

## Chapter 1

### The Agent-Based Perspective on Imitation

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#### 1.1 Introduction

This chapter presents the agent-based perspective on imitation. In this perspective, imitation is best considered as the behavior of an *autonomous agent* in relation to its environment, including other autonomous agents. We argue that such a perspective helps unfold the full potential of research on imitation and helps in identifying challenging and important research issues. We first explain the agent-based perspective and then discuss it in the context of particular research issues in studies with animals and artifacts, with reference to chapters presented in this book. At the end of the chapter we briefly introduce the individual contributions to this book and provide a roadmap that helps the reader in navigating through the exciting and highly interwoven themes that are presented in this book.

In order to focus discussions, we explain the agent-based perspective with particular consideration of the *correspondence problem*, an important issue in research on imitation which is discussed in more detail in chapter 2. For the purpose of this chapter, the

correspondence problem can be characterized as follows: Given an imitator (a biological or artificial system) trying to imitate a model (the biological or artificial system to be imitated), how can the imitator identify, generate and evaluate appropriate mappings (perceptual, behavioral, cognitive) between its own behavior and the behavior of the model? In order to illustrate this problem figure 1.1 shows different tetrapod bodies. Arrows indicate where one would intuitively, and based on knowledge of the tetrapod body plan, identify structural correspondences. Movements of these agents and their interactions with the environment are however different, *e.g.* what is the corresponding movement of a human to a dolphin flapping its hind flipper? Even two members of the same species have different embodiments, due to individual differences, developmental differences (ontogeny), environment, experience, and other factors.

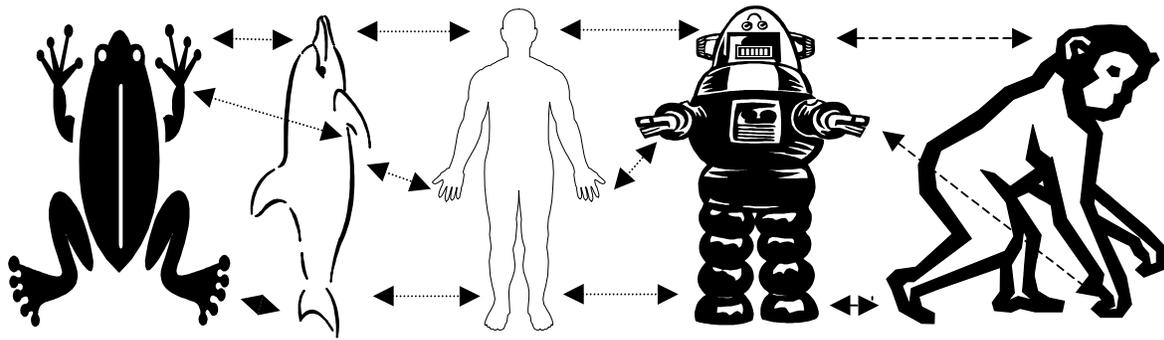


Figure 1.1: Structural homologies among tetrapod animals/artifacts.

However, even systems with very dissimilar bodies and body plans such as a hummingbird, a helicopter and a humble bee can achieve the same behavior "hovering", exploiting the same laws of physics, see figure 1.2. Thus, even among agents with very dissimilar bodies, it makes sense to talk about imitation being realized, if appropriate correspondences exist.

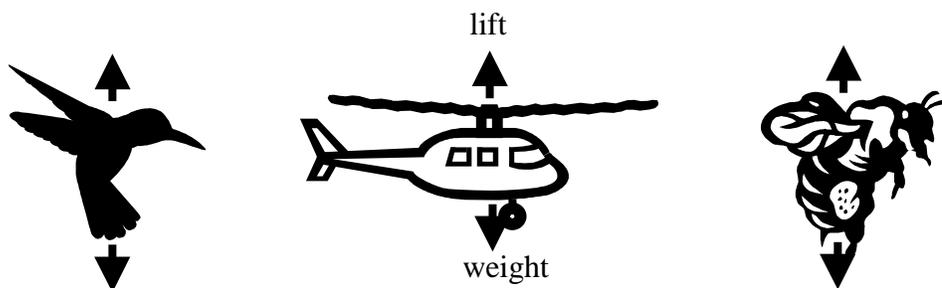


Figure 1.2: Achieving hovering behavior with dissimilar bodies.

## 1.2 The Agent-Based Perspective: Imitation in Context

In this chapter (see also chapter 2) we discuss correspondences between systems (animals or artifacts) with different or similar bodies. Often, research on imitation with artifacts views imitation as an efficient *mechanism* which can be exploited to implement socially mediated learning and adaptation. What we would like to argue in this chapter is that in order to better understand the whole scope and potential of imitation in animals and artifacts, as well as its phylogeny and ontogeny in biological systems, an agent-based perspective is beneficial and necessary. This means, imitation is best considered as the behavior of an *autonomous agent* in relation to its environment. In other words, viewing

imitation solely as a *mechanism* which can be isolated from the system, its embodiment and its environment and then generalized as a general-purpose mechanism *e.g.* for social learning, significantly narrows the field of study, and is likely to unnecessarily confine the application of research on imitation to the area of machine learning. As we will show below when discussing this viewpoint in the context of particular research questions, an agent-based perspective prevents us from a too narrow interpretation of what imitation is and what important parameters are that need to be considered in research on imitation. What can be gained from this perspective? To give two examples: historically, in robotics research, research on imitation is often devoted to the development of a robot control architecture that identifies salient features in the movements of an (often visually observed) model, and maps them appropriately to motor outputs of the imitator (cf. one of the first examples of robotic imitation in (Kuniyoshi *et al.* 1990, 1994)). Model and imitator are usually not *interacting* with each other, neither are they sharing and perceiving a common *context*. Also, the *social dimension* of imitation (and corresponding issues of when and why should an agent imitate) is usually ignored. Robotics research is easily biased towards separating the *mechanism* of *e.g.* learning by imitation from the phylogenetic and ontogenetic history of imitation, and the particular embodied and situated context in which imitation occurs in nature. Thus, robotics research has often been limited to the question *how* to imitate, focusing on the 'here and now', *i.e.* focusing on a particular robotic system and its imitation 'task', prespecified by the experimenter. Not unsurprisingly, this has led to very diverse approaches to robot controllers for imitative learning, and the difficulty to generalize to different contexts and different robotic platforms. An exception and example where an architecture developed for *learning by imitation* has been applied to different

robot platforms and contexts is described by Billard (this volume). However, it remains to be seen how such an approach could be realized for *learning/trying to imitate*, an at present unsolved and open research problem. So far, the exploration of the design space of architectures and models for imitation is usually neither systematic nor theory-driven.

Novelty and other issues regarding the general nature of imitation as discussed in animal imitation research usually do not play a significant role in robotics imitation research. However, as we discuss below, an agent-based perspective has a broader view and includes five central questions ("*Big Five*") in designing experiments on research on imitation, namely who, when, what, and how to imitate, in addition to the question of what makes a successful imitation. A systematic investigation of these research questions could therefore shed light on the full potential of imitation from an agent-based perspective. That might lead to robots that can recognize good teachers, select what to imitate on their own, and imitate when appropriate, e.g. imitate in order to acquire new skills or imitate as a means of communication with other agents. Such agents might be able to apply and control imitation as part of their larger behavior repertoire, part of their strategy to survive in a social world, rather than being machines that are designed solely as imitating machines.

The possible contribution of the agent-based perspective to research on animal imitation is quite different: it might help in concretizing models and theories on animal imitation by drawing attention to the *how* question: How are particular elements of a model or theory based in mechanisms at a level of description such that agent-based physical or computational models can be built that might validate these models or theories? Biologists try to understand a biological system by analyzing and describing it, but they traditionally

do not attempt to synthesize a machine that might look and behave like the animal. But a robotic experiment that is based on the implementation of a particular model of animal imitation could validate the model, in the sense that it can show that the model really works, at least for a particular agent and environment set up. Conversely, it could reveal gaps, inconsistencies, levels of detail not fleshed out in theory, as well as overlooked issues and assumptions. Experiments with artifacts can confirm whether a particular model is *sufficient* to generate imitative behavior. Of course such experiments cannot replace studies with animals that need to show whether the model holds true for animal systems. But studies with robotic and computational agents might identify new research questions and inspire studies with animals. For example, the correspondence problem which has been identified as an important problem in imitation with artifacts (see the next chapter), has not been discussed extensively in research on animal imitation. A potential explanation might be that animals that do imitate 'naturally' tend to imitate conspecifics, *i.e.* members of the same species having bodies very similar to their own. Size differences might still be obvious (*e.g.* when an infant chimpanzee imitates her mother), but generally we do not ask questions like "why is the infant responding to arm movements with arm movements?" Building a robot which is responding to a particular observed movement with a particular response lets us appreciate the full complexity of the correspondence problem, that is seemingly solved with ease by animals that imitate (compare chapter 3 on dolphin imitation).

In order to justify the agent-based perspective on imitation, we now first explain and define the concept of autonomous agent and show the implications of applying this concept to the

study of imitation. We then give examples from the study of imitation in animals and artifacts which support this agent-based perspective.

### **Biological and Constructed Agents**

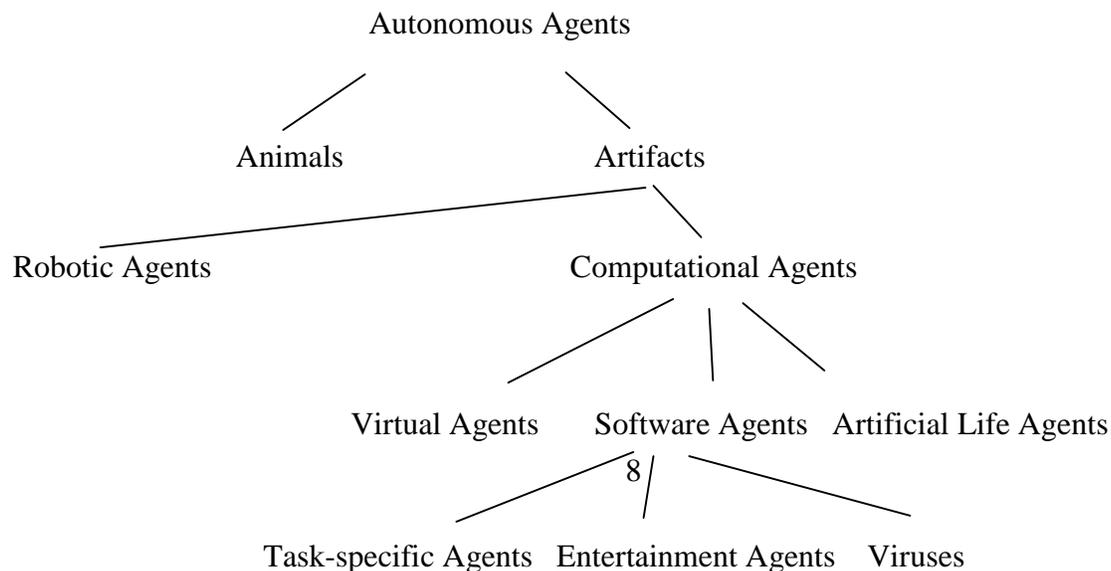
Recently, the concept of agents and autonomous agents has attracted significant attention in areas as diverse as Artificial Intelligence, Economics, Artificial Life, and Social Sciences; for overviews and reviews on agent-based modeling and agent research, see *e.g.* Wooldridge & Jennings 1995; Bradshaw 1997; Jennings *et al.* 1998; Dautenhahn 1998, Dautenhahn 2000b. The concept of agent goes back to Carl Hewitt's computational *actor* model published in 1977 (Hewitt, 1977) that suggested to model problem-solving as the activity of a society of primitive objects, the actors, that cannot be decomposed further (*cf.* Minsky, 1985). In the actor programming methodology actors are executed concurrently and interact purely locally by sending messages to each other. Control is therefore decentralized in a society of self-contained actors that locally know about each other.

In particular in the 1990's the terms *agent* and *autonomous agent* became widely used in both the robotics as well as Artificial Intelligence community. Based on an interest in animals and robotic agents, Luc Steels (Steels, 1995) characterized an autonomous agent as 1) a system, consisting of a set of elements interacting with each other and the environment, 2) performing a particular function for another agent or system, and 3) as capable of maintaining itself, *i.e.* a self-sustaining system. In the area of software systems a variety of properties of agents have been identified and discussed by Wooldridge and Jennings (1995):

- *Autonomy*: agents operate without direct intervention of humans or others, and have some kind of control over their actions and internal state.
- *Social ability*: agents interact with other agents and possibly humans via some kind of agent-communication language.
- *Reactivity*: agents perceive their environment (the physical world, a user via graphical user interface, a collection of other agents, the internet, combinations of these), and respond in a timely fashion to changes that occur in it.
- *Pro-activeness*: agents do not simply act in response to their environment, they are able to exhibit goal-directed behavior by taking the initiative.

Other, more specific attributes of agency like mobility, rationality and others are often added to the above list in stronger notions of agency. A widely known definition of an *autonomous agent* was proposed by Franklin and Graesser (1997):

An *autonomous agent* is a system situated within and a part of the environment that senses that environment and acts on it, over time, in pursuit of its own agenda



and so as to affect what it senses in the future.

Figure 1.3: A taxonomy of autonomous agents, modified from (Franklin & Graesser, 1997).

This definition is very attractive since it applies easily both to animals and artifacts. Franklin and Graesser (1997) propose a natural kinds taxonomy of agents. Figure 1.3 shows a modification of this taxonomy adapted to the specific subject of this chapter.

Biological agents are historical agents, situated in time and space, their morphologies and behavior reflect the "history" of phylogeny and ontogeny, that also makes every biological agent unique. This applies to a single-cell organism such as *E. coli* or *Paramecium* as well as to multicellular organisms. Experiences during the life time of an organism are shaping its body, behavior and mind. This is particularly developed in organisms that can actively remember the past, reconstruct their history. In (Dautenhahn, 1996) the term *autobiographic agent* is defined as follows: "Autobiographic agents are agents which are embodied and situated in a particular environment (including other agents), and which dynamically reconstruct their individual *history* (autobiography) during their lifetimes".<sup>1</sup>

An autonomous agent perspective on imitation means that an agent is more than a Xerox machine that is producing photocopies, more than a puppet-on-a-string robot tele-controlled by a skilled operator (such a perspective is therefore narrower than the definition

of imitation as discussed by Mitchell (this volume)). An *autonomous, autobiographic agent* is able to represent, access and to some extent control its behavior and relationship to the (social) environment, based on experiences in the past and predictions about the future. Based on its phylogeny and ontogeny, an animal agent anticipates what is likely to happen next, and prepares itself to act appropriately in response (W. J. Smith, 1996). This does not mean that the remembering, anticipation and prediction need to be “conscious” in any sense. Indeed, these notions apply as much to bacteria and bugs as they do to mammals, including humans.

Now, what does this short review of the concept of autonomous agents contribute to imitation and the correspondence problem? To begin with, it provides a common viewpoint applicable to both animals and artificially constructed agents and thus bridges biology and the sciences of the artificial. If animals, robots, and software agents are all instances of *agents*, then general principles and problems of autonomous autobiographic agents inhabiting a shared context arise repeatedly in the designs of their imitative and social learning abilities. These designs may be those of nature, whose secrets biologists and psychologists attempt to unravel, or they may be artificial ones, which roboticists and other system builders seek to engineer.

It is an interesting observation that in fields as diverse as software engineering, cognitive science, and robotics, where researchers try to understand natural intelligence and attempt to describe, model, simulate and build systems that show (aspects of) natural intelligence,

the concept of *autonomous agents* has proved to be valuable, despite the fact that in particular in the early years the concept was often used very vaguely and diversely. It is obviously advantageous to think about distinct, self-contained, autonomous entities as the basic objects of study. We might even speculate about the evolutionary origin of this tendency to conceptualize the world in terms of interacting agents: According to the *Social Intelligence Hypothesis* the evolution of primate intelligence is linked with an increase of the complexity of primate social life (see articles in Byrne & Whiten 1988, Whiten & Byrne 1997). The argument suggests that during the evolution of human intelligence a transfer took place from social to non-social intelligence so that hominid primates could transfer their expertise from the social to the non-social domain (see review in Gigerenzer 1997). An interesting aspect of this kind of transfer is given by Mithen (1996), who explains the evolution of anthropomorphic thinking with an accessibility between the domains of social intelligence and natural history intelligence so that "people could be thought of as animals, and animals could be thought of as people", (Mithen 1996, p. 224).

Furthermore, the accessibility between the domains of social and technical intelligence led to the possibility of thinking about people in terms of objects to be manipulated, in a similar way as physical objects can be manipulated. If this overlap between the technical and social domain is mutual, then this could explain why we tend to think of artifacts in terms of social entities. Reeves and Nass (1996) have convincingly shown that humans tend to treat computers (and media in general) as people, and the same is suggested for robots (Bumby and Dautenhahn, 1999). Treating robotic and software agents as people opens up a rich source of knowledge of the social world, knowledge about relations,

communication, cooperation, etc. Recognizing the power of harnessing such correspondences between natural agents for predicting each other's behavior suggests that they might be profitably applied in developing certain artificial ones. As a design paradigm to help ground meaning in interactive constructive biology and computational systems, Nehaniv (1999a, 1999b) has advocated the application of such “egomorphic principles”—*i.e.* useful metaphors and mappings in design that exploit correspondences of an agent's *first person* embodiment with that of other agents, in effect, making them into *second persons*. Similarly, using an agent-based perspective in the study of imitation can give us access to a rich source of knowledge that we have on biological agents. An agent is situated in time and space, agents are not identical, they have a unique perspective and life-history reflected in their behavior and their bodies. Also, a biological agent occupies a particular *ecological niche* representing its particular biotic and abiotic relationships with the environment, it is as such experiencing, responding to, creating, and being part of its *Umwelt*, its own individual surrounding world (Uexküll 1909); compare also Fritz and Kotrschal's ethological approach to avian imitation (this volume).

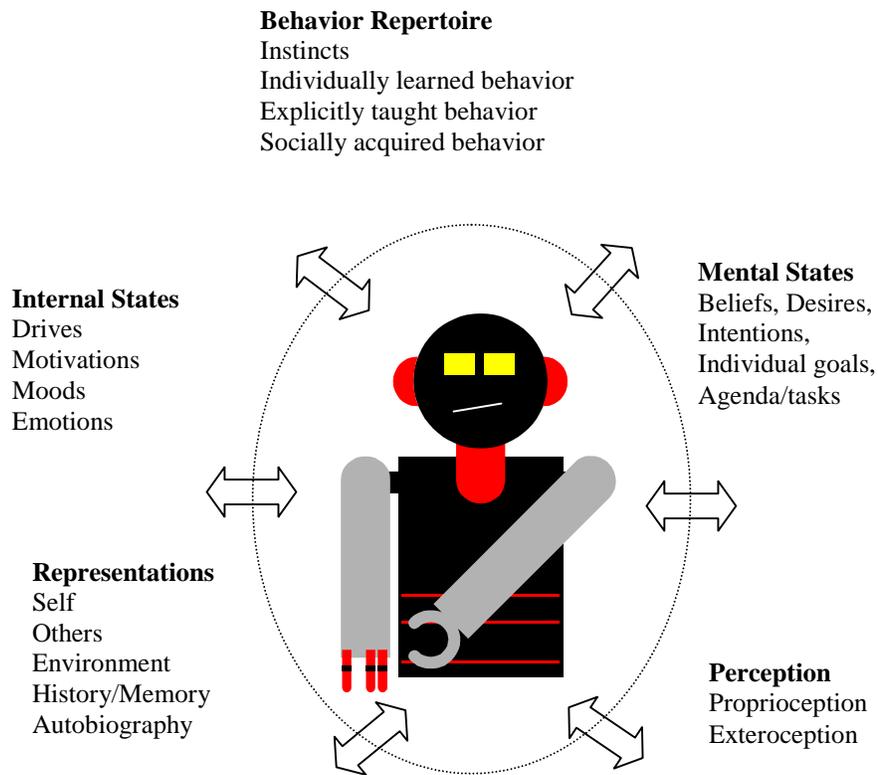


Figure 1.4: A hypothetical *autonomous, autobiographic agent*: situated in time and space, historically grounded, and structurally coupled with its environment (embodied).

Figure 1.4 shows a hypothetical agent and aspects of its embodiment that can be modeled in order to make it an autonomous, autobiographic agent (the list is not exhaustive, and depending on the particular design philosophy adopted by the designer those issues might be addressed in a variety of ways and with different emphasis).

Let us now discuss a few consequences of this agent-based perspective on imitation, with a particular focus on the correspondence problem.

### **Agents are part of a (social) environment: the case of enculturated agents**

Autonomous *social agents* are embedded in a social and cultural environment. As pointed out *e.g.* by Herman (this volume) and by Call and Carpenter (this volume), the issue of *enculturation* plays an important part in discussions on the interpretation of experiments which are designed to show whether certain animals can imitate or not (Tomasello *et al.*, 1993; Whiten & Custance, 1996; Hayes & Hayes, 1952). Apes who are raised by humans and grow up in a typically human social and cultural environment are more likely to demonstrate imitative abilities than apes who are mother-reared. Herman (this volume) discusses that enculturation might play a role in his studies with captive dolphins who have intensive daily contact with humans. Distinctive differences between imitative abilities of mother-reared versus enculturated apes are also noted. Tomasello *et al.* (1993) systematically studied the skills of apes to reproduce modeled actions. Subjects included mother-reared chimpanzees and bonobos, enculturated chimpanzees and bonobos, and two-year old human children. Results show that the mother-reared non-human apes hardly show any imitative learning of novel actions (both with respect to ends and means of the actions). In contrast, the enculturated apes and the human children showed much more frequent imitative learning, without any significant differences in frequency between species. Call and Carpenter (this volume) argue for an enhanced ability of enculturated apes to pay attention to actions, rather than results as compared to mother-reared apes. For some animals, being immersed in human culture may influence the ontogeny of imitative abilities, social animals such as apes show the ability to respond to an exposure to human culture. How these influences work is still an open question. According to Call and

Carpenter (this volume), enculturation might influence the development of attention mechanisms so that animals focus on different sources of information in the environment (in particular in the behavior of the animal to be imitated). A similar hypothesis is discussed by Tomasello (1999), who suggests that in human-like cultural environments apes receive a kind of *socialization of attention*. Being surrounded by humans who show them things, point towards objects, encourage (and even reinforce) imitation, and teach them special skills — all of which involve a referential triangle of human, ape and a third entity — seems to encourage a development of cognitive achievements in apes similar to those of human children, although differences between cognitive skills in enculturated apes and human children remain apparent. However, enculturation seems to affect cognitive skills and imitation in apes. In the context of the correspondence problem the enculturation effect might change the animal's attention to different aspects of the corresponding behavior and the relationship of demonstrator, imitator and possibly other objects. If enculturation effects on attention as proposed by Call and Tomasello can be confirmed, at least for human-raised apes, trying to account for these effects will pose an interesting challenge for theories and models of imitation.

Other types of influences may play a role. Growing up in a human family means that a lot of time is spent on social interactions, in particular young animals receive an enormous amount of attention. Imitative and rhythmic interaction games (comprising e.g. vocalizations and body movements) between infants and caretakers, such as imitation and turn-taking, play an important part in the development of social cognition and communication in the young human animal (Bullowa, 1979; Uzgiris *et al.*, 1989; Meltzoff,

1996; Meltzoff & Moore, 1999, Nadel *et al.*, 1999; Trevarthen 1977; Trevarthen *et al.* 1999, Heimann & Ullstadius, 1999; Butterworth, 1999; Uzgiris, 1999). Imitation plays an important part in play and social learning in humans, including adults and children. An animal which grows up in close contact with humans may experience an enormous amount of attention, engagement, and positive feedback with respect to imitative and coordinated behavior between humans and the non-human animal. This might have several influences on the cognitive development of the animal, to name a few: The fact that an imitative action—even an accidental one— may receive positive feedback and attention could increase the animal’s motivation and tendency to imitate. Without this encouragement to imitate during social development an animal might not consider imitation to be a desirable goal. Also, in a human-populated environment an animal is likely to frequently observe imitated actions, humans imitating each other or the animal. This might influence the way sequences of actions are observed, structured and organized — the reader may compare discussions on action- versus program-level imitation, string-parsing, or sequence versus hierarchy-copying (Byrne & Russon, 1998; Byrne, 1999; Whiten, this volume). Also, structure of observed behavior needs to be mapped on corresponding structures of behavior that can be generated by the observer. Thus, enculturation might influence processes involved in the correspondence problem. In particular, the *motivation* to observe an action and its *salience* for the animal may be strongly affected by the details of enculturation. Often, humans serve as models for tests on imitation in non-human apes. However, from a non-human ape's point of view the behavior of humans, who also come in various other roles, *e.g.* as keepers, experimenters, observers, etc., and who are not necessarily considered part of the family, might not necessarily be mapped to their own behavior. Similarly, Whiten (this

volume), when describing experiments where humans serve as models for chimpanzee imitation, discusses the need to do comparable studies with chimpanzee models.

Enculturated bottlenosed dolphins are a good example of animals who seem to readily 'solve the correspondence problem' and identify mappings between their own actions and those of conspecifics or of humans (Herman, this volume), although the differences between the body shapes and behaviors of dolphins and humans are larger than differences between humans and non-human apes. Perhaps enculturated animals understand better what they are 'supposed' to do in an imitation task, given that they had been exposed to numerous examples of social interactions and imitation with and among humans. This does not exclude the possibility that imitative behavior might also be prevalent in natural populations of the highly social dolphin, as evidenced for example by signature whistle matching recently documented for wild dolphins (Janik, 2000). Animals with strong individual-specific social relationships generally employ communication systems including signature signals for recognition (Tyack, 2000). The imitation of signaling and other behaviors thus appears to be strongly connected with such sociality, and with the evolution of symbolic communication.

Social relationships between model and imitator might also influence the readiness of an animal to imitate. In children's play or interactions between infants and human caretakers, imitation usually occurs spontaneously. In research into animal imitation, the animals often go through an intensive training period in order to make an experimental approach possible. In contrast, social learning in the wild happens spontaneously, influenced by

social networks and relationships among group members, as for example in socially transmitted behavior in Japanese macaques described by Huffman (1996). As in the case of dolphins, captive animals with intensive human contact often socially bond with their trainers. They might be highly motivated since they want to please the human, in addition to wanting positive feedback (such as food rewards).

An interesting example of the importance of social roles and relationships for teaching African Grey parrots the correct labels of objects and other skills is described by Pepperberg (this volume). A *model/rival technique* is used in order to teach the bird: This technique involves two humans and the bird. One human serves as a model for the bird's correct responses, shows aversive consequences for errors, and is also competing with the bird for the trainer's attention. The trainer and model/rival then switch roles. This method has proved to be most effective, and shows that the specific (social) structure of this training procedure is, in comparison to other training techniques, most likely to result in successful vocal learning.

To summarize, the autonomous agent perspective that acknowledges individualized social and historical grounding (phylogenetic and autobiographic) suggests that research on imitation should consider the social and cultural influences, including relationships, social networks, and the individual kinds of interactions an animal is involved in during its ontogeny. Controlling these parameters is problematic if not impossible for experimental approaches to animal imitation. However, experiments with advanced artifacts that can

engage in social interactions with humans and that will be able to build up relationships with them (Breazeal & Scassellati, this volume) might give valuable insights into this area.

### **Understanding others' minds (and perceptions)**

Heyes and colleagues (Heyes & Dawson, 1990; Heyes *et al.*, 1992) reported on evidence of observational learning or imitation using a bidirectional control procedure where a trained rat (demonstrator) pushes a joystick in either of two directions. Later an observer rat is placed in the chamber with the joystick. Observer rats seemed to show the tendency to push the joystick in the same direction (in space as well as relative to the body) as the demonstrators. However, later studies showed that odor cues on the joystick are sufficient if not necessary to account for the results (Mitchell *et al.*, 1999). For olfactory dominant species like rats or dogs experiments that test for imitation via visual observation are therefore likely to be effected. This example shows the difficulty in interpreting an imitation experiment with animals: one often cannot know (and/or control) what goes on in an animal's mind, what it is currently perceiving, and which sensory inputs provide salient features which influence the animal's behavior. For humans and other primates vision is generally an important sensory modality, but even within the sensory modality different inputs can have different salience. Generally, one needs to consider the possibility that different types of sensory input might have different salience for different kinds of species. To give an example: the salience of species-typical features (which might be substantially different from humans) plays an important role in discussions on self-recognition/self-awareness in primates. Gallup (1970) developed an experimental procedure which is

intended to formally test for self-awareness, the *mirror-test*. The first step of this procedure is to expose the animal to a mirror. Then, a dye mark is applied to the animal's eyebrow, ear (or other visually inaccessible parts of the body/head), while the animal is anesthetized (or otherwise it could be made sure that the animal is unaware of the changes to his body). Then, the animal is again exposed to a mirror and the responses were recorded. Humans more than about 2 years old and great apes show self-recognition, typically inspecting their 'modified' body part in the mirror, trying to remove the mark, etc. Many subsequent studies show that humans older than 2 years, chimpanzees, gorillas, and orangutans, but not most monkey species showed self-directed behavior when tested by Gallup's procedure (*cf.* Parker *et al.*, 1994). Mirror-guided body inspection is often taken as a sign of self-recognition/self-awareness, *i.e.* to realize that the reflected image represents "one's self", and not a different animal, with important implications for questions on animals' understanding of the social world (theory of mind, mindreading, *e.g.* Premack & Woodruff 1978; Baron-Cohen, 1995; Heyes, 1998). The results have therefore often been interpreted in terms of fundamental cognitive differences of apes and other primates (*e.g.* Povinelli & Preuss, 1995). Experiments with the mirror-test and its implications have been critically analyzed (*e.g.* Mitchell, 1993; Heyes, 1994), and also challenged experimentally. Yet Hauser *et al.* published experimental evidence in 1995 of self-recognition in cotton-top tamarins (*Saguinus oedipus*) using a variation of Gallup's mirror-test: instead of placing a dye-mark on the eyebrow, the white hair on the tamarins' head was color-dyed (Hauser *et al.*, 1995). Among many species of tamarins, only the cotton top tamarin has a distinctive and species-typical tuft of white hair on the top of its head. Discussions on methodological problems of both the original mirror-test, as well as results of Hauser *et al.* can be followed

up, for example, in (Anderson & Gallup, 1997; Hauser & Kralik, 1997). New experimental paradigms will shed more light on the question on individual, developmental, and species differences of self-awareness and performance in the mirror-test (see discussion in Tomasello & Call, 1997, 331 ff.). The importance of this discussion for imitation lies in the question of why animals might fail the mirror test. They might fail because of an absence of the concept of 'self', but they might fail *e.g.* because of the lack of salience of the dye-mark. For all monkey species staring is typically an aggressive threat. Thus, monkeys tend to only stare briefly at the mirror, which, according to Hauser *et al.* (1995), does not suffice to recruit the attention necessary to discover correspondences between the own body and the mirror image. The mirror test might therefore be an appropriate test for self-recognition in humans, for whom mirrors are an important cultural artifact and who spend a significant amount of time in front of a mirror. However, for other animals, less visually oriented or who pay different attention to specific features of another's animal body, this test might be inappropriate. Similarly, testing whether an animal can imitate or not requires an insight into how animals perceive the world. An agent-based perspective on imitation and the correspondence problem demands an analysis of different ways in which animals understand and perceive the world. Artifacts might provide interesting tools in order to investigate the 'other minds' problem. Building an artifact with possibly very different ways and modalities of perceiving the world (*e.g.* a robot with infra-red or ultra-sonic sensors, a software agent getting input from the environment via streams of data following a fixed protocol), requires different types of correspondences between the model and the imitator's perceptions. Such types of experiments could go far beyond the traditional robotics approach to imitation that involves two robots of the same kind imitating each other.

**Novelty: Can there be imitation without learning?**

Often, imitation is discussed as a form of social or observational *learning*. Early on, imitation had been defined as "learning to do an act from seeing it done" (Thorndike, 1898). Indeed, the investigation of imitation in robotics and software agent research is deeply motivated by the promise of having an effective and efficient means of teaching the robot or agent new skills and competencies. A new paradigm of robot programming could be achieved using such 'programming by showing'. Likewise, many definitions of imitation require the imitated action or behavior either to be novel in contrast to 'instinctive tendencies' (Thorpe, 1956; Visalberghi & Fragaszy, this volume), or, in broader definitions of imitation, to be novel in contrast to 'designed' and familiar actions that are already in the behavioral repertoire of an animal or artifact (Mitchell, 1987). Recognizing that no imitation can be exact, Whiten and Ham (1992) define imitation as a process in which an individual "learns some aspect(s) of the intrinsic form of an act" from another.

Nevertheless, there are several fundamental problems with demanding novelty and learning of imitated behavior. In degenerate cases, it may be that only the sequencing or combination of actions already in the repertoire is novel in an observed behavior (*cf.* the discussion of "horizontal processes" in the associative sequence learning theory of Heyes and Ray (2000) and Heyes (this volume)). Such a combinatorially novel sequence might be copied immediately, or even as it is being performed by a demonstrator. It might not be retained at all, so there may be no grounds to claim that anything has been learned; or it

might be performed after a long delay and possibly in similar or more general contexts. So even in blind copying, there can at least be the novelty of sequencing. A novel behavior can consist of a new combination of familiar actions. In saying that an animal is "copying a novel act", novelty is always relative; there are degrees of novelty, and in particular any behavior is always related to acts already in the repertoire (Whiten, 1999 pers. comm). For example, experiments on tool use often involve manipulations and actions that in themselves are not novel (*e.g.* Nagell *et al.* (1993) studying social learning with chimpanzees and human children involving rake-like tools to access food; the same task studied with orangutans by Call & Tomasello (1994); or, Whiten (this volume), studying chimpanzees and children manipulating an artificial fruit to access food). Such tasks involve basic actions like picking up, pushing, pulling, turning objects, etc., which are familiar to the animal, but only a specific subset of all possible combinations of actions in a sequence of actions leads to success, *e.g.* in terms of food access. Also, what kind of action is 'novel' for a particular animal is impossible to judge without knowing its complete *history* from birth, a requirement which is unrealistic to fulfill for field studies, and immensely difficult even in the case of animals reared under close observation by humans. Moreover, even exactly the same behavior can have a different meaning when applied to a different context. In these cases, there can be novelty in the sequencing or organization of familiar behavioral components, or novelty in the application of familiar behavioral patterns in a new context or for a new purpose. If a human infant learns by observation that an umbrella protects from rain, using exactly the same tool for the protection of intense sunlight cannot be judged 'novel' from the point of view of tools and actions involved, but fulfills the novelty criterion with respect to environmental features. But what if the child

later uses the umbrella to hide from her parents, or to fight off an aggressive dog? Such examples indicate that an infant observing an adult using an umbrella for protection against rain can potentially use many different sources of information in the observed action in constructing an imitative action: information on actions (exact movements and sequences of movements for opening the umbrella and positioning it correctly above one's head), state changes or results (standing under the umbrella away from the rain), and goals (not getting wet); see also discussion by Call & Carpenter (this volume). Additionally, the observing child can learn about more generic affordances of the umbrella, as a means to actively control and protect oneself from the impact of the environment (rain drops, sun beams, eye gaze). There seems to be no clear way for an observer to draw a line in the sand demarcating imitation. There is a continuum when a behavior is applied in contexts increasingly removed from the context in which the behavior was observed. This continuum extends from, on the one hand, *imitation* (or even '*blind-copying*') and, on the other hand, *generalization* (or even *insight*) in the application of old or observed behaviors in new contexts, including possibly the application of known actions or tools in new settings in ways that have never been observed. Since imitated actions are constructed by an agent, they depend on the agent's embodiment and the way the agent interacts with the environment. In addition to learning very specific behaviors, an agent might learn about general means to control its interactions with the environments, *i.e.* by using tools as extensions of its embodiment. Thus, although a behavior itself might not be novel, a novel usage in a different context can be an important generalization step for an agent with potentially great adaptive value. Like any behavior produced by an agent, an imitated

behavior does not exist in a vacuum, it is constructed by a particular agent, dependent on its specific embodiment, and mediated by the environment.

But even if the imitating agent's behavior does not change and if it does not learn anything, imitation — in the sense of producing similar behavior — can have a great adaptive value. Navigating in an unknown landscape is greatly simplified if roads exist, *i.e.* if one can follow the paths other people took, either by following particular cars or following the roads which as cultural artifacts represent collective experiences. Likewise, one can follow directions literally, *i.e.* without trying to understand the directions, namely without creating a mental map. A great advantage of such a following strategy (either literally following another agent in space, or following instructions) is the simplicity in processing the information. Observation of actions may be supplanted by communication, with explicit instructions, possibly yielding something akin to imitation (see Goodenough, this volume). If the instructions are robust and come from a reliable source, then such a strategy might work well. However, it can break down if the environment and/or the relationship of the agent towards its environment changes. For example the instructions say "take the exit at junction 11" (but junction 11 is closed), or the robot's batteries are going down so that "turn left 90 degrees" results in turning left 78 degrees, or the robot learned to grasp a cup and is confronted with a wine glass. Thus, in addition to identifying results and goals, the capacity for generalization is important for being able to apply an imitated behavior in a new context. Without such generalization the matching action will be limited to a particular context, identical or very similar to the context where the behavior was originally observed. In extreme cases, with no learning or novelty present, the matching behavior could only

occur in an extremely limited context while the behavior to be matched is simultaneously being observed. *Imitation* here does not require memorizing, learning, or generalizing behavior, it only requires:

- 1) identifying the appropriate model behavior,
- 2) mapping of the model behavior to a corresponding behavior of the imitating agent,
- 3) selecting and executing this corresponding behavior.

In robotics experiments the *following strategy*, which implements such a procedure in the context of movements in a two-dimensional space, has proved quite successful for certain kinds of learning by imitation, whereby imitation and correspondences of behavior were 'engineered' (not learned) according to the above mentioned procedure (Dautenhahn 1994; Hayes & Demiris 1994; Demiris & Hayes 1996; Dautenhahn 1995; Gaussier *et al.* 1998; Billard & Dautenhahn 1997, 1998, 1999; Billard, this volume). Once two agents share a common context and enough corresponding perceptions of the environment (see Nehaniv & Dautenhahn, 2001) a follower agent could learn by imitation from a teacher agent, *e.g.* how to travel a maze or how to label its experiences with 'words' from a common vocabulary. Thus, for an autonomous agent imitation can be adaptive, *i.e.* beneficial to the survival of the individual agent, without involving any explicit learning of the imitated behavior. In such cases, the results of the imitated behavior might be beneficial (*i.e.* when the imitating agent follows another agent to a specific area of interest, *e.g.* a charging station), or the imitative behavior can serve as a powerful 'social bonding' mechanism that creates a shared context which supports social learning (see discussions in Billard & Dautenhahn 1998, 1999). Based on recent discussions on 'mirror' neurons and the neurobiological origin of imitation in primate evolution, one might speculate that *mirror*

*neurons* are nature's solution – at least in some primates – to solving the correspondence problem, namely in creating a common shared context and shared *understanding* of actions and affordances (see below) between two agents (see discussion by Arbib, this volume).

### **Imitation, Development, Communication, and Culture**

In human primates imitation plays an important role for the individual's social acquisition of a variety of skills, ranging from vocal imitation in language games to imitation of body movements (*e.g.* when instructed how to tie shoelaces). However, imitation has also important implications at the level of human culture: social learning is an important requirement for the development of culture in animals (Bonner, 1980; Whiten *et al.*, 1999; Reader & Laland, 1999), and in particular human culture (Dawkins, 1976). Imitated behaviors or "memes" — are said to be *replicators* in human culture (although the meme is still rather unsatisfactorily defined as a unit of replication) — and are spreading through various forms of imitation, very broadly construed; varieties are formed and selected in a Darwinian dynamic by the biological and cultural environment, which they may, in turn, shape (Dawkins, 1976; Blackmore, 1999, 2001; Goodenough, this volume).

Also, as already indicated in (Byrne & Russon, 1998) at least in human culture imitation is an important *medium of communication*. Imitation is an important mechanism of social learning in human culture, but also a powerful means of signaling interest in another person, used for purposes of communication. According to Nadel *et al.* (1999) immediate imitation is an important *format of communication* and milestone in the development of intentional communication, linking the imitator and the imitatee in synchronized activity

that creates intersubjective experience, sharing topics and activities, important for the development from primary to pragmatic communication (see also Billard, this volume). Infants are born ready to communicate by being able to reciprocate in rhythmic engagements with the motives of sympathetic partners (Trevarthen *et al.*, 1999). Importantly, the development of human social cognition and communication are so deeply dependent on imitative, social encounters of the developing infant that they are likely to shape human culture, and human culture is likely to be shaped by them. This presents an exciting area for further studies on the origins and mechanisms of human culture (*cf.* Uzgiris, 1999; Butterworth, 1999).

Imitating another person, in particular on the level of characteristic vocal or body movement behaviors, is often used by actors to impersonate historical or contemporary characters. Conspicuous imitation of someone's behavior can be an indication of disapproving mockery. Even unconscious temporal synchronization and rhythmic coordination of movements between people plays an important role in communication and interaction in human culture and proxemics (the study of humans' perception and use of space, *cf.* Hall 1968, 1983). Temporal synchronization of behavioral dynamics has also been implemented in studies with robot-human interaction (Dautenhahn 1999). Children are encouraged to emulate role models, who exhibit desirable behavior and character. In fashion and sports imitation can also be a kind of flattery: copying a particular style invented by a colleague means paying a compliment in human culture. Even in science the invention of new techniques, methods and theories by a single individual will only survive in the scientific culture if they are imitated and adopted by others. As cultural replicators,

scientific theories are modified and refined through generations of Hegelian dialectic, Popperian falsification, and paradigm shifts of scientific discourse (Kuhn 1962).

### **Just Puppets on Strings?**

For generations humans have been entertaining with circus animals that were trained to "imitate" human behavior (bears riding a bicycle, chimpanzees dressed up like humans and smoking a cigar, etc.). In satire, cartoons with non-human animals that undoubtedly represent politicians and other human contemporary figures are a widely used artistic vehicle. Surprisingly, as discussed in (Mitchell, this volume) while children's imitation skills are generally highly regarded and a rich source of entertainment and amazement ("look, he uses the spoon like his father!"), imitation in non-human animals is often dismissed as "just imitating", in particular if cognitive abilities of non-human animals are at stake. Similar to the circus bear that is riding a bicycle, or the animal actor showing greater-than-life intelligence on television, in public opinion we are possibly biased to believe that a "trick" is used when they are shown non-human animals imitating. Notably, robots (in particular humanoid robots that have a similar body shape and movement repertoire as humans) that show imitative abilities often attract huge public (media) attention, as described in Atkeson *et al.* (2000). It is relatively easy to give the impression of *e.g.* a humanoid robot imitating a human, from an observer point of view: Theoretically, instead of having the robot imitating a robot, a human who is skilled enough can (with imperceptible delay) imitate the robot, or, knowing the robot's behavior in advance, could "demonstrate" actions that the robot is then sure to "imitate", even if the robot has no perception of the human at all. Playback of a captured data-stream of human joint

articulations on a robotic hand or humanoid body is an instance of matching behavior, but is even weaker than 'blind-copying' since the hand or body does never perceive the actions it latter matches, like a marionette on strings. Similarly, a compact-disc player does not imitate nor even blindly copy vocal performance. Thus, the observation that a biological and an artificial agent are nearly simultaneously performing the same movements does not necessarily reveal anything about imitation. However, programming a robot to perform interesting movements (in particular human-like, smooth movements as they can be observed in dancing) is substantially more difficult than training a dog to dance, let alone the question of imitation (*cf.* Atkeson *et al.*, 2000). In the case of the dog we are already dealing with an animal that is capable of showing a variety of different behaviors. Also, it is a very social and socially susceptible animal that is bonded with a human trainer and tries to please him. Thus, a dog is already a socially intelligent autonomous agent and in training it we can build on these skills. Building truly autonomous robots that can be taught a variety of skills in a variety of situations has become more realistic than 10 years ago, but is still a challenging and exciting research endeavour (see contributions by Demiris, Billard, Breazeal & Scassellati, and Mataric in this volume). Two major problems in agent imitation that become apparent in robot imitation are

1) the problem of *perception*, comprising information on states in the environment as well as states of the agent itself with respect to the environment, *i.e.* proprioception and kinesthesia. These are highly developed in humans and other animals, playing a central part in motor control and regulating animal-environment interactions, but are often extremely underdeveloped and impoverished in robots; and

2) the "*Big Five*" central issues for designing experiments on imitation with autonomous agents<sup>2</sup>: *Whom* to imitate (Who is a good teacher? Can a learner become a teacher?<sup>3</sup>), *when*

to imitate (play context, teaching, exploration, etc.), *what* to imitate (states, actions, goals, as discussed in chapter 2 or results, actions, goals in Call & Carpenter's terminology, this volume), *how to map* observed to imitated behavior (*the correspondence problem*<sup>4</sup>), and *how to evaluate* the success of the attempt at imitation (degrees of success; see chapter 2 and (Nehaniv & Dautenhahn, 1998, 2001)).

From an autonomous agent perspective on imitation we might distinguish two cases of when imitation can be observed in an agent: the imitative behavior might result from specific imitation mechanisms which are part of the agent's cognitive and behavioral architecture, or they might result from the interaction of the agent with its environment, so that the "imitated behavior" (as perceived and described by a human observer) is an emergent behavior that is based on simpler mechanisms (cf. discussion in Noble & Todd, this volume). Generally, humans show a tendency for anthropomorphism or *behavior reading* (Mitchell and Hamm, 1997). However, many in particular social behaviors which appear well organized and structured result from principles of self-organization and local agent-agent plus agent-environment interactions. The organization of social insect societies gives a good example of impressive global patterns (*e.g.* termite mounds) that emerge from distributed interactions (see discussions in Theraulaz & Bonabeau 1999; Bonabeau & Dorigo & Theraulaz 1999, Dautenhahn 2000a). Such studies (and supporting evidence from simulations with computer programs and mobile robots) show convincingly that complex behavior need not result from the cognitive or behavioral complexity of the animal, or the complexity of the control program of a robot.

**Interactive Emergence: Niches and Design Spaces.** In the domain of social interactions, self-organization of social behavior is not limited to social insect societies. Often, even in a small group of agents or in dyadic interactions, being endowed with a set of mechanisms that allow local interaction with the environment, produces behavior that appears to be based on complex mechanisms of social control.<sup>5</sup> In (Hendriks-Jansen, 1996) the notion of *interactive emergence* is discussed with respect to behavior-based robots (*e.g.* see Brooks, 1991) and mother-infant interactions. Imitation games between infants and their caretakers and peers are an example of the emergence of imitation: although from an observer point of view it appears as if the players follow an external rhythm, the rhythm and turn-taking behavior is created by the "players" in a particular social context. For the study of imitation this has important implications, and points towards the importance of research into the emergence of imitation: how can imitative behavior emerge from non-imitative behavior, what are the basic behavioral (perceptual? cognitive?) components and conditions that are *necessary and sufficient* to produce imitation in a particular social context. Also, how do transitions from non-imitative to imitative behavior occur and how can this approach be exploited to control social interactions, *e.g.* in robot-human interaction? Research into the interactive emergence of imitation is sparse (*cf.* Breazeal & Scassellati, this volume), but might help us to explore the design space of robotic solutions to the *Big Five* challenges. Also, this design space needs to be linked with sets of requirements determined by the concrete properties of the agent and its embodiment with respect to the environment. Aaron Sloman has called these sets of requirements *niche spaces* (Sloman, 1995). Different types of robotic control architectures might map to (different sets of) requirements for different types of robots or other agents. To date, most robotic research is *a priori* constraining the

design space (*e.g.* by fixing whom, when and what to imitate) and focusing on a particular architecture providing a fixed solution to the question of how to imitate. Likewise, the evaluation of the success of imitation is then often based on techniques specific to the concrete experimental set up. This approach has been necessary primarily for practical reasons, *i.e.* due to the difficulty of working experimentally with physical robots. Such proof-of-concept implementations have demonstrated what is possible, but they make it difficult to make comparisons and evaluations across different experimental set ups. However, for the long term vision of interdisciplinary research on imitation, an autonomous agent viewpoint might help in developing a *science of imitation* by systematically exploring design spaces, niche spaces and mappings between the two.

For biological systems, design and niche spaces of different species are interrelated by an evolutionary history. It is speculation to suggest that *e.g.* all primates, all mammals, or all vertebrates might share the same neurobiological mechanisms underlying imitation. It is however unlikely that choices are arbitrary, and discussions have begun on whether the neurobiology of human imitative skills is based on mirror neurons first discovered in monkeys (see discussions in Arbib, this volume; Gallese *et al.*, 1996; Rizzolatti *et al.*, 1998). In addition to informing models and architectures on imitation for robotic agents (*e.g.* Demiris 1999; Demiris & Hayes, this volume; Billard, 2001), such findings can provide data on the internal structure of the design space. Such knowledge can even make the link to other cognitive human skills like language (see Arbib, this volume; Rizzolatti & Arbib, 1998), and even social understanding and empathy (Gallese & Goldman, 1998). Thus, research on imitation addresses different fascinating facets of animal social minds, in

the case of human primates ranging from: 'do as I do' as a means of teaching/instruction/play, to 'you are like me' and imitation games that build scaffolding for the development of social cognition and social bonding, to potential (at present still speculative) implications for 'I could be you' (Dautenhahn 1997), *i.e.* empathic understanding as the strongly bonding mechanism between human beings and possibly other non-human animals (*cf.* O'Connell, 1995; Gallese & Goldman, 1998). For artificial agents such as robots empathic skills could be the first step towards becoming truly socially intelligent agents (Dautenhahn 1997; Dautenhahn 2000c).

### **1.3 Overview of Chapters**

The 22 chapters in this book each address different aspects of research on imitation. We deliberately avoided grouping the chapters into the two categories 'animals' and 'artifacts', since this would have been counterproductive to an integrated, interdisciplinary viewpoint. Instead we have adopted an agent-based perspective as outlined above and arrange the chapters along common themes that would have been obscured by a "traditional" split into the natural, the artificial and the theoretical sections. The book thus follows a thread of related issues and topics that meanders through the key aspects of the field of imitation. A pictographic overview and "roadmap" is shown in figure 1.5.

*[INSERT FIGURE 1.5 AS FULL PAGE ABOUT HERE]*

Figure 1.5: Roadmap showing the structure of this volume. Numerals indicate chapter numbers, and serve to situate chapters with respect to relevant nearby issues and topics. See

table of content for chapter titles and authors. Note that some chapter numbers occur more than once in the roadmap.

In the following we trace this thread to briefly introduce the remaining chapters.

In chapter 2, Chrystopher L. Nehaniv and Kerstin Dautenhahn discuss "The Correspondence Problem", that we already mentioned briefly in this chapter. The authors provide a framework that allows a unified treatment of the problem of imitation for possibly dissimilar bodies (correspondence problem) with respect to animals and artifacts by clarifying what it means for the behaviors of different agents to match, and the measures of such matching.

In chapter 3, "Vocal, Social, and Self Imitation by Bottlenosed Dolphins", Louis M. Herman reviews experimental evidence for imitation of self and others by enculturated bottlenosed dolphins. He gives a comprehensive overview of the study of imitation in dolphins during intra- and interspecies interaction. The studies investigate a variety of different modalities of imitation, comprising auditory and visual imitation, behavioral synchrony, imitation controlled by gestures, imitation of televised models and human body postures, imitation of self, etc. Particularly intriguing are data where dolphins seem to instantaneously and simultaneously imitate each other. Other cases of dolphin imitation illustrate that they employ appropriate correspondences in mapping movements and body parts when imitating human trainers.

Another highly social species of animals is studied in chapter 4 by Irene M. Pepperberg which addresses "Allospecific Referential Speech Acquisition in Grey Parrots (*Psittacus erithacus*): Evidence for Multiple Levels of Avian Vocal Imitation". Her results indicate an elaborate interspecies correspondence here in the vocal and auditory domain, as well as evidence of an interspecific correspondence in conceptual abilities and the referential and predicative use of speech by the parrots. As with Herman's discussion of dolphin imitation, enculturated Grey parrots learn from human trainers and generalize their knowledge to interactions with others when provided a particular social context, as exemplified by Pepperberg's highly successful model/rival technique with role reversal adapted from Todt (1975).

Johannes Fritz and Kurt Kotrschal discuss "On Avian Imitation: Cognitive and Ethological Perspectives" in chapter 5. In contrast to Herman's and Pepperberg's chapters which show inter-species imitation (human-dolphin, dolphin-dolphin (but human-mediated), human-parrot), this chapter focuses on social learning among birds. Research on social learning in a variety of different bird species is addressed. Experiments on social learning and imitation in different bird species are reviewed in the light of possible social cognitive mechanisms. An ethological perspective on the study of social learning in common ravens (*Corvus corax*) is discussed, focusing on food scrounging. The authors argue for taking into account the social, ecological and life history contexts of social learning that are often neglected in laboratory studies. Discussions of experiments with common ravens and other bird species lead to the development of a model of the relationship between scrounging and

learning. Social conditions (social relationship between 'producer' and 'scrounger') and ecological conditions are important factors in this model. This work is put in the broader context of a synthesis of cognitive and ethological approaches.

In Henry Lieberman's chapter "Art Imitates Life: Programming by Example as an Imitation Game" (chapter 6), the social context of imitation is quite different from the previous chapters. Here, social learning is studied as a means of machine learning in which an artifact (software) learns tasks from a human. This programming-by-example (PBE) approach can result in more natural human-computer interfaces where humans can demonstrate the computer what to do, rather than going down to the level of arcane programming languages. Interestingly, Lieberman is also currently studying the PBE paradigm with Irene Pepperberg's Grey parrots. Future experiments in this domain may show whether one day non-human animals could program computers by example.

A machine learning perspective is also given in chapter 7, "Learning to Fly" by Claude Sammut, Scott Hurst, Dana Kedzier and Donald Michie, a classic paper reprinted here that shows the application of behavioral cloning techniques to the problem of learning to fly a simulated aircraft by observing the control actions of human pilots. The authors show how subsymbolic skill-level knowledge can be extracted from the behavior of humans, knowledge that is normally not or cannot be articulated explicitly. For example, humans cannot usually explain how it is that they ride a bicycle, walk, or catch a ball. The authors illustrate how techniques of behavioral cloning build up decision trees, giving rules capturing such knowledge from the behavior of human pilots, whereby different trees

control behaviors appropriate in different subgoal contexts along an overall flightplan. The decision trees, given current state and sensory readings, determine control actions on the aircraft's various actuators. This allows an autopilot, which is a "behavioral clone" of the human pilot, to successfully take-off, circle back, and land the aircraft.

The structure of knowledge that is necessary in order to transfer skills from one system to another is also an important component of Andrew Whiten's chapter "Imitation of Sequential and Hierarchical Structure in Action: Experimental Studies with Children and Chimpanzees" (chapter 8). Imitation of sequential and hierarchical structure in object manipulation is studied with the 'artificial-fruit' paradigm, involving an artifact that can be manipulated only in particular ways and (if operated successfully) then provides a reward. Results suggest that hierarchy-copying and sequence-copying are two separate and important aspects of what constitutes copying of a behavioral 'program'. Whiten argues for further extensive comparative studies with different animal species that might shed more light on these two types of imitation and their natural occurrence.

Josep Call and Malinda Carpenter's "Three Sources of Information in Social Learning" (chapter 9) clarifies the relationship between emulation and other types of social learning. The chapter then discusses differences of what kind of information an imitator might focus on while observing a demonstrator, and how this could result in different types of social learning. The chapter outlines a new, multidimensional framework for investigating social learning that is based on analyzing different types of information (goals, actions, results) that imitating agents are able to extract from observing the model agents. Shifting between

and exploiting various sources of information is discussed with respect to humans, apes and individuals with autism. Advantages of this framework for animals and artifacts are discussed. Similar to Whiten's chapter, the proposed framework points to the need for extensive comparative studies across different species, in order to clarify the nature of different types of social learning as they can be observed in biological systems.

Michael Arbib's chapter "The Mirror System, Imitation, and the Evolution of Language" (chapter 10) bridges the gap between imitation as it can be observed today, and the neurobiological evolutionary 'history' of imitation in humans. Based on recent experiments with monkeys, Arbib outlines a hypothetical history of human imitation, ranging from "I know what you do" to "I understand what you say". This argument includes an interesting link between body movements, body language, gestural communication, sign language, and 'human' language. The latter is often described as 'unique' to humans and in this way isolating humans from the rest of the animal kingdom. Arbib's ideas might therefore have important implications for studies on teaching non-human animals sign language, accounting for the language-readiness of human infants, and reconstructing an evolutionary history of human language.

Aude Billard's chapter gives a concrete example of how implementations of minimal systems with language-like features could employ imitation as a social bonding mechanism that allows an imitator robot to learn a vocabulary from a demonstrator robot. In "Imitation: A Means to Enhance Learning of a Synthetic Proto-Language in Autonomous Robots" (chapter 11), the learning architecture (a recurrent neural network) is tested in different

experimental set ups, including robot-robot as well as robot-human interaction. Robots equipped with such a learning architecture can be taught a vocabulary of 'words' (symbolic body movements or labels) if a skilled teacher is available that provides consistent behavior. Particularly important in these experiments is the fact that the 'meaning' of 'words' is experienced by the learner robot based on its own proprioceptive and extero-perceptions.

Chapter 12, "Rethinking the Language Bottleneck: Why Don't Animals Learn to Communicate?" by Michael Oliphant, discusses experiments that demonstrate that learning word-meaning pairs is neither computationally expensive nor even difficult, and can be realized with relatively simple neural networks. Unlike in simulations, 'meaning' in nature does not exist independently of agents (Nehaniv, 1999a,b). Oliphant argues that fact that learned symbolic systems of communication (verbal or movement based) seem not to be widespread in the animal kingdom might therefore be due to the problem of detecting the 'meaning' of symbols in learning such a system. This nicely links back to the issue of mirror-neurons and Michael Arbib's chapter relating between primate imitation and language. The mirror-neuron system and areas of the human brain associated with language might thus support language-readiness in humans by providing access to the meaning of others' movements and gestures in terms of what the corresponding movements and their affordances could mean for oneself.

The mirror-system, and data from developmental psychology on imitation in infants, have also inspired the development of robot control architectures, as described by John Demiris

and Gillian Hayes in chapter 13, "Imitation as a Dual-Route Process Featuring Predictive and Learning Components: A Biologically-Plausible Computational Model". This model of primate imitation mechanisms is experimentally tested with simulated robots, where an observing robot is imitating particular movements, namely sign language 'words' that are part of the international standard semaphore code (ISSC). The model combines a passive route to imitation (perceive – recognize – reproduce) with an active route that internally generates movements where the imitator puts itself in the place of the demonstrator. Then, it selects one which predicts the demonstrator's behavior best. Experimental results with this computational model yield interesting predictions which might inspire future experiments on primate imitation mechanisms and in particular the mirror neuron system. This chapter presents the first experimentally tested robot control architecture for imitation that is inspired by the mirror neuron system.

While the chapter by Demiris and Hayes focuses on the plausibility of the robot's control architecture for imitation, in chapter 14, "Issues in Building Robots that Imitate People", Cynthia Breazeal and Brian Scassellati focus on designing and programming a humanoid robot so that it produces imitative and other socially plausible behaviors in interaction with humans. The chapter discusses main problems and challenges of this approach. Particularly interesting is that social interaction, *e.g.* imitative turn-taking games, can emerge from the dynamics and regulation of meaningful social interaction, in the same way as the structure and rhythms of imitation games played by an infant and her caretaker that are not imposed by an external or internal clock or supervisor.

This focus on face-to-face interaction dynamics contrasts with Maja J. Mataric's discussion of "Sensory-Motor Primitives as a Basis for Imitation: Linking Perception to Action and Biology to Robotics" (chapter 15). She proposes a model of imitation based on sensori-motor primitives, supported by evidence on movement perception in humans and the neurobiological basis of motor control. Different robotics test-beds and experimental methods are discussed, involving a variety of different artifacts, e.g. a simulated humanoid and different types of mobile robots. Results of these experiments are interpreted with respect to the proposed model of imitation. This chapter illustrates a particular design perspective based on sensory-motor primitives. These primitives could also serve as atomic units in building up a partial solution to the correspondence problem; compare chapter 2. Ultimately one can expect that a synthesis is required between work on correspondences, a focus on the control architecture (as it is done *e.g.* in Demiris and Hayes' work, chapter 13), and the consideration of the social context, as we see it in Billard's and Breazeal and Scassellati's work (chapters 11 and 14).

In research that is constructing robots that imitate usually the term 'imitation' is not clearly distinguished from other forms of social learning or copying, since any kind of social learning or copying at all, *e.g.* with a humanoid robot, is difficult to accomplish. From a conceptual point of view this is however an important issue, and is discussed in more detail by Jason Noble and Peter Todd in chapter 16, "Imitation or Something Simpler? Modelling Simple Mechanisms for Social Information Processing". Here, the authors address the perennial question 'what is imitation?' in the more general context of social learning mechanisms, from a bottom-up point of view that is concerned with building minimal

systems that achieve particular behavior. They describe how some simple mechanisms applied in a collection of robotic agents could give rise to various well-known phenomena that look at first sight very much like imitation (*e.g.* contagion and stimulus enhancement). An important aspect is hereby the role of the observer.

"Imitation as a Perceptual Process" (chapter 17) by Robert W. Mitchell complements this approach by starting off with a definition of imitation that can be applied across biological and artificial systems. Applying this definition he identifies different types of design processes that lead to different types of imitation. Mitchell then discusses the important role of perceptual matching in animal imitation, in particular, kinesthetic-visual matching. He argues that perceptual matching is a significant factor in imitation, and that one particular form of perceptual matching, namely kinesthetic-visual matching, is essential for bodily and facial imitation and self-recognition, and probably also important for pretense and for recognizing that one is being imitated by another. The argument is discussed with respect to different species of animals (humans at different stages in their ontogeny, children with autism, apes, monkeys and other mammal species, birds). Implications for the design of machines that imitate are outlined.

Elisabetta Visalberghi and Dorothy Fragaszy's "Do Monkeys Ape? - Ten Years After" (chapter 18) gives an excellent example of problems and issues involved in animal imitation research, based on their long-term research with capuchin monkeys. The authors here use a definition of imitation that demands novelty of the acquired behavior. The results suggest that social partners do affect many aspects of behavior in capuchins, but that they do not imitate or learn unlikely behaviors from one another. Since capuchin monkeys

are social learners, but do not show imitation, the same might be true for many, if not all monkey species. Data on social learning in capuchin monkeys support the domain-general view of their social learning abilities, namely what they learn socially seems consistent with what they learn in individual contexts. The authors discuss this conclusion in the general context of research on animal imitation and recent findings on the mirror neuron system. Controversies on mechanisms and the nature of social learning and imitation in different species of animals are certain to be ongoing in the field of animal behavior research; compare the recent suggestion of true imitation in marmosets (*Callithrix jacchus*) (Voelkl & Huber, 2000).

"Transformational and Associative Theories of Imitation" (chapter 19) by Cecilia Heyes reviews a range of existing theories of the proximate psychological mechanisms of imitation distinguishing *transformational theories*, which suggest that most of the information required for behavioral matching relies on internal cognitive processes for its generation, from *associative theories*, which claim that this information is principally derived from experience. She outlines a new, *Associative Sequence Learning Theory (ASL)*, which makes testable predictions. ASL suggests that imitation is mediated by associative processes establishing correspondences in *horizontal* (temporal sequencing) and *vertical* (sensory-motor) dimensions. She argues that approach provides a more satisfactory and predictive framework than existing theories, in particular, for handling the important problem of *perceptual opacity* of some imitated behaviors which yield very dissimilar sensory inputs when observed than when executed, e.g. facial expressions as opposed to the movement of distal appendages or vocalizations.

"Dimensions of Imitative Perception-Action Mediation" (chapter 20) by Stefan Vogt addresses the question of how action is informed by perception (perception-action mediation), an important issue for cognitive-psychological research on imitation. Experiments with human subjects are reviewed in order to illustrate the important research issues. In light of such experiments and other evidence from the behavioral and neuroscience literature, Vogt proposes a distinction between *parameter imitation* (via a dorsal stream) which focuses on only specific aspects of a model's behavior and *action imitation* (via a ventral stream) for complete actions (or sequences of actions). He argues that neither type of imitation is guided by a detailed representation derived from the model. The former type allows for fast incorporation of highly particular aspects of the model's behavior into the observer's, while in the latter type the observer's own motor action repertoire is accessed on a high level of coding.

In "Goal Representations in Imitative Actions" (chapter 21), Harold Bekkering and Wolfgang Prinz discuss possible cognitive mechanisms that underlie imitative performance in human infants and children. They focus on the "when", "how" and "what" of imitation, surveying and presenting evidence from imitation in children for a *goal-directed theory of imitation*. This theory argues that the action recognition process is guided by an interpretation of observed motor patterns as goal-directed behaviors, and that these goals can later activate a motor program to attain corresponding effects (possibly organized in a sequence or hierarchy). This is related to what in the artifact community has been called *functional imitation* (Demiris & Hayes, 1997) or *effect-level imitation* (Nehaniv & Dautenhahn 1998b, 2001). The authors briefly overview other approaches, such as active

intermodal mapping theory (AIM) of Meltzoff and Moore (*e.g.* Meltzoff 1996; Meltzoff & Moore 1999) and statistical parsing theories (*e.g.* of Byrne and Russon (1998), Byrne (1999)), arguing that these do not account for certain data on imitation in children, but that the goal-directed theory does. Their analysis suggests that data on imitation in children cannot be explained without the assumption that it relies on observable goals and inferences about the actor's intentions in an observed act.

The final contribution in this volume, "Information Replication in Culture: Three Modes for the Transmission of Culture Elements through Observed Action" (chapter 22) by Oliver R. Goodenough, addresses imitation from the point of view of cultural transmission. Goodenough argues that cultural transmission occurs through the imitation of *actions*, rather than of ideas, giving rise to a significant transmission bottleneck in that the action must actually be observed and lead to another (replicated) action. He classifies cultural transmission into three general modes of action: uncoded (non-linguistic behavior), partially coded (stories), and fully coded (formulas). He also discusses how external storage (*e.g.* in writing) and how compression via language help avoid this transmission bottleneck. For example, multiple streams of replication go through stories – relating to the actions that the story encourages and relating to the replication of the story itself. Such a role for story-telling in cultural transmission need not be limited to human agents, but also has an interpretation for constructed agents via the notion of transmission of partially-coded episodic experiences of autobiographic agents (Dautenhahn 1996, Nehaniv 1997, Nehaniv & Dautenhahn 1998a, Nehaniv *et al.* 1999, Dautenhahn, to appear). Goodenough's three modes could provide a useful conceptual framework for such analogues of human

story-telling in autonomous agents by shedding light on connections to imitation. By focusing on human cultural transmission, this final chapter of the book draws a full circle back to the issues discussed here and in the earlier chapters, namely the social context of imitation.

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### Endnotes

<sup>1</sup> The notion of autobiographic agent is strongly inspired by research in psychology on human autobiographical memory, e.g. in (Nelson 1993, Conway 1996).

<sup>2</sup> See also (Breazeal & Scassellati, this volume), (Noble & Todd, this volume), and (Bekkering & Prinz, this volume).

<sup>3</sup> This particular scenario is studied in (Billard & Dautenhahn, 2000). Here, in a group of nine (simulated) robotic agents, learner agents can become teachers once they are 'confident' enough of a vocabulary that they have learned by imitation; see also (Billard, this volume).

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<sup>4</sup> The correspondence problem is particularly obvious in the case of dissimilar bodies, *e.g.* when a robot imitates a human. Correspondences apply to positions, postures and movements of the bodies of both model and imitator, and to actions (which need *not* be movements) and the state changes these induce, as well as to *correspondences of perception* which are necessary so that model and imitator can share perceptions of a *shared context*, see discussions in (Nehaniv & Dautenhahn, 2001; Billard, this volume).

<sup>5</sup> In (Dautenhahn, 1998a, 1998b) we explain the issue in more detail and its implications. The phrase "the social world is its own best model", inspired by (Brooks, 1991), captures the principle of interactive emergence of social behavior.