1 Growing Babies and Robots

Human development is one of the most fascinating phenomena in nature. Babies are born as helpless individuals, with simple motor and cognitive skills not even sufficient to allow them to survive and fend for themselves without the support of their parents and caregivers. However, within a few years, they reach a sophisticated level of mental development. A ten-year-old child can play chess and computer games, solve increasingly complex math problems, master one or more languages, build a theory of mind of self and others, cooperate altruistically with peers and adults, excel at gym exercises, and use complex tools and machines. These slow but impressive developmental changes pose a series of key questions on the understanding of human development: What are the mechanisms that allow the child to develop autonomously such mental capabilities? How does the social and physical environment, with which the child interacts, shape and scaffold the child's developing cognitive skills and knowledge? What is the relative contribution of *nature* (i.e., genes) and *nurture* (i.e., environment) in the development of human intelligence? What do qualitative stages during development, and body and brain maturational changes tell us about the mechanisms and principles supporting development?

Developmental psychology is the discipline that aims at understanding the child's autonomous mental development, through field and laboratory experiments with children of different ages and varying cultural backgrounds, and through comparative psychology studies. These empirical investigations lead to the definition of theories and hypotheses of motor, cognitive, and social development and to the identification of general developmental principles underlying the acquisition of mental capabilities.

Such a growing set of empirical data and theoretical knowledge on human development, in addition to benefiting human sciences such as psychology, philosophy, and cognitive science, can have tremendous technological implications. If we understand the underlying principles and mechanisms of the development of natural cognition in human babies through social interaction, we can use this knowledge to inform the design of cognitive capabilities in artificial agents such as robots. Such principles and mechanisms can be implemented in the cognitive architecture of robots and tested through developmental experiments with robots. This is the aim of developmental robotics, ~~and this volume will explore the current~~ achievements and challenges in the design of autonomous mental development via social interaction in robots and the benefit of a mutual interaction between developmental psychologists and developmental roboticists.

1.1 Developmental Theories of Nature and Nurture

One of the oldest, and endless, debates in psychology, as well as in philosophy, is the contribution of nature and nurture in the development of human intelligence. The baby's prolonged interaction with its physical and social environment is essential to, and significantly influences, its full mental development. At the same time, the baby's genome plays a fundamental role both in the physical and cognitive development of the child. Some traits, especially physical body characteristics, but also cognitive skills such as color perception, can be strongly determined by the baby's own genes, with little influence of environmental phenomena.

This debate has led to various developmental psychology theories on the role of nature versus nurture (Croker 2012). Nativist theories tend to stress the fact that children are born with innate, domain-specific knowledge, which is the result of direct influence of the genes on mental development, with little or no influence from the environment. One of the best-known nativist theories is Chomsky's hypothesis on the language acquisition device and universal grammar (Chomsky 1957; Pinker 1994; see also Pinker and Bloom 1990). This nativist theory proposes that children are born with innate knowledge of linguistic and syntactic principles, whose parameters are then fine-tuned through experience of the language of their parents. In other fields, Leslie (1994) hypothesized that children are born with a theory of mind, and Wynn (1998) that they have innate knowledge of math concepts. On the opposite end, empiricist theories stress the importance of the social and cultural environment in cognitive development. This is the case of Vygotsky's (1978) sociocultural theory, where the role of adults and peers is essential to guide the child to exploit her "zone of proximal development," meaning, the space of the infant's potential capabilities. Similarly, Bruner's socio-cognitive theory of development (Bruner and Haste 1987) stresses the importance of social interaction and interpersonal communication in the various stages of learning. Tomasello (2003) proposes an empiricist theory of language development based on the principle of constructivist and emergent development, whereby the child constructs her own language competence through interaction with other language-speaking agents.

Within these extremes, Piaget (1971) has proposed one of the most influential theories in developmental psychology that combines the contribution of nature and nurture mechanisms. The key tenet of Piaget's theory is that a child goes through different *stages* of development, where at each stage the infant develops qualitatively different and increasingly complex *schemas*, the building block of intelligence. These stages are influenced by maturational constraints, determined by genetic influence, and called "epigenetic" in Piaget's theory (ibid.). However, the child goes through a process of *adaptation*, where the contribution of the external environment is important in the adaptation of existing schemas to new knowledge (assimilation) and the modification and creation of new schemas (accommodation). Piaget proposed four key stages of development of mental capabilities, with a particular focus on the development of thinking capabilities and the origin of abstract thought schemas in sensorimotor knowledge. In the Sensorimotor Stage (Stage 1, 0–2 years old), the child starts with the acquisition of sensorimotor schemas, which initially consist of motor reflexes. In the Preoperational Stage (Stage 2, 2–7 years old), children acquire egocentric symbolic representations of objects and actions, which allow them to represent objects even when these are not visible (object permanence task, when the child understands that a moving object reappears after hiding behind an obstacle). In the subsequent Concrete Operational Stage (Stage 3, 7–11 years old) children can adopt other people's perspectives on object representation and perform mental transformation operations on concrete objects (e.g., liquid conservation task). This finally leads to the Formal Operational Stage (Stage 4, 11+ years old) with the acquisition of full abstract thinking capabilities and complex problem-solving skills. Piaget's theory and stages will be further described in chapter 8, on the models of abstract knowledge.

Another theory that considers the simultaneous contribution of biological and environmental factors is Thelen and Smith's (1994) dynamic systems theory of development. This considers the complex dynamic interaction of various neural, embodiment, and environmental factors in the self-organization of cognitive strategies (see section 1.3.1 for more details).

The nature/nurture debate and nativist/empiricist theories have significantly influenced other fields interested in intelligence, specifically in artificial intelligence and robotics. When building artificial cognitive systems, as with adaptive agents in artificial intelligence and with cognitive robots in robotics, it is possible to use a nativist approach. This implies that the agent's cognitive architecture is fully predefined by the researcher, and does not change significantly during the agent's interaction with the environment. On the other end, the utilization of a more empiricist approach in artificial intelligence and robotics requires the definition of a series of adaptation and learning mechanisms that allow the agent to gradually develop its own knowledge and cognitive system through interaction with other agents and human users. The developmental robotics approach presented in this volume mostly follows a balanced nativist/empiricist approach to robot design as it puts a great emphasis on the development of the robot's capability during interaction with the environment, as well as on the maturational and embodiment factors that constrain development. In particular, Piaget's

balanced

theory, in addition to being the most influential theory in developmental psychology, has strongly influenced the field of developmental robotics, including the use of the term "epigenetic" in the "Epigenetic Robotics" conference title series. This is because Piaget's theory emphasizes the sensorimotor bases of mental development and the balanced biological and environmental approach.

Together with Piaget, another well-known developmental psychologist, Lev Vygotsky, has also significantly influenced the field of developmental robotics. Vygotsky's theory puts much emphasis on the role of social environment on mental development and on the effects that the social and physical environment have on the *scaffolding* of the child's cognitive system during development (Vygotsky 1978). His insights have therefore contributed to social learning and human-robot imitation studies, and to the developmental robotics theory of scaffolding (Asada et al. 2009; Otero et al. 2008; Nagai and Rohlfing 2009).

In the following sections, after defining developmental robotics and presenting a brief historical overview, we will discuss the main defining characteristics and principles of this approach, which combines the dynamic interaction of biological and cultural phenomena in the autonomous mental development of robots.

1.2 Definition and Origins of Developmental Robotics

definition of DevRob

Developmental robotics is the *interdisciplinary approach to the autonomous design of behavioral and cognitive capabilities in artificial agents (robots) that takes direct inspiration from the developmental principles and mechanisms observed in the natural cognitive systems of children.* In particular, the main idea is that the robot, using a set of intrinsic developmental principles regulating the real-time interaction between its body and brain and its environment, can autonomously acquire an increasingly complex set of sensorimotor and mental capabilities.

Developmental robotics relies on a highly interdisciplinary effort of empirical developmental sciences such as developmental psychology, neuroscience, and comparative psychology; and computational and engineering disciplines such as robotics and artificial intelligence. Developmental sciences provide the empirical bases and data to identify the general developmental principles, mechanisms, models, and phenomena guiding the incremental acquisition of cognitive skills. The implementation of these principles and mechanisms into a robot's control architecture and the testing through experiments where the robot interacts with its physical and social environment simultaneously permits the validation of such principles and the actual design of complex behavioral and mental capabilities in robots. Developmental psychology and developmental robotics mutually benefit from such a combined effort.

Historically, developmental robotics traces its origins to the years 2000–2001, in particular in coincidence with two scientific workshops that, for the first time, gathered together scientists interested in developmental psychology principles in both humans and robots. These workshops had been preceded by some work and publications advocating an explicit link between human development and robotics, such as in Sandini, Metta, and Konczak (1997); Brooks et al. (1998); Scassellatti (1998); and Asada et al. (2001).

The first event was the Workshop on Development and Learning (WDL) organized by James McClelland, Alex Pentland, Juyang (John) Weng, and Ida Stockman and held on April 5–7, 2000, at Michigan State University, in East Lansing, Illinois. This workshop subsequently led to the establishment of the annual International Conference on Development and Learning (ICDL). At the WDL the term "developmental robotics" was publicly used for the first time. In addition, the workshop contributed to the coinage of the term "autonomous mental development," to stress the fact that robots develop mental (cognitive) capabilities in an autonomous way (Weng et al. 2001). Autonomous mental development has in fact become a synonym for developmental robotics, and is the name of the main scientific journal in this field, *IEEE Transactions on Autonomous Mental Development.*

The second event to contribute to the birth of developmental psychology as a scientific discipline was the First International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems, which again led to the establishment of the subsequent Epigenetic Robotics (EpiRob) conference series. This workshop was organized by Christian Balkenius and Jordan Zlatev, and was held at Lund University (Sweden) September 17–19, 2001. The workshops borrowed the term "epigenetic" from Piaget. As noted earlier, in Piaget's Epigenetic Theory of human development, the child's cognitive system develops as a result of the interaction between genetic predispositions and the organism's interaction with the environment. As such the choice of the term "epigenetic robotics" was justified by Piaget's stress on the importance of the role of interaction with the environment, and in particular on the sensorimotor bases of higher-order cognitive capabilities. Moreover, this early definition of epigenetic robotics also complemented Piaget's sensorimotor bases of intelligence with Lev Vygotsky's emphasis on social interaction (Zlatev and Balkenius 2001).

In addition to the term "developmental robotics" used in this volume and in other review publications (e.g., Metta et al. 2001; Lungarella et al. 2003; Vernon, von Hofsten, and Fadiga 2010; Oudeyer 2012), and the related term "cognitive developmental robotics" used in Asada et al. (2001, 2009), in the literature other names have been proposed to refer to the same approach and interdisciplinary field. Some authors prefer the term "autonomous mental development" (Weng et al. 2001), while others use the term "epigenetic robotics" (Balkenius et al. 2001; Berthouze and Ziemke 2003).

The use of these different terms mostly reflects historical factors, as discussed, rather than real semantic differences. As a matter of fact, in 2011 the two communities of the ICDL conference series (preferring the term "autonomous mental development") and of the EpiRob series (preferring the term "epigenetic robotics") joined forces to organize the first joint International Conference on Developmental and Learning and on Epigenetic Robotics (IEEE ICDL-EpiRob). This joint conference, continued since 2011, has become the common home for developmental robotics research, with a web presence on http://www.icdl-epirob.org, through the activities of the IEEE Technical Committee on Autonomous Mental Development, which coordinate such joint efforts.

1.3 Principles of Developmental Robotics

The field of developmental robotics has been strongly influenced by developmental psychology theories, as seen in section 1.1. As discussed, developmental robotics models follow an approach based on the coupled interaction of both nativist and empiricist phenomena, though with a stronger emphasis on environmental and social factors. The consideration of the influence of biological and genetic factors includes the effects of maturational phenomena in both the agent's body and brain, the exploitation of embodiment constraints for the acquisition of sensorimotor and mental capabilities, and the role of intrinsic motivation and the instinct to imitate and learn from others. Empiricist and constructivist phenomena considered in developmental robotics research include a focus on situated learning and the contribution of both the social and physical environment in shaping development, and of an online, open-ended and cumulative acquisition of cognitive skills. Moreover, both biological and environmental factors are coupled in an intricate and dynamic way resulting in stage-like qualitative changes of cognitive strategies dependent on a nonlinear dynamical system interaction of genetic, embodiment, and learning phenomena.

A series of general principles can be identified that reflect the numerous factors and processes implicated in the design of autonomous mental development in robots and that have guided developmental robotics practice. These principles can be grouped as shown in table 1.1, and will then be briefly analyzed in the following subsections.

1.3.1 Dynamical Systems Development

An important concept taken from mathematics and physics, and which has significantly influenced general theories of human development, is that of *dynamical systems*. In mathematics, a dynamical system is characterized by complex changes, over time, in the phase state, and which are the result of the self-organization of multifaceted interactions between the system's variables. The complex interaction of nonlinear phenomena results in the production of unpredictable states of the system, often referred to as *emergent* states. This concept has been borrowed by developmental psychologists, and in particular by Thelen and Smith (1994; Smith and Thelen 2003), to explain child development as the emergent product of the intricate and dynamic interaction of many decentralized and local interactions related to the child's growing body and brain

Table 1.1
Principles and characteristics of developmental robotics

	Principles	Characteristics
1	Development as a dynamical system	Decentralized system Self-organization and emergence Multicausality Nested timescales
2	Phylogenetic and ontogenetic interaction	Maturation Critical period Learning
3	Embodied and situated development	Embodiment Situatedness Enaction Morphological computation Grounding
4	Intrinsic motivation and social learning	Intrinsic motivation Value systems Imitation
5	Nonlinear, stage-like development	Qualitative stages U-shaped phenomena
6	Online, open-ended, cumulative learning	Online learning Cumulative Cross-modality Cognitive bootstrapping

and her environment. Thus Thelen and Smith have proposed that the development of a child should be viewed as change within a complex dynamic system, where the growing child can generate novel behaviors through her interaction with the environment, and these behavioral states vary in their stability within the complex system.

One key concept in this theory is that of *multicausality*, for example, in the case when one behavior, such as crawling and walking, is determined by the simultaneous and dynamic consequences of various phenomena at the level of the brain, body, and environment. Thelen and Smith use the example of the dynamic changes in crawling and walking motor behaviors as an example of multicausality changes in the child's adaptation to the environment, in response to body growth changes. When the child's body configuration produces sufficient strength and coordination to support its body through the hands and knee posture, but not to support upright walking, the child settles for a crawling strategy to locomote in the environment. But when the infant's body growth results in stronger and more stable legs, the standing and walking behavior emerges as the stable developmental state, which as a consequence destabilizes, and gradually replaces, the pattern of crawling. This demonstrates that rather than following a predetermined, top-down genetic-controlled developmental trajectory that first controls crawling and then walking, the locomotion behavior is the result of self-organizing dynamics of decentralized factors such as the child's changing body (stronger legs and better balance) and its adaptation to the environment. This illustrates the principle of multicausality, as there are many parallel factors causing varying behavioral strategies.

Another key concept in Thelen and Smith's dynamic systems view of development is that of *nested timescales*, in other words, neural and embodiment phenomena acting at different timescales, and all affecting development in an intricate, dynamic way. For example the dynamics of the very fast timescale of neural activity (milliseconds) is nested within the dynamics of the other slower timescales such as reaction time during action (seconds or hundreds of milliseconds), learning (after hours or days), and physical body growth (months).

One of the best-known developmental psychology examples used by Thelen and Smith to demonstrate the combined effects of the concepts of multicausality and nested timescales is that of the A-not-B error. This example is inspired by Piaget's object permanence experiment, when one toy is repeatedly hidden under a lid at a location A (right) during the first part of the experiment. Toward the end of the task, the experimenter hides the same toy in the location B (left) for a single trial, and then asks the child to reach for the object. While infants older than twelve months have no problem in reaching for the toy in its correct location B, unexpectedly most eight-to-ten-month-old infants produce the curious error of looking for the object in location A. This error is only produced when there is a short delay between hiding and reaching. While psychologists such as Piaget have used explanations based on age (stage) differences linked to qualitative changes in the capability to represent objects and space, a computational simulation of the dynamic system model (Thelen et al. 2001) has demonstrated that there are many decentralized factors (multicausality) and timing manipulations (nested timing) affecting such a situation. These for example depend on the time delay between hiding and reaching, the properties of the lids on the table, the saliency of the hiding event, the past activity of the infant, and her body posture. The systematic manipulation of these factors results in the appearance, stopping, and modulation of the A-not-B errors.

The use of a dynamical systems approach as a theory of development, and the general dynamic linking of body, neural, and environmental factors, have had significant influence in developmental robotics research, as well in other fields of robotics and cognitive systems (Beer 2000; Nolfi and Floreano 2000). This theory has been applied for example to developmental robotics models of early motor development, as in Mori and Kuniyoshi's (2010) simulation on the self-organization of body representation and general movements in the fetus and newborn (section 2.5.3). Also a developmental robotics model of early word learning (Morse, Belpaeme, et al. 2010) uses a setup similar to the A-not-B error to investigate dynamics interactions between embodiment factors and higher-order language development phenomena (section 7.3).

1.3.2 Phylogenetic and Ontogenetic Interaction

Discussion of the dynamical systems approach has already stressed the importance of different timescales during development, including the ontogenetic phenomena of *learning*, over a timescale of hours or days, and *maturational* changes, occurring for periods of months or years. An additional, slower, timescale to consider when studying development is that of the phylogenetic time dimension, that is, the effect of evolutionary changes in development. Therefore the additional implication of the interaction between ontogenetic and phylogenetic phenomena should be considered in robotics models of development.

In this section we will discuss the importance of maturational changes, as these more closely relate to phylogenetic changes. The effect of cumulative changes due to learning new behaviors and skills will be discussed in sections 1.3.5 and 1.3.6.

Maturation refers to changes in the anatomy and physiology of the child's brain and body, especially during the first years of life. Maturational phenomena related to the brain include the decrease of brain plasticity during early development, and phenomena like the gradual hemispheric specialization and the pruning of neurons and connections (Abitz et al. 2007). Brain maturation changes have also been evoked to explain the critical periods in learning. Critical periods are stages (window of time) of an organism's lifespan during which the individual is more sensitive to external stimulation and more efficient at learning. Moreover, after a critical period has ended, learning becomes difficult or impossible to achieve. The best know example of critical period (also known as the sensitive period) in ethology is Konrad Lorenz's study on imprinting, that is, the attachment of ducklings to their mother (or to Lorenz!), which is only possible within the first few hours of life and has a long-lasting effect. In vision research, Hubel and Wiesel (1970) demonstrated that the cat's visual cortex can only develop its receptive fields if the animal is exposed to visual stimuli in the first few months of life, and not when there is total visual deprivation by covering the kitten's eyes. In developmental psychology, the best-studied critical period is that for language learning. Lenneberg (1967) was one of the first to propose the critical period hypothesis for language development that claims that the brain changes occurring between the age of two and seven years, specifically for the hemispheric specialization gradually leading to lateralization of the linguistic function in the left hemisphere, are responsible for the problems in learning language after this age. The critical period hypothesis has also been proposed to explain the limitation in the acquisition of a second language after puberty (Johnson and Newport 1989). Although this hypothesis is still debated in the literature, there is general agreement that brain maturation changes significantly affect language learning beyond the period of puberty.

Maturation in the body of the child is more evident given the significant morphological changes a child goes through from birth to adolescence. These changes naturally affect the motor development of the child, as in Thelen and Smith's analysis of crawling and walking. Morphological changes occurring during development also have implication for the exploitation of embodiment factors, as discussed in section 1.3.3, on the morphological computation effects of embodiment.

Some developmental robotics models have explicitly addressed the issue of brain and body maturation changes. For example, the study by Schlesinger, Amso, and Johnson (2007) models the effects of neural plasticity in the development of object perception skills (section 4.5). The modeling of body morphology development is also extensively discussed in chapter 4 on motor development.

The ontogenetic changes due to maturation and learning have important implications for the interaction of development with phylogenetic changes due to evolution. Body morphology and brain plasticity variations can in fact be explained as evolutionary adaptations of the species to changing environmental context. These phenomena have been analyzed, for example, in terms of genetic changes affecting the timing of ontogenetic phenomena, known as heterochronic changes (McKinney and McNamara 1991). Heterochronic classifications are based on the comparison of ontogenies that differ for the onset of growth, the offset of growth, and the rate of growth of an organ or a biological trait. Namely, the terms "predisplacement" and "postdisplacement" refer respectively to an anticipated and a postponed onset of morphological growth, "hypermorphosis" and "progenesis" refer respectively to a late and an early offset of growth, and "acceleration" and "neoteny" refer respectively to a faster and a slower rate of growth. Heterochronic changes have been used to explain the complex interaction between nature and nurture in models of development, an in Elman et al.'s (1996) proposal that the role of genetic factors in development is to determine the architectural constraints, which subsequently control learning. Such constraints can be explained in terms of brain adaptation and neurodevelopmental and maturational events.

The interaction between ontogenetic and phylogenetic factors has been investigated through computational modeling. For example, Hinton and Nowlan (1987) and Nolfi, Parisi, and Elman (1994) have developed simulation models explaining the effects of learning in evolution, as for the Baldwin effect. Cangelosi (1999) has tested the effects of heterochronic changes in the evolution of neural network architectures for simulated agents. Furthermore, the modeling of the evolution of varying body and brain morphologies in response to phylogenetic and ontogenetic requirements is also the goal of the "evo-devo" computational approach. This aims at simulating the simultaneous effects of developmental and evolutionary adaptation in body and brain morphologies (e.g., Stanley and Miikkulainen 2003; Kumar and Bentley 2003; Pfeifer and Bongard 2007). Developmental robotics models normally are based on robots with fixed morphologies and cannot directly address the simultaneous modeling of phylogenetic changes and their interaction with ontogenetic morphological changes. However, various epigenetic robotics models take into consideration the evolutionary origins of the ontogenetic changes of learning and maturation, especially for studies including changes in brain morphology.

1.3.3 Embodied, Situated, and Enactive Development

Growing empirical and theoretical evidence exists on the fundamental role of the body in cognition and intelligence (*embodiment*), the role of interaction between the body and its environment (*situatedness*), and the organism's autonomous generation of a model of the world through sensorimotor interactions (*enaction*). This embodied, situated, and enactive view stresses the fact that the body of the child (or of the robot, with its sensors and actuators), and its interaction with the environmental context determines the type of representations, internal models, and cognitive strategies learned. As Pfeifer and Scheier (1999, 649) claim, "intelligence cannot merely exist in the form of an abstract algorithm but requires a physical instantiation, a body."

In psychology and cognitive science, the field of embodied cognition (aka grounded cognition) has investigated the behavioral and neural bases of embodiment, specifically for the roles of action, perception, and emotions in the grounding of cognitive functions such as memory and language (Pecher and Zwaan 2005; Wilson 2002; Barsalou 2008). In neuroscience, brain-imaging studies have shown that higher-order functions such as language share neural substrates normally associated with action processing (Pulvermüller 2003). This is consistent with philosophical proposals on the embodied mind (Varela, Thompson, and Rosch 1991; Lakoff and Johnson 1999) and situated and embodied cognition (Clark 1997).

In robotics and artificial intelligence, embodied and situated cognition has also received great emphasis through the approach of embodied intelligence (Pfeifer and Scheier 1999; Brooks 1990; Pfeifer and Bongard 2007; Pezzulo et al. 2011). Ziemke (2001) and Wilson (2002) analyze different views of embodiment and their consideration in computational models and psychology experiments. These different views range from considering embodiment as the phenomenon of the "structural coupling" between the body and the environment, to the more restrictive "organismic" embodiment view, based on the autopoiesis of living systems, that is, that cognition actually is what living systems *do* in interaction with their world (Varela, Thompson, and Rosch 1991). Along the same lines, the paradigm of enaction highlights the fact that an autonomous cognitive system interacting in its environment is capable of developing its own understanding of the world and can generate its own models of how the world works (Vernon 2010; Stewart, Gapenne, and Di Paolo 2010).

Embodied and situated intelligence has significantly influenced developmental robotics, and practically any developmental model places great emphasis on the relation between the robot's body (and brain) and the environment. Embodiment effects concern pure motor capabilities (morphological computation) as well as higher-order cognitive skills such as language (grounding). *Morphological computation* (Bongard and Pfeifer 2007) refers to the fact that the organism can exploit the body's morphological properties (e.g., type of joint, length of limbs, passive/active actuators), and the dynamics of the interaction with the physical environment (e.g., gravity) to produce intelligent behavior. One of the best-known examples of this is the passive dynamic walker, that is, bipedal robots that can walk on a slope without any actuator, thus not requiring any explicit control, or bipedal robots only requiring minimal actuation to start movement (McGeer 1990; Collins et al. 2005). The exploitation of morphological computation has important implications for energy consumption optimization in robotics, and for the increasing use of compliant actuators and soft robotics material (Pfeifer, Lungarella, and Iida 2012).

On the other end, an example of the role of embodiment in higher-order cognitive functions can be seen in the models of the grounding of words in action and perception (Cangelosi 2010; Morse, Belpaeme, et al. 2010, see section 7.3) and the relationship between spatial representation and numerical cognition in psychology and developmental robotics (Rucinski, Cangelosi, and Belpaeme 2011, see section 8.2).

1.3.4 Intrinsic Motivation and Social Learning Instinct

Conventional approaches to designing intelligent agents typically suffer from two limitations. First, the objectives or goals (i.e., the value system) are normally imposed by the model-builder, rather than determined by the agent themselves. Second, learning is often narrowly restricted to performance on a specific, predefined task. In response to these limitations, developmental robotics explores methods for designing *intrinsically motivated* agents and robots. An intrinsically motivated robot explores its environment in a completely autonomous manner, by deciding for itself what it wants to learn and what goals it wants to achieve. In other words, intrinsic motivation enables the agent to construct its own value system.

The concept of intrinsic motivation is inspired by a variety of behaviors and skills that begin to develop in infancy and early childhood, including diverse phenomena such as curiosity, surprise, novelty seeking, and the "drive" to achieve mastery. Oudeyer and Kaplan (2007) propose a framework for organizing research on models of intrinsic motivation, including two major categories: (1) knowledge-based approaches (which are subdivided into novelty-based and prediction-based approaches), and (2) competence-based approaches. Within this framework, a large number of algorithms can be defined and systematically compared.

Novelty-based approaches to intrinsic motivation often utilize mobile robots, which learn about their environments by exploring and discovering unusual or unexpected features. A useful mechanism for detecting novelty is habituation: the robot compares its current sensory state to past experiences, devoting its attention toward situations that are unique or different from those that have already been experienced (e.g., Neto and Nehmzow 2007).

Prediction-based approaches are a second type of knowledge-based intrinsic motivation, as they also rely on accumulated knowledge. However, in this case prediction-based models explicitly attempt to predict future states of the world. A simple example could be a robot that pushes an object toward the edge of the table, and predicts that it will make a sound when it drops on the floor. The rationale of this approach is that incorrect or inaccurate predictions provide a learning signal, that is, they indicate events that are poorly understood, and require further analysis and attention. As an example of this approach, Oudeyer et al. (2005) describe the Playground Experiment, in which the Sony AIBO robot learns to explore and interact with a set of toys in its environment.

The third approach to modeling intrinsic motivation is competence based. According to this view, the robot is motivated to explore and develop skills that effectively produce reliable consequences. A key element of the competence-based approach is *contingency detection*: this is the capacity to detect when one's actions have an effect on the environment. While the knowledge-based approach motivates the agent toward discovering properties of the world, the competence-based approach, in contrast, motivates the agent to discover *what it can do* with the world.

Child development research has shown the presence of social learning capabilities (instincts). This is evidenced for example by observations that newborn babies have an instinct to imitate the behavior of others from the day they are born and can imitate complex facial expressions (Meltzoff and Moore 1983). Moreover, comparative psychology studies have demonstrated that 18- to 24-month-old children have a tendency to cooperate altruistically, a capacity not observed in chimpanzees (Warneken, Chen, and Tomasello 2006).

As we highlight in chapter 3, the development of intrinsic motivation has direct implications for how infants perceive and interact with others. For example, young infants quickly learn that people in their environment respond contingently to their movements and sounds. Thus, babies may be intrinsically motivated to orient toward and interact with other people.

Developmental robotics places a heavy emphasis on social learning, and as demonstrated in the numerous studies discussed in chapter 6, various robotics models of joint attention, imitation, and cooperation have been tested.

1.3.5 Nonlinear, Stage-Like Development

The literature on child psychology has plenty of theories and models proposing a sequence of developmental *stages*. Each stage is characterized by the acquisition of specific behavioral and mental strategies, which become more complex and articulated as the child progresses through these stages. Stages are also linked to specific ages of the child, except for individual differences. Piaget's four stages of development of thought are the prototypical example of a theory of development centered on stages (chapter 8). Numerous other examples of stage-based development exist, and a few will be described in the chapters that follow, as Courage and Howe's (2002) timescale of self-perception (chapter 4), Butterworth's (1991) four stages of joint attention and Leslie's (1994) and Baron-Cohen's (1995) stages of the theory of mind (chapter 6), the sequential acquisition of lexical and syntactic skills (chapter 8), and the stages of numerical cognition and of rejection behavior (chapter 9).

In most theories, the transition between stages follows nonlinear, qualitative shifts. Again, in the example of Piaget's four stages, the mental schemas used in each stage are qualitatively different, as they are the results of accommodation processes that change and adapt the schema to new knowledge representations and operations. Another well-known developmental theory based on qualitative changes during development is the Representational-Redescription Model of Karmiloff-Smith (1995). Although Karmiloff-Smith explicitly avoids the definition of age-determined stage models, as in Piaget, her model assumes four levels of development going from the use of implicit representation to different levels of explicit knowledge-representation strategies. When a child learns new facts and knowledge about specific domains, she develops new representations, which are gradually "redescribed" and increase the child's explicit understanding of the world. This has been applied to a variety of knowledge domains such as physics, math, and language.

The nonlinearity of the developmental process and the qualitative shifts in the mental strategies and knowledge representations employed by the child at different stages of development have been extensively investigated through "U-shaped" learning error patterns and with the vocabulary spurt phenomenon. The prototypical case study of the U-shaped phenomenon in child development is in the patterns of errors produced by children during the acquisition of the verb morphology for the English past tense. The (inverted) U-shaped phenomenon consists of the low production of errors at the beginning of learning, which is then followed by an unexpected increase in errors, subsequently followed by an improved performance and low error production again. In the case of the English past tense, initially children produce few errors as they can say the correct past tense for high-frequency irregular verbs, such as "went," and the correct "ed" suffix form for regular verbs. At a later stage, they pass through a stage of "over-regularization," and start producing morphological errors for irregular verbs, as with "goed." Eventually, children can again distinguish the multiple forms of irregular past tenses. This phenomenon has been extensively studied in psychology, and has caused heated debate between the proponents of a rule-based strategy for syntax processing (Pinker and Prince 1988), and the advocates of a distributed representation strategy, which is supported by demonstration that connectionist networks can produce a U-shaped performance by using distributed representations (e.g., Plunkett and Marchman 1996). U-shaped learning phenomena have also been reported in other domains, such as in phonetic perception (Eimas et al. 1971; Sebastián-Gallés and Bosch 2009), face imitation (Fontaine 1984), and in Karmiloff-Smith's (1995) explanation of a child's performance and errors due to the changing representational strategies.

The vocabulary spurt phenomenon in lexical acquisition is another case of nonlinear and qualitative shifts during development. The vocabulary spurt (also called the "naming explosion") occurs around the eighteen- to twenty-four-month period, when the child goes from an initial pattern of slow lexical learning, with the acquisition of few words per month, to the *fast mapping* strategy, whereby a child can quickly learn tens of words per week by single exposure to the lexical item (e.g., Bloom 1973; Bates et al. 1979; Berk 2003). The vocabulary spurt typically happens when a child has learned around 50–100 words. This qualitative change of strategy in word learning has been attributed to a variety of underlying cognitive strategies, including the mastering of word segmentation or improvements in lexical retrieval (Ganger and Brent 2004).

Many developmental robotics studies aim to model the progression of stages during the robot's development, with some directly addressing the issue of nonlinear phenomena in developmental stages as a result of learning dynamics. For example Nagai et al. (2003) explicitly modeled the joint attention stages proposed by Butterworth (1991). However, the model shows that qualitative changes between these stages are the result of gradual changes in the robot's neural and learning architecture, rather than ad hoc manipulations of the robot's attention strategies (see section 6.2). Some models have also directly addressed the modeling of U-shaped phenomena, such as in the Morse et al. (2011) model of error patterns in phonetic processing.

1.3.6 Online, Open-Ended, Cumulative Learning

Human development is characterized by online, cross-modal, continuous, open-ended learning. *Online* refers to the fact that learning happens while the child interacts with its environment, and not in an offline mode. *Cross-modal* refers to the fact that different modalities and cognitive domains are acquired in parallel by the child, and interact with each other. This is for example evidenced in the interaction of sensorimotor and linguistics skills, as discussed in the embodiment section 1.3.3. *Continuous* and *open-ended* refers to the fact that learning and development do not start and stop at specific stages, but rather constitute a lifelong learning experience. In fact, developmental psychology is often framed within the wider field of the psychology of life cycles, ranging from birth to aging.

Lifelong learning implies that the child *accumulates* knowledge, and thus learning never stops. As seen in the previous sections, such continuous learning and accumulation of knowledge can result in qualitative changes of cognitive strategies, as in the language vocabulary spurt phenomenon, and in Karmiloff-Smith's theory on the transition from implicit to explicit knowledge through the Representational-Redescription model.

One consequence of cumulative, open-ended learning is *cognitive bootstrapping*. In developmental psychology, cognitive bootstrapping has been mostly applied to numerical cognition (Carey 2009; Piantadosi, Tenenbaum, and Goodman 2012). According to this concept, a child acquires knowledge and representation from learned concepts (e.g., numerical quantities and counting routines) and then inductively uses this knowledge to define the meaning of new number words learned subsequently, and with a greater level of efficiency. The same idea can be applied to the vocabulary spurt, in which the knowledge and experience from the slow learning of the first 50–100 words causes a redefinition of the word learning strategy, and to syntactic bootstrapping, by which children rely on syntactic cues and word context in verb learning to determine the meaning of new verbs (Gleitman 1990). Gentner (2010) has also proposed that general cognitive bootstrapping is achieved through the use of analogical reasoning and the acquisition of symbolic relationship knowledge.

Online learning is implemented in developmental robotics, as will be demonstrated in most of the studies presented in the next chapters. However, the application of cross-modal, cumulative, open-ended learning, which can lead to cognitive bootstrapping phenomena, has been investigated less frequently. Most of the current models typically focus on the acquisition of only one task or modality (perception, or phonetics, or semantics, etc.), and few consider the parallel development, and interaction, between modalities and cognitive functions. Thus a truly online, cross-modal, cumulative, open-ended developmental robotics model remains a fundamental challenge to the field.

The presentations of various examples of developmental robotics models and experiments will show how most of the preceding principles guide and inform the design of the cognitive architecture and the experimental setups of developmental robots.