges of cooperative behaviors (e.g., grooming, food tolerance or aggressive coalitions) are frequently observed (Dugatkin 1997; Cheney 2011).

The analysis of how group-living animals distribute their cooperative behaviors among group mates has revealed some common features that can be observed across a variety of settings and species.

First, group-living animals show differentiated social relationships: each group member interacts/cooperates frequently with some group mates and rarely, if ever, with others.

As a result, pairs of animals from the same social group may widely differ in their frequency of interaction.

Second, a positive relation is often found across pairs between cooperation given and received (Schino 2007; Schino and Aureli 2008; Seyfarth and Cheney 2012).

Among the several hypotheses that theoretical and evolutionary biologists have proposed to explain the evolution of cooperative behaviors (West et al. 2007) reciprocity is perhaps the most debated, and reviews of its empirical evidence have

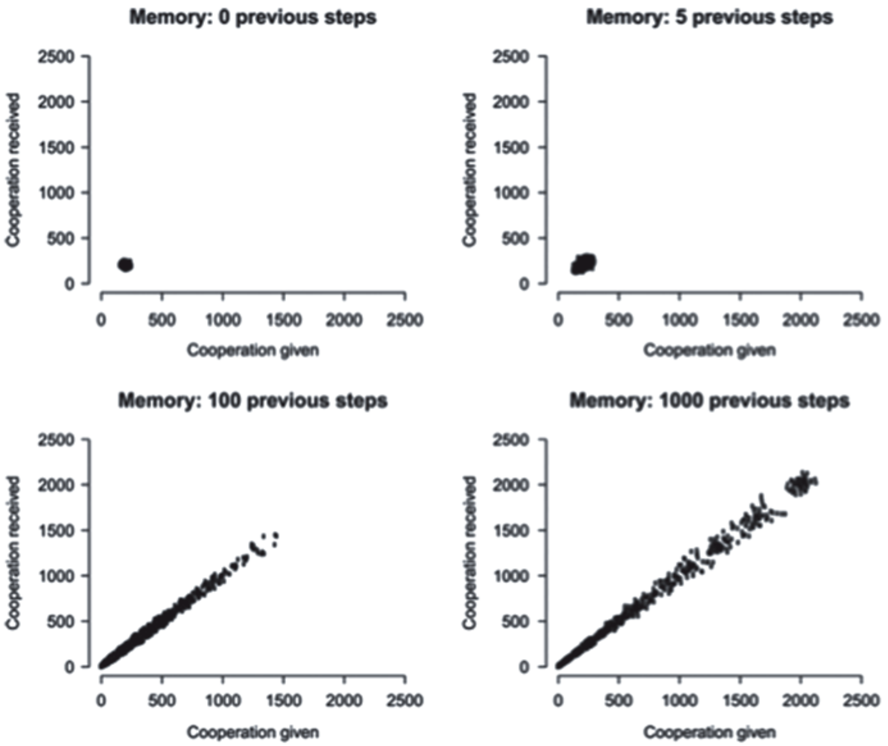


**Fig. 2.2** Correlation coefficient between cooperative acts given and cooperative acts received calculated on sociometric matrices obtained as output of an ABM of cooperative behavior based on partner choice

reached widely diverging conclusions (Cheney 2011; Clutton-Brock 2009; Schino and Aureli 2009).

Part of this confusion stems from a failure to appreciate that two different processes can underlie reciprocation.

The first process, that we could define as "temporal relations between events", is a strictly within-pair process: individual A behaves cooperatively towards individual B in relation to how B has previously behaved towards A. Each A–B dyad is conceptually isolated from all others (i.e., the presence and behavior of other individuals do not affect the behavior of A–B).

This is essentially equivalent to Bull and Rice (1991) "partner-fidelity model", to Noë (2006) "partner control model" and to classical reciprocal altruism (Trivers 1971). The classical iterated prisoner's dilemma belongs to this category of models.

The second process, that we could define as "partner choice based on benefits received", is an across-pair process with a strong comparative component: individual A behaves cooperatively towards individual B rather than individual C in relation to a comparison of how B and C have behaved towards A.

This is essentially partner choice based on outbidding competition (Noë and Hammerstein 1994) and it is equivalent to Bull and Rice (1991) and to Noë (2006) “partner-choice model” (see also Eshel and Cavalli-Sforza 1982 for an earlier study).

Empirical evidence shows reciprocal exchanges of cooperative behaviors depend more commonly on partner choice based on benefits received than on within-pair temporal relations between events (Tiddi et al. 2011; Fruteau et al. 2011).

Despite its prevalence, partner choice has been widely neglected as a general explanation for the evolution of cooperative behaviors (Sachs et al. 2004).

Theoretical modeling has focused mostly on the analysis of within-pair temporal relations between events, and a vast literature exists on the possible strategies that can promote the evolution of cooperation through this process (Bshary and Bronstein 2011; Nowak 2006; Nunn and Lewis 2001; Lehmann and Keller 2006; André and Baumard 2011).

In contrast, theoretical models of the evolution of cooperation by partner choice are comparatively rare. In some of the few existing examples, partner choice is based on the general tendency of potential partners to cooperate, rather than on actual cooperation received by each partner (Barclay 2011; Roberts 1998). As such, these models seem more relevant to indirect than to direct reciprocity. In other modeling attempts, partner choice is included in the form of the possibility to terminate a within-pair series of cooperative interactions (Sherratt and Roberts 1998; Johnstone and Bshary 2002). The relative lack of models of partner choice based on benefits received is puzzling, considering its obvious relevance for group living animals.

When developing a theoretical model of a biological phenomenon or system, one can aim either at reproducing important features of the target system “as is” (for cooperative exchanges, see Roberts 1998), or at modeling its evolution, i.e., at reproducing the changes that would occur across generations as a result of natural selection (Axelrod and Hamilton 1981).

Ideally, however, a good model should be able to reproduce both aspects of the phenomenon and if (and only if) both tests are successful a stronger case for the relevance of the principles underlying the model in explaining the target system being modeled could be made.

In this perspective ABM represent the ideal modeling tool candidate to accomplish both tasks.

## *2.3.2 Why Agent-based Models and not Other Modeling Approaches?*

### 2.3.2.1 Bottom-up Vs top-down Approach

We already tried to stress this point above in this chpater. The main difference between traditional analytical modeling (AM) and ABM is that the former is a perfect example of top-down approach, while the latter is based on the bottom-up “philosophy”.

AMs simplify the real phenomenon or system as much as possible to identify the minimal requirements (e.g., parameters) allowing the model to exhibit (almost)

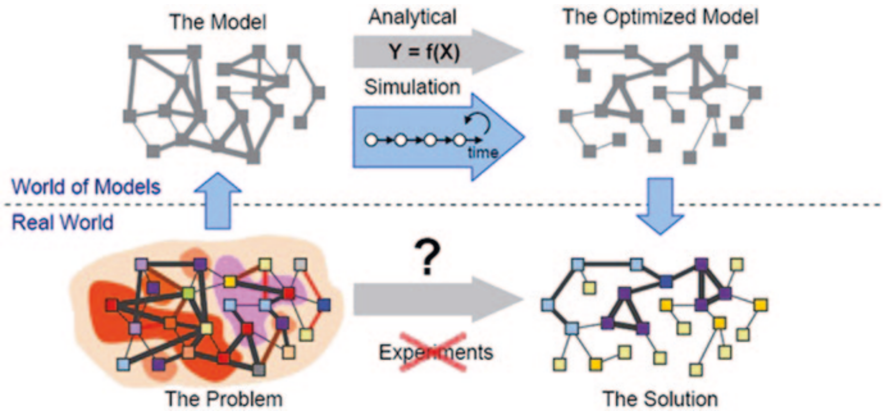


**Fig. 2.3** A comparison of analytical and simulative approaches

the same behavior (i.e., dynamics and equilibria) we can observe in reality. This of course implies that strong assumptions and simplifications need to be made in order to make the model manageable from an analytical point of view (i.e., the model needs to be solvable—there should be a solution). So, for instance, cooperation can be modeled as one of different possible outputs of a two players game, as in the case of the Prisoner Dilemma (Axelrod 1984).

ABM adopts the opposite approach, where in principle there is no limit in the definition of heterogeneous properties of individual units or agents; each agent can be different, can behave differently and can interact with other agents and the environment in a different way. The emergent behavior of the whole system is possible because the definition of individual properties, behaviors and relationships (i.e., the micro-macro path).

Moreover, ABM allows us to deal with complex systems and dynamics that per definition exhibit a non-linear behavior. In this perspective, ABM represents a useful approach to model feedbacks, loops and complex causal relationships (e.g., the downward causation Kim 1992) (Fig. 2.3)

#### 2.3.2.2 Too-Complex Dynamics and Behaviors (e.g., Impossible To Model Using an Analytical Approach)

Sometimes ABM can be the only way to model a real phenomenon or system. ABM allows us to deal with a limited number of variables and parameters, simply because the analytical model itself would not be solvable otherwise; moreover, if there is no single solution to the analytical model, ABM is often used to approximate the behavior of the original model by simulating a certain amount of times (i.e., runs) the behavior occurs starting from randomly selected initial conditions (i.e., combinations of parameters).

#### 2.3.2.3 In-Silico Data Generator

ABM can be looked at as an in-silico generator of data—a huge amount of data that could hardly be collected using an empirical or observational approach.

Of course, since they are affected by initial stochastic conditions, ABMs need to be run several times using the same set of parameters then averaged; but the very good news is that such outputs can be then used as any other kind of empirical data, applying exactly the same statistical analyses and metrics. Thus, the advantage in using ABMs as generators of data is very clear.

I had the chance to explore the usefulness and scientific relevance of using ABM in investigating social behaviors and dynamics in living organisms. In the following sections of this chapter I will present additional interesting case studies to show how the adoption of the ABM approach to investigating social behaviors and dynamics (henceforth SBD) can also be relevant and useful in other scientific domains and at different scales.

## 2.4 Social–Ecological Systems

The study of the complex social–ecological systems (SES) was inaugurated a few decades ago by a group of ecologists and economists interested in investigating the complex interconnections and tensions between (complex) ecological systems and (complex) social systems living in, and operating on, such ecologies.

A social–ecological system consists of a combination of biological, geological, and physical units and associated social actors and institutions.

Social–ecological systems present some specific characteristics, such as complexity and adaptation, and are delimited by spatial or functional boundaries surrounding particular ecosystems (Fig. 2.4).

A social-ecological system can be defined as (Redman et al. 2004, p. 163):

- A coherent system of biophysical and social factors that regularly interact in a resilient, sustained manner;
- A system that is defined at several spatial, temporal, and organizational scales, which may be hierarchically linked;
- A set of critical resources (natural, socioeconomic, and cultural) whose flow and use is regulated by a combination of ecological and social systems; and
- A perpetually dynamic, complex system with continuous adaptation. (Machlis et al. 1997; Gunderson and Holling 2002; Berkes et al. 2003)

Researchers have used the concept of social–ecological systems to emphasize the integrated concept of humans in nature and to stress that the distinction between social systems and ecological systems is artificial and arbitrary (Berkes et al. 2001)

While resilience has a somewhat different meaning in social and ecological contexts (Adger 2000), the SES approach holds that social and ecological systems are linked through feedback and loop mechanisms, and that both display resilience and complexity (Berkes et al. 2003).

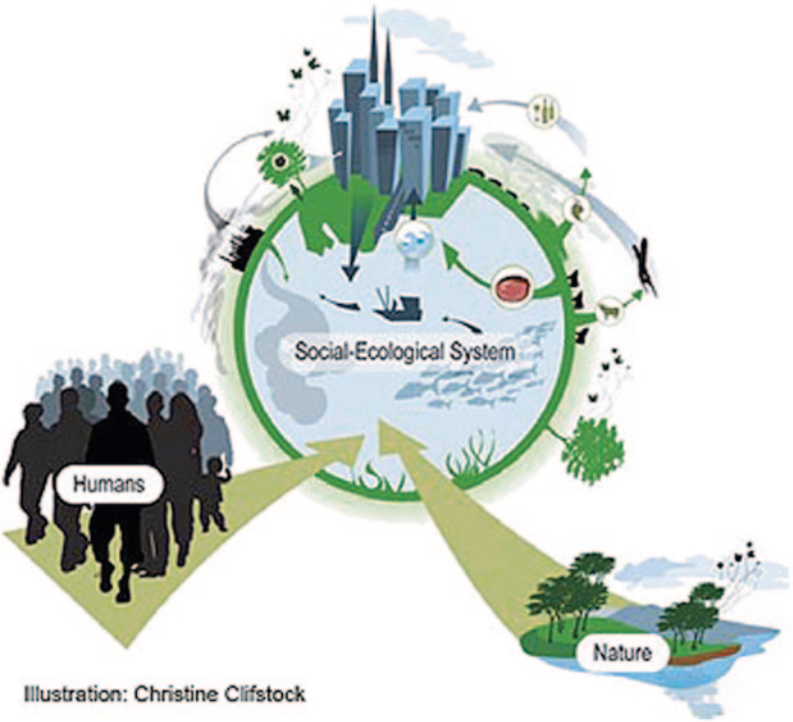


**Fig. 2.4** An illustration of the concept of SES from *Sustainable Development Update,* Issue 1, Volume 8, 2008. The *Sustainable Development Update* (SDU) focuses on the links among ecology, society, and the economy. It is produced by Albaeco, an independent, nonprofit organization. *SDU* is produced with support from Sida, the Swedish International Development Cooperation Agency, Environment Policy Division (Dr. Fredrik Moberg, Editor)

Until the appearance of this new field of scientific investigation a few decades ago, the interaction and co-operation between social sciences and natural sciences was very limited and thus so was the study of social-ecological systems. While, on the one hand, traditional ecologists had tried to ignore human actions in specific ecologies, on the other hand, researchers from social science disciplines had ignored the environment's role in defining and affecting human activity (Berkes et al. 2003).

Although some eminent thinkers (e.g., Bateson 1979) had tried to fill the gap between natural and cultural spheres, the larger part of sociological studies focused on investigating processes within the social domain only, considering ecosystems as "black boxes" (Berkes et al. 2001) and assuming that if the social system performs adaptively or is well organized institutionally it will also manage the environmental resource base in a sustainable fashion (Folke 2006).

This framework changed through the 1970s and 1980s with the rise of several social sciences subfields explicitly including the environment (Berkes et al. 2003).

Among them, environmental ethics arose from the need to develop a philosophical framework for relations between humans and the environment where they live

(Berkes et al. 2001); political ecology, from the need to expand ecological concerns to the include cultural and political activity within an analysis of socially constructed ecosystems (Greenberg and Park 1994); environmental history, from the growing collection of material documenting different relationships between societies and their environment; ecological economics, from examining the link between ecology and economics and integrating the scientific framework of economics within the concept of the ecosystem (Costanza et al. 2001); common property, from the integration of resource management and social organization and the analysis of how institutions and property-rights systems deal with the dilemma of the "tragedy of the commons" (McCay and Acheson 1987; Berkes 1989); and, finally, from traditional ecological knowledge, which refers to ecological understanding built, not necessarily by experts, but more simply by people who live and use the resources of a particular place (Warren et al. 1995).

Each of the six summarized areas represents a scientific "bridge," combining a natural science and social science perspective (Berkes et al. 2003).

SES theory had been inspired by systems ecology and complexity theory; nevertheless, the concept of SES does not conceptually overlap those of system ecology and complex systems.

The studies of SES include some central societal concerns (e.g., equity and human well-being) that have traditionally received little attention in complex adaptive systems theory (It should be noted that there is growing attention in this direction and an academic proliferation of institutes and programs integrating the former with the latter—see, e.g., the Julie Ann Wrigley Global Institute of Sustainability at ASU, the Atkinson Center for a Sustainable Future at Cornell University, or the Sustainable Systems Program of the School of Natural Resources and Environment at University of Michigan); and conversely, there are areas of complexity theory (e.g., quantum physics) that have little direct relevance for understanding SES (Cumming 2011) (at least thus far to our knowledge).

SES theory incorporates ideas from theories relating to the study of resilience, sustainability, robustness, and vulnerability (e.g. Levin 1999; Berkes et al. 2003; Gunderson and Holling 2002; Norberg and Cumming 2008). While SES theory draws on a range of discipline-specific theories, such as island biogeography, optimal foraging theory, and microeconomic theory, it is much broader than any of these individual theories alone (Cumming 2011).

Because of its recent development and scientifically young age, SES theory has emerged from a combination of disciplinary platforms (Cumming 2011), while the notion of complexity developed through the work of many scholars, notably the Santa Fe Institute (2002). From this perspective it could be argued that complex system theory is one of the most important "intellectual parents" of SES (Norberg and Cumming 2008). However, due to the social context in which SES research operates, and the potential (and sometimes actual) impact of SES research on policy recommendations that will have consequences on real people's lives, SES research has been considerably more "self-sustaining" and more "pluralistic" than complexity theory has ever acknowledged (Cumming 2011).

Studying SESs from a complex-system perspective is a fast-growing interdisciplinary field which can be interpreted as an attempt to link different disciplines into a new body of knowledge that can be applied to solve some of our most serious actual environmental problems (Cumming 2011).

Management processes in the complex systems can be improved by making them adaptive and flexible and able to deal with uncertainty and volatility, and by building in the capacity to adapt to change. SESs are both complex and adaptive, meaning that they require continuous testing and study in order to develop the knowledge and understanding needed in order to cope with change and uncertainty (Carpenter and Gunderson 2001).

A complex system differs from a simple system in that it has a number of attributes that cannot be observed in simple systems, such as emergence, self-organization, non-linearity, uncertainty, and scale (Berkes et al. 2003; Norberg and Cumming 2008). As argued above, ABM is one of the best conceptual and scientific tools to implement models that are able to deal with such properties.

Emergence is the appearance of behavior that could not be anticipated from knowledge of the parts of the system alone.

Self-organization is one of the defining properties of complex systems. The basic idea is that open systems will reorganize themselves at critical points of instability. Holling's adaptive renewal cycle is an illustration of reorganization that takes place within the cycles of growth and renewal (Gunderson and Holling 2002). The self-organization principle, operationalized through feedback and loop mechanisms, applies to many biological and social systems and even to mixtures of simple chemicals. High-speed computers and nonlinear mathematical techniques help simulate self-organization by yielding complex results and yet strangely ordered effects. The direction of self-organization will depend on such things as the system's history; it is path dependent and difficult to predict (Berkes et al. 2003).

Nonlinearity is related to fundamental uncertainty (Berkes et al. 2003). It generates path dependency, which refers to local rules of interaction that change as the system evolves and develops. A consequence of path dependency is the existence of multiple basins of attraction in ecosystem development and the potential for threshold behavior and qualitative shifts in system dynamics under changing environmental influences (Levin 1998).

Scale is important when dealing with complex systems. In a complex system many subsystems can be distinguished; and since many complex systems are hierarchic, each subsystem is nested in a larger subsystem (Allen and Starr 1982). For instance, a small watershed may be considered an ecosystem, but it is a part of a larger watershed that can also be considered an ecosystem and an even larger one that encompasses all the smaller watersheds (Berkes et al. 2003). Phenomena at each level of the scale tend to have their own emergent properties, and different levels may be coupled through feedback relationships (Gunderson and Holling 2002). Therefore, complex systems should always be analyzed or managed simultaneously at different scales.

### *2.4.1 Role of Traditional Knowledge in SES*

Berkes and colleagues (Berkes et al. 2001) distinguish four sets of elements which can be used to describe social–ecological system characteristics and linkages: ecosystems, local knowledge, people and technology, property-rights institutions (for an updated theory of role of traditional knowledge see Fig. 2.5 from Tengö, M., Brondizio, E. S., Elmqvist, T., Malmer, P., & Spierenburg, M. (2014). Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach. Ambio, 43(5), 579–591.

Acquiring knowledge about SESs is an ongoing, dynamic learning process, and such knowledge often emerges within institutions and organizations. The effectiveness of this process requires the involvement of institutions and may be implemented by means of multi-level social networks. It is thus the communities which interact with ecosystems on a daily basis and over long periods of time that possess the most relevant knowledge of resource and ecosystem dynamics, together with associated management practices (Berkes et al. 2000). Some scholars have suggested that management and governance of SESs may benefit from a combination of different knowledge systems (McLain and Lee 1996); others have attempted to import such knowledge into the scientific knowledge field (Mackinson and Nottestad 1998). There are also those who have argued that it would be difficult to separate these knowledge systems from their institutional and cultural contexts (Berkes 1999) and those who have questioned the role of traditional and local knowledge

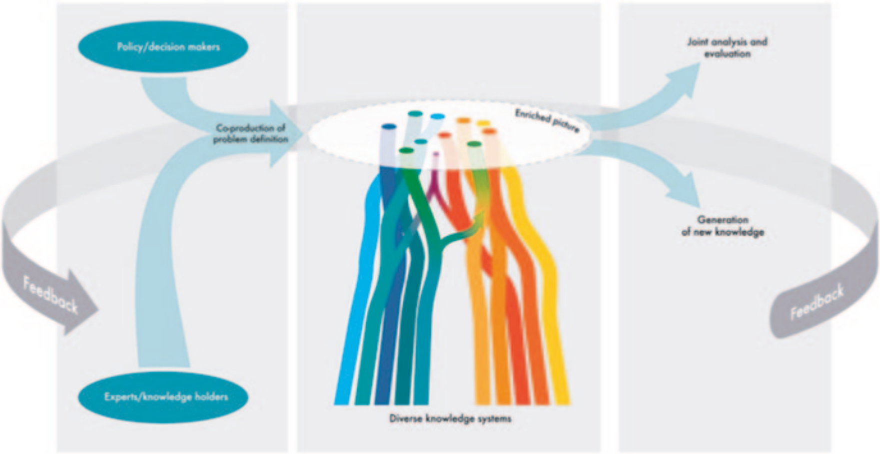


**Fig. 2.5** Outlining three phases of a multiple evidence base approach, emphasizing the need for co-production of problem definitions as well as joint analysis and evaluation of the enhanced picture created in the assessment process. Phase 1 concerns defining stakeholders, problems, and goals in a collaborative manner. Phase 2 entails bringing together knowledge on an equal platform, using parallel systems of valuing and assessing knowledge, and Phase 3 is the joint analysis and evaluation of knowledge and insights to generate multilevel synthesis and identify and catalyze processes for generating new knowledge

systems in the current situation of pervasive environmental change and globalized societies (Krupnik and Jolly 2002).

Other scholars have claimed that valuable lessons can be extracted from such systems for complex system management, lessons that also need to account for interactions across temporal and spatial scales and organizational and institutional levels (Pretty and Ward 2001), in particular during periods of rapid change, uncertainty, and system reorganization (Berkes and Folke 2002).

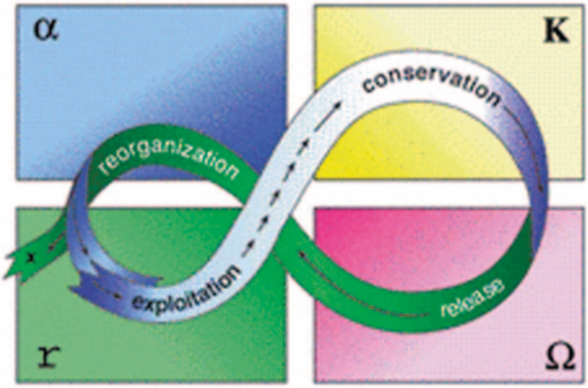
### 2.4.2 The Adaptive Cycle

The adaptive cycle, originally conceptualized by Holling (1986), interprets the dynamics of complex ecosystems in response to perturbations and change. In terms of its dynamics, the adaptive cycle has been described as moving slowly from exploitation (r) to conservation (K), maintaining and developing very rapidly from K to release (W), and continuing rapidly to reorganization (a) and back to exploitation (r) (Gunderson and Holling 2002).

Depending on the particular configuration of the system, it can then begin a new adaptive cycle or alternatively it may transform into a new configuration, shown as an exit arrow (see Fig. 2.6). The adaptive cycle is one of the five heuristics used to understand social–ecological system behavior (Walker et al. 2006), the other four heuristics being resilience, panarchy, transformability, and adaptability. Each of these concepts is of considerable conceptual appeal and is claimed to be generally applicable to ecological and social systems as well as to coupled social–ecological systems (Gunderson and Holling 2002).

The two main dimensions that determine changes in an adaptive cycle are connectedness and potential (Gunderson and Holling 2002). The connectedness dimension is the visual depiction of a cycle and stands for the ability to internally control its own destiny (Holling 2001). It "reflects the strength of internal connections that mediate and regulate the influences between inside processes and the outside world"

**Fig. 2.6** Panarchy—graphical representation



(Gunderson and Holling 2002, p. 50). The potential dimension is represented by the vertical axis, and stands for the "inherent potential of a system that is available for change" (Holling 2001, p. 393). Social or cultural potential can be characterized by the "accumulated networks of relationships-friendship, mutual respect, and trust among people and between people and institutions of governance" (Gunderson and Holling 2002, p. 49). According to the adaptive cycle heuristic, the levels of both dimensions differ during the course of the cycle along the four phases. The adaptive cycle thus predicts that the four phases of the cycle can be distinguished based on distinct combinations of high or low potential and connectedness.

### *2.4.3 Adaptive Governance and SES*

The resilience of social–ecological systems is related to the degree of the shock that the system can absorb and remain within a given state (Evans 2011). The concept of resilience is a promising tool for analyzing adaptive change towards sustainability because it provides a way for analyzing how to manipulate stability in the face of change.

In order to emphasize the key requirements of a social–ecological system for successful adaptive governance, Folke and colleagues (Folke et al. 2002) contrasted case studies from the Florida Everglades and the Grand Canyon. Both are complex social–ecological systems that have experienced unwanted degradation of their ecosystem services but differ substantially in terms of their institutional make-up.

The governance structure in the Everglades is dominated by the interests of agriculture and environmentalists who have been in conflict over the need to conserve the habitat at the expense of agricultural productivity throughout history. Here, a few feedbacks between the ecological system and the social system exist, and SES is unable to innovate and adapt (the α-phase of reorganization and growth).

In contrast, different stakeholders have formed an adaptive management workgroup in the case of Grand Canyon, using planned management interventions and monitoring to learn about changes occurring in the ecosystem, including the best ways to subsequently manage them. Such an arrangement in governance creates the opportunity for institutional learning to take place, allowing for a successful period of reorganization and growth. Such an approach to institutional learning is becoming more common as NGOs, scientist, and communities collaborate to manage ecosystems (Evans 2011).

### *2.4.4 Links to Sustainable Development*

The concept of social–ecological systems has been developed in order to provide both promising scientific gains as well as to impact problems of sustainable development. A close conceptual and methodological relation exists between the analysis of social–ecological systems, complexity research, and transdisciplinarity. These three research concepts are based on similar ideas and models of reasoning. Moreover, the research on social–ecological systems almost always uses a transdisciplinary approach in order to achieve and ensure integrative results. Problems of sustainable development are intrinsically tied to the social–ecological system defined to tackle them. This means that scientists from the relevant scientific disciplines or field of research as well as the involved societal stakeholders have to be regarded as elements of the social–ecological system in question.

## 2.5 Earth System Dynamics and the Syndromes Approach

### *2.5.1 Syndromes Concepts*

The main idea behind the "syndromes" approach (see Petschel-Held et al. 1995) is to couple the dynamics of ecosphere and anthroposphere.

The "holistic" approach proposed by Schellnhuber, Petschel-Held, and their colleagues (Schellnhuber et al. 1997; Petschel-Held et al. 1999; Petschel-Held and Reusswig 1999) aims at considering the Earth System itself as a sort of "system of systems," where the massive use of simulations of social- and ecological dynamics may help us to better understand the complex behavior of our planet.

The main criticism of different approaches (mainly, those considering models of the Earth System where the main effort is trying to reproduce and mimic micro-behaviors and properties of different components, more than dynamics) is that "analogous modeling by reproduction of the quantitative actual structure of the system may gain forecasting and hindcasting power only when the degree of sophistication becomes excessive" (Schellnhuber et al. 1997) (i.e., which, an exact copy of the real system of course, is scientifically quite useless).

The "syndromes" approach postulates that the overall phenomenon "Global Change" should be investigated as a co-evolutionary process of dynamic partial patterns and that these patterns "are bundles of interactive processes that are widespread and appear repeatedly in typical combination—the syndromes of global change".

In this perspective, syndromes are not simple complexes of causes and effects; they are patterns of interactions, frequently presenting feedbacks (see the concept of emerging cooperative phenomena in complex systems science).

Syndromes have a clear qualitative identity that cannot be quantified or measured using algorithms, metrics, or values. Because of this "soft identity" of syndromes and their interdisciplinary composition (syndromes are "active zones" of problematic environmental and development processes, rather than static patterns), we need specific and sometimes innovative methods of investigation, such as decomposition of complex functional networks, qualitative reasoning concepts, modeling of fuzziness and uncertainty, knowledge-acquisition strategies, and set-values analysis.

We have to take into account about 80 operating symptoms in doing a diagnosis of Earth System syndromes (contributing to the presence of different syndromes), such as urban sprawl, increasing significance of NGOs, terrestrial run-off changes deposition and accumulation of waste, increasing mobility, tropospheric pollution, and increasing consumption of energy and resources.

The names of these symptoms have to be interpreted as guiding headlines and not as definitions; they concern different spheres (e.g., atmosphere, biosphere, anthroposphere) and focus on qualitative and quantitative changes of the Earth System.

For Global Change analysis purposes the simple identification of symptoms is not sufficient; what is also crucial is the way they interact with each other. Such interactions have one "target symptom" and one or more "source symptoms" representing the causal connections between the symptoms involved.

The symptoms metaphor represents a dynamic and trans-disciplinary language to describe the Global Change phenomena. Symptoms indicate possible critical shifts towards nonsustainability. Since Global Change mainly refers to "anthropogenic" processes, symptoms usually are either direct expressions of human actions (for example, change of consumption patterns) or they are indirectly induced by it (for example, anthropogenic climate change). Thus, the micro–macro links, connections, and dynamics are critical for the syndromes approach; behaviors, habits, and interactions at the individual level may produce significant and critical effects at the global level (e.g., at the group, ecosystem, Earth System level).

The Earth System is not only a functional unit, it is a geographical one as well. This means that the correct use of the syndromes approach has to consider also the spatial scale of symptoms; otherwise there is a risk that important elements of the examined phenomenon may be missed.

## 2.6 Conclusions

This chapter presented an overview of some interesting applications of the agent-based modeling approach for investigating social behaviors and dynamics in living organisms; we also presented additional scientific domains (namely, the Social–Ecological Systems and Earth System Dynamics scientific fields) where ABM already represents or potentially could represent a very useful and promising approach.

Some of the main social behaviors and dynamics investigated in living organisms were presented—such as cooperation, information transmission and communicative systems, culture and imitation—in an effort to highlight the crucial role played by cognitive mechanisms and processes (e.g., social cognition).

ABM was analyzed as a scientific method and tool, and the argument was made that it may represent the best approach to dealing with complex nonlinear phenomena and dynamics.

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