Robot-Based Explorations in a Liberal Arts Environment

Franklyn Turbak, Department of Computer Science(PI)
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Project Summary

We propose to purchase a collection of robot kits to enable the incorporation of robot-based activities into undergraduate science courses within a liberal arts setting. Our goal is to increase the level of engagement of liberal arts students, particularly women, in the physical sciences and engineering by providing experiences that capture the excitement, spirit, and intellectual substance of these disciplines. We are developing an introductory robot-based design course that highlights connections between physics, computer science, mathematics, and biology. Additionally, the surprising versatility of robots makes them useful in a wide range of existing computer science and physics courses.

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Wellesley College

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1. Results From Prior Support

Neither of the investigators for this proposal have received support from the NSF pertaining to undergraduate education in the last five years. However, the co-investigator, Robert Berg, was a co-investigator on a College Science Instrumentation Program grant that was funded by the NSF in 1987 -1988. A description of the results from this grant are described in Professor Berg's biographical sketch.

2. Project Narrative

a. The Current Situation

Wellesley

Wellesley College is a private liberal arts college devoted to the undergraduate education of women. Wellesley's 2300 students come from 50 states and over 60 foreign countries and include over 750 members of ethnic minorities. There are over 320 faculty members, of whom 75% hold Ph.D.s and 55% are women. The very low student/faculty ratio (just over 7/1) results in small class sizes and offers excellent opportunities for students to pursue research projects with faculty members. Exchange programs allow students to take advantage of programs at MIT, Brandeis, and Babson.

Wellesley has a long tradition of encouraging its students to participate in the sciences. It was the second college in the country (after MIT) to offer an undergraduate physics laboratory. There continues to this day to be a strong emphasis on laboratory-based instruction across the science curriculum.

Wellesley places many of its science majors in top graduate programs. According to the NFS/SRS Survey of Earned Doctorates, during the period from 1985 -- 1990, more female recipients of Ph.D.s in science and engineering received their undergraduate degree from Wellesley than from any other liberal arts college. Among universities in general, Wellesley ranked 16th as the undergraduate institution of female recipients of Ph.D.s in science and engineering during this time.

Wellesley's science departments (including astronomy, biology, chemistry, computer science, geology, mathematics, physics, and psychology) are all located in a single building, the Science Center, that was specifically designed to foster interdisciplinary contact. The Science Center houses state-of-the-art teaching and research facilities, including the Science Library (100,000 volumes) and the College's academic computers. Recently, the Science Center underwent major ($19 million) renovations and expansions to keep pace with the changing needs and growth in the sciences. The overwhelming majority of this new space is occupied by the physics and computer science departments.

The computer science department has four full-time Ph.D. faculty members, one masters-level lecturer, and one masters-level laboratory instructor. The department serves approximately 25 majors, and typically has between 10 and 15 graduating seniors each year. Each year the department also serves about 200 non-majors seeking to fulfill liberal arts distribution requirements. The physics department has six full-time Ph.D. faculty members and three masters-level laboratory instructors. The department currently has approximately 20 majors and has recently averaged 8 graduating seniors per year. Enrollments in introductory courses are over 300 per year. Almost all of the introductory physics courses have a laboratory component.

Relevant Resources

Wellesley has a strong commitment to educational technology. The campus is equipped with abundant classroom and laboratory space housing state-of-the-art equipment. Wellesley is fully-networked and has computer clusters that provide over 100 Macintosh computers for student use. The college supports several programs, including Educational Research and Development (ER&D) and the Learning and Teaching Center (LTC), that provide incentives for faculty to use technology in the curriculum in innovative ways. In fact, the pilot course described later is made possible by internal funding from ER&D.

Curricular Need

In the traditional undergraduate liberal arts science curriculum, students are typically presented with a body of scientific knowledge, but are rarely asked to become active participants in the scientific enterprise. Laboratory courses can give a window into this process, but they are often exercises in technique in which students are only asked to replicate known results. Unlike their friends in the arts, science students rarely have an opportunity to engage in interdisciplinary, hands-on, creative projects of their own choosing, especially at the introductory level. Is it any surprise that most Wellesley non-science majors never take any science or math courses beyond the required minimum, and even science majors find that there is little creative latitude in their courses?

The problem is particularly acute among women. The Pathways Report [Rayman, 1993] identified a number of factors which seemed to be important in determining whether the women in the survey group decided to pursue scientific careers:

- Access to research opportunities outside the scope of standard course work. These experiences are most effective when they occur early in the student's academic career.

- Science and engineering as cooperative enterprises. Women are more likely to be attracted to science if it is perceived as a cooperative enterprise, seeking a goal that will be beneficial to society, rather than a lone, abstract pursuit.

- The presence of hands-on discovery-oriented work is critical.

There are several obvious deficiencies in the "standard" physical science and engineering curricula in these regards. It is notoriously difficult to provide early research opportunities in disciplines such as physics because the necessary theoretical grounding and laboratory skills are not in place until late in a student’s undergraduate career. Courses organized around weekly problem sets and periodic written examinations reinforce the notion that these disciplines involve mostly solitary effort and do little to foster a sense of science as a social enterprise. This is particularly unfortunate, because *in practice* science and engineering are more and more becoming collaborative efforts. Finally, there is little hands-on, discovery-based learning, even in laboratory courses. Rarely do students get to *design* the experiment themselves or to experience the thrill of discovering answers that their instructor does not already know.

Noteworthy exceptions to the standard curriculum are video-based projects that are used in some Wellesley physics courses [Ducas, 1987]. In these projects, students use video cameras to record physical phenomena that interest them and then analyze the resulting footage in terms of the concepts they are learning in their courses. Student engagement in these projects is high because they are constructing knowledge in a way that is personally meaningful to them. We are searching for other kinds of projects that will increase the investment that students have in their work.

We believe that robot-based projects have a similar potential for encouraging students to become more personally involved with the material they are learning. Simple circuits built in an introductory electronics class typically serve no larger purpose, but many of them can be motivated as robot sensors. In an introductory mechanics class, friction is usually discussed abstractly in terms of bricks sliding down inclined planes; it could be motivated much more concretely via experiences involving the traction of a robots wheels. Introductory programming classes typically use unexciting numerical examples to illustrate simple programming constructs; these could be much better motivated in the context of a physical robot whose behavior the students are trying to control. In short, the robot is a versatile “object to think with” that supports accessible and engaging projects in a wide range of scientific and engineering disciplines.

Wellesley provides an ideal atmosphere in which to develop these activities. Current research suggests that women do best at learning science in an all-women environment [Tidball 1980, 1986; Astin, 1993; Henderson et al., 1994]. Explanations for this often point to the loss of self-confidence and intimidation that women frequently experience in co-ed situations. The problem is exacerbated by the fact that women are less likely to have grown up tinkering with mechanical toys, hacking around on computers, or playing with electronics hobby kits. But, for these very reasons, it is important that women college students are given opportunities to develop skills and confidence in these areas.

2. Development Plan

We plan to enhance student engagement in a number of computer science and physics courses by using robots as a basis for motivating projects and examples. The kinds of robots we have in mind are those developed by the Epistemology and Learning Group of the MIT Media Lab [Martin, 1992]. They consist of a custom microprocessor board (the Programmable Brick [Sargent et al., 1995]) that receives inputs from sensors (e.g., touch, light, sound, temperature, and magnetic field sensors) and controls actuators (e.g., motors, lights, speakers, infrared transmitters). The body of the robot is constructed out of Lego components: bricks, gears, pulleys, wheels, etc. The robot is controlled by programs written in Brick Logo, a variant of the popular Logo educational programming language [Papert, 1980]. Programs are developed on a traditional computer and are then downloaded onto the Programmable Brick. The simple and modular interfaces evident at the mechanical level (Lego parts), the electronics level (sensors and actuators that plug into ports on the Programmable Brick), and the programming level (Brick Logo procedures) make these robots accessible to non-engineering students and encourage hands-on experimentation.

Learning activities based on these robots have a proven track record at other institutions. MIT's 6.270 intersession course is a popular activity in which students devote large amounts of time and energy to building a robot that will compete against other robots in a contest [Martin, 1992; Martin, 1994]. Lego-based robots have successfully been used to support constructionist learning activities in numerous grade school and high school classrooms [Resnick, 1988; Resnick & Ocko, 1991]. One vivid and relevant example is captured in a recent cover article of the journal *Science* [Benditt, 1993]. The cover photograph shows a team from an all-girl sixth grade science club that participated with great success in the preliminary rounds of the MIT robot contest.

The challenge of bringing robots to Wellesley is to develop activities that are appropriate for an undergraduate liberal arts environment. Although many of our students would be excited by an MIT-style robot contest, most would not have the engineering background to participate in such an intensive project. Instead, we seek to underscore connections between robots and the scientific disciplines with which our students are more familiar. At the same time, we wish to use the robots as vehicles for introducing important engineering and design ideas that are often lacking in a liberal arts science education.

There are two major ways in which we plan to use robots in the curriculum:

1. As the focus of a new introductory laboratory course that introduce students to science and engineering via robot design projects.

2. As a source of projects and examples in existing computer science and physics courses.

2.1 New Robot Design Course

We are searching for new ways to spark student interest in science, both to attract more students to scientific disciplines as well as to increase scientific literacy in the general student body. Robot-based projects are a particularly promising way of connecting diverse disciplines in an introductory design experience that is both engaging and accessible to novices:

- Even simple robot projects touch upon a variety of different disciplines, including physics, mechanical and electrical engineering, computer science, and mathematics. By emphasizing "robot behaviors", connections can also be made with biology and psychology.

- Because they are perceived as fun and interesting, robots can attract humanities students to science and technology and to allow these students to experience science and technology as hands-on participants, not as detached observers.

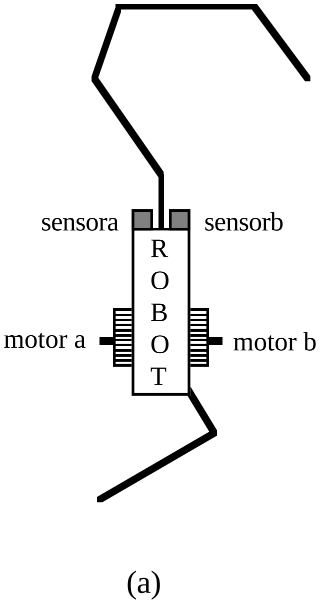
- While not a "research experience" in the strictest sense, robot design projects contain many of the valuable characteristics of a research project. They can help instill in students a spirit of experimentation and provide experience in attacking problems that do not have a single, previously known answer.

- Robotics projects naturally support collaborative learning experiences, an important element in making science seem more humane and in preparing students for the way science and engineering are usually practiced in the world.

Note that these advantages specifically address the deficiencies reported in the Pathways Report [Rayman, 1993] that are discussed above.

In light of these advantages, we are developing an introductory interdisciplinary science laboratory course based on robots. Our course will begin by introducing students to a few examples of simple robots that exhibit interesting behavior. In the context of these concrete examples, we will explore how the mechanical, electronic, and computational facets of the robots contribute to their behavior. Students will get hands-on experience with these different facets by modifying the existing robots to exhibit different behaviors. The capstone experience of the course will be an activity in which teams of students collaborate on designing and constructing a robot project of their own choosing.

As an example of the kind of simple robots we have in mind, consider the line-following robot designed and constructed by physics student Ruth Chuang ‘96 during this past summer. This robot is a two-wheeled vehicle equipped with two reflectance sensors that can distinguish between a white table-top and strips of black tape (see Figure 1(a)). The robot can “follow” strips of tape by turning the right wheel forward when the left sensor is over the tape and turning the left wheel forward when the right sensor is over the tape. This control algorithm is easily expressed via the Brick Logo program in Figure 1(b).



```
to see_line :sensor
  output :sensor > 100
end

to go_right
  b, off   ; turn motor b off
  a, on    ; turn motor a on
end

to go_left
  a, off b, on
end

to go_forward
  a, on b, on
end

to follow_the_line
  go_forward
  loop [if see_line sensora [go_left]
        if see_line sensorb [go_right]]
end
```

(b)

Figure 1. (a) shows the structure of the line-following robot. (b) is the complete Brick Logo program that makes the robot follow the line.

The line-following robot is a good starting point for many projects. What would it take to make the robot stop at the edge of the table or at the end of a line? Could the robot follow the line with only one sensor? How could a clap sensor be added so that the robot could be turned on and off via a clap of the hands?

Like many robots, the line-following robot suggests connections with physical organisms. Design challenges that inspire students to make connections to biological systems are particularly appealing to us, in part because of the strong interest Wellesley students have in the subject. (Biology is the most popular science major at Wellesley and nationwide has the largest percentage of women participants of any of the sciences.) One design challenge might be to build a robot which can navigate by using a scheme reminiscent of a real biological system. Here are some scenarios that we can imagine emerging from such a challenge:

- Ulana shows Sara an article that suggests that the hammerhead sharks navigate by sensing differences in magnetic field between sensors located along the width of their distinctively shaped heads [Klimley, 1995]. Using two magnetic field sensors mounted on a simple mobile robot, they experiment with this sort of navigation. (Our experimentation with magnetic field sensors indicates that such a project is feasible.)

- Sonya and Zheng are taking the Biology of Brain and Behavior laboratory with Wellesley Assistant Professor of Biology Joanne Berger-Sweeney. Professor Berger-Sweeney shows her students a recent research project that involves mice running through mazes. This inspires the two to build a robot that is capable of navigating through a maze.

- Caitlin is a history major who comes from Austin, Texas, which is renowned for its bat population. She knows that bats use sound to navigate, but wants to get a better understanding of this process. She teams up with Ji Young and Heather to build a robot that navigates by sonar sensors.

The animal metaphor is a rich source of robot projects. A variety of tropisms and phobias (such as the attraction of moths to light or the light avoidance of hermit crabs) can easily be modeled with simple robots (e.g. see [Braitenberg, 1984]). A wide variety of other phenomena, including means of locomotion, cooperation among social insects, and predator/prey interactions are suitable for robot-based explorations [Resnick, 1988; Jones and Flynn, 1993].

There are a host of interesting projects that are inspired by areas other than biology. For example, Marie Hwang, a Wellesley multimedia arts student, has suggested an interactive kinetic sculpture as a robot project she is interested in undertaking. Rebecca Lippmann, a Wellesley physics student, wants to build a copycat musical robot that, when it hears a musical note, will play that note on a xylophone.

Although the course is mainly a project-based laboratory experience, we also plan to have a series of tutorials that address core issues such as:

- Mechanical design: building robust structures, friction, gearing, motors.
- Sensors: sensitivity, calibration, noise.
- Programming: variables, control structures, procedures, concurrency, robot control idioms.
- Engineering issues: resource limitations, design tradeoffs, simulation vs. the real thing.

We have taken several steps towards the development of the robot design course. During the summer of 1995, with the help off Ruth Chuang ‘96, we purchased, assembled, and experimented with two Programmable Brick robot kits. We have recently received a small grant from Wellesley's Educational Research and Development program to purchase four more robots. We will use these robots in a pilot robot design course that we are offering during the 1996 January intersession period. This will be an intensive three-week non-credit course for ten to twelve students based on the robot design course sketched above. Many students have already expressed an interest and we believe that we will easily be able to attract this number of committed participants from a broad range of backgrounds. In keeping with the spirit of a pilot course, we plan a rather open-ended design challenge: students, working in teams of two or three, will be asked to design and build a robot capable of displaying a "talent" of their own choosing. The course will culminate in a robot talent show that will be open to the public.

We view the pilot course as the first step in establishing a permanent robotics presence at Wellesley. We are holding a second pilot course for January 1997, and afterwards plan to institute a regular for-credit robot design laboratory course as part of the Wellesley curriculum. This will fit into Wellesley’s campus-wide initiative to develop and support multidisciplinary courses.

2.2 Robots in Existing Courses

In addition to developing the robot design course, we are planning to incorporate robot-based activities into a number of existing physics and computer science courses. The fact that Lego-based robots are perceived as fun, relevant, and interesting makes them good sources of motivational examples and engaging projects. As indicated by the following examples, robots can serve as a unifying thread for many topics throughout the curriculum.

- Modern Electronics Laboratory (Physics 219). In this course, students build and test breadboard circuits following the Horowitz and Hill curriculum. As a final project in the current Wellesley version of this course, all the students collaborate to build a simple microcomputer and use it to control a LEGO-based robot. We believe that the course could be improved by incorporating robots from the beginning. Robots can be used to motivate circuits and make them more meaningful to students. For example, a simple switch becomes a touch sensor; a current to voltage circuit with a photodiode becomes a light sensor. If we had more robots, students could work in smaller teams on projects of their own choosing.

- Introductory Mechanics courses (Physics 104 and 107). We believe that many of the fundamental concepts of mechanics can be made more accessible and engaging by demonstrating them in the context of robots. Concepts like force, torque, work, and friction can be brought to life by discussing them in the context of mobile robots that students interact with in laboratory sessions. For example, designing a gear train that will transmit power from the motor to the wheels of an effective bullodozer robot requires students to think about all of these concepts.

- Introductory Computer Science courses (CS 100 and 111). CS 110 is a broad introduction to computer science for non-majors; CS 111 is a more focused introduction to programming for majors. Both courses introduce programming concepts like variables, procedures, control structures, and simple data structures. All too often, introductory programming examples illustrating these concepts have a contrived quality (e.g., summing up numbers in an array, searching a student database). Programs for controlling a robot can illustrate many of the basic concepts in a more motivational way, because students *care* about the outcome. This approach is similar in spirit to approaches like Logo turtles [Papert, 1980; Resnick, 1994] or Karel the Robot, except that programs would be controlling the behavior of a real robot rather than a simulated one. We would be building on the success of the LEGO/Logo at the grade school level [Resnick, 1988], but adapting it to the college curriculum.

- Artificial Intelligence (CS 232): In the past, the artificial intelligence course has focused on traditional topics like knowledge representation, problem solving, search, expert systems, language, and vision. In order to reflect current trends in the field, we believe that at least some portion of the course should be devoted to robots and intelligent agents. Lego robots would be a natural vehicle for illustrating this material and serving as a basis for projects. They would complement the NSF-supported wheelchair robot that is being developed by Holly Yanco, another member of the computer science department.

- Programming Languages (CS 251): The programming languages course covers a variety of programming paradigms: functional, imperative, object-oriented, logic-oriented, and concurrent programming. In the past, the coverage of concurrency have been somewhat abstract and contrived; robots and the Brick Logo language provide excellent concrete examples of essential uses of concurrency in a real system. For example, consider modifying the line-following robot discussed above so that it stops when a touch sensor is triggered. Brick Logo allows the line-following and stopping procedures to be implemented as separate procedures that run concurrently. Without concurrency, it would be necessary to circumvent modularity and modify the line-following loop to also check for depression of the touch sensor.

- Computer Architecture (CS340): This course introduces students to the abstraction layers that separate simple computers from the electrical components out of which they are constructed. In the laboratory component of the course, students collaborate to build a simple computer. The Programmable Brick is an excellent example of a simple microprocessor-based computer, and would be a worthwhile topic of study as additional example of a simple computer architecture.

Introducing robots into most of these courses would not require major reorganizations. Rather, we imagine that they could be introduced gradually in the form of a demonstration, assignment, or project; further activities would be developed informed by the success of earlier ones. We expect that incorporating robots into several courses would have unifying and synergistic effects on the curriculum; students would be able to relate the topics of different courses in the context of a familiar object.

Although the number of courses listed above is large, the number of robots required need not be. Many of the courses have small enrollments, and even for the ones with larger enrollments (the mechanics and introductory computer science classes), activities could be scheduled in such a way to share the robots between them.

c. Equipment

We propose to purchase a collection of 20 robot kits to enable the incorporation of robot-based activities into undergraduate science courses. These kits are inherently versatile, which makes it easy to use them in many different parts of the curriculum. Each kit is comprised of the following basic elements:

- A Handy Board programmable brick [Martin, 1995];
- assorted motors and actuators;
- assorted sensors;
- assorted of LEGO Technic parts.

We are requesting a total of 20 kits, in addition to the six we already have, based on the following considerations. We intend to limit the enrollment in the robot design course to 24 students, since this is as large a number that can reasonably be handled by the teaching configuration of one professor and one lab instructor. Since students typically work in pairs, this course will require at least 12 kits. The other kits will be shared among the other courses mentioned above. We would also like to allow for the possibility of leaving some on of the more successful creations on public display from time to time, much the way art work is displayed in a museum.

The Handy Boards require some assembly work, mostly soldering. We are requesting funds to hire students to do the assembly work. Student involvement at this stage should help further increase their sense of have having built robots from the ground up. In addition, the Wellesley Science Center employs a full time electronics technician and a half time machinist who are available to help in the Programmable Brick assembly.

The only significant other equipment needed for the projects are Macintosh computers , on which students will write their Brick Logo programs. As seen in Appendix a, Macintoshes are abundant at Wellesley.

d. Faculty Expertise

Professor Franklyn Turbak (PI) is an Assistant Professor in the Computer Science Department and is an expert in programming languages. He has over ten years of experience in teaching programming languages and related areas, and is particularly interested in approaches that help to make programming easier to learn. He is currently completing a programming languages text in collaboration with Professor David Gifford at MIT. His research interests include visual programming languages, modularity mechanisms, and educational computing. Professor Turbak has used Lego robots to introduce elementary school students to programming and mechanics. He is also the designer and implementer (with Mitchel Resnick) of the popular Haymarket expert systems exhibit at The Computer Museum in Boston.

Professor Berg is an experimental physicist who has been teaching and doing research at Wellesley for ten years. He has taught our laboratory electronics course on 4 different occasions and has gained useful robot-related experience in this context. Professor Berg has also been involved in developing many of our undergraduate physics laboratory experiences.

Professor Berg will be on sabbatical during the 1996 calendar year. He will be a Visiting Professor at the MIT Media Lab, working with the research group of Mitchel Resnick, who is an Assistant Professor in the Epistemology and Learning Group. This group's work is centered around the use of new technology and media to create environments that facilitate learning about science and technology. The MIT robot contest grew out of work from this group. The group continues to work on improving and modifying the design environment so that robot projects can be extended to various audiences. Professor Berg will collaborate with the group in their on-going work on the Programmable Brick. This will afford us the opportunity to take advantage of the expertise within Professor Resnick's group at MIT while developing our project.

e. Dissemination and Evaluation

The projects that we propose to develop at Wellesley can serve as a model for robot design initiatives at other liberal arts colleges. Dissemination of our ideas will be aided by our collaboration with the Learning and Epistemology Group at the MIT Media Lab, which is recognized throughout the world as a leader in this field. In addition to publishing journal articles, we plan to make our course materials available electronically on the World Wide Web.

Workshops are an effective means of sharing with faculty and students at other liberal arts colleges the kinds of robot-based explorations that we will be developing. We plan to seek funding for such a workshop from the NSF’s Undergraduate Faculty Enhancement program.

Another way that our project will have an impact beyond Wellesley is through our association with The Computer Clubhouse at The Computer Museum in Boston. The Computer Clubhouse is an educational outreach program of The Computer Museum. At the Clubhouse, young people (ages 10-16) use powerful computer tools to work on extended projects related to their own interests and experiences. The Clubhouse focuses on youth from under-served communities, who would not otherwise have access to technological tools and activities. As part of her Honors Thesis, Wellesley student Ruth Chuang is acting as a mentor at the Clubhouse, involving young people in robot-related projects. We expect that in the future Wellesley students will continue to be involved with the Clubhouse.

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4. Biographical Sketches

Franklyn Albin Turbak

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Education

S.B., MIT Dept. of Electrical Engineering and Computer Science, May 1986.
S.M., MIT Dept. of Electrical Engineering and Computer Science, May 1986.
Ph.D., MIT Dept. of Electrical Engineering and Computer Science, February 1986.

Professional Experience

MIT Dept. of Electrical Engineering and Computer Science.
    1994: Postdoctoral Associate.
Wellesley College, Department of Computer Science.
    February 1995 to present: Assistant Professor.

Honors and Awards

ITT Rayonier Scholarship, 1980.
Carleton E. Tucker Award, 1986. (M.I.T. EECS teaching award.)
Instructorship-G Award, 1986. (Special teaching rank awarded by MIT EECS Dept. for recognition of excellence in teaching.)
Goodwin Medal, 1990. (MIT institute-wide graduate student teaching award for "conspicuously effective teaching")

Publications (limit of 5)

Grasp: A Visible and Manipulable Model for Procedural Programs. S.M. Thesis, Massachusetts Institute of Technology, May 1986.
"Intelligent Information-Sharing Systems", with Thomas Malone, Kenneth Grant, Stephen Brobst, and Michael Cohen. *Communications of the ACM,* May 1987.
"Understanding Procedures as Objects", with Michael Eisenberg and Mitchel Resnick. In Gary M. Olson, Sylvia Sheppard, and Elliot Soloway, *Empirical Studies of Programmers: Second Workshop*. Norwood, New Jersey: Ablex, 1987.
"Creatures of Habit: A Computational System to Enhance and Illuminate the Development of Scientific Thinking", with Roy Pea and Michael Eisenberg. In *Proceedings of the Tenth Annual Conference of the Cognitive Science Society.* Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1988.
Slivers: Computational Modularity via Synchronized Lazy Aggregates, Ph.D. dissertation, Massachusetts Institute of Technology, January 1994.

Teaching

MIT EECS Department. Seven terms of teaching experience as recitation instructor and teaching assistant, 1984-1992. Courses taught include Programming Languages (a graduate core course), Structure and Interpretation of Computer Programs (SICP), and Signals and Systems.

MIT Lincoln Laboratory, lab assistant for accelerated version of MIT's SICP course. October 1985.

MIT. Summer Program. Teaching assistant for two-week version of SICP presented to professors and professional engineers. Summers 1987-1991.

Stoneham School District. Led after-school Lego/LOGO course for elementary school students. Fall 1990.

Hogeschool Utrecht, The Netherlands. Invited to lead one-week version of SICP course. October 1991.

Hewlett Packard, Palo Alto, CA. Invited to lead two-week version of SICP course. June, 1992.

MIT EECS Department. Gave four lectures in graduate programming languages course. Fall 1994.

Wellesley College. Courses taught include Data Structures, Algorithms, and Theory of Programming Languages. 1995 -- present.

Students Supervised

Graduates: David Espinosa (doctoral dissertation reader).
Undergraduates: Ruth Chuang, Ramona Filipi.

Collaborators and Advisors

Harold Abelson, Robert S. Berg, Andrea diSessa, D. Austin Henderson, David K. Gifford, David McAllester, Gerald J. Sussman, Richard C. Waters.

Robert S. Berg

Education

A.B. Physics, Princeton University, 1978.
M.A. Physics, University of California, Berkeley, 1981.
Ph.D. Physics, University of California, Berkeley, 1985.

Experience

ASSOCIATE PROFESSOR OF PHYSICS (tenured), Wellesley College (1990 -Present).

VISITING PROFESSOR, MIT Media Lab, Learning and Epistemology Group (1996 calendar year).

ASSISTANT PROFESSOR OF PHYSICS, Wellesley College (1985 -1990).

RESEARCH ASSISTANT, Department of Physics, University of California, Berkeley (1980 - 1985). Advisor: Prof. Peter Yu.

SENIOR TECHNICAL ASSOCIATE, Bell Laboratories, Murray Hill, New Jersey (1978 - 1979). Supervisor: Dr. R. E. Walstedt.

Publications (limit of 5)

R. S. Berg, P.Y. Yu and E.R. Weber, "Raman Spectroscopy of Intrinsic Defects in Electron and Neutron Irradiated GaAs", Applied Physics Letters **47**, 515 (1985).

R. S. Berg, and P.Y. Yu, "Enhancement of Defect Induced Raman Modes at the Fundamental Absorption Edge of Electron Irradiated GaAs", Physical Review B15 **33**, 7349 (1986).

R. S. Berg, Nergis Mavalvala, Heidi Warriner, and Bin Zhang, "Anisotropic Introduction of Intrinsic Defects Monitored by Raman Scattering", Physical Review B15, **39** 6201 (1989).

R. S. Berg, Nergis Mavalvala, Tracie Steinberg, and F. W. Smith, "Raman Study of Defects in a GaAs Buffer Layer Grown by Low Temperature Molecular Beam Epitaxy", IEEE Journal of Electronic Materials, **19**, 1323 (November, 1990).

R. S. Berg and Nina Schwartz, "Home-Built Fourier Transform Nuclear Magnetic Resonance Spectrometer for Use in an Advanced Laboratory Course", (Submitted to The American Journal of Physics).

Grant History

1986 -1988 *Research Corporation* (sole investigator) "Resonant Raman Scattering as a Probe of Deep Levels in Semiconductors" $24,000.

1987- 1988 *College Science Instrumentation Program of the National Science Foundation* (Theodore Ducas was the principal investigator and Robert Berg, William Quivers, and Dominique Fourguette were co-investigators.) "Equipment for Modern Spectroscopic ($70,000; Half of this amount was provided in the form of "matching funds" by Wellesley College.)

1988 - 1990 *Hughes Foundation* (This was part of a much larger grant that from the Hughes Foundation to Wellesley College) "Nuclear Magnetic Resonance Spectrometer for Teaching" ($25,000).

1988 - 1990 *National Science Foundation, RUI program of Solid State Physics Division* (sole investigator) "Resonant Raman Scattering as a Tool for Studying Point Defects in Semiconductors" ($104,500).

1991 - 1993 *W. M. Keck Foundation* "Establishment of Advanced Laboratory Experiments in a Quantum Mechanics Course" ($25,000).

1995 - 1996 *Wellesley College, Instructional Technology Grant*, (with Franklyn Turbak, Wellesley College Computer Science Department) "A Robot Design Course for Wintersession" ($2500).

Teaching Experience

I have taught most of the courses offered at Wellesley College including: Introductory Mechanics, Introductory Electricity and Magnetism, Frontiers of Physics (a course for non-science majors), Waves and Vibrations and Special Relativity, Laboratory Electronics, Advanced Mechanics, Quantum Mechanics, and Applications of Quantum Mechanics (with advanced lab). With support from grants from the College Science Instrumentation Program of the NSF, The W. M. Keck Foundation, and The Hughes Foundation , I have played a major role in developing an advanced laboratory course for Wellesley physics students. The laboratory exercises that I developed for this course include "Fourier Transform Nuclear Magnetic Resonance with a Home-Built Spectrometer", "Exciton Absorption in Cuprous Oxide and Semiconductor Quantum Wells", and "High Resolution Spectroscopy With a Tunable Diode Laser: The Hyperfine Structure of Rubidium".

Students Supervised

Undergraduates**:** Erika Abbas, Alice Abbott, Ruth Chuang, Jen Glass, Vivian Jung, Mary Nergis Mavalvala, Nina Schwartz

5. Budget

Item	How many	Unit Price (list)	Unit Price (discounted)	Total Cost (discounted)
Robot Kit	20	750	750	15,000

Here is a breakdown of the items that comprise *each* kit. This list was formulated based on our experience building these robots, along with our colleagues at the MIT Media Lab who have had extensive experience organizing robot design projects:

Item	How many	Unit Price (list)	Unit Price (discounted)	Total Cost (discounted)
Parts for Handy Board Programmable Brick†	1	250	250	250
Labor costs for assembling each Handy Board‡	-	100	100	100
Motors	4	25	25	100
Assorted sensors	10	15 (avg.)	15	150
Assorted LEGO Technic parts	hundreds			150

Total project cost:	$15,000
Non-NSF contribution:	$7,500
NSF request:	$7,500

† We have arrived at this description and cost for the kits based on our experience building these kinds of robots over the last year and after consultation with our colleagues at the MIT Media Lab.

‡ There are about 15 hours of labor, mostly soldering work, involved in assembling the Handy Boards. We plan to employ students for this task.

6. Current and Pending Support

7. ILI-IP Appendices

a. Major equipment

Computer Science Department

The computer equipment available to our students for course work and research is listed below. Most relevant to this proposal are the Macintosh computers, which is the platform that Brick Logo is designed to run on.

Quantity	Brand	Model
15	Macintosh	IIci
1	Macintosh	Quadra 700
2	Macintosh	Quadra 950
15	IBM workstations	RS6000 320
1	MasPar	MP-1101D
3	Sun workstations	SPARC 2GS
1	Silicon Graphics	GR2 EG Indigo

Physics Department

3	Macintosh	PowerPC 7100
1	Macintosh	Quadra 850AV
1	Macintosh	IIfx
3	Macintosh	SE30
10	assorted IBM-PC compatible computers	

b. Course Descriptions

Pilot Robot Building Course: Build a LEGO Robot!

In this intensive introductory course, we will teach you how design and assemble robots out of a Programmable LEGO Brick, sensors and motors and program your creation to do your bidding. You will be able to show off your creation at Robot Talent Show at the end of January. No prerequisites. Not just for scientists; all creative people are encouraged to sign up. (Offered during WinterSession, January, 1996. Enrollment limited to 10 students.)

Computer Science Courses

110 Computers and Programming

A broad introduction to computer science. Topics include: computer logic and organization, program translation, models of computation, decidability, and the impact of computers on society. Students learn the science and art of programming by building a Macintosh application using HyperCard. Open to all students. No prior background with computers or mathematics is expected. Students considering additional computer science courses should take 111, not 110. (110 is offered each year during both the Fall and Spring semesters. Enrollment is 60 students per semester.)

111 Introduction to Computer Science

Introduction to problem-solving through computer programming. Introduces the fundamentals of programming in PASCAL, a high-level language that is widely used in computer science education and practice. Through assignments, students develop interactive programs to create graphics, play games, maintain records, analyze data and perform numerical computations. Students can elect to complete an extended programming project of their own design. Open to all students. Required for students who wish to major in computer science or elect more advanced courses in the field. (111 is offered each year during both the Fall and Spring semesters. Enrollment is 60 students per semester.)

232 Artificial Intelligence

An introduction to Artificial Intelligence (AI), the design of computer systems that possess and acquire knowledge and can reason with that knowledge. Topics include knowledge representation, problem solving and search, planning, vision, language comprehension and production, learning, and expert systems. To attain a realistic and concrete understanding of these problems, CommonLisp, an AI language, will be taught and used to implement the algorithms of the course. Prerequisite: 230 or by permission of the instructor. (230 is offered each year during the Fall semester. Enrollment is 10 students per semester.)

251 Theory of Programming Languages

An introduction to the theory of the design and implementation of contemporary programming languages. Topics include the study of programming language syntax, comparison of different types of language processors, study of language representations, and comparison of different language styles, including procedural, functional, object oriented, and logic programming languages. Prerequisite: 230. (251 is offered each year during the Spring semester. Enrollment is 15 students per semester.)

340 Computer Architecture with Laboratory

An examination of computer hardware organization. Topics include: architecture of digital systems (gates, registers, combinatorial and sequential networks), fundamental building blocks of digital computers, control logic, microprogramming, microprocessor, pipelined and multiprocessor systems and new technologies. The course includes one three-hour digital laboratory appointment weekly. 1.25 units of credit. Prerequisite: 240. Alternate year course. Offered in 1994-95. Not offered in 1995-96. (340 is offered alternate years during the Spring semester. Enrollment is 10 students per semester.)

Physics Courses

104 and 107 Introductory Physics I with Laboratory

Principles and applications of mechanics. Includes: Newton's laws, conservation laws, rotational motion, oscillatory motion, and gravitation. (104 is offered each year in the Fall. 107 is offered in both the Fall and the Spring. The total enrollment in these courses averages 175 students per year.)

219 Modern Electronics Laboratory

Primarily a laboratory course emphasizing construction of both analog and digital electronic circuits. Intended for students in all of the natural sciences and computer science. Approach is practical, aimed at allowing experimental scientists to understand the electronics encountered in their research. Topics include diodes, transistor amplifiers, op amps, digital circuits based on both combinational and sequential logic, and construction of a microcomputer based on a 68008 microprocessor programmed in machine language. Two laboratories per week and no formal lecture appointments. 1.25 units of credit. Prerequisites: Physics 106 or 108 or permission of instructor. (Offered in alternate years. Average enrollment 8 students. Not required for physics majors.)

To Do:

* What happened to Tidball references?

* Natural History reference

* Benditt picture?

* Robbie add advisors and advisees to bibliographic sketch

* Stress Feasibility

* Karel the Robot

* Programmable Brick reference

* References to Legos used in elementary school situations

* Check stats on non-science majors taking science courses.

One vivid and relevant example is captured in the attached photograph, which appeared recently on the cover of the journal Science [Benditt, 1993]. The photograph shows a team from an all-girl sixth grade science club that participated with great success in the preliminary rounds of the MIT robot contest. [Are we going to include the picture?]

We were aided in this process by Wellesley physics student Ruth Chuang '96; we are encouraged by the fact that, even though she had little electronics experience and no programming experience, Ruth successfully built a line-following robot.

Additionally, Programmable Bricks can be use as portable, versatile measuring and data-gathering devices when they are not part of a robot. [Programmable brick + sensor valuable by itself. No need for R2D2.]
[Specifics?]

Chandler, D. L. (1992). Robotics soccer gives ideas a fighting chance. February 10, 1992. *The Boston Globe*.

Recent Student Projects Supervised by Robert Berg

Ruth Chuang '96 is currently involved in an Honors Thesis that is being co-advised by Franklyn Turbak of the Computer Science Department. Her project, which she began this past summer with support from a Ford Foundation Faculty Collaboration Grant, involves helping to create a robot design course at Wellesley.

Nina Schwartz '95, currently a first year graduate student in Biophysics at the University of Rochester, did an Honors Thesis in which she used our home-built NMR spectrometer to perform magnetic resonance imaging and to do fourier transform spectroscopy in fluorocarbon compounds.

Vivian Jung '96 spent part of the summer of 1994 working on an experiment to use laser diodes to perform high resolution atomic spectroscopy measurements

Erika Abbas '94, currently a second year graduate student in Materials Science at MIT, did an Honors Thesis in which she studied optical properties of the EL2 defect in gallium arsenide that was grown by low temperature molecular beam epitaxy.

Jen Glass, '93, currently a third year graduate student in Physics at Berkeley, used laser diodes to do Raman studies of gallium arsenide.

Mary Alice Abbott '92, currently a fourth year student in the MD/PhD program at the University of Massachusetts, did a Honors Thesis entitled "Ocean Waves".

Nergis Mavalvala, '90, currently a sixth year graduate student in Physics at MIT did an Honors Thesis on Raman scattering as a probe of intrinsic defects in gallium arsenide that was grown by low temperature molecular beam epitaxy.