3 Developmental Robotics

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3.1 Introduction

In this chapter we introduce "developmental robotics" in the context of cognitive robotics. Developmental robotics can be defined as "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" (Cangelosi and Schlesinger 2015, 4). Developmental robotics relies on a highly interdisciplinary effort of developmental psychology, neuroscience, and comparative psychology with robotics and artificial intelligence. In particular, developmental sciences such as child psychology provide the empirical bases to identify the general developmental principles, mechanisms, models, and experimental protocols guiding the design of cognitive robots and their testing in situated developmental robotics experiments. Given this close interaction, developmental psychology and developmental robotics can also mutually benefit from such a combined effort (Cangelosi and Schlesinger 2018).

Developmental robotics is based on the vision that a baby robot, using developmental principles and mechanisms regulating the real-time interaction between its body, brain, and environment, can autonomously acquire an increasingly complex set of sensorimotor and mental capabilities. Thus, within the wider approach of cognitive robotics, developmental robotics specializes in its emphasis on the design of baby robots with an autonomous capability to acquire ever-more-complex skills.

Historically, the field of developmental robotics has also been known as "cognitive developmental robotics" (Asada et al. 2001), "autonomous mental development" (Weng et al. 2001), and "epigenetic robotics" (Zlatev and Balkenius 2001). Asada et al. (2001) proposed "cognitive developmental robotics" as a new paradigm for the design of humanoid robots. Lungarella et al. (2003) published the first survey paper on developmental robotics. Asada et al. (2009) later proposed a systematic survey of the early cognitive developmental robotics approaches. More recently, Cangelosi and Schlesinger (2015) provided a comprehensive review of the field in their book *Developmental Robotics: From Babies to Robots*.

In this chapter we will first consider the theoretical background of cognitive developmental robotics, focusing on epistemological paradigm shifts from human-object dichotomy to human-machine physical and mental interaction. Based on this background, “physical embodiment” and “social interaction” are introduced as key concepts of developmental robotics (Asada et al. 2009). We will then extend this to the six defining principles of developmental robotics proposed by Cangelosi and Schlesinger (2015), with brief examples of each.

3.2 Theoretical and Philosophical Background

Asada (2019) has proposed a general outline of the theoretical and philosophical background of the relationship between consciousness, humans, and objects/technology at the origin of cognitive developmental robotics. The discussion below follows the concepts introduced in Tani (2016) but adds further consideration of the contribution of the philosophers Kant and Vico (figure 3.1).

Initially, Descartes advanced mind-body dualism,[1] establishing the relationship between mind and body or things, and laid the foundation for modern philosophy. Then Vico opposed Cartesianism and all reductionism, asserting the verum factum principle that truth is verified only by creation or invention, not by observations, as proposed in Cartesianism.[2]

Husserl, Heidegger, and Merlot-Ponty presented important concepts such as embodiment, interaction, and intersubjectivity (see Tani 2016) and noted that the essence of reality is lost by discriminating between humans and objects (cf. Asada [2019] for more details on this issue).

In his moral philosophy, Kant spoke from the perspective of morality as an obligatory act—that is, “what should be.”[3] In today’s world, due to technological progress, interacting with objects exposes the limits of anthropocentric thinking. Peter-Paul Verbeek has shown a typical example of such a situation when he and his wife entered the ultrasound examination room. He mentioned in the preface of *Moralizing Technology: Understanding and Designing the Morality of Things* that “even though the technology in the ultrasound practice clearly had moral significance, it did not directly steer our behavior. Rather, it helped to shape our experience of our unborn child and the interpretive frameworks that guided our actions and decisions. By us, this technology had not simply granted us a ‘peek into the womb’; it had reorganized the relations between our unborn child and ourselves” (Verbeek 2011). As he mentioned, this is one aspect of the moral significance of technology, and the fixed view of Kant’s moral philosophy seems unable to handle appropriate relationships with these technologies. Foucault’s (1994) moral ethics, or “what we like to be,” are considered more relevant.

Figure 3.1 shows a paradigm shift from mind-body dualism, which emphasizes the relationship between humans and objects by anthropocentric thinking (above the thick broken line in the figure), to a concept that emphasizes both the importance of a creation-based viewpoint and societal impacts (below the thick broken line in the figure). In other words, objects and technologies have come to judge and commit to decision-making via machine learning represented by deep learning, such as autodrive, and the structure and mechanism of free will and consciousness have gradually been revealed in neuroscience, physiology, and cognitive sciences. This is because traditional views of consciousness and autonomy no longer function in modern disciplines.

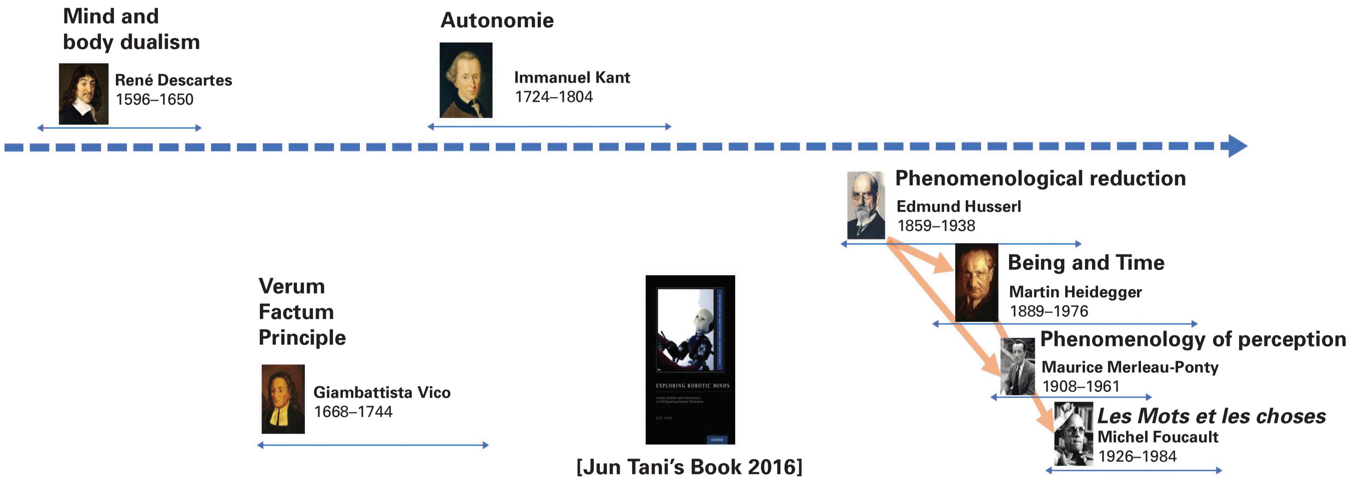


Figure 3.1
Outline of the philosophical background of the relationship between humans and things (technology).

All these theoretical considerations have significantly influenced the approach of cognitive developmental robotics (Asada et al. 2009; Asada 2019). These epistemological concepts advocate the importance of physical embodiment and social interaction, which have influenced the wider field of cognitive robotics, as discussed in chapter 1. Before introducing the key principles and related studies of developmental robotics, we review the developmental process of the human fetus and infant, which will have an impact on the design issues and approaches of developmental robotics.

3.3 A Brief Overview of the Development of the Human Fetus and Infant

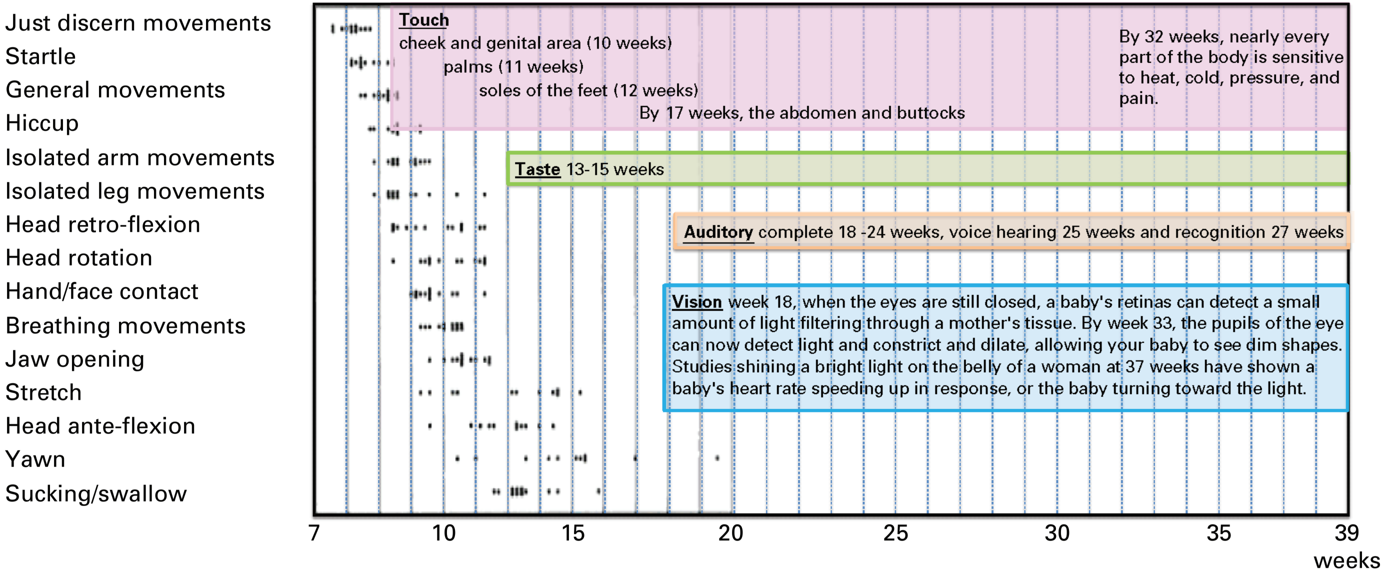
Advanced imaging technologies such as three-dimensional ultrasound movies have enabled the observation of various kinds of fetal movements in the womb after several weeks of gestation. This reveals the possibility of the fetus learning in the womb (Hopson 1998). De Vries et al. (1984) reported that fetal motility started from the early state of "just discern movements (7.5 weeks)" to the later state of "sucking and swallow (12.5–14.5 weeks)" through "startle, general movements, hiccup, isolated arm movements, isolated leg movements, head retroflexion, head rotation, hand/face contact, breathing movements, jaw opening, stretch, head anteflexion, and yawn." Campbell (2004) also reported that the eyes of the fetus open around twenty-six weeks' gestation and that the fetus often touches their face with the hands during embryonic weeks twenty-four and twenty-seven.

Touch is the first sense to develop in the fetus, followed by the other senses, such as taste, hearing, and vision. Chamberlain stated that just before eight weeks' gestational age, the first sensitivity to touch manifests in a set of protective movements to avoid a mere hair stroke on the cheek. From this early stage, experiments with a hair stroke on various parts of the body show that skin sensitivity quickly extends to the genital area (ten weeks), palms (eleven weeks), and soles (twelve weeks). These areas of first sensitivity will have the greatest number and variety of sensory receptors in the adult. By seventeen weeks, all parts of the abdomen and buttocks become sensitive. Skin is marvelously complex, containing a hundred varieties of cells that seem especially sensitive to heat, cold, pressure, and pain. By thirty-two weeks, nearly every part of the body is sensitive to the same light stroke of a single hair. Both hearing and vision start to function about eighteen weeks after gestation and fully develop at around twenty-five weeks.

Moreover, it is reported that visual stimulation from the outside of the maternal body can activate the fetal brain (Eswaran et al. 2002). Figure 3.2 summarizes the emergence of fetal movements with the development of the fetal senses reviewed above.

After birth, infants are supposed to gradually develop body representation, categories for graspable objects, capability of mental simulation of actions, and so on through learning processes. For example, controlling the hand at the fifth month means learning the forward and inverse models of the hand. Table 3.1 shows typical behaviors and their corresponding targets to learn.

Our growing understanding of the early stages of fetus and infant development have been very influential in developmental robotics. Asada et al. (2009) analyzed in detail a wide set of pioneering developmental robotics models of early fetal and infant development. Two three-dimensional simulation models of the fetus and newborn infants were developed by



Touch
cheek and genital area (10 weeks)
palms (11 weeks)
soles of the feet (12 weeks)
By 17 weeks, the abdomen and buttocks

By 32 weeks, nearly every part of the body is sensitive to heat, cold, pressure, and pain.

Taste 13-15 weeks

Auditory complete 18 -24 weeks, voice hearing 25 weeks and recognition 27 weeks

Vision week 18, when the eyes are still closed, a baby's retinas can detect a small amount of light filtering through a mother's tissue. By week 33, the pupils of the eye can now detect light and constrict and dilate, allowing your baby to see dim shapes. Studies shining a bright light on the belly of a woman at 37 weeks have shown a baby's heart rate speeding up in response, or the baby turning toward the light.

Figure 3.2
Emergence of fetal movements and the senses. *Source:* Adapted from fig. 1 in de Vries et al. 1984.

Table 3.1
Infant developmental behavior and learning targets

Month—behavior	Learning targets
5 hand regard	Forward and inverse models of the hand
6 finger the another's face	Integration of visuotactile sensation of the face
7 drop objects and observe the result	Causality and permanency of objects
8 hit objects	Dynamic modeling of objects
9 drum or bring a cup to mouth	Tool use
10 imitate movements	Imitation of unseen movements
10 rudimentary sympathy	Feel pain and empathy
11 grasp and carry objects to others	Action recognition and generation, cooperation
12 pretend	Mental simulation

Source: Adapted from Asada et al. 2009.

Kuniyoshi and colleagues within the Japan Science and Technology Agency Exploratory Research for Advanced Technology (JST ERATO) Asada project. The first model (Kuniyoshi and Sangawa 2006) provided the initial, minimally simple body model of fetal and neonatal development. The subsequent fetus model (Mori and Kuniyoshi 2010) produced a more realistic rendering of the fetus's sensorimotor apparatus and a stronger focus on learning experiments. These models offer a useful research tool to investigate prebirth sensorimotor development by providing a realistic representation of the fetus's sensors and the reaction of the body to gravity and the womb border and environment. The first model, for instance, was used to study the role of general embodied developmental principles in early sensorimotor learning. In particular, it aimed at exploring the hypothesis that partially ordered embodiment dynamical patterns emerge from the chaotic exploration of body-brain-environment interactions during gestation. These patterns lead, later in development, to the emergence of meaningful motor behavior such as rolling over and crawling motions in neonates.

3.4 Six Principles of Developmental Robotics

Figure 3.3 shows the six principles of developmental robotics, centering two key concepts, embodiment and social interaction. Embodiment, or physical embodiment, is a fundamental constraint for infants (humans and robots) to learn sensorimotor mapping through interaction with the environment. Related research topics are motor babbling and body representation (body schema or body image) through crossmodal association (e.g., Mannella et al. 2018). These topics lead to the emergence of the early concept of the self, often called the "ecological self" (Neisser 1994) through embodied, situated, and enactive development. The ecological self is also called the temporary self or, according to Gallagher (2000), the minimal self, involving a sense of agency or a sense of ownership of motion.

The early stage of social interaction can be observed as infant-caregiver interaction. Intrinsic motivation and social-learning instinct (Baldassarre and Mirolli 2013; Ishihara et al. 2011) inside the agents play important roles in developing various behavioral and cognitive functions, such as imitation (e.g., gesture, vocalization, and joint attention), turn taking, and so on.

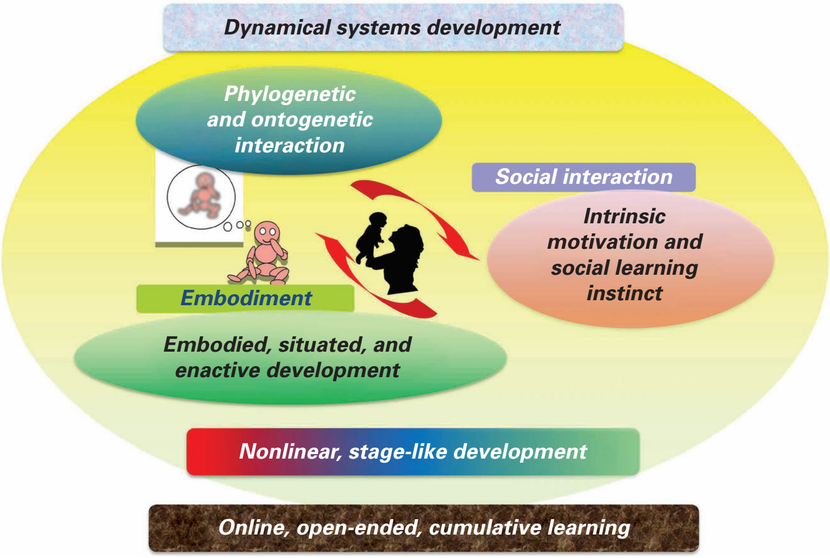


Figure 3.3
Principles of developmental robotics.

Both phylogenetic and ontogenetic interactions occur during the above developmental processes. Innate functions are regarded as assumptions, and learning targets are set at each stage of development. The learning results become the assumptions for the next stage of learning, and vice versa—that is, the assumptions at the current stage might be the results of learning during the previous stage. Thus, nonlinear stagelike learning develops (Lee et al. 2007).

Developmental pathways are diverse, from typical development to atypical, and this also holds true for developmental robots. These pathways are expected to share several key points that enable social interactions from different pathways, and learning continues beyond different stages in terms of a lifelong scale as a whole. It is an online, open-ended, cumulative learning process.

Thelen and Smith (1994) proposed the dynamical systems approach as a developmental psychology theory, and several computational-modeling methods attempt to reproduce nonlinear, dynamic developmental processes of coupled interactions involving the classical nature-nurture issue.

In the following sections, we will describe in detail the six key defining principles of developmental robotics, as proposed in Cangelosi and Schlesinger (2015). The presentation of each principle will refer to certain seminal developmental psychology studies and related developmental robotics models.

3.4.1 Dynamical Systems Development

In mathematics, a dynamical system is characterized by complex changes, over time, in the phase state that result from 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. In child psychology this concept has been borrowed by Thelen and Smith (1994) 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 and the 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 behavior through 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 analyzed the dynamic changes in crawling and walking as an example of multicausality changes in the child's adaptation to the environment, in response to body growth. When the child's body configuration produces sufficient strength and coordination to support them through the hands and knees posture but is not strong enough for 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 stops, the pattern of crawling. This demonstrates that 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.

Another key concept in the dynamical systems view of development is that of *nested timescales*. That is, neural and embodiment phenomena act at different timescales and affect development in an intricate, dynamical 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 action-reaction time (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 and then, toward the end of the task, is hidden in a location B (left) for a single trial, and the child is asked 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 children err in looking for the object in location A. Although psychologists such as Piaget have used explanations based on age (stage) differences linked to qualitative changes in the ability to represent objects and space, a computational simulation of the dynamical system model (Thelen et al. 2002) has demonstrated that many decentralized factors (multicausality) and timing manipulations (nested timing) affect 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, and the past activity of the infant and their body posture.

The use of a dynamical system approach as a theory of development has had significant influence in developmental robotics research, as well as in other cognitive robotics areas (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. In Meola et al. (2015) and Mannella et al. (2018), the initial dynamical movements of a robot, analogous to Piaget's circular reactions, were progressively shaped into purposeful actions. Additionally, a developmental robotics model of early word learning (Morse et al. 2010) uses a similar setup to the A-not-B error to investigate dynamic interactions between embodiment factors and higher-order language development phenomena. Tani (2016) also showed approaches to neurorobotics based on the idea of dynamical systems.

3.4.2 Embodied, Situated, and Enactive Development

Chapter 1 has already discussed the role of *embodiment* in robot design. In addition, two more concepts have influenced developmental robotics models. One is the role of interaction between the body and its environment (*situatedness*), and the other looks at the organism's autonomous acquisition of a model of the world through sensorimotor interactions (*enaction*).

Ziemke (2001) and Wilson (2002) analyzed different views of embodiment and their consideration in computational models and psychology experiments. These views ranged from considering embodiment as the phenomenon of "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 et al. 1992). 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 generating its own models of how the world works (Vernon 2010; Stewart et al. 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, brain, and environment. Embodiment effects concern pure motor capabilities (morphological computation) as well as higher-order cognitive skills such as language (grounding) and imagination. Hoffmann et al. (2010) surveyed various approaches to body representations in robotics. Among them, body image/schema acquisition by Yoshikawa et al. (2002), Fuke et al. (2007), and Hikita et al. (2008) focused on crossmodal association and self-organizing maps, both of which are powerful methods in developmental robotics. Yamada et al. (2016) showed a brain-body interaction in the fetus utilizing 2.6 million spike neurons and a realistic musculoskeletal model, although it was computer simulation.

On the other end, an example of the role of embodiment in higher-order cognitive functions can be seen in models of the grounding of words in action and perception (Cangelosi 2010; Morse et al. 2010), the relationship between spatial representation and numerical cognition in psychology and developmental robotics (Rucinski et al. 2011; see also chapter 22), and the relationship between sensorimotor behavior and imagination processes (Seepanomwan et al. 2015).

3.4.3 Intrinsic Motivation and Social-Learning Instinct

Developmental robotics explores methods for designing *intrinsically motivated* agents and robots who can define their own goals and value systems (see chapter 13; Baldassarre and

Mirolli 2013). 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 et al. (2007) proposed a framework for organizing research on models of intrinsic motivation, including two major categories: 1) knowledge-based approaches (later subdivided into novelty-based and prediction-based approaches; Barto et al. 2013) 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 study robots that 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 to situations that are unique or different (e.g., Vieira Neto and Nehmzow 2007).

Prediction-based approaches use knowledge-based intrinsic motivation to explicitly attempt to predict future states of the world (Schmidhuber 2010). 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 learned to explore and interact with a set of toys in its environment.

The third approach to modeling intrinsic motivation is competence based. The robot is motivated to explore and develop skills that effectively produce reliable consequences (Barto et al. 2004; Santucci et al. 2016). A key element of the competence-based approach is contingency detection (Jacquey et al. 2019): this is the capacity to detect when one's actions have an effect on the environment. While the knowledge-based approaches motivate 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 instinctually imitate the behavior of others from the very first day of life and can imitate complex facial expressions (Meltzoff and Moore 1977). Moreover, comparative psychology studies have demonstrated that eighteen-to-twenty-four-month-old children have a tendency to cooperate altruistically, a capacity not observed in chimpanzees (Warneken et al. 2006).

Developmental robotics places a heavy emphasis on social learning; various robotics models of joint attention, imitation, and cooperation have been tested. Nagai et al. (2003b, 2006) showed the early developmental model of joint attention, and Sumioka et al. (2010) proposed a contingency model for joint attention. Asada (2016) reviewed modeling approaches to early vocal development through infant-caregiver interaction. Imitation and cooperation have been other hot topics in general, with representative studies introduced by Cangelosi and Schlesinger (2015).

3.4.4 Phylogenetic and Ontogenetic Interaction

Two different timescales must be considered in developmental robotics: 1) the ontogenetic phenomena of learning, over a timescale of hours or days, with maturational changes occurring for periods of months or years and 2) the phylogenetic phenomena of evolutionary changes. Therefore, the additional implication of the interaction between ontogenetic and phylogenetic phenomena should be considered in developmental robotics models of development.

The whole process of development can be observed as a heterogeneous interaction between phylogenetic constraints and ontogenetic processes. Therefore, the issues are not a simple dichotomy of "nature versus nurture." Ridley (2003) reframed this dichotomy in terms of "nature via nurture." Although it has been said that "ontogeny recapitulates phylogeny," it does not seem so simple. Both processes are highly intertwined and show a broad and dynamic landscape as a result.

Maturation refers to changes in the anatomy and physiology of both 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 the gradual hemispheric specialization and pruning of neurons and connections (Abitz et al. 2007). Brain maturation changes have also been evoked to explain the critical period in learning. Critical periods are stages (windows of time) of an organism's life span during which the individual is more sensitive to external stimulation and more efficient at learning. Moreover, after the critical period has ended, learning becomes difficult or impossible. The best-known example of a critical period (aka a "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 Wisel (1970) demonstrated that the cat's visual cortex can only develop its receptive fields if the animal is exposed to visual stimuli during the first few months of life and not when it experiences total visual deprivation as a kitten by having its eyes covered.

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 (1994) analysis of crawling and walking. Morphological changes occurring during development also have an implication for the exploitation of embodiment factors, as discussed in 3.4.2.

Some developmental robotics models have explicitly addressed the issue of brain and body maturation changes. For example, the study by Schlesinger et al. (2007) modeled the effects of neural plasticity in the development of object perception skills.

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 contexts. These phenomena have been analyzed in terms of genetic changes affecting the timing of ontogenetic phenomena, known as *heterochronic changes* (McKinney et al. 1991). Heterochronic changes have been used to explain the complex interaction between nature and nurture in models of development, as 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 et al. (1994) have developed simulation models explaining the effects of learning in evolution, as in the Baldwin effect. Cangelosi (1999) 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 to simulate 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 2006).

Developmental robotics models are normally based on robots with fixed morphologies and cannot directly address the simultaneous modeling of phylogenetic changes and its 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. Nagai et al. (2006) compared performances in terms of the timing parameter that controls the learning phase for joint attention. One is a fixed time schedule in which the learning phase shifts to the next one (phylogenetic constraint), and the other depends on the learning result—that is, shifting to the next learning phase if the target of the current learning phase is achieved (ontogenetic constraint). Because this is a case of brain maturation, the fixed time schedule for the timing parameter could be arbitrary, allowing the designer to tune anyway. However, in the case of body maturation it may interfere with the learning process, accelerating or decelerating the process to some extent. This seems to be a typical case of a heterogeneous interaction between the phylogenetic and ontogenetic processes. Although the brain maturation process was not clearly described, Yamada et al. (2010) showed two kinds of computer simulations for the fetus and the infant that indicated body maturation.

3.4.5 Nonlinear, Stagelike 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. Piaget's (1952) four stages of development of thought is the prototypical example of a theory of development centered on stages. Numerous other examples of stage-based development exist (Courage and Howe 2002; Butterworth and Jarrett 1991).

In most theories, the transition between stages follows nonlinear, qualitative shifts. 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). 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, they develop 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, has been extensively investigated through U-shaped learning-error patterns and the vocabulary spurt phenomenon—that is, the sudden growth of the vocabulary after a slow word-acquisition stage (Elman et al. 1996).

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. Ogino et al. (2006) proposed an active lexicon-acquisition method based on curiosity to partially model the vocabulary spurt phenomenon. Nagai et al. (2003a) explicitly modeled the joint attention stages proposed by Butterworth and Jarrett (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. Some models have also directly addressed the modeling of U-shaped phenomena, such as the Morse et al. (2011) model of error patterns in phonetic processing. Asada (2015) proposed a conceptual model for the development of artificial empathy that shows a stagelike development starting from emotional contagion through emotional/cognitive empathy to sympathy/compassion. Lee et al. (2007) proposed the lift constraint, act, and saturate method for which robots can develop increasingly complex skills by "saturating" the acquisition of knowledge at a certain level of competence and thus release the possibility of learning at a more complex level.

3.4.6 Online, Open-Ended, Cumulative Learning

Human development is characterized by online, crossmodal, continuous, open-ended learning. "Online" refers to the fact that learning happens while the child interacts with the environment and not in an off-line mode. "Crossmodal" refers to the fact that different modalities and cognitive domains are acquired in parallel by the child and interact with each other. "Continuous" and "open-ended" refers to the fact that learning and development do not start and stop at specific stages but rather are lifelong learning experiences (Baldassarre and Mirolli 2013).

Online learning is currently implemented in developmental robotics. However, the application of crossmodal, 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, and so on), and few consider the parallel development, and interaction, between modalities and cognitive functions. Thus, a truly online, crossmodal, cumulative, open-ended developmental robotics model remains a fundamental challenge for the field.

3.5 Conclusion

The numerous philosophical consideration and research issues, challenges, and principles discussed have led to the creation of numerous developmental robotics models exploring a wide range of behavioral and cognitive skills. In many of the chapters of part III, which focus on cognitive robotics models of specific sensorimotor and cognitive functions, we will see further examples of developmental robotics models and experiments. For example, chapter 13 is largely based on developmental approaches, and chapter 18 and 20 present various developmental robotics models of social and linguistic skills.

Additional Reading and Resources

- The most comprehensive overview of the field of developmental robotics: Cangelosi, Angelo, and Schlesinger, Matthew. 2015. *Developmental Robotics: From Babies to Robots*. Cambridge, MA: MIT Press.
- Seminal review paper on the initial theoretical issues and pioneering models of baby robots: Asada, Minoru, Koh Hosoda, Yasuo Kuniyoshi, Hiroshi Ishiguro, Toshio Inui, Yuichiro Yoshikawa, Masaki Ogino, and Chisato Yoshida. 2009. "Cognitive Developmental Robotics: A Survey." *IEEE Transactions on Autonomous Mental Development* 1 (1): 12–34.
- A rich theoretical and computational analysis of principles and models of cognitive and developmental robotics: Tani, Jun. 2016. *Exploring Robotic Minds: Actions, Symbols, and Consciousness as Self-Organizing Dynamic Phenomena*. Oxford: Oxford University Press.

Notes

1. Substance dualism, material-centered dualism, spiritual dualism, classical dualism, and so on, https://www.iep.utm.edu/dualism/.
2. Wikipedia, "Giambattista Vico," https://en.wikipedia.org/wiki/Giambattista_Vico.
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