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.

The main assumption beyond ABM is the possibility of dealing with the heterogeneity of individual units of the model (i.e., agents) and emergent properties and dynamics in complex systems.

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 oppo-

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site perspective, i.e., the so-called bottom-up perspective, where the main effort of 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; Campenni 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 programming language: 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

Animal social behavior and cognition are characterized by a certain number of different capacities, such as social learning, gaze following, theory of mind, and imitation; moreover, most animals show at different degrees of complexity a system of communication that allows them to express a wide range of emotions, moods, social relationships, and mental representations, sharing many mechanisms typical of the human language.

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.

Over the last years, researchers working in the field of comparative social cognition have begun to include in the range of their investigation non-primate mammals (dogs, rats, goats), many bird species (among corvids, jays, crows, ravens), reptiles, fish, and social insects (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 cum grano salis, 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.

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 when 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 the section 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).

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