2

What Is Human–Robot Interaction?

What is covered in this chapter:

- The academic disciplines that come together in the field of human–robot interaction (HRI).
- The barriers created by the disciplines' different paradigms and how to work around these.
- The history and evolution of HRI as a science.
- Landmark robots in HRI history.

Human–robot interaction, or HRI, is commonly referred to as a new and emerging field, but the notion of human interaction with robots has been around for as long as the notion of robots themselves. Isaac Asimov, who coined the term *robotics* in the 1940s, wrote his stories around questions that take the relationship between humans and robots as the main unit of analysis: "How much will people trust robots?"; "What kind of relationship can a person have with a robot?"; "How do our ideas of what is human change when we have machines doing humanlike things in our midst?" (see page 237 for more on Asimov). Decades ago, these ideas were science fiction, but nowadays, many of these issues are real and present in contemporary societies and have become core research questions in the field of HRI.

This chapter aims to set the table for the rest of the book. Because HRI is an incredibly diverse field, Section 2.1 highlights and explains the main themes included in this book. Section 2.2 covers the interdisciplinary nature of this field, and the consequences for research and robot design are explored. Finally, Section 2.3 provides a timeline of the development of (social) robots and gives an overview of the robots most commonly used in HRI.

Distinguishing physical and social interaction: Robotics at large has traditionally been concerned with the creation of physical robots and the ways in which these robots manipulate the physical world. HRI adds to this and is concerned with the ways in which robots interact with people as part of their social world and how people respond to the presence of robots. For example, when a robot picks up a box in an empty warehouse or cleans an office building after hours, it is sensing and acting in the physical world alone and dealing with the physics of its own body

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and its environment. But when the robot takes the box to a warehouse worker who needs to fill it with appropriate materials, delivers coffee to a customer in a café, or chases children around in a courtyard, it is not only dealing with the physical motions needed for those actions, but it must also address the social aspects of the environment. For example, it needs to consider where the children, customers, or the office workers are; how to approach them in a way that is safe and that they consider appropriate; and how to follow the appropriate social rules of the interaction. Such social rules might be obvious to humans, such as acknowledging the presence of others, knowing who is "it" in a game of tag, and saying "you're welcome" when someone says "thank you." But for a robot, all these social rules and norms are unknown and require the attention of the robot designer. These concerns make HRI questions different from those pursued in robotics alone.

As a discipline, HRI is related to human–computer interaction (HCI), robotics, artificial intelligence, the philosophy of technology, psychology, and design. Scholars trained in these disciplines have worked together to develop HRI, bringing in methods and frameworks from their home disciplines and also developing new concepts, research questions, and HRI-specific ways of studying and building the robots that interact with people.

What makes HRI unique? Clearly, the interaction of humans with social robots is at the core of this research field. These interactions usually include physically embodied robots, and their embodiment makes them inherently different from other computing technologies. Moreover, social robots are often perceived as social actors bearing cultural meaning and having a strong impact on contemporary and future societies. Saying that a robot is embodied does not mean that it is simply a computer on legs or wheels. Instead, we have to understand how to design that embodiment, in terms of both software and hardware, as is commonplace in robotics, and in terms of its effects on people and the kinds of interactions they can have with such a robot.

A robot's embodiment sets physical constraints on the ways in which it can sense and act in the world, but it also represents an *affordance* for interaction with people. The robot's physical makeup elicits people to respond in a way similar to that in which they interact with other people. When a robot has eyes, people make the assumption that the robot can see them. When the robot has a mouth, people assume that the robot can talk. The robots' human-likeness enables humans to use their existing experience of human–human interaction to understand and participate in human–robot interaction. These experiences can be very useful in framing an interaction, but they can also lead to frustration if the robot cannot live up to the users' expectations (as discussed in more detail in Chapter 8).

HRI focuses on developing robots that can interact with people in various everyday environments. This opens up technical challenges resulting from the dynamics and complexities of humans and the social environment. This

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Figure 2.1 Honda developed the Asimo robot from 2000 through 2018. (Source: Honda)

also opens up design challenges—related to robotic appearance, behavior, and sensing capabilities—to inspire and guide interaction. From a psychological perspective, HRI offers the unique opportunity to study human affect, cognition, and behavior when individuals are confronted with social agents other than humans. Social robots, in this context, can serve as research tools to study psychological mechanisms and theories.

From the very first mention of the term *robot* in Karel Čapek's play *Rossum's Universal Robots*, our vision of the ideal robot has focused on mimicking humanlike capabilities, often represented by a humanoid form, either in a full body, as in Honda's ASIMO (see Figure 2.1), or in parts, such as by robot arms or their more anthropomorphic representation in Sawyer robots. When we look at the current state of the art in HRI, however, we see that robot embodiments are much more diverse—spherical robots can roll around and interact with children (e.g., Sphero, Roball); robots can fly in the air (e.g., drones) or go underwater (e.g., OceanOneK); robots can mimic animals so that they can encourage petlike interactions with people (e.g., Paro) or even interact with their biological counterparts in nature (e.g., squirrel robot); and robots can look like objects (e.g., suitcases, trash cans, boxes) or common devices, such as buses and cars, and take many other forms. One of the exciting things about HRI is that it can expand our visions of what robots and our interactions with them could be like beyond the familiar anthropomorphic notions.

When robots are not just tools but also teammates, collaborators, companions, guides, tutors, and other types of social interaction partners, their study and design as part of HRI bring up many different questions about interpersonal relationships and societal development, both in the present and in the future. HRI research includes issues related to the social and physical design of technologies, as well as societal and organizational implementation and cultural sense-making, in ways that are distinct from related disciplines.

2.1 The focus of this book

HRI is a large, multidisciplinary field, and this book provides an introduction to the problems, processes, and solutions involved. This book enables the reader to gain an overview of the field without becoming overwhelmed with the complexities of all the challenges that we are facing, although we do provide references to relevant literature, which interested readers might want to investigate at their leisure. This book provides a much-needed introduction to the field so that students, academics, practitioners, and policymakers can become familiar with the future of how humans will interact with technology.

This book is an introduction, and as such, it does not require extensive knowledge in any of the related fields. It only requires the reader's curiosity about how people and robots can and should interact with each other.

After introducing the field of HRI and how a robot works in principle, we focus on the robots' designs. Next, we address the different interaction modalities through which humans can interact with robots, such as through speech or gestures. We also consider how we can understand and study how people perceive robots. The processing and communication of emotions is the next challenge we introduce before reflecting on the role that robots play in the media. The research methods chapter introduces the unique issues that researchers face when conducting empirical studies of humans interacting with robots. Next, we cover the application areas of social robots and their specific challenges before discussing broader societal and ethical issues around the use of social robots. The book closes with a look into the future of HRI.

2.2 HRI as an interdisciplinary endeavor

HRI is multidisciplinary and problem-based field by nature and by necessity. HRI brings together scholars and practitioners from various domains: engineers, psychologists, designers, anthropologists, sociologists, and philosophers, along with scholars from other application and research domains. Creating a successful human–robot interaction requires collaboration from a variety of fields to develop the robotics hardware and software, analyze the behavior of humans when interacting with robots in different social contexts, and create the aesthetics of the embodiment and behavior of the robot, as well as the required domain knowledge for particular applications. This collaboration can be difficult due to the different disciplinary jargon and practices. The common interest in HRI among this wide variety of participants, however, is a strong motivation for familiarizing oneself with and respecting the diverse ways of acquiring knowledge. HRI is, in this multidisciplinary sense, similar to the field of human–computer interaction (HCI), although dealing with embodied interactions with intelligent agents in diverse social contexts differentiates HRI from HCI.

The various disciplines that contribute to HRI differ from each other in terms of their shared beliefs, values, models, and exemplars (Bartneck and Rauterberg, 2007). These aspects form a "paradigm" that guides their community of theorists and practitioners (Kuhn, 1970). Researchers within a paradigm share beliefs, values, and exemplars. One way of understanding the difficulties of working together on a shared project can be based on three barriers (see Figure 2.2) that can occur between designers [D], engineers [E], and scientists (particularly social scientists) [S]:

1. Knowledge representation (explicit [S, E] versus implicit [D]);
2. View on reality (understanding [S] versus transforming reality [D, E]); and
3. Main focus on (technology [E] versus human [D, S]).

Barrier 1: Engineers [E] and scientists [S] make their results explicit by publishing in journals, books, and conference proceedings or by acquiring patents. Their body of knowledge is externalized and described to other engineers

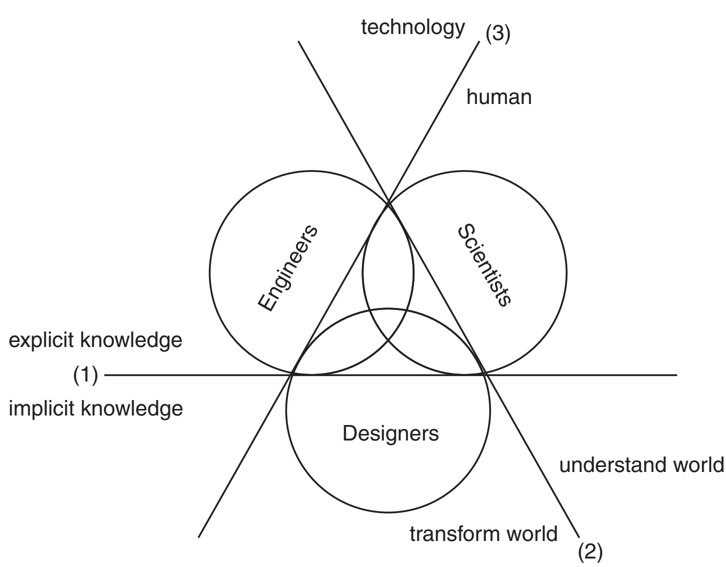

Figure 2.2 HRI taps into several disciplines, and barriers are often experienced between these.

or scientists. These two communities revise their published results through discussion and control tests among peers. On the other hand, designers' [D] results are mainly represented by their concrete designs. The design knowledge necessary to create these designs lies within the individual designer, mainly as implicit knowledge, often referred to as *intuition* and described to the community in general principles.

Barrier 2: Engineers [E] and designers [D] transform the world into preferred states (Simon, 1996; Vincenti, 1990). They first identify a preferred state, such as the connection between two sides of a river, and then implement the transformation, which in our example would be a bridge. Scientists [S] mainly attempt to understand the world through the pursuit of knowledge covering general truths or the operation of general laws; although suggestions for intervention and transformation can be extrapolated from scientific work, they are often outside the purview of the scientific work itself.

Barrier 3: Scientists [S] and designers [D] are predominantly interested in humans in their role as possible users. Designers are interested in human values, which they transform into requirements and, eventually, solutions. Scientists in the HCI community are typically associated with the social or cognitive sciences. They are interested in the users' abilities and behaviors, such as perception, cognition, and action, as well as the way these factors are affected by the different contexts in which they occur. Engineers [E] are mainly interested in technology, which includes software for interactive systems. They investigate the structure and operational principles of these technical systems to solve certain problems.

Being aware of these disciplinary differences before embarking on an HRI project can help establish fruitful collaboration that takes into account the different types of knowledge and practice of the different disciplines. It is clear that an HRI project can bring in expertise from all of these different disciplinary types, but not every HRI project can afford to have dedicated specialists from all these disciplines. Many projects will also need to include people from additional disciplines, such as ethicists or education researchers, and application domains, such as health practitioners or educators. HRI researchers often need to wear several hats, trying to gain expertise in a variety of topics and domains. Although this approach may reduce the problems of finding common ground, it is quite limiting. We often do not know what we do not know. It is therefore important to either engage with all or many of the involved disciplines directly or at least communicate with experts in the respective fields. As the field of HRI grows and matures, it has also been expanding to include more and more different disciplines, frameworks, and methods (e.g., historians, performers), which can require an even more expansive set of knowledge requirements. In this case, we suggest also getting used to reading broadly, not just in your own discipline or subdomain of HRI but also in related fields, to understand how your own work fits into the bigger picture. When developing specific HRI applications, it is also crucial to collaborate with domain experts, including potential users and stakeholders, in the design—from the beginning of the project—to make sure to ask relevant

Figure 2.3 The Mirokai robot by Enchanted Tools, France. It combines omnidirectional navigation with two robot arms and a back-projected face. (Source: Enchanted Robots)

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questions, use appropriate methods, and be aware of the potential broader consequences of the research to the application domain.

2.3 The evolution of social robots and HRI

The concept of "robot" has a long and rich history in the cultural imagination of many different societies, going back thousands of years to tales of humanlike machines, the later development of automata that reproduce certain human capabilities, and more recent science-fiction narratives about robots in society. Although these cultural notions of robots may not always be technically realistic, they color people's expectations of and reactions to robots.

The first mention of "social robot" in print was in 1935, when it was used as a derogatory term for a person having a cold and distant personality.

> Toadying and bootlicking his autocratic superiors, he is advanced to preferment. He is a business success. But he has sacrificed all that was individual. He has become a social robot, a business cog. (Sargent, 2013, p. 92)

In 1978, the first mention of "social robot" was made in the context of robotics. An article in *Interface Age* magazine described how a service robot, in addition to skills such as obstacle avoidance, balancing, and walking, would also need social skills to operate in a domestic setting. The article calls this robot a "social robot."

Ever since the concept of "robot" emerged, first in fiction and later as real machines, we have pondered the relationship between robots and people and how they could interact with each other. Every new technological or conceptual development in robotics has forced us to reconsider our relationship with and perception of robots.

When the first industrial robot, the Unimate, was installed at General Motors' Inland Fisher Guide Plant in Ewing Township, New Jersey, in 1961, people did consider how they would interact with the robot, but they were more concerned about the place robots would take among human workers. People who saw behavior-based robots for the first time could not help but marvel at the lifelike nature of the robots. Simple reactive behaviors (Braitenberg, 1986) implemented on small mobile robots produced machines that seemed injected with the very essence of life. Scurrying and fidgeting around the research labs of the 1990s, these robots evoked humanlike character traits and fundamentally changed our idea of how intelligence, or at least the appearance of intelligence, could be created (Brooks, 1991; Steels, 1993). This led to the creation of robots that used fast, reactive behavior to create a sense of social presence.

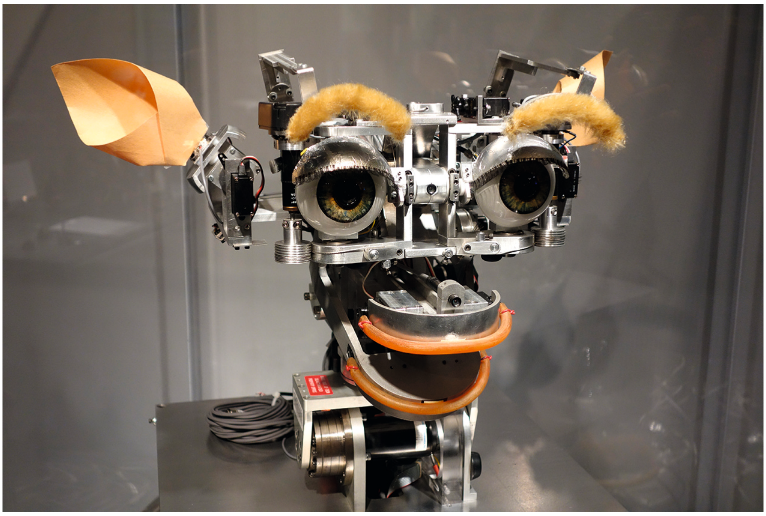

Figure 2.4 Kismet (1997–2004), an early example of social human–robot interaction research from the Massachusetts Institute of Technology. (Source: Daderot)

An early example of a social robot is Kismet (see Figure 2.4). Developed at the Massachusetts Institute of Technology in 1997, Kismet was a robot head-and-neck combination mounted on a tabletop box. Kismet could animate its eyes, eyebrows, lips, and neck, allowing it to pan, tilt, and crane its head. Based on visual and auditory input, it reacted to objects and people appearing in its visual field. It extracted information on visual motion, visual looming, sound amplitude, and emotion from speech prosody, and it responded by animating its facial expressions, ears, and neck and by babbling in a nonhuman language (Breazeal, 2003). Kismet was surprisingly effective in displaying a social presence, even though the control software only contained a small selection of social drives. It did so not only with its hardware and software architectures but also by taking advantage of human psychology, including what is known as the "baby schema," a predisposition to treat things with big eyes and exaggerated features in social ways despite their lack of fully functional social skills (Jia et al., 2015).

Like many robots in the early days of social robotics and HRI, Kismet was a bespoke robot, available to researchers in only one laboratory and requiring constant effort by students, postdocs, and other researchers to keep up and build up the robot's capabilities. These limitations understandably constrained the number of people and the range of disciplines that could participate in HRI in the field's early days. More recently, HRI research has been bolstered by the availability of reasonably priced commercial platforms that can be readily purchased by laboratories. These have expanded both the replicability and comparability of HRI research across labs, as well as the range of people who can engage in the discipline.

A number of commercially available robots have had a significant influence on the field. We will discuss some of the most commonly used ones here, but this list is by no means intended to be exhaustive because new robots get released, established robots get discontinued, and existing robots not

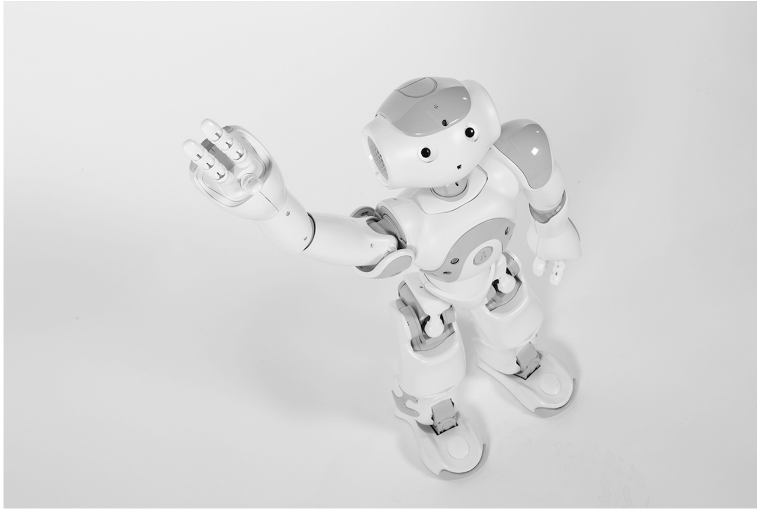

Figure 2.5 Nao (2006–present), a 58-cm-tall humanoid robot, one of the most popular research platforms in social robotics.

previously used in HRI get adopted and adapted for social robotics research. The robots discussed here, however, have all made their mark on the field and will be reemerging throughout this book.

Perhaps the most influential robot in the field of social robotics is the Nao robot (see Figure 2.5). Nao was originally developed by the French company Aldebaran Robotics, which was acquired by Softbank Robotics in 2015 and, in the process, became Softbank Robotics Europe until it was sold in 2022 to the German United Robotics Group, which renamed it back to Aldebaran Robotics. Nao was first sold in 2006, and due to its affordability (a Nao costs under 10,000 USD), robustness, and ease of programming, it became a widespread robot platform for studying HRI. Because of its size, it is also highly portable, allowing for studies to be run outside the lab. Another small humanoid robot that became available on the market later on is QT, by LuxAI, designed for use in research and educational contexts.

Aldebaran Robotics also created Pepper, an adolescent-size humanoid with a tablet built into its chest (see Figure 2.6). Some stores use Pepper to attract visitors and market products and services. The production of Pepper robots was reportedly discontinued in 2020, although at the time of writing, the robot was still available for purchase.

Taking it down a few notches in terms of size and complexity, the Keepon robot (see Figure 2.7), developed by Hideki Kozima, is a minimal robot consisting of two soft yellow spheres to which a nose and two eyes are added. The robot can swivel, bend, and bop, using motors worked into the base of the robot (Kozima et al., 2009). Keepon was later commercialized as an affordable toy (priced at 40 USD), and through some moderate hacking, it can be used as a research tool for HRI. Studies with the Keepon robot convincingly demonstrated that a social robot does not need to appear humanlike; the simple form of the robot is sufficient to achieve interaction outcomes where one might assume the need for more complex and humanlike robots.

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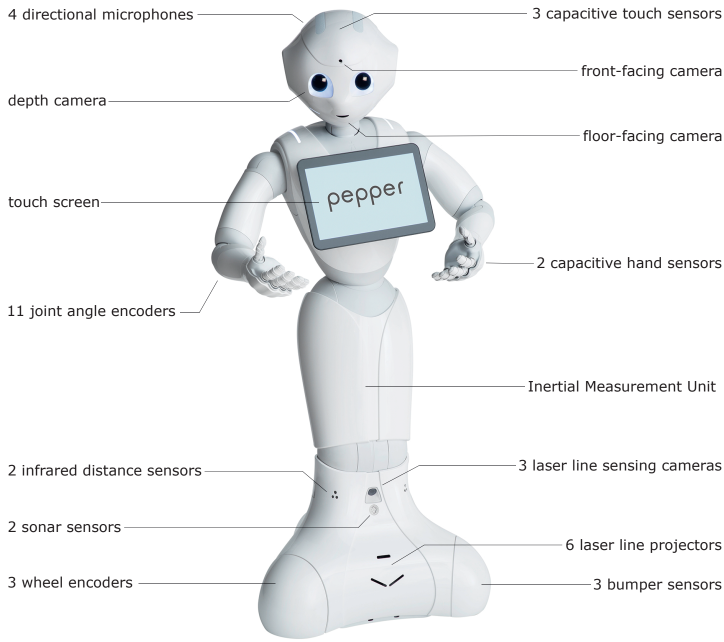

Figure 2.6 Pepper robot (2014–present) and its sensors (Source: Pepper Robot by SoftBank Robotics and Philippe Dureuiltoma)

Another simple design robot, the Paro companion and therapy robot (see Figure 2.8), shaped like a baby seal, has been particularly popular in the study of socially assistive robots in eldercare, as well as other scenarios. Paro has been commercially available (price: around 7,500 USD) in Japan since 2006 and in the United States and Europe since 2009 and is a robust platform that requires almost no technical competence to operate. Paro has therefore been used by various psychologists, anthropologists, and health researchers, both to study the potential psychological and physiological effects on people and to explore ways in which robots might be adopted in healthcare organizations. The simplicity of the robot's operation and its robustness enable its use in many different contexts, including in long-term and naturalistic studies. At the same time, the fact that it is a closed platform—which does not allow robot logs or sensor data to be extracted from the robot or allow the robot's behaviors to be changed—poses some limitations for HRI research.

The Baxter robot, sold by Rethink Robotics until 2018, is both an industrial robot and a platform for HRI (see Figure 2.9). The robot's two arms are actively compliant: in contrast to the stiff robot arms of typical industrial robots, Baxter's arms move in response to an externally applied force. In combination with other safety features, the Baxter robot is safe to work near, which makes it suitable for collaborative tasks. In addition, Baxter has a display screen mounted at head height on which the control software can display facial animations. Baxter's face can be used to communicate its internal state, and its eye fixations communicate a sense of attention to the human coworker.

Figure 2.7 Keepon (2003–present), a minimal social robot developed by Hideki Kozima. The robot was later commercialized as an affordable toy. (Source: Hideki Kozima, Tohoku University)

Figure 2.8 Paro (2003–present), a social robot made to resemble a baby harp seal. Paro is provided as a social companion robot. (Source: Courtesy of AIST, www.aist.go.jp)

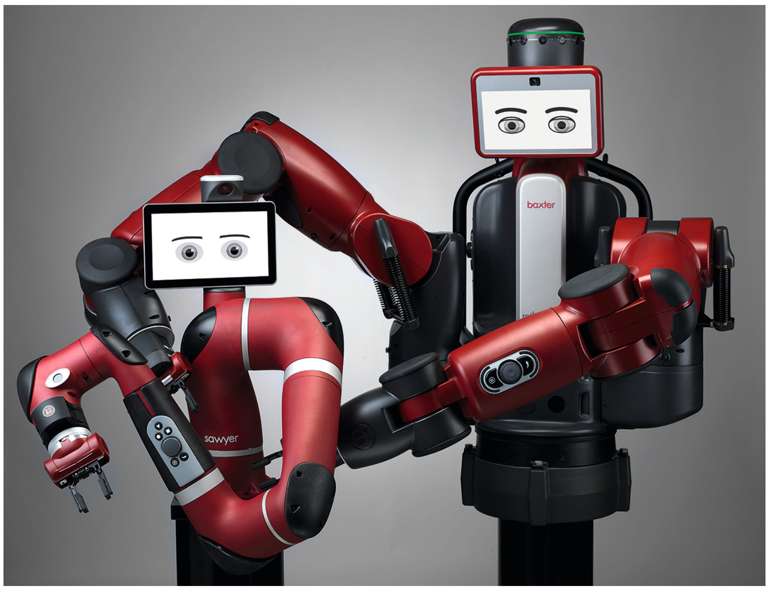

Figure 2.9 Baxter (2011–2018) and Sawyer (2015–2018), industrial robots with compliant arms by Rethink Robotics. Baxter was the first industrial robot to include social interaction features on an industrial manipulator. (Source: Rethink Robotics, Inc.)

In 2017, Anki launched the Cozmo robot (see Figure 9.4), which was followed up in 2018 by Vector. In 2020 Anki was taken over by Digital Dream Labs, which released a second version of both robots in 2021. Although both robots are comparable in design, Cozmo has been designed primarily as an educational or research tool, with its behavior being customizable via an app or directly through coding (using Python). Vector, on the other hand, is more autonomous, responds to voice commands, and comes with predesigned behaviors. Cozmo and Vector cost around 500 USD and have both been used in HRI research.

Robots that were not explicitly designed to be used for HRI can also be used or even modified for HRI studies. The most commercially successful home robot is still the iRobot Roomba vacuum-cleaning robot (price ranging from 500 to 3,000 USD, depending on how intense of a cleaning the user wants), millions of which have been sold around the world. Roombas not only are an interesting agent for use in studying the public's relationship with robots (Forlizzi and DiSalvo, 2006) but also have been modified

Figure 2.10 Aibo ERS-1000 robot (2018–present). (Source: Copyright of Sony Corporation)

and hacked for HRI research. iRobot also makes educational robots, the Root (250 USD) and the Create (300 USD), which lack the vacuuming component and can be used in research and educational applications of robots.

Another consumer robot that has been used in HRI research is Aibo, an example of an animal-like robot, which was created by Sony and looks like a dog with a somewhat mechanical appearance (see Figure 2.10) and has the ability see, hear, feel touch, make sounds, wag its ears and tail, and move around on its four legs. The first Aibo models were sold in 1999, and sales were discontinued in 2006. Eleven years later, sales of new models started again, priced at roughly 3,000 USD.

Finally, Amazon released the Astro household robot in 2022 (see Figure 2.11). This home monitoring robot integrates the artificial intelligence assistant Alexa with a knee-high tablet mounted on a three-wheeler. It can be used for home security (as a remote-controlled camera on wheels); delivering messages and small items around the house; and all tasks commonly associated with tablets, including video calls, streaming of shows and movies, and looking up information online.

Figure 2.11 The Astro (2022–present) integrates Amazon's Alexa in a robotic platform and can be used as a home-monitoring system. (Source: Amazon)

Although the availability of affordable commercial robots with open application interfaces caused a proliferation of HRI studies, a second development has allowed for in-house-built social robots. New developments in mechatronic prototyping mean that robots can be modified, hacked, or built from scratch. Three-dimensional (3D) printing, laser cutting, and the availability of low-cost single-board computers have made it possible for researchers to build and modify robots in a short time and at minimal cost—both full-scale humanoids, such as InMoov (see Figure 2.12), and small robots, such as Blossom (Suguitan and Hoffman, 2019) or Ono (Vandevelde et al., 2016) (see Figure 2.13).

As you can see, the variety of robot hardware opens up endless research questions that can be addressed from a multidisciplinary perspective. Section 3.2 goes into more detail on the different types of robots. For an overview of the many robots available, you can explore the databases that were put

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Figure 2.12 InMoov (2012– present) can be built using rapid-prototyping technology and readily available components. The InMoov robot is an open-source social robot.

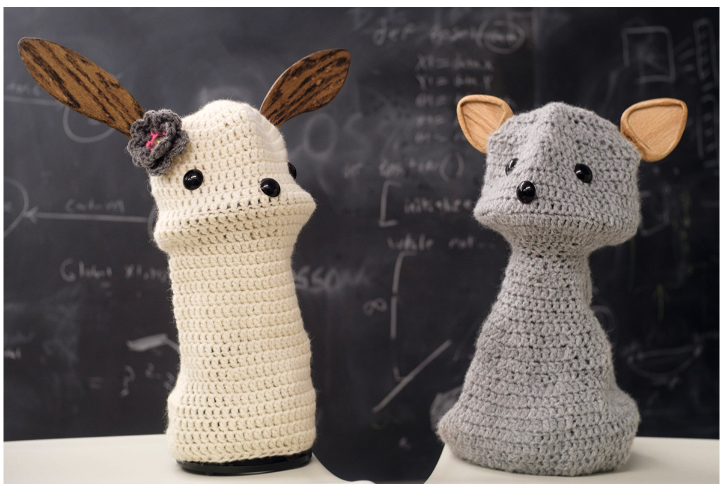

Figure 2.13 Blossom (2019– present) is an open-hardware, open-source tensile robot that you can handcraft and accessorize. Here, they wear a crocheted cover. (Source: Courtesy of the Cornell Human-Robot Collaboration and Companionship Lab. Photo: Dorin Haver)

together by Anthropomorphic roBOT (ABOT)[1] and the Institute of Electrical and Electronics Engineers (IEEE).[2]

Unlike other disciplines, HRI places particular emphasis on investigating the nature of social interactions between humans and robots, not only in dyads but also in groups, institutions, and sooner or later, in our societies. As will become clear in this book, technological advancements are a result of joint

[1] See www.abotdatabase.info
[2] See https://robotsguide.com/robots/

interdisciplinary efforts that have important societal and ethical implications. Keeping these in mind by doing human-centered research will hopefully lead to the development of robots that are widely accepted and that serve humans for the greater good.

Questions for you to think about:

- The HRI field draws insights from many other fields, but what other fields could benefit from research in HRI?
- Are you a designer, engineer, or social scientist? Try to imagine a situation in which you are collaborating with others to construct a robot (e.g., if you are an engineer, you are now working with a designer and a social scientist on this endeavor). How is your way of working different from the approaches the other teammates might use?
- What is the main difference between the disciplines of HRI and HCI, and what makes HRI unique as a new field?

2.4 Exercises

The answers to these questions are available in the Appendix. The asterisks next to each exercise denote the difficulty level, from * (least difficult) to ***** (most difficult).

**** Exercise 2.1 Disciplines** What is the main difference between the disciplines of HRI and HCI? Select one option from the following list:

1. HRI uses only one computer, whereas HCI uses many computers.
2. HRI focuses on embodied social agents, whereas HCI focuses on interactions with computers.
3. HCI focuses on computers, whereas HRI focuses on humans.
4. Robots don't use computers.
5. HRI focuses on the interaction between machines, whereas HCI focuses on the interaction between humans.

*** Exercise 2.2 Your background** What is your educational/professional background? (This exercise may help you become more aware of from which angle you'll most likely approach HRI.) Although you might have more than one background, select your main background from the following list:

1. Social sciences (psychology, sociology, anthropology, etc.)
2. Engineering (computer science, mechanical engineering, electrical engineering, mechatronics, etc.)
3. Design (interaction design, product design, user experience designer)

***** Exercise 2.3 What makes robots social and good?** Watch these two videos, and then answer the two questions that follow.

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- Cynthia Breazeal, "Developing Social and Empathetic A.I.," https://youtu.be/T52g7dCxJ4A
- Henry Evans and Chad Jenkins, "Robots for Humanity," https://youtu.be/aCIukWXmlV4

1. Cynthia Breazeal says Kismet is the "first social robot." What makes Kismet (and the other robots discussed in this chapter) social? Would you say robots are social in a different way from people, and if so, how?
2. Breazeal talks about how artificial intelligence can be designed to be more helpful to humans, and Evans and Jenkins demonstrate some ways in which robotic embodiment can extend human capabilities. What did you find compelling about these possibilities for using robots "for the social good"? Can you think of any social issues that you or members of your community face in which the types of robotic capabilities that Breazeal, Evans, and Jenkins discuss could be helpful?