55. Robots for Education

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This chapter provides an overview of the key ingredients that make successful education robots possible. Two very popular outlets for public interaction with robots are the robot tournament and the informal learning venue (e.g., the science museum). Section 55.2 provides a survey of the very popular world of robot-themed tournaments, which have already impacted tens of thousands of students across diverse geographic and age group boundaries [55.1–5]. Section 55.5 provides an overview of robotic installations in informal learning spaces. Robotic technology has now proven to have sufficient robustness and engagement to be a principal component of interactive exhibitry for a new generation of hands-on, active-learning museums [55.6].

To make interactive, educational robots successful, a new level of technology robustness and standardization is required, and significant progress has been made on this front in the past decade. Educational robot devices consist of both hardware (preassembled or as kits or components) and software (both as source code and programming environments). Section 55.3 discusses physical robot platforms that have achieved notable success, while Sect. 55.4 describes both low-level controllers that interface those platforms to high-level computation, as well as the top-level programming environments themselves.

Finally, an important class of tool in the study and execution of educational robotic systems is the ability to evaluate the efficacy of a robot system formally in an educational context. Numerous tools from human–computer interaction, cognitive psychology, and education have demonstrated their usefulness in this regard. Section 55.6 summarizes the manner in which conventional analytical tools may be used to evaluate unconventional educational programs that tap robotic technologies as learning tools across a variety of ages and in both formal and informal learning venues.

In recent years robots have penetrated the education market, both as motivational tools for research programmes and as concrete, real-world deployments that demonstrate the state of the art in robotic technologies. The newest education robots, and even entertainment robots to some degree, share the notable feature of human–robot interaction with the general public. In contrast to a space exploration robot or a nuclear cleanup robot, these newest, interactive robots do not function solely with the well-trained specialist; they interact with individuals and groups with the goal of inspiring learning, providing engaging recreation, and even providing therapeutic value.

55.1 The Role of Robots in Education

Education is itself a broad area of application for robotics, with a rich history that started at least with notions of active learning disseminated by Seymour Papert and others [55.7]. Karel the Robot still serves as a metaphor for concrete activity in numerous introductory programming courses. Karel the Robot is merely an on-screen simulation of a two-dimensional robotic world. This first of three roles that robots can play in the educational setting is the *robot as a programming project*. The robotic system is a focus of problem set assignments, a black box to be programmed in order to create a concrete physical manifestation of the art of computer programming. Numerous studies have shown that poor engagement and retention statistics in courses such as Introduction to Programming (CS1) often stem from students' inability to see how the skills they learn can have a concrete impact on what they care about: their physical world, their friends, and family. Physical robot programming projects can cast coding problems into the real world, making those skills push back on one's world, and thereby achieve a level of significance and engagement that, for instance, computation of the Fibonacci sequence on a computer screen cannot inspire [55.8–16].

The second role for educational robotics is that of the *robot as a learning focus*. Mechatronics-style courses can focus on the creation and use of a physical robot as a goal in and of itself. Robots do this by stimulating general interest in science, technology, and engineering, and thereby show students that they can have an active role in shaping technology in their future. Such an application-oriented class has great benefits in cases where students learn best through integrative, project-oriented learning, and such classes have demonstrated significant lifelong-learning results in areas such as teamwork, problem-solving, and self-identification with technology-focused careers [55.7, 17–21]. In the United States, the National Academy of Engineering has identified trends reporting dropping technology literacy as troubling phenomena throughout the nation. Programs that reconnect students with complex mechatronic systems, providing the self-empowerment for lifelong, active relationships to technology artifacts, serve as one possible avenue to stem this dangerous trend away from knowledge about the technology artifacts on which society depends so completely. Demonstrated learning themes in educational analyses include the following.

55.1.1 Interest in Science and Engineering

The study of robotics can be sufficiently rewarding, intellectually and emotionally, as to generate general enthusiasm for the follow-on study of science and engineering. Some educational robotics programs have shown promise in increasing retention rates among female students [55.22, 23], who are underrepresented in technology-focused fields.

55.1.2 Teamwork

An important result of team-based project-based robotic building experiences is that those with low self-esteem in their technology capability, teamwork skills, and communication skills can find measured improvement, leading to mitigation of fear towards working in teams on high-technology ventures [55.19, 21].

55.1.3 Problem Solving

The study of a systems engineering phenomena – a complex robot system – provides lessons in hierarchy, risk mitigation, planning and diagnosis that far outweighs the benefits of silo-driven, single-topic explorations of debugging and problem analysis. The resulting problem solving and decomposition skills have lifelong applicability to any complex system, see e.g., [55.7].

The third role for educational robots is that of the *robot as a learning collaborator*. In this case students are not designing robots, but rather conducting inquiry during which a high-functioning robot can serve as an all-season companion, aide, and even intellectual foil [55.24, 25]. Robots that have social capabilities are well suited in this regard, and this is an area where the potential for application greatly outweighs what has, so far, been achieved. There are two reasons why such a social role for robots in education holds particular promise. First, because of their novelty, robots can inspire dedication in learning, just as is possible in the case of the above two roles. Second, students have few preconceived expectations for the behavior of robots. In therapeutic cases, such as students with autism spectrum disorder (ASD), the robot can play an important role, as studies have shown that those students place disproportionate interest in mechanical systems [55.24, 26]. In all cases the interaction can itself be a form of discovery and engagement quite different from traditional, more staid educational methods, and thus this can even border on the application area of entertainment robotics.

55.2 Educational Robot Tournaments

Competition catches people's attention and makes them want to get involved. This is true in almost all fields of endeavor. In education, competitions are commonplace from spelling bees to science fairs. Over the past 20 years robotic competitions have also come into their own; garnering the level of attention from students, teachers, and parents previously found almost exclusively in more traditional sports.

In this section we provide a brief history of robot tournaments, look at some of the popular current tournaments, and overview how they are being used to supplement standard educational curricula.

55.2.1 Origins

In 1970 professor H. H. Richardson adopted MIT's Introduction to Design Course (course 2.70), in the Mechanical Engineering (ME) department, and transformed it into a design contest. He had the students work in teams to design and create machines that would be operated by the students to compete against one another. As the course evolved over the years, and under new instructors, it became both popular and famous.

Several students in the Electrical Engineering and Computer Science department at MIT, envious of the ME course decided to create their own, more autonomous version of both the course and the contest. Since 1987, MIT students have held the 6.270 course during the intercession between the fall and spring semesters. While initially simulation, by 1991 the contest involved untethered autonomous robots in a head-to-head elimination tournament [55.27]. While only open to MIT students and, with the exception of the occasional documentary, poorly publicized, these two courses have become the models for many teleoperated machine contests and robot contests around the world.

55.2.2 A Taxonomy of Robot Tournaments

There are many possible ways to distinguish the multitude of activities often lumped together as robot contests. For our purposes here we will us the following qualities.

Autonomy

The level of autonomous action that robots exhibit during a tournament varies widely. Some tournaments are completely radio controlled (e.g., *BEST*™ [55.28]) with no independent actions or decisions being undertaken by the 'robots' in the tournament. In other contests, the machines are teleoperated – still under real-time control by their operators, but doing some processing on the commands, and sometimes mixing in feedback from onboard sensors (e.g., *FIRST*® [55.5]). Autonomous robot contests have little or no interaction by the robot operators, but even in completely autonomous robot contests there is a spectrum. Some autonomous robots simply replay a canned set of actions – operating completely open loop. Others control all of their actions based on feedback from onboard sensors, and still others *learn* as they go, modifying not only their actions, but their internal programming as well. One generalization that can be made with regards to robot tournaments and education is that a contest that is more autonomous usually has more educational content in the areas of software/programming, while contests with little or no autonomy emphasize the mechanical design and physical implementation aspects of robotics.

Performance Versus Opposition

Some robotics tournaments are based on ranking the absolute performance of the robot against the course. Other tournaments have contestants ranked based on their triumph over a series of specific opponents. In the latter case, it does not matter how well the victorious robot performs in a given round, as long as it performs better than its opponent for that round. Trinity College's *Firefighting Robot Contest* [55.29] (TCFFHRC) ranks teams by how quickly they can carry out the task (locating and extinguishing a candle) and is an example of a performance-based tournament. The scoring in *RoboCup Junior Dance* [55.3] is more subjective, but is still based on individual performance against an absolute scale. Sumo contests such as [55.30] are opposition-based tournaments sometimes known as head-to-head. Performance-based contests allow robot designers to implement more intricate strategies, since the environment is more predictable than if there were an opposing robot running amok through the course. In oppositional tournaments, robots must be designed to cope with the actions of their opponents. Both types of tournaments have their merits and each allows detailed problem solving. In theory, most people find head-to-head tournaments more exciting and entertaining. However, as with traditional human sumo, head-to-head tournaments often involve head-to-head collisions followed by lengthy, and less exciting, periods of robots trying to push or disentangle themselves from their opponents.

Heritage: Fixed Game Versus New Game Every Year

Is it more educational for students to examine how others have tried to solve a problem and then build on that to create their own incremental solution? Or is it better for students to tackle something new, without extensive examination of precedent? The educational community does not have a definitive answer, but different robot tournaments can be used to support the educational methodology of choice. Tournaments such as *Robocup* [55.32] are prime example of tournaments with a long heritage. In addition to the game and rules being well known (derived from soccer) and essentially remaining unchanged from year to year, there are a number of annual publications (e.g., [55.33]) that detail successful robots and techniques used in that year's contests. *Robocup* is a study in steady incremental improvement. Other contests, such as the *Botball*® robot tournament, use a different game every year. One of the motivations for doing this is so that established teams obtain the game rules at the same time as new teams – so whether experienced or not, everyone has to build a new system for the new task, and has the same amount of time to do so [55.4]. As with all of these dimensions, there is no clear advantage of one methodology over the other. Some educators prefer to have a new activity every year to help keep themselves and their students engaged. Others prefer to have the same game every year, with the accompanying wealth of lessons learned and how-to guides that process makes available.

Table 55.1 presents a number of established robot tournaments using this taxonomy, although this is not a complete listing. Readers interested in finding out more information about a particular tournament should consult the cited website. All of the tournaments below are for students, though the age eligibility and level of adult involvement varies widely between the events.

55.2.3 The Entertainment Link

Tournaments are used (rather than a course assignment or demonstration) in part because of their entertainment value. A tournament is hopefully engaging to both the participants and the audience. However, the entertainment value of a tournament may not be linked to the technical sophistication of the robots. *Battlebots*® and its variations have been very successful as mass market entertainment. These robots are typically radio controlled, and while sometimes mechanically sophisticated, they are computationally simplistic. The Association for the Advancement of Artificial Intelligence (AAAI) *mobile robot contest* [55.34] usually has very computationally sophisticated robots – however that sophistication usually has an accompanying decrease in audience entertainment value. AAAI robots strive to do what everyday humans easily do – go to specific places, manipulate household objects, give talks, and answer questions, but the robots tend to be much slower than humans performing these activities. *Battlebots* do what humans are not allowed to do — use power tools and blunt instruments to demolish their op-

Table 55.1 Examples of different types of robot tournaments

Tournament	Web	Autonomy	Contest type	Heritage	Notes
BEST	[55.28]	Radio control (R/C)	Head to Head (HtH)	New	
Botball	[55.1]	Autonomous	HtH + Points	New	Multiple robots per entry
FIRST	[55.5]	Teleop	HtH	New	Students teamed with engineers
Micro Maze	[55.31]	R/C to auton.	Time.	Fixed	Cubic cm robots
Sumo	[55.30]	R/C to auton.	HtH	Fixed	Divisions based on weight & autonomy
RoboCup	[55.32]	Autonomous	HtH	Fixed	Teams of robots
RC Jr. Dance	[55.3]	Autonomous	Points	N/A	Very free form
TCFFHRC	[55.29]	Autonomous	Time	Fixed	Random placement of fire

Fig. 55.1 Middle-school students present their paper at the National Conference on Educational Robotics (NCER)/Botball conference and then have their autonomous machine-vision-guided robots score points in the tournament

ponents. In robot tournaments, as in the movie business, violence is often more entertaining then demonstrations of intellectual ability and human activity.

55.2.4 Tournaments for Education

Professional organizations such as the AAAI, Institute of Electrical and Electronics Engineers (IEEE), and others often hold tournaments for their student members at their major conferences. For these organizations, the purpose of the tournament is to attract students to attend the conference and become active in the organizations. The activity of building the robot also sharpens the students' skills and gets them excited about technologies and businesses linked to that organization and motivates them to pursue relevant degrees [55.35].

Many universities and colleges use robot tournaments as part of their curricula. Some create class tournaments (e.g., MIT 6.270) or use standard games such as *Beyond Botball* [55.36] that are distributed for that purpose. Others use some of the tournaments mentioned in Table 55.1 as projects for their curricula [55.37].

However, the bulk or robot tournaments are aimed at middle- and high-school students. Here the motivation is not so much to teach detailed skills as to spark creativity while at the same time emphasizing basic concepts and an appreciation for the fundamentals of science, technology, education, and mathematics [55.38]. Some tournaments have added activities such as documentation, presentation, reports, and even tests [55.39] to reinforce and expand upon these fundamentals (Fig. 55.1). To assist educators in guiding the students, many tournaments have curriculum materials linked to their activities. National Aeronautics and Space Administration (NASA) has collected links to many of these materials and made them available on the Internet [55.40]. Evaluating the effectiveness of these materials and programs in meeting their educational goals is the subject of Sect. 55.6.

55.3 Education Robot Platforms

Education robot platforms fall into one of two main categories. The first is the research platform. These expensive, precision robot platforms were built to support research in robotics and related disciplines, or as research projects in their own right. Many of the humanoid robots discussed elsewhere in these volumes are examples of this. These robots, such as Honda's *Asimo*, are used for advanced research as well as for entertainment. Other less sophisticated but still precise and expensive platforms are used as the basis for the museum robots discussed in Sect. 55.5.

A second class of education platforms (and the ones to be discussed in this section) are lower-cost robot platforms, or platform kits. These platforms are inexpensive, exist in large numbers, and are widely used in schools and by hobbyists.

Fig. 55.2 (**a**) Hero-1, (**b**) Hemisson, and (**c**) Amigobot

Education robots really got their start in the early 1980s with the introduction of the Heathkit *Hero-1* (Fig. 55.2a). Hero robots were sold as kits, both to keep the price down and to encourage users to learn how robots were made. However, while detailed assembly instructions were included, no information on the theory or principles behind the assembly were given; the kits, by themselves, did not provide a satisfactory educational experience. Unfortunately, neither the Hero robots, nor several other similarly sized and priced personal robots that came out in the 1980s, reached a level of capability and ease of use to attract an economically viable customer base. Heathkit and the other companies have since gone out of business.

In the intervening years several other companies have tried to make personal robot systems. Many of these companies started with more capable research robots. With few exceptions, these companies have faded away or gone into other markets. Most of the companies now mass marketing education robots do so as a side business. The primary business for most of these companies is consumer electronics, toys, and with one noticeable exception consumer robots that were supposed to be neither educational nor entertaining.

K-Team [55.41] is one of the few companies making robot platforms specifically for the education market. The *Hemisson* (Fig. 55.2b) is a low-cost, less compact version of K-Team's Khepera research robot. It has reduced computational power and few sensors when compared to most research robots, but is priced and designed for robotics classes in secondary and university classes. Activemedia is the other research robot company that produces lower-cost educational robots. Their *Amigobot* platform is shown in Fig. 55.2c.

The LEGO® Mindstorms RCX was the first robotic platform from the LEGO company, and has had broad appeal across many demographics. The LEGO computation systems are discussed in Sect. 55.4. However the LEGO blocks themselves have been a mechanical prototyping system for robots long before LEGO ever introduced their own controllers. The LEGO bricks make RCX a good tool for early and fast robotic explorations. The newly released LEGO robot system, Mindstorms NXT (Fig. 55.3a) has a new processor and some new sen-

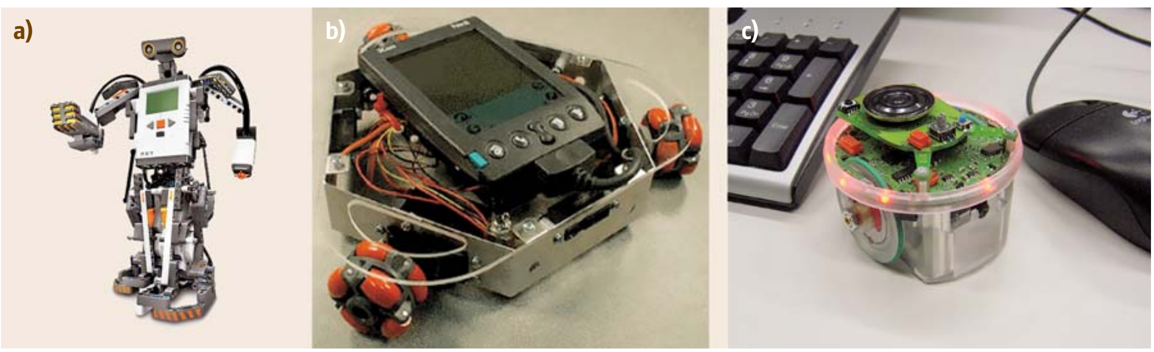

Fig. 55.3 (**a**) LEGO NXT, (**b**) PPRK, and (**c**) e-puck robots

Fig. 55.4 **(a)** Garcia, **(b)** ER1, and **(c)** KHR-1 robots

sors, but relies on the popular LEGO Technics building system for all of the mechanics.

The Palm Pilot Robot Kit (PPRK) platform [55.42] (Fig. 55.3b) is a low-cost kit combining a mobile base and a personal digital assistant (PDA), originally a PALM Pilot. The PALM provides computational power and a graphical user interface for robot control, and communicates with lower-level robot driver circuitry via the PALM's serial port. The result is a very compact omnidirectional platform with three distance sensors (in its basic configuration) that constitutes a starter kit for those who want to begin by building their own robot from kit parts.

E-puck [55.43] (Fig. 55.3c) is the first desktop robot (70 mm in diameter) based on an open-hardware concept. Equipped in its basic version with a diverse sensor package (three-dimensional accelerometer, proximity sensors, three microphones, color camera), several actuators (stepper motors, speakers and numerous LEDs), Bluetooth® communication and a good processor capable of signal processing (dsPIC family), it is relatively inexpensive due to its simple mechanics. It is a desirable tool for education in technical schools and universities.

The Garcia robot from Acroname [55.44] (Fig. 55.4a) is a small-size platform (25 cm × 18 cm × 10 cm) that can be extended with a XScale-based board. It is sufficiently small to develop experiments in small environments and yet this robot is sufficiently large for diverse payloads, including a small manipulator mechanism and an array of sensors.

The ER1 robot from Evolution Robotics [55.45] (Fig. 55.4b) constitutes a simple extruded aluminum frame kit supporting a laptop and equipped with stepper motors and wheels. This robot focuses interaction on the onboard laptop, enabling onboard computation as well as onboard vision via a universal serial bus (USB)-based camera. This robot system, which is going out of production, comes with a sophisticated software environment for navigation and visual recognition of artifacts in the robot's field of view.

The KHR-1 [55.46] (Fig. 55.4a) is an initial humanoid robot at an affordable price, based on a set of 17 servomotors. The growing family of humanoid robots

Fig. 55.5 **(a)** Robosapien, **(b)** Roomba, and **(c)** Create robots

still depends upon large numbers of servo actuators and very few sensors; however, due to the draw of humanoid robots, these kits are nonetheless excellent motivational tools.

Robsapien [55.47] is a popular toy humanoid robot (Fig. 55.5b). Because this is an infrared (IR)-controlled toy, using the IR link from a computer or PDA is relatively straightforward. Some hobbyists have hacked deeper into the system so that the Robosapien can be used as a fully fledged computer controllable robot platform.

The iRobot® *Roomba*® [55.48] (Fig. 55.5c) is a mass-produced, inexpensive household vacuum robot (33 cm × 33 cm × 7 cm). With millions sold, the Roomba is currently the most common robot in the world. The Roomba was not initially meant to be an education robot – but rather a service robot doing dirty and dull work. However, much like the Robosapien, the robot hobbyists quickly started using the Roomba as a platform, and starting in 2005, iRobot responded to requests and included an exposed serial port and released an application programming interface (API) for controlling the Roomba and reading its sensors from an external computer [55.49]. A community of Roomba hackers has come into existence using Roombas for everything from musical instrument digital interface (MIDI) devices to security robots [55.50]. Many schools are adopting the Roomba, combined with one of the controllers described in Sect. 55.4.1, as a platform for classes and experimentation. A new product, the iRobot *Create*™ was released in 2007. This product is a Roomba without the vacuum or brushes, but with additional interfaces to encourage experimentation. The iRobot Create can be purchased with a processor of its own or easily interfaced with robot processors such as the XBC [55.51] or small low-power general-purpose processors such as the *Gumstix*™ [55.52, 53].

55.4 Education Robot Controllers and Programming Environments

Education and entertainment activities in robotics sometimes run at cross purposes. For entertainment we want robots that are active and very easy to use and to control. Products like the LEGO Mindstorms provide both a robot controller and a programming environment that meets those criteria.

However, when it comes to robot education, it is important to remember that in most cases we are using robots to inspire and motivate students to learn many things, of which robotics is just one. Robotics educators, especially at the K-12 (students aged approximately 5–18 years level, are hoping to teach students general science, programming, math, and engineering techniques. The toy programming environments used in some products such as Mindstorms may be inappropriate for this mission.

This section overviews some of the popular robot controllers and programming environments. Usually the two are linked, but there are some environments that work with several different controllers and vice versa.

As with the robot tournaments described in Sect. 55.2, many of the robot controllers and their programming environments in use for tournaments and by hobbyists can trace their origins back to the MIT 6.270 course [55.27]. At an even more fundamental level, the origin of most robot controller starts with the Motorola 68HC11 processor.

55.4.1 Robot Controllers

The venerable HC11 is a single-chip processor with small amounts of onboard flash and random-access memory (RAM) memory. It also has a number of input/outputs (I/O) and timing ports that make it relatively easy to interface to sensors and external devices. The 8-bit HC11 uses the same instruction set as the Motorola 6800 series of processors, which have been in existence in one form or another for more than three decades.

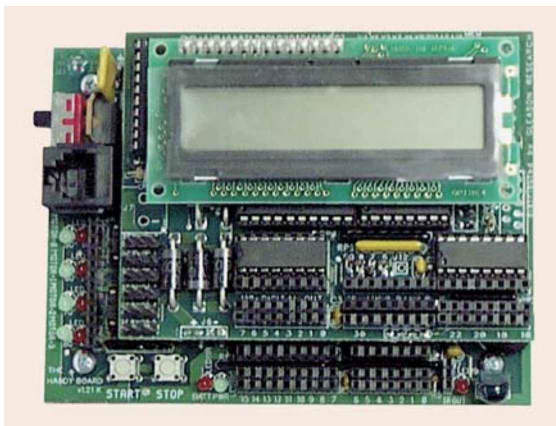

Fig. 55.6 The HandyBoard with its expansion board

The HC11 was used by Anita Flynn and Joe Jones in a board for the MIT robot talent show in 1991, which spawned the Book Board [55.54], the MIT 6.270 board, and Fred Martin's Handyboard. The last of these became the de facto high-end robot controller for hobbyists and autonomous robot contests for most of the 1990s.

The Handyboard (Fig. 55.6) can provide pulse-width modulation (PWM) control for four direct-current (DC) motors, read eight digital and eight analog sensors, control a couple of light-emitting diodes (LEDs) and has a 32-character display. With the expansion board, eight lines of digital.input-output (DIO) and control for six R/C servos is also added. The Handyboard can be programmed using 6811 assembly language and several other languages including Java and C.

The other low-cost commercial robot controller in widespread use throughout the 1990s was the BASIC Stamp [55.55] (Fig. 55.7). This programmable interrupt controller computer (PIC)-based controller could be programmed in a special (often assembly language-like) version of the BASIC language. While very small in memory, and usually requiring supplementary electronics for most sensors and actuators, the Stamp was very popular because of its low cost and flexibility.

In the late 1990s, spurred on in large part by the growing interest in robot tournaments, a renaissance in robot controller hardware started making available a number of controllers ranging from advanced PICs to full-blown personal computers (PCs). A sampling of some of the controllers now available is presented in Fig. 55.8

The RCX (Fig. 55.7) and its successor, the soon to be released NXT (Fig. 55.3a), are widely available controllers from LEGO. These are very easy to interface to the special sensors and motors produced by LEGO, using variations of LEGO's brick interface. However, this simplicity of use makes it more difficult to connect to other sensors and motors. These foolproof interfaces also take up a lot of physical space, limiting the controllers to just a few sensors and actuators. While the central processing units (CPUs) are relatively powerful, most of this horsepower remains unused because of the limitations of the interface. However, these controllers are not very expensive, are mass produced, and require absolutely no knowledge of electronics, mechanics (or when using LEGO's software) programming in order to get them to control simple robots.

For the more technically inclined hobbyist or student, but one on a stricter budget, there are the PIC-based controllers. The OOPic system [55.56] (Fig. 55.8), uses an object-oriented programming system, and includes

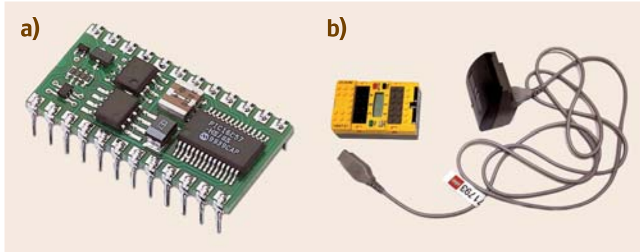

Fig. 55.7 **(a)** The BASIC Stamp 2 and **(b)** the LEGO RCX

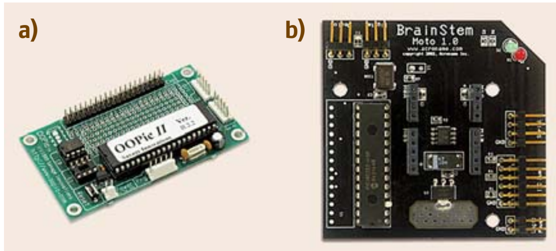

Fig. 55.8 **(a)** The OOPic Controller and **(b)** the Brainstem MotoBoard

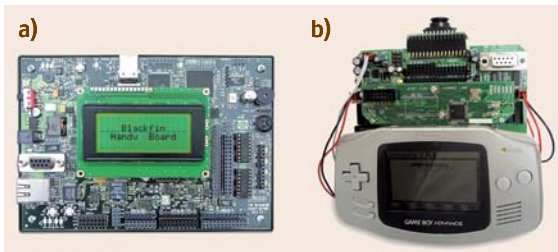

Fig. 55.9 **(a)** The Black Fin Handy board and **(b)** the Xport Botball Controller (XBC) with camera

much, but not all, of the interface electronics needed to get a robot up and going.

Acroname's Brainstem system [55.57] (Fig. 55.8) uses a small reduced-instruction-set computer (RISC) processor to create a low-cost modular controller. Modules are linked over an inter-integrated-circuit (IIC) bus. The Brainstem is programmed in the tiny embedded application (TEA) language, a variant subset of the C language.

For more capability including proportional–integral–derivative (PID) motor control and vision processing there are controllers such as KIPR and Charmed Labs, XBC [55.58] (Fig. 55.9), and the Blackfin Handy Board [55.59] (Fig. 55.9). Both of these boards share the same basic architecture of a RISC processor combined with a field-programmable gate array (FPGA). The FPGA comes preprogrammed with a variety of useful functions (e.g., motor control) but can be reconfigured if desired. The processor runs user code and uses the FPGA to handle hardware-related library calls. Both of these boards contain ports for connecting with complementary metal–oxide–semiconductor (CMOS) cameras.

The XBC uses a Nintendo GameBoy Advance as part of its architecture to provide processor, display, and user buttons. This provides the user with a color graphics screen on the robot that can be used for displaying text and images and for setting parameters. This is especially useful for tuning vision parameters, as the camera output (processed or raw) can be redirected to the screen.

55.4.2 Edutainment Programming Environments

Many of the lower-priced controllers (e.g., BASIC Stamp) have limited options for programming environments, while the higher-end controllers such as the XBC can accept cross-compiled programs in most languages.

The LEGO processors are shipped with a graphical programming environment. While sometimes limiting in what can be programmed, the environment is highly intuitive. A more capable (and not quite as intuitive) graphical programming environment based on LabVIEW has been created for the LEGO processors and has been used in a number of schools [55.60].

For educational environments where the robotics experience is serving as an introduction to programming, there are a few good choices. There are Java, C, and other language implementations specific to one or more of the processors above.

One the most popular (because it runs on many of the processors and under all major operating systems and is free) is Interactive C or IC [55.61]. IC provides a fully integrated development environment (IDE) including an editor, compiler/interpreter and controller simulator. IC implements a subset of American National Standards Institute (ANSI) C, the primary missing functionality being in pointer arithmetic. Other differences between IC and and standard C are there to protect the novice user (e.g., IC performs array bounds checking during runtime).

IC also has an interpreted interaction window which allows the user to try out C expressions or function calls, query global variables, etc. either to the actual hardware or to the hardware simulator. The IC environment also provides utilities such as uploading global array data from the robot hardware to the PC, providing memory maps of the program on the controller, colorization, block-level indentation, and interactive documentation from the editor. The IC runtime environment provides library functionality for multithreading.

IC is used regularly in a number of the robotics tournaments described in Sect. 55.1. It is also being widely used in introductory programming courses [55.62] robotics courses [55.63] and for more advanced courses such as in the teaching of neural nets and control [55.64].

IC uses a virtual machine model that runs on the processor, allowing it to be ported to new robot controllers with relative ease.

55.5 Robots and Informal Learning Venues (Museums)

Robots are objects of great attraction and can have a large number of modalities for establishing a strong interaction with humans. It is therefore not surprising that one of the first applications of mobile robots have been robot guides in research labs and later in museums and exhibitions. SHAKEY (Fig. 55.10a), developed at SRI in the early 1980s is often considered the first mobile robot [55.65]. It was able to move wooden blocks according to verbal commands given via a keyboard. Probably the first robot exposed to untrained visitors was POLLY, developed to give simple lab tours at MIT's artificial intelligence (AI) laboratory in the early 1990s [55.66]. The only communication input was vision; visitors waved their feet if they wanted a lab tour. Whereas these early solutions were landmarks in their time, more recent tour robots offer a much richer interaction and are able to navigate in the somewhat more complex and dynamic environment of museums and exhibitions. One of the first examples of these next-generation tour-guide robot prototypes is Jijo-2, demonstrated in the late 1990s [55.67] (Fig. 55.10c). However, it was operated under laboratory conditions and only by people that were more or less familiar with the robot.

55.5.1 Tour-Guide Robot Examples

The first real tour-guide robot, called Rhino, was deployed for six days in the Deutsches Museum in Bonn during the summer of 1997. It was freely navigating

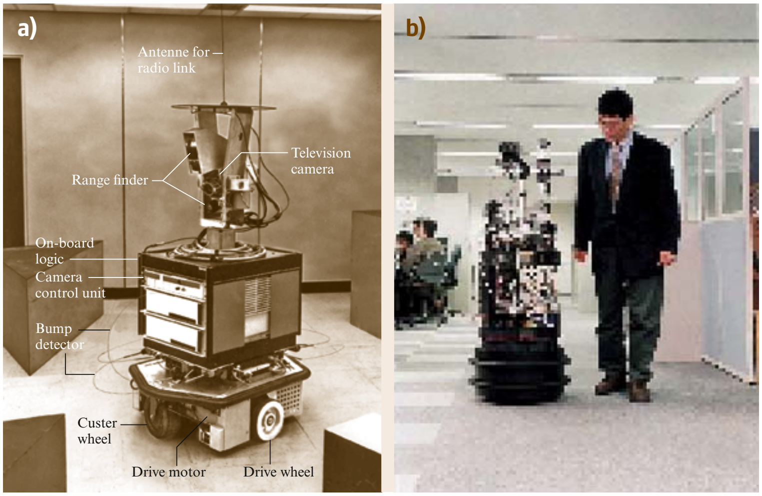

Fig. 55.10a,b The SHAKEY Robot developed in the 60-ties at SRI **(a)** and the Jijo-2 Robot giving a tour at the National Institute of Advanced Industrial Science and Technology (AIST) **(b)**

and equipped with speech synthesis (output) and buttons for user input. The robot's main tasks were to get people involved and to support them in navigating through the environment. The experience gained in this short-term installation showed a strong need for enhanced human–robot interaction [55.68] (Fig. 55.11a).

A first step towards a more appealing interaction was realized with Minerva, which was operated for two weeks in late summer 1998 in the Smithsonian's National Museum of History, Washington DC, USA [55.69] (Fig. 55.11b). One version of Minerva was equipped with a caricature face (eyes, eyebrows, mouth), enabling it to appear to express its feelings and entertain the visitors. In addition to on-site interaction, Minerva was accessible for tours via the Internet from remote sites. According to a study, people perceived the robot's intelligence similar to that of a dog. This basic experience was further expanded in a European project towards two installations of tour-guide robots enabling telepresence in museums and fairs [55.70]. The robot Albert, developed in this project, was equipped with a commercially available speech recognition system that enabled on-site visitors to give spoken commands.

Hermes is a robot from the Universität der Bundeswehr München that was demonstrated at various fairs and exhibitions in 2001 and 2002 [55.71] (Fig. 55.12a). Equipped with two arms, Hermes is able to conduct simple fetch and carry tasks. However, his mobility was typically limited to a very small and well-structured area.

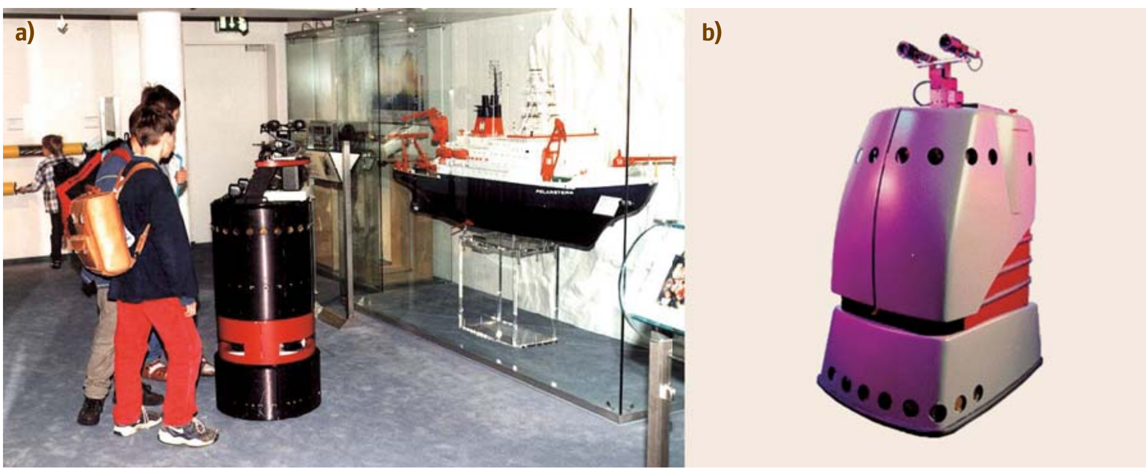

Fig. 55.11a,b Rhino **(a)**, (University of Bonn) and Minerva **(b)**, (Carnegie Mellon University, University of Bonn)

Fig. 55.12a,b Chips developed at Carnegie Mellon University **(a)** and Hermes, a humanoid interaction robot developed at Universität der Bundeswehr München **(b)**

Using an off-board microphone, Hermes was able to get simple spoken commands based on keywords.

The first robots deployed in a museum for a long period were Chips (Fig. 55.12b) and its successors SWEETLIPS and JOE, developed by Carnegie Mellon University and Mobot Robotics [55.72, 73]. Installed in 1998, they were operated for several years in the Carnegie Museum of National History, the Hall of North America Wildlife, and the Heinz History Center, respectively. All robots used specially deployed color landmarks for localization, and a touch screen for enhanced audiovisual interface. The robots primary goal was to attract visitors to less frequented areas and to enhance the learning rate during the visit. They were conceived as educators offering background information about the exhibition through their audiovisual touch screen. A study done along with the installation of Chips showed that the learning success rate increased by more than 50% when visitors (children and adults) were guided by the robot through the exhibition [55.72].

Fig. 55.13 The Inciting, the Instructive, and the Twiddling robot amusing and informing peoples at the Communication Museum, Berlin. These very attractive robots have been developed at Fraunhofer Institute for Manufacturing Engineering and Automation (IPA)

The Inciting, the Instructive, and the Twiddling robots were developed by the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) in Stuttgart (Fig. 55.13) [55.74]. These very appealing robots use old-fashioned technology elements such as a mechanical scale, as design elements, and have been running in the Communication Museum of Berlin since 2000. They attract and greet visitors (The Inciting), offer introductions to the museum (The Instructive), and play with a big ball (The Twiddling). They have no input device to give commands, but are very expressive and playful through their appearance and body motions.

The largest installation of tour-guide robots, in terms of number of robots and accumulated operation hours, was realized with a fleet of 11 RoboX robots at the Swiss National Exhibition Expo 02 in 2002 [55.75, 76] (Fig. 55.14). The robots presented the robotics exhibition and themselves through synthesized speech in four languages. A special programming interface enabled easy implementation of different scenarios using speech and sounds, facial expressions (two independent pan-tilt eyes, eyebrows), display of icons in one eye, body motion, and navigation as output modality, and the buttons, face tracking, people tracking and an analysis of the global visitor distribution in the exhibition as input modality. Two robots were equipped with speech recognition enabling simple spoken commands like yes/no in four languages [55.77]. After finishing their job at Expo 02, the RoboX robots found a second life as research platforms and were installed in other exhibitions and as TV moderators by BlueBotics.

Rackham is a tour-guide robot deployed in 2004 at the Mission Biospace Exhibition in Toulouse, France [55.78, 79] (Fig. 55.15a). This robot, developed by the Laboratoire d'Architecture et d'Analyse des Systèmes (LAAS) in Toulouse, has an enhanced audiovisual output system and obtains user commands via a touch screen. The animated helmet together with the touch screen are used as a focal point of attraction to this very futuristic robot. Once a visitor is detected by the pan-tilt camera in the helmet, the robot explains its utilization

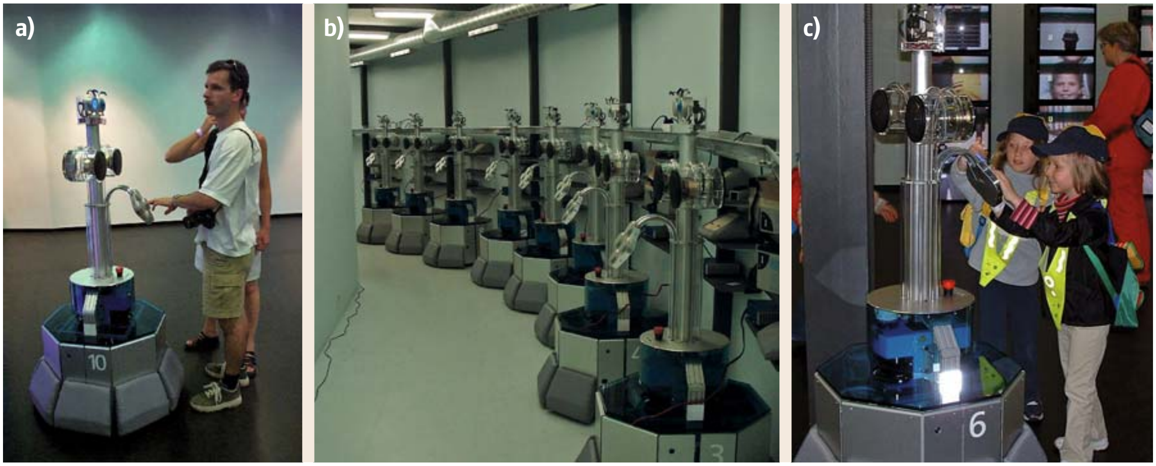

Fig. 55.14a–c The family of 11 RoboX tour guide developed by the EPFL gave tours during five months to over 650,000 visitors at the Swiss National exhibition Expo 02

and offers its services. This installation is also used as an experimental environment for further research.

More recent tour-guide robot platform developments are focusing on enhanced human–robot interaction and more humanoid appearance. One illustration is Brion, which learns the environmental setting from humans through an enhanced dialog system [55.80]. Voice and gesture recognition are the main inputs for driving the dialogue with the human that is based on a finite state machine (FSM). The humanoid exhibition robot Repliee Q1 has been developed at Osaka University. It consists of an artificial human upper body with a very realistic appearance (Fig. 55.15b). Repliee Q1 communicates through speech, enhanced facial expressions and body language. It has a tactile skin over the entire body, able to sense being touched and react to it. During the 2005 World Expo in Japan, Repliee Q1 was offering its services at an information desk. The next generation of Repliee is intended to have actuated legs for full motion abilities.

More sophisticated robots will be deployed in informal learning venues as tour guides and teachers soon. They have the potential to offer a more appealing and lasting learning experience. However, there is still important research and technological advancement required. Until then, robots can only partially compete with a human guide.

55.5.2 Lessons Learned

Through the various installations presented above, new insights on the design of tour-guide robots and the user's

Fig. 55.15a,b Rackham is a tour-guide robot deployed at the Mission Biospace Exhibition in Toulouse, France **(a)**. The Repliee Q1 humanoid robot **(b)** was at the information counter at the 2005 World Expo in Japan. It was developed by Osaka University

behaviors were gained. Various details can be found in [55.69, 72] and [55.76]. At informal learning venues it is nearly impossible to instruct the visitors on how to operate the robots. Thus the robot's interactivity has to be plug-and-play. This is only possible if design and functionality are harmonically integrated and the robot's intention and internal states are transparent and understandable for the visitor. Design creates expectations, e.g., a humanoid appearance makes visitors believe that the robot has similar competence as a human. A robot that speaks is also expected to understand spoken dialog. In general, the public has the tendency to overestimate the robot's competence because most people only know robots from science-fiction movies or futuristic research documentaries.

Visitors are curious, but also impatient and rude. Therefore tour-guide robots have to allow visitors to discover new elements in a fast rhythm, have to be very dynamic and fast responding, and should be robust against harsh treatment. If possible, visitors will sit and hang on the robot or hit the bumpers. On the other hand, visitors are respectful with elements that look fragile, e.g., they will not touch the eyes of the robot. The most appealing interactions are often elements such as obstacle avoidance or even security buttons because the feedback is immediate and easy to understand. It is therefore of crucial importance that the actions of the robot are immediately responsive to users' needs and wishes. A delay of only one second to a pushed button is often too much and will often incite inappropriate reactions from the visitors, such as hammering on the button.

A successful installation of robots in informal learning venues must be carefully designed according to the functionalities and services they are intended to offer. Form has to follow function.

55.6 Educational Evaluation of Robot Programs

An important aspect of assessment, beyond technical evaluation, is educational evaluation: how does human–robot interaction change models of learning and identities with respect to technology; and how is this done in educationally appropriate ways? We find several techniques to be applicable during each of the following phases of an educational project:

- design-time assessment: the creation phase of an educational robot system
- formative evaluation: during execution of an educational robot program
- summative evaluation: following completion of an educational program

This section will identify relevant tools for design, formative, and summative evaluation that we borrow from the human–computer interaction community and the cognitive-educational analysis community. These tools are well suited to helping researchers understand and quantify how educational robots can impact learning in the classroom and, beyond the classroom, in informal learning venues such as museums and after-school workshops.

55.6.1 Design-Time Assessment

The field of human–computer interaction (HCI) offers formal and heuristic techniques for addressing interfaces between humans and technology [55.81, 82]. Current HCI practice often focuses on user-centered design, which suggests that understanding the user and the entire task can help us be better designers. One specific HCI technique, contextual inquiry and design, is especially useful for both informal and formal learning venues where robots will interact directly with students as users. Contextual inquiry guides the collection of background data concerning interactions taking place before inclusion of the new, to-be-designed robotic technology, and is often achieved through the collection and analysis of direct interviews and observations. The process includes identifying and polling various stakeholders in the educational environment, from the classroom as a whole to individual educators and mentors.

A second HCI activity, modeling, guides the creation of pictorial flow diagrams that identify the most important features of the environment in which the robotic educational technology is to be used. *Workflow* describes the communication necessary for the classroom activities. *Sequence* identifies actual sequences of action required for various activities in the classroom (or museum). *Artifact* captures the relationship of existing tools required for activities to be performed successfully. Finally the *physical model* identifies how space is used, which can be notable in the case of the design and potential inclusion of mobile robots in spaces that were generally not designed for them in the first place, such as conventional laboratories and, even worse, regular lecture halls.

Why do all the above? Because it is a principled way of understanding existing environments. This in turn facilitates design-time judgments in regards to the best manner in which to add a new technology, such as interactive robots, while maximizing the chances that the technology is a real success. However, it is the continual cycle of evaluations during the implementation phase that is critical to a positive outcome. So in summary design-time data collection and assessment helps set the stage and control expectations. Formative evaluations and feedback into the continuing design process, as described below, help keep the engineering on a path to success.

55.6.2 Formative and Summative Evaluation

Traditional school-based assessments of learning, for instance course surveys or exam grades, are useful as coarse-resolution data collection devices. However, these do not provide sufficient detail to build models of how learning is proceeding with or despite of technology changes, nor how further technology changes may improve learning. Furthermore, especially in informal settings such as museums, school-based assessments are even more inappropriate. In such settings significant learning results from communication. As groups of visitors or teams of students use and talk about a museum exhibit or project challenge, they construct a shared understanding of the content and context of the challenge. There is an outstanding body of work in the education community that focuses on this form of conversation and learning. The following references are excellent starting points [55.83–87]. Applying this education learning strategy to educational robotics yields wonderfully rich analyses in terms of how the robots change conversations in the classroom [55.88].

In education learning, tools include broad evaluation tools for qualitatively and quantitatively constructing a model of learning across the classroom and deep, focused tools for studying the specific communication-oriented mechanisms of learning that may inform patterns of change and exploration at the student and team level. In terms of broad tools, written student surveys are one useful data collection tool. A combination of linear, quantitative queries (called Likert scales) coupled with open-ended essay questions such as *What is the most important concept you learned this week?* invite both statistical analysis of raw results and thematic analysis of self-reported challenges and successes by the students themselves. Recorded interviews with students, individually or in teams, provides even richer information due to the ability to ask complex *What have you learned?* questions appropriate for open-ended analysis, again in terms of thematic content. A deep, focused tool that is expensive in terms of analyst resources but generates very useful information is the ethnography, whereby a trained observer spends, for instance, one week tracking all the activities of two teams in the classroom, including conversations within the team, among team members and other pupils, and between the team and the course instructors and teaching assistants [55.89–91]. Ethnography is intended to detail the learning and problem-solving process that occurs in class on a minute-by-minute basis.

Taken as a whole, the above collected data can then be analyzed by thematic content, for themes such as those listed in Sect. 55.1. Statistical significance and correlation tests can be applied to the quantitatively derived results of coding all such information to yield information on how the frequency of learning themes appearing in conversation increases or decreases, and how specific themes become more refined or specific in students' speech over the duration of the course.

However, assessment of the educational value of robotics programs such as those described in Table 55.1 is often more difficult than evaluating programs in more traditional disciplines. There are widely accepted textbooks and curricula for many disciplines, but not yet for robotics. Additionally, the different educational robotics programs described earlier take a variety of approaches towards education.

Many programs (e.g., FIRST LEGO League and RoboCup Jr) are large but are implemented at the local level, so the experience for students can vary tremendously from one locale to another. The more standardized programs (e.g., Botball and FIRST) have different educational models. FIRST uses an inspirational model where students work with professional engineers. Botball follows a more traditional high-school model of education where the teachers are trained in the techniques and principles, so that they may guide the students at a high level, but all of the work (both design and implementation) is done by the students.

Because robotics can serve as an unfamiliar tool for many students in such courses and programs, evaluation of how this unfamiliar, potentially rich interactive tool impacts student learning and perceived interest levels in science and technology is a common focus of educational robotics assessment. This trend is exacerbated because these programs, which involve tens or even hundreds of thousands of students, are implemented by nonprofit companies and volunteers that lack specific funds and training for formal assessment. For these reasons, formal assessment of the programs tends to be based on student and/or teacher surveys rather than rigorous testing, and the assessment usually focuses on specific issues (e.g., gender issues in technology education) where assessment-specific funding may be available.

As educational robotics becomes more mainstream, we can expect that evaluation will shift from general enthusiasm about science, technology, engineering, and mathematics (STEM) learning to specific learning advantages derived from such robot-inclusive coursework for follow-on coursework in diverse disciplines such as biology, physics, and computer science.

55.7 Conclusions and Further Reading

This chapter has given an overview of many, but by no means all, of the educational robot hardware and programs currently available. Websites such as robots.net and robotevents.com attempt to maintain lists of the rapidly evolving field of educational robot tournaments. Keeping track of the latest hardware and software tools are more problematic. Some additional sources for these topics, and others covered in this chapter include: *Robots for Kids, Exploring new technologies for learning*, edited by Druin and Hendler; *Robotic Explorations: A Hands-On Introduction to Engineering* [55.92], by Martin; *Where the Action Is, Foundations of embodied interaction*, by Dourish; *Piaget's theory of cognitive development* [55.93], by Wadsworth; and *Computer as Theater* [55.94], by Laurel.

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