1 What Is Cognitive Robotics?

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1.1 Context and Definition

The wider field of robotics concerns the building of hardware mechatronics platforms with sensors and actuators to perform actions in the physical world and the designing of software solutions to link sensing and actuation in a purposeful—that is, intelligent—and adaptive way to achieve the task goal, with a variable degree of autonomy. This is captured, for example, in Matarić's (2007, 2) definition of a robot as "an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals."

If we focus on the software side of robotics, the tools and approaches to building goal-oriented intelligent and adaptive capabilities in robots greatly overlap with the approaches and methods of artificial intelligence (AI). These range from good old-fashioned AI (GOFAI) knowledge-based reasoning and planning systems to the latest machine-learning algorithms of deep neural networks and reinforcement learning. Such a field combining robotics and AI can be referred to as "intelligent robotics" or, as recently proposed by Murphy (2019), "AI robotics." Murphy (2019, 7) defines an intelligent robot as "a physically situated intelligent agent." This designation is grounded in the concept of a robot being *physically situated* in the real world with an embodied physical structure suitable to perform a set task and the concept of an *intelligent agent* as a system that perceives its environment and takes actions to maximize its chances of success at adapting to the world. Such a definition and concepts of an intelligent robot practically coincide with Matarić's general definition of a robot. In fact, the difference between (software) robotics and intelligent robotics is a really fuzzy distinction, as no researcher is really claiming to want to build "dumb" robots. Even the goal of modeling "Dumb Animals and Stupid Robots," as Barbara Webb (1993) framed her project on the robot cricket, requires the use of nontrivial computer science and AI methods.

What is cognitive robotics then? Is it the same as intelligent robotics (AI robotics)?

Different definitions of cognitive robotics (CR hereafter) have been offered in the literature. In 1997 Stein proposed the first definition of CR when presenting the architectural principles for CR. Stein (1997, 471) defines CR as "the effort to build a physically embodied intelligent system—draws much of its approach from the cognitive sciences and natural examples of embodied intelligent systems." Kawamura and Browne (2009, 1) define CR as the "design and use of robots with humanlike intelligence in perception, motor control and high-level cognition," stressing the need for interdisciplinary contributions from the various fields of robotics, AI, cognitive science, neuroscience, biology, philosophy, psychology, and cybernetics. Metta and Cangelosi (2012, 613) have proposed that CR is "the use of bio-inspired methods for the design of sensorimotor, cognitive, and social capabilities in autonomous robots." All these definitions emphasize the role of an interdisciplinary approach to robot design and a focus on humanlike and bioinspired functions ranging from sensorimotor to higher-order cognitive functions, up to social skills. In particular, a fundamental influence in CR comes from the cognitive sciences, especially the disciplines interested in human cognition, such as psychology and neuroscience. This humanlike focus, however, does not exclude complementary insights from animal cognition and neuroscience in the design of bioinspired cognitive robots, such as tortoises and crickets (cf. Walter's tortoises in sections 1.2 and 1.3.1).

Other researchers have characterized CR primarily as the distinctive focus on integrating higher-order functions, such as reasoning, to complement the standard intelligent robotics focus on sensing and action. De Giacomo (1998, 1), in the organization of the first meeting explicitly dedicated to CR (the 1998 Association for the Advancement of Artificial Intelligence [AAAI] Winter Symposium on Cognitive Robotics—see section 1.3.2), defined CR as the field "concerned with integrating reasoning, perception and action within a uniform theoretical and implementation framework." Levesque and colleagues also focused on higher-order functions when defining CR as the "study of the knowledge representation and reasoning problems faced by an autonomous robot (or an agent) in a dynamic and incompletely known world" (Levesque and Lakemeyer 2008, 869; see also Levesque and Reiter 1998). As we will see in section 1.2, the emphasis on reasoning skills in the definition of CR is related to some of the influence of early AI knowledge representations experts in CR.

To summarize and integrate the various historical contributions to the characterization of CR, we would like to propose a comprehensive definition of CR that combines the above emphases on bioinspired—that is, humanlike and animallike—behavior and intelligence and on the distinctive interdisciplinary approach with strong contributions from the cognitive and neural sciences and from biology:

Cognitive robotics is the field that combines insights and methods from AI, as well as cognitive and biological sciences, to robotics.

Most of the current CR models typically focus on the design of one, or few, bioinspired sensorimotor and cognitive skills, as is the case in the CR models presented in part III of this volume. However, some works in CR also underscore the modeling of a system-level integration of a range of cognitive functions—for example, linking higher-level functions in reasoning and social skills with sensorimotor knowledge.

Now that we have defined CR, is this field the same as intelligent robotics (AI robotics)? In science it would be impossible, and counterproductive, to try to create an artificial, rigid distinction between different (sub)disciplines and approaches. Though one main distinction between CR and intelligent robotics lies in CR's strong emphasis on designing bioinspired and cognitively inspired cognitive robots, in reality a continuum exists between the two fields. On one hand, there are CR models strictly constrained to known biological mechanisms that are built to simulate and replicate the cognitive development phenomena observed in natural organisms. This is the case, for example, with Mori and Kuniyoshi's (2010) realistic rendering of the human fetus in their model of prenatal motor skill development (chapter 3) and of Morse et al.'s (2015) replication of child psychology experiments on the embodiment cues in early language learning (chapter 20). On the other hand, researchers have realized a variety of cognitive skills in intelligent robots via a combination of AI techniques without any justification for their biological inspiration or function.

The framing of CR as an integrative, systemic approach to modeling humanlike cognition in robots also explains its close link to the cognate modeling area of cognitive systems and its associated definition of cognition. The field of cognitive systems (a.k.a. artificial cognitive systems) refers to the creation of machines and software systems with humanlike cognition—that is, the "capacity for self-reliance, for being able to figure things out, for independent adaptive anticipatory action" (Vernon 2014, 2). Cognitive systems also tend to focus on higher-level cognition, on structured representations and systems perspectives, on influence from human cognition, and on exploratory research (Langley 2012). Cognitive systems as a discipline typically refers to the wider area of cognitive modeling with simulated and virtual agents, as well as physical robots, and to a variety of software-based agents and hardware-based smart objects (Morris et al. 2005; Vernon 2014). In its broadest sense, this has been extended to the design of intelligent human-computer interaction systems (a.k.a. cognitive systems engineering; Woods and Roth 1988) and to general-purpose AI systems such as the IBM Watson application (High 2012). With respect to CR, there is a good index of overlap when we consider the subareas of cognitive systems using physical robots, including cognitive systems of simulated robotics agents with a high degree of fidelity to the replication of body-environment physics dynamics.

Vernon (2014) considers four aspects when modeling artificial cognitive systems: 1) how much inspiration we take from natural systems, 2) how faithful we try to be in copying them, 3) how important we think the system's physical structure is, and 4) how we separate the identification of cognitive capability from the way we eventually decide to implement it. These aspects provide a method to position individual cognitive systems (and CR) models in a two-dimensional space where one axis defines the spectrum ranging from purely computational approaches to models strongly inspired by biological models, and the other axis defines the level of abstraction of the target biological model.

An important contribution from the field of cognitive systems is that of providing a more comprehensive operational definition of cognition. Following Vernon's (2014, 8) detailed characterization of cognition in artificial cognitive systems, cognition can be defined as "the process by which an autonomous system perceives its environment, learns from experience, anticipates the outcome of events, acts to pursue goals, and adapts to changing circumstances." Thus, cognition can be seen as a systemwide process that integrates all of the capabilities of the agent within the key attributes of autonomy, perception, learning, anticipation, action, and adaptation. In particular, cognition can be represented as a cycle of anticipation, assimilation, and adaptation, embedded within a continuous process of action and perception and dynamically adapting via learning (figure 1.1).

This definition of cognition, and the identification of its six key attributes, can explain the variety of skills and capabilities the agent should possess: goal-oriented behavior,

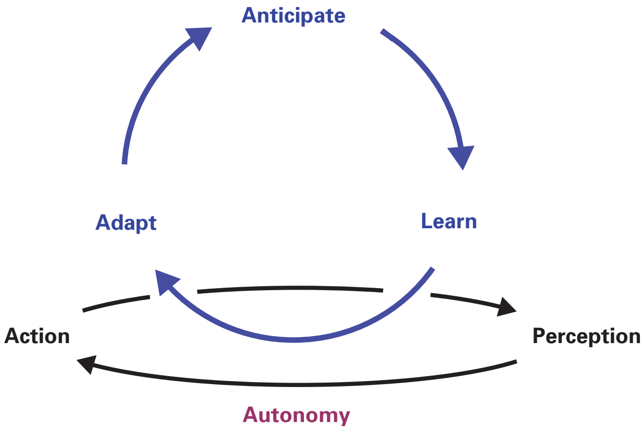

Figure 1.1
The six key attributes of cognition in artificial cognitive systems. *Source:* Adapted from Vernon 2014.

autonomy, interaction via cooperation and communication, intention reading, interpretation of expected and unexpected events, prediction of the outcome of its own and of others' actions, action selection and evaluation, adaptation to changing circumstances, learning from experience, and monitoring and correcting its own performance (Vernon 2014).

This view of cognition is in line with the systemic and wider coverage of lower-level (perception and action) to higher-level (anticipation) capabilities of robots in CR. However, it places an emphasis on modeling the dynamic processes of cognition (assimilation, adaptation, learning). This is consistent with dynamical systems approaches in CR, such as in developmental robotics (cf. chapter 3).

The combined focus on the systemic and integrated approach to cognition, on the modeling of bioinspired humanlike and animallike cognitive capabilities, and on the interdisciplinarity approaches to CR, as reflected in its definition above, will characterize the review of the state of the art in the chapters that follow. Of course, not all individual CR models aim to model the full breadth of behavioral and sociocognitive skills in a single robot. Typically, a specific CR model will implement a subset of such humanlike (and/or animallike) capabilities, depending on the specific task and skills the robot has to perform or the cognitive mechanisms the robot's model aims to operationalize and evaluate. This will be the case for most of the CR models and experiments presented in part III, with each chapter focusing primarily on a specific capability, from sensing, navigation, and manipulation to social and language skills to higher-level reasoning and consciousness.

Next we will look at the main epistemological and theoretical approaches to modeling behavior and intelligence that influenced and bootstrapped the emergence of the field of CR in the late 1990s. We will then summarize the origins and historical developments of CR.

1.2 Inspiration Principles and Theories

The early approaches to CR were influenced by both theoretical and computational stances in the modeling of behavior and cognition, in particular by the embodied cognition standpoint (e.g., Clark, Pfeifer) and by computational approaches to AI modeling of behavior-based robotics and of higher-order reasoning function (e.g., Brooks). A further inspiration, particularly important from a historical point of view, was the direct influence of pioneering works on synthetic methods for modeling simple, animallike organisms (Walter, Braitenberg) and early computational neuroscience models for robotics (Edelman, Krichmar). Below we briefly discuss the specific theoretical and modeling works that motivated robotics researchers to take on the cognitive and bioinspired approach to intelligent robots and CR.

1.2.1 Embodied Cognition Theories

Embodied cognition is the approach to studying natural intelligent systems that underscores the roles of sensorimotor knowledge and representation and the interaction between our own body and the environment in producing intelligent behavior. In particular, the strong embodied cognition thesis states that the body plays a significant causal role, as a physically constitutive role, in the agent's cognitive processing (Wilson and Foglia 2017). A related approach is that of grounded cognition (Barsalou 2008; Pezzulo et al. 2013), which emphasizes the sensorimotor ("modal") nature of the representations and internal simulation mechanisms (Vernon 2014). See chapter 11 for a detailed discussion on embodiment and embodied cognition.

Embodied cognition has affected various disciplines, including psychology (Pecher and Zwaan 2005; Barsalou 2008); cognitive sciences (Clark 1999); neuroscience (Pulvermüller and Fadiga 2010); and various computational modeling fields, such as language grounding (Cangelosi 2010), sensorimotor schema learning (Lara et al. 2018), and computational embodied neuroscience (Caligiore et al. 2010). Chapter 11 will also provide a detailed discussion of this issue and its specific contribution to CR.

In the very early stages of CR, there were two main theoretical stances on embodied cognition that have since been explicitly acknowledged to have influenced the very first cognitive robots. These are Andy Clark's (1999) theory on embodied cognitive science and Rolf Pfeifer's embodied intelligence and morphological computation stance.

Clark and Grush (1999) have specifically proposed a theoretical stance for a path toward CR. This is based on the "Cartesian agent" metaphor—that is, the combination of directly embodied, coupled, real-world action-taking with a decoupled, off-line reasoning capability. Thus, the cognitive phenomena of an agent involve off-line reasoning, which is vicarious environmental exploration and an internal representation.

This focus on the capability of having off-line reasoning functions grounded in embodied experience has had a strong impact on CR (Kawamura and Browne 2009) and has also contributed to some of the early CR emphasis on modeling knowledge representation and reasoning in robots (Levesque and Reiter 1998; Aiello et al. 2001).

This epistemological focus on higher-order cognition complements a parallel emphasis on the ability to develop cognition through sensorimotor coordination. This is the main stance proposed by Pfeifer and colleagues (Pfeifer and Scheier 2001; Pfeifer and Bongard 2006). Such an embodied cognition view is exemplified by the concept of "morphological computation"—that is, that certain sensorimotor and cognitive control processes are performed by the body and its interaction with the environment, rather than being performed by the brain. Pfeifer and Bongard (2006) use the example that the muscles and tendons of the human leg are elastic, and this directly influences locomotion control. When the leg impacts the ground while running, the knee performs small adaptive movements without neural control. Thus, the control is supplied by the muscle-tendon system itself, which is part of the morphology of the agent. This morphological computation principle can also be exploited in robotics. A direct example of this is the “passive walker” (Collins et al. 2005; McGeer 1990), a simple robot that exploits gravity with a sloped track and the structure of two legs with flexible knees to move in a downward direction. This is possible without requiring any electric motors or electrical energy.

This attention to sensorimotor embodiment for cognition has greatly affected the development of CR, as many of the early cognitive robots have exploited the morphological computation principles (chapter 11). This is the case, for example, with soft robots exploiting the dynamics of the soft material of sensors and actuators (chapters 6 and 8), with evolutionary and swarm robotics for the automatic design of coupled body-brain-environment systems (chapters 4 and 5), and with developmental robotics and its application of the embodied cognition principles to motor development models (chapter 3).

1.2.2 AI and Knowledge-Based Systems

The classical (GOFAI) approach to AI, with its focus and breadth of methods for knowledge-based systems, symbolic representation, and reasoning, was also one of the key influences on CR. We have already mentioned early work by Levesque, Reiter, De Giacomo, and colleagues in the bootstrap of the CR discipline and community. In the 1998 AAAI Winter Symposium on Cognitive Robotics, many of the participants contributed to a “Cognitive Robotics Manifesto” with the explicit aim of modeling high-level robotic control in which robotic agents require reasoning using explicit knowledge representation systems that lead to a decision on how to act (Levesque and Reiter 1998; Aiello et al. 2001).

This approach follows the paradigm of perception-*reasoning*-action (or sense-*plan*-act), with a strong emphasis on the AI methods and models for reasoning/planning to connect robot sensing and action. It often involves the methods of situation calculus, description logic, and geometric reasoning typically applied to planning for action and navigation for the RoboCup challenge and mobile robot platforms (e.g., Woodbury and Oppenheim 1988; Aiello et al. 2001; but see Asada and von Stryk [2020] for a recent discussion of the scientific and technological challenges offered by the RoboCup challenge).

1.2.3 Behavior-Based Robotics

A different path to CR emerged from the alternative approach to AI based on the behavior-based robotics and the subsumption architecture proposed by Brooks (1991, 1996; Arkin 1998). In strong opposition to AI’s symbolic and representational methods, Brooks claims that intelligent behaviors can be achieved by reactive architectures, with a direct sense-act cycle and without the need for intermediate (symbolic) representations. This is exemplified by Brooks’s (1991) “Intelligence without Representation” nouvelle AI manifesto paper.

After the initial focus on mobile robot models of animal behavior (leading to the iRobot Roomba commercial vacuuming robot), the behavior-based robotics approach led to modeling behavior and cognition in humanoid robots (Brooks 1996; Matarić 1998). This included projects on the COG and the KISMET platforms (Brooks and Stein 1994; Brooks et al. 1998). This work explicitly led to an interdisciplinary approach using behavior-based robotics as a tool for the synthesis of artificial behavior and the analysis of natural behavior, taking direct inspiration from cognitive science, neuroscience, and biology with methods from artificial life, evolutionary computation, and multiagent systems (Breazeal 2004). In the CR movement, this is closely linked to the development of evolutionary and swarm robotics (chapters 4 and 5, respectively).

1.2.4 Synthetic Methodologies

The "synthetic methodology" and "synthetic neural modeling" approaches to behavioral and cognitive modeling have also influenced CR (Krichmar 2012). These are methodologies based on the idea of recreating, in a simulated virtual environment or via physical platforms, embodied agents with a brain-inspired control system. They offer a balanced approach that emphasizes the intertwined interaction of the brain, the body, and the environment. The main synthetic methodologies directly influencing CR have come from Grey Walter's "tortoises," Valentino Braitenberg's "vehicles," and Chris Langton's "artificial life" systems.

Grey Walter was a neuroscientist and pioneer in synthetic approaches to behavioral and cognitive modeling. In the late 1940s and early 1950s, he developed a set of electromechanical robots, called tortoises, capable of performing simple tasks such as phototaxis, following a light, and homing behavior, going to a battery-charging station. Walter's first robot was called Machina Speculatrix, from the Latin verb *speculari*, which means "to explore," as the tortoise actively explored the environment, as an animal would. Walter nicknamed two of the prototype robots ELSIE (from Electromechanical robot, Light Sensitive with Internal and External stability) and ELMER (ELectroMEchanical Robot; Walter 1950, 1953). He also proposed an electrical learning circuit named CORA (COnditioned Reflex Analogue) to model Pavlovian conditioning (Walter 1951). These systems implemented simple neural circuits. The focus on synthetic and neuroinspired modeling has galvanized many researchers in CR. For example, the Darwin series of robots developed by Edelman and colleagues (1992; Krichmar and Edelman 2003) follow on this synthetic methodology for mobile robots but with a stronger emphasis on using computational neuroscience models. This has led to the development of the CR neurorobotics approach (see chapter 2).

A subsequent synthetic modeling approach was proposed by the psychologist Braitenberg. In his well-known volume *Vehicles: Experiments in Synthetic Psychology*, Braitenberg (1986) describes a series of theoretical (fictional) models of simple mobile agents (i.e., vehicles). For example, Vehicle 1 is the simplest agent, with one sensor and one motor, and is capable of getting around by going straight with variable speeds depending on temperature sensors. Braitenberg describes a set of agents of increasing complexity in their sensorimotor system and the connectivity pattern between their sensors and motors and speculates on their ability to show behaviors that he describes as "fear and aggression" (Vehicle 2) and "love" (Vehicle 3).

These simple but elegant models of control in mobile agents have significantly influenced the field of CR, and of robotics and AI in general, as they provide an analysis of different control systems and their role in understanding behavior and cognition. For example, Hogg et al. (1991) developed a set of Braitenberg "creatures" as LEGO robots implementing and extending the various vehicles, and Hallam et al. (2002) used evolutionary computation to model the evolution of the spiking networks of Braitenberg's controllers.

The third CR influential synthetic approach is that of artificial life (ALife; Langton 1997). This uses a prototypical synthetic methodology, as it aims to “synthetize” lifelike behavior and agents, in simulation and hardware. ALife models and applications go well beyond behavior and cognitive modeling; for example, they can be used to study artificial plants and artificial chemistry. In the early stage of ALife, significant emphasis was placed on agent and robot modeling, such as the CR evolutionary and swarm robotics approaches derived from building ALife agents (Steels and Brooks 1995). More recently, ALife has focused on synthetic biology and artificial chemistry, as well as on the origins of life.

1.3 History of Cognitive Robotics

Figure 1.2 gives a syncretic overview of the milestones in the history of CR, starting from the early attempts to model humanlike (and animallike) robots, which we call the “prehistory” of CR (from the early 1950s to the 1980s), to the period of the official start and establishment of the roots of CR (in the 1990s), to the contemporary evolution, diversification, and growth of various CR approaches (from 2000 onward). These historical developments will be discussed in detail.

1.3.1 Prehistory (1950–1980)

The tortoise robot models developed by Grey Walter (1950, 1953) in the early 1950s at the Burden Neurological Institute in Bristol, UK, can be considered the very first step in the (pre)history and origins of CR. Their novel synthetic methodology, the behavior-modeling focus, and the neuroinspired learning architecture pioneered by Walter have left a significant legacy not only in the field of CR but in the fields of robotics and AI in general (Holland 2003a, 2003b).

The 1960s saw the creation of the first intelligent robot, Shakey (Rosen et al. 1969; Nilsson 1984; see figure 1.2). It was developed between 1966 and 1972 at the Artificial Intelligence Center of the Stanford Research Institute (now SRI International). Shakey was a mobile robot capable of planning, route finding, and rearranging simple objects. The control architecture integrated sensing and action with the robot’s “model of the world.” This was implemented as a collection of predicate calculus statements in an indexed data structure, with five classes of entities (doors, wall faces, rooms, objects, robots) and a set of primitives to describe these entities in the model (e.g., distance between entities). For problem-solving, it used the QA3.5 theorem-proving system (Nilsson 1984). Shakey, and subsequent intelligent robots such as Flakey with its ability to follow and communicate with people, were the first platforms to experiment with linking AI with robotics, thus also influencing the AI robotics origins of CR.

The decade of the 1980s saw the creation of some of the seminal works that later influenced the development of CR. These include Braitenberg’s vehicles theoretical analysis and Brooks’s behavior-based robotics developments, as discussed in 1.2 (see figure 1.2). In the 1980s there is one work that, to the best of our knowledge, contains the first mention of the term “cognitive robotics.” This is the book *Principles and Elements of Thought Construction, Artificial Intelligence and Cognitive Robotics* by Charles Bowling (1987). It proposes a cognitive architecture for a simplified AI application based on the object calculus lattice (OCL) method.

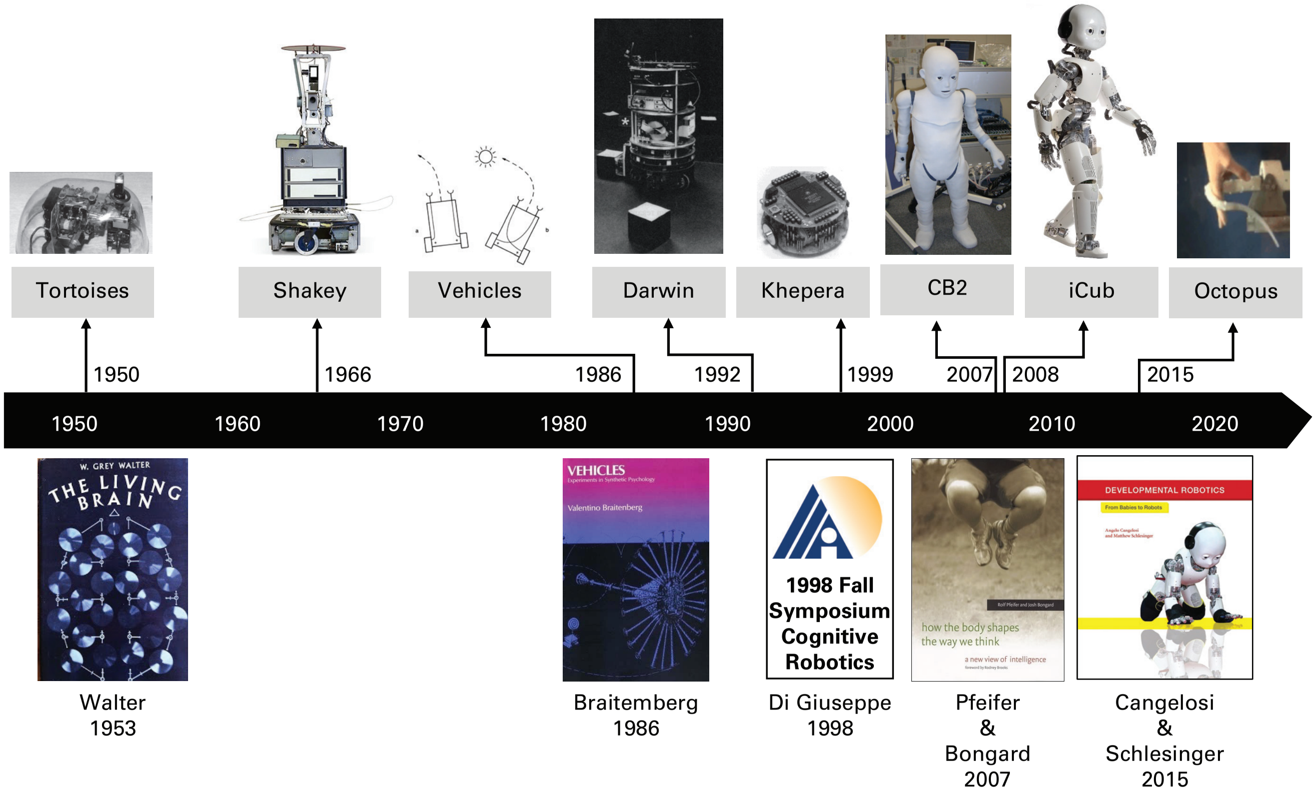

Figure 1.2
The history of cognitive robotics with robot and book milestones.

1.3.2 Establishing Roots (1990s)

The first established gathering of a community explicitly using the title "Cognitive Robotics" and working at the interface of AI and robotics was the 1998 AAAI Fall Symposium on Cognitive Robotics (De Giacomo 1998). Giuseppe De Giacomo chaired it, with a strong presence from Ray Reiter's team and their innovative work combining logic and reasoning capabilities in intelligent robots. In fact, this pioneering event helped roboticists to stress the higher-level cognitive functions of reasoning in action and perception robotic systems. It led to the "Cognitive Robotics Manifesto" (Levesque and Reiter 1998; Aiello et al. 2001). This event also provided the first definition of CR as the field "concerned with integrating reasoning, perception and action within a uniform theoretical and implementation framework" (De Giacomo 1998).

Other signs of the first attempts to focus on cognitively inspired robotics came from various groups working in AI and robotics, in addition to the work in behavior-based robotics and embodied cognition discussed above. In Japan, researchers working on cognitive skills design in humanoid robots started to define some of the principles of CR, such as exploring cognitive processes in systems with advanced cognitive functions by means of a "constructive approach" realized by repeating hypotheses and verification using robots (Asada et al. 1999).

1.3.3 Growth, Diversification, and Funding (2000s)

The CR roots established in the late 1990s, feeding from parallel contributions from the areas of behavior-based robotics, embodied cognition, and cognitive systems, led to a burst of growth in CR in the early to mid-2000s that still continues to this day. This is reflected by the flourishing workshops and special issues and seminal volumes in CR as well as further expansion of the associated CR approaches of developmental robotics, evolutionary robotics, and neurorobotics. For example, in 2002 leading pioneers in CR gathered in Bristol, UK, for the International Workshop on Biologically Inspired Robotics, dedicated to William Grey Walter (WGW02; Damper 2003; Holland 2003a). Another AAAI Winter Symposium on "The Intersection of Cognitive Science and Robotics: From Interfaces to Intelligence" was organized in 2004 (Shultz 2004). Other events included the 2006 Cognitive Robotics, Intelligence and Control Workshop (COGRIC) in Reading, UK (Becerra et al. 2006), the 2010 Dagstuhl Seminar "Cognitive Robotics" (Lakemeyer et al. 2010), and the 2013 international symposium in Osaka on "Past and Future Directions of Cognitive Developmental Robotics."

This period also led to the diversification and growth of parallel, crosscutting CR approaches, each focusing on a specific learning or behavioral mechanism. These include developmental robotics, neurorobotics, evolutionary robotics, swarm/collective robotics, and soft robotics (as per part I of this volume).

The field of cognitive developmental robotics (Lungarella et al. 2003; Asada et al. 2009; Cangelosi and Schlesinger 2015) started in the early 2000s with the Workshop on Development and Learning (WDL; April 5–7, 2000, East Lansing, IL; cf. Weng et al. 2001) and the First International Workshop on "Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems" (EpiRob; September 17–19, 2001, Lund, Sweden; Zlatev and Balkenius 2001). The diffusion of baby robot platforms, such as the open systems iCub robot (Metta et al. 2008, 2010) and the CB2 robot (Minato et al. 2007), significantly contributed to the growth of developmental robotics research (see figure 1.2 for the iCub and CB2 robots). See Cangelosi and Schlesinger (2015) and chapter 3 for a more recent and comprehensive review of the work in this field.

The field of neurorobotics is the subarea of CR that centers on the use of computational neuroscience and neuromorphic systems to control the robot's behavior and cognitive system (Browne et al. 2009; Krichmar 2012; see also chapter 2). This followed the early Darwin mobile robot models in the mid-1990s (Edelman et al. 1992) and led to numerous applications to mobile and humanoid robots, including the use of a neuromorphic system directly implementing hardware with neuron-like circuits (Rast et al. 2018) and the more recent neurorobotic platform in the Human Brain Project (Knoll and Gewaltig 2016).

Evolutionary robotics (Nolfi and Floreano 2000) is the CR approach to modeling the autonomous design of cognitive functions in robots via the use of evolutionary computation algorithms (see also chapter 4). This approach actually started in the mid-1990s, with subsequent growth in the 2000s along the wider evolutionary computation field and the CR/systems-oriented conference series "SAB: Simulation of Adaptive Behavior" and "ALIFE Artificial Life." Evolutionary robotics benefited from the design and ease of access to small mobile robots in research laboratories, such as the Khepera robot (Mondada et al. 1999; see figure 1.2).

The field of swarm robotics can be seen as the application of swarm intelligence to robotics (see also chapter 5). This goes back to the early 1990s (e.g., Kube and Zhang 1992), with significant growth in the 2000s (e.g., Dorigo and Şahin 2004; Şahin 2004). The initial research in this field was mainly characterized by the transferring of biological principles, such as self-organization, to multirobot systems (Kube and Zhang 1992). Research in swarm robotics today generally focuses on specific methodologies, such as collective decision-making, as well as work toward applications—for example, for applications in sea monitoring, agriculture, and search and rescue.

More recently, the field of soft robotics has emerged as a branch of robotics, including CR, where soft and deformable materials are employed to endow robots with the ability to achieve more conformable, flexible, adaptable, and robust behaviors (Laschi et al. 2016; see chapter 6). This can also lead to the development of biomimetic (e.g., animal-inspired) robots such as octopus robots (Cianchetti et al. 2015; figure 1.2). This emphasizes concepts such as functional materials, deformable structures, and adaptive sensor morphology, which will be further discussed in chapter 6. The ability to devise and mimic unique, complex body dynamics and interactions with the physical world makes soft robots an exciting new field, where the limits of the (rigid) robots of the past century can be overcome for further understanding of bioinspired robotics and embodied cognition.

This period also saw interest and financial investment from various funding agencies worldwide in the growing areas of cognitive systems and CR. In 2002 the US Defense Advanced Research Projects Agency (DARPA) launched an initiative in cognitive systems to "develop the next generation of computational systems with radically new capabilities, 'systems' that know what they're doing" (Brachman and Lemnios 2002).

The European Commission identified "Cognitive Systems" as one of the funding priorities for the new Sixth Framework Programme (FP7; 2002–2006), which then took on a more robotics-focused initiative with the "Cognitive Systems, Interaction and Robotics" priority in the Seventh Framework Programme (FP7; 2007–2013; Maloney 2007). Examples of influential CR projects from these framework programs are RobotCub (which led to the iCub's cognitive robot platform development; Metta et al. 2010; see also chapter 7; robotcub.org), CoSy for human-robot interaction using context-specific (situation and task) knowledge (Christensen et al. 2010), ITALK on developmental robotics for language grounding (Cangelosi et al. 2010), and POETICON/POETICON++ on the synthesis (poesis) of sensorimotor representations and natural language in everyday human interaction (Pastra 2008). This initiative also led to the funding of the network action grant EUcognition (www.eucognition.org/).

In 2003 the UK government's Office of Science and Technology established a Foresight Project on "Cognitive Systems," with subsequent interdisciplinary project funding from across the country's different councils. This used the working definition of "Cognitive systems—natural and artificial—sense, act, think, feel, communicate, learn and evolve" (UK Foresight 2003; Morris et al. 2005). In this program, (cognitive) robotics was explicitly seen as a major example of one of the possible cognitive systems branches (along with computers, wearables, smart things, and so on).

In Japan, this led to the funding of large, collaborative projects in CR such as the Japan Science and Technology Agency Exploratory Research for Advanced Technology (JST ERATO) Asada Synergistic Intelligence Project and two Japan Society for the Promotion of Science (JSPS) Grants-in-Aid on "Constructive Developmental Science."

1.4 Book Structure

This volume aims to provide a comprehensive, up-to-date overview of the state of the art in CR. As such, the chapters were authored by the leading international experts in the field, including many of the pioneers in CR.

In part I, we will first cover the main CR approaches or subareas—namely, neurorobotics, developmental robotics, evolutionary robotics, swarm robotics, and soft robotics.

Part II focuses on the methods and concepts common to most CR models and applications. It includes two chapters introducing the robot platforms and simulators and the bioinspired robot sensor and actuator technologies, a chapter providing an overview of machine-learning methods for CR, and two chapters on cognitive architectures and the concept of embodiment. It also contains a chapter on ethics for robotics, which is a fundamental concept in CR.

Part III is a series of chapters covering the whole spectrum of cognitive capabilities. Each chapter focuses on one specific behavioral/cognitive ability. Where appropriate, the chapter includes an explicit discussion of the bioinspired and cognitively inspired studies and theories that incited the subsequent robot models and experiments. This section of the book specifically includes chapters on the CR models of intrinsic motivation, visual perception, navigation and mapping, manipulation, human-robot interaction (HRI) decision and control, social cognition, human-robot interaction, language and communication, reasoning and knowledge representation, abstract concepts, and, finally, robot and machine consciousness.

This volume can be used to learn about the full breadth of approaches, methods, concepts, and models in CR—for example, for graduate students and researchers or as a reference book for a targeted effort on specific topics and work.

Each chapter also contains a section titled "Additional Reading and Resources" listing seminal papers and books in the specific topics covered by the authors, as well as links to internet and code resources. For general CR resources, see the "Introduction to Cognitive Robotics" course (www.cognitiverobotics.net). For pointers to software resources on CR, refer to the resources page of the Institute of Electrical and Electronics Engineers (IEEE) Technical Committee for Cognitive Robotics (http://www.ieee-coro.org).

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