A Robot-based Laboratory for Teaching Artificial Intelligence

A Collaborative Proposal to
Instrumentation and Laboratory Improvement Program
Instrumentation Project (ILI-IP)
Division of Undergraduate Education
Directorate for Education and Human Resources
National Science Foundation
for a period of 24 months
June 1, 1996 to May 31, 1998

Submitted by

Lisa Meeden
Computer Science Program
Swarthmore College
Swarthmore, PA 19081
meeden@cs.swarthmore.edu

Deepak Kumar
Department of Mathematics
Bryn Mawr College
Bryn Mawr, PA 19010
dkumar@cs.brynmawr.edu

November 14, 1995

1 Project Summary

There is a growing consensus among computer science faculty that it is quite difficult to teach the introductory course to Artificial Intelligence well. This is because AI lacks a unified methodology, it overlaps with many other disciplines, and involves a wide range of skills from very applied to quite formal. This proposal addresses these problems by (1) offering a unifying theme that draws together the disparate topics of AI; (2) focusing the course syllabus on the role AI plays in the core computer science curriculum; and (3) motivating the students to learn by using concrete, hands-on laboratory exercises. The proposed theme is to conceive of each topic in AI (such as search, planning, learning, vision) as a robotics task and then to have the students build their own robots and program them to accomplish the tasks. By constructing a physical entity in conjunction with the code to control it, the students have a unique opportunity to directly tackle many central issues of computer science including the interaction between hardware and software, space complexity in terms of the memory limitations of the robot's controller, and time complexity in terms of the speed of the robot's action decisions. More importantly, the robot theme provides a strong incentive towards learning because students want to see their inventions succeed.

The goal of this proposal is to equip two identical robotics laboratories for teaching AI, one at Swarthmore College and one at Bryn Mawr College. Each laboratory will contain a collection of robot building stations as well as one sophisticated off-the-shelf robot to demonstrate more advanced topics to the students. The deliverable for this project will be a laboratory manual that is closely integrated with a semester long AI course syllabus. The manual will be developed collaboratively and tested separately at the participating institutions. The overall effectiveness of this project will be determined by student feedback and performance. The project results will be disseminated through a variety of channels: a SIGART column on AI Education, special conference tracks on AI Education, summer training workshops for AI educators, and through world wid web repositories on AI. This proposal offers a remedy for the difficulties facing AI educators by offering a cohesive framework for the presentation of the material that emphasizes AI's relationship with computer science and motivates the students to learn.

Contents

2 Results from Prior NSF Support

The principal investigator and the co-principal investigator have had no prior support pertaining to undergraduate education.

3 Narrative

3.1 The Present situation

This proposal involves a collaborative initiative among two undergraduate institutions—Swarthmore College and Bryn Mawr College. It also indirectly impacts undergraduate education at a third institution, Haverford College. All three colleges are located in close proximity and are part of a tri-college consortium. The proposal is a request for equipment to enhance the teaching of the undergraduate Artificial Intelligence course at the participating institutions.

Founded by the Religious Society of Friends in 1864, Swarthmore College is a small liberal arts college of about 1,300 students which offers the Bachelor of Arts degree to students in the Humanities, the Social Sciences and the Natural Sciences, and the Bachelor of Science degree to students in Engineering. Swarthmore has a demonstrated record of educational excellence and is recognized as one of the top liberal arts institutions in the nation. The faculty of 157 is 69% tenured and the student-faculty ratio is 8.5 to 1. The sciences have a distinctive profile at Swarthmore. The College seeks to provide its undergraduates with extensive laboratory experience, with emphasis on original faculty research projects that include students at every level of the science curriculum. As a result, Swarthmore students are drawn into the science pipeline in numbers disproportionately high when compared to the nation's colleges and research universities. This year, 41% of the students in the junior and senior classes are majoring in science or engineering, and the class of 1995 showed a 17% increase in science graduates over the previous year. Forty percent of recent science graduates entered graduate school in the sciences, 20% pursued medical degrees, 30% took related positions in industry, research or education, and only 10% pursued education and employment opportunities unrelated to their baccalaureate majors. Of the students who receive degrees from the Computer Science Program, 50% pursue graduate programs, primarily in Computer Science, Engineering, Mathematics, or Psychology.

The Computer Science Program at Swarthmore places a strong emphasis on the theoretical foundations of computing as well as giving students many opportunities for hands-on experiences with the newest software and hardware. Composed of two full-time faculty and one half-time faculty (shared with the Engineering Department), the ten-year old Computer Science Program offers majors, concentrations, and honors. In a typical year, two to five students graduate with a major from the Program, and three to eight graduate with a concentration in the Program. Roughly 180 students are served in the Program's courses per year. The College has several instructional MacIntosh laboratories that are used for teaching the department's introductory courses, while the department has one student laboratory containing Sun workstations and one faculty laboratory for robotics research.

The curriculum in the first two years of the major consists of small classes (less than 25 students) covering the fundamentals of computer science. Two of these introductory courses are taught completely in a closed laboratory setting. During each class meeting students listen to a brief lecture on a new topic and then spend the remaining class time implementing the ideas for themselves. We have found that this hands-on approach has given the students a much firmer understanding of the key concepts than a more traditional lecture format did. The goal of this proposal is to allow the Program to expand this successful student-centered framework to the Artificial Intelligence course by equipping a robotics laboratory. The Computer Science Program at Swarthmore College has a successful tradition of offering laboratory-based courses that would be significantly enhanced by the addition of an undergraduate robotics laboratory.

Founded in 1885, Bryn Mawr College is well-known for the excellence of its academic programs. Bryn Mawr combines a distinguished undergraduate college for about 1200 women with two nationally-ranked, coeducational graduate schools (Arts and Sciences, and Social Work and Social research) with about 600 students. As a women's college, Bryn Mawr has a longstanding and intrinsic commitment to prepare individuals to succeed in professional fields in which they have been historically underrepresented.

At Bryn Mawr, computer science is a new and evolving program. The Co-PI started his career in Fall 1993 in the Department of Mathematics to develop a new curriculum in computer science in cooperation with Haverford College, a small coeducational liberal arts college with close ties to Bryn Mawr College. Currently, the combined two-college program is at the level of three and one-third full-time equivalent faculty. The Bryn Mawr–

Haverford computer science program offers a minor and a concentration in computer science for students majoring in *any* program offered by the college. Additionally, it also offers the opportunity for students to design an independent major in computer science. The design of the evolving program is based on the recommendations included in the ACM/IEEE Joint Computer Science Curriculum as well as some of the later developments [18, 8]. Between the two colleges, the course offering schedule is tightly coordinated to accommodate a complete coverage of the core computer science courses as well as several upper-level elective courses. Each year, approximately 200-250 students enroll in various computer science courses offered at Bryn Mawr and Haverford.

The proposed laboratory is directed primarily at upper-level undergraduates taking the course, Artificial Intelligence (CS 372 at Bryn Mawr, CS 63 at Swarthmore) and the course Building Intelligent Robots (CS 91 at Swarthmore). The organization and needs of the targeted courses are described below.

Building Intelligent Robots (CS 91 at Swarthmore): This course is being taught for the first time in the current semester. Twenty-five students wanted to take the course, but enrollment was capped at 15 because of equipment restrictions. There were no prerequisites; consequently the students came from a wide variety of disciplines including computer science, economics, engineering, English, mathematics, psychology, and religion. Throughout the course as the students learn about robot control techniques they implement them directly on their own robots which they constructed from scratch. The students used the materials in the PI's small robotics research laboratory. Students had to work in teams of three or four while sharing only two PCs for the entire class of 15. Despite the students' frustrations with having to share equipment, they were extremely positive about their overall experience in the course as is evident from these comments taken from their midterm course evaluations:

- You learn so much more when you actually have to put theory into practice with your own hands.
- We get to learn how to actually do something as opposed to learning about how it works.
- Being able to design completely from scratch has been extremely helpful.

- Although reading about things is interesting, actually having to apply what we've learned increases our retention rate tremendously. In addition, its much more involved to have to actually deal with the physical problems (like carpets!). Knowing theory is nice, but it just doesn't beat a good, solid working knowledge built upon experience.

Artificial Intelligence (CS 63 at Swarthmore): This course has been taught as part of the Computer Science Program since its inception. There is currently no limit on enrollment and there are typically 15 students in the course. The course has two prerequisites: the first programming course for majors done in Scheme, and a Data Structures course. The experience in Scheme prepares the students for the extensive laboratory work required in Common Lisp. The unifying theme of the course is *agents*—entities that perceive and act. Using this theme AI is seen as the study and construction of rational agents who can reason, communicate, and learn. Currently because of the limited amount of robotics equipment, the students focus primarily on *simulated agents* rather than *physical robots*.

Artificial Intelligence (CS 372 at Bryn Mawr): This course was designed by the Co-PI (Kumar) and was added to the curriculum in 1994. In its initial offering the course had an enrollment of 15 students (which was the listed capacity) 9 of which were from Bryn Mawr and the remaining 6 from Haverford. The course has a prerequisite, Programming Paradigms (CS 246), that prepares students for programming in Common Lisp and Prolog [8]. The course is project-oriented: 50% of the grade in the course is based on laboratory programming assignments involving various topics like search, game playing, natural language understanding, expert systems, and semantic network-based knowledge representation and reasoning. Has not had a unifying theme to draw topics together.

All three institutions (Swarthmore, Bryn Mawr, Haverford) strongly believe in promoting undergraduate research. Emphasis is placed on involving undergraduate students in research through the college's summer research programs as well as other nation-wide programs like the NSF Research Experiences for Undergraduates program, and the CRA Distributed Mentor project. Exceptionally talented students are encouraged to participate in the Honors Programs (a senior-year research project culminating in an Honor's Thesis). Both the PI and Co-PI are currently involved with robotics-based research in another collaborative effort involving the development of hybrid AI architectures that are comprised of a higher-level, symbolic reasoning, planning and acting system coupled with a lower-level, neural-network based learning and reactive system driving a small robot. The current proposal would facilitate a significant transition of bringing research directly into the classroom as well as add an exciting new dimension to the research possibilities offered to students in the tri-college communities.

3.2 Development plan

The plan is to integrate the construction of physical robots behaving as embedded agents into the laboratory component of the introductory AI courses. We intend to accomplish this in three stages: (1) To acquire robot building kits, computers, and robot programming environments (software), (2) To experiment with the kits in order to develop laboratory exercises integrated with the AI course. This will result in the preparation of a laboratory manual for use in the course. (The exercises used in the Building Intelligent Robots course will serve as a starting point.) (3) To integrate the developed laboratory into the teaching of AI (CS 63 at Swarthmore and CS 372 at Bryn Mawr). The major purpose of introducing robot-based laboratory exercises is to emphasize the role of AI as a study of advanced algorithms, to introduce a new and exciting approach towards the teaching of AI, and to provide a hands-on flavor of building real-world physical agents. By its very nature, the proposal involves the integration of intelligent systems, hardware interfacing, the physical embodiment of algorithms, and their evaluation. The laboratory will also be utilized to encourage undergraduate students to pursue honors theses and undergraduate research dealing with building physical agents.

3.2.1 A New Direction for the Teaching of AI

It has recently been acknowledged that introductory Artificial Intelligence is a difficult course to teach well [4, 7]. Several issues contribute to this predicament: breadth *vs* depth; formalist *vs* applied; the old and traditional *vs* the new and innovative; the roles philosophy, cognitive science, linguistics, and psychology should play; and so on [17]. Our approach to the design of the syllabus of our introductory AI course is based on a balance between three issues: (1) the role AI plays in the core computer science curriculum as a study of advanced algorithms; (2) the incorporation of only the most important ideas from the traditional AI syllabi; and (3) an agent-centric unifying theme for the disparate topics that make up the discipline.

The first issue identifies the need for placing AI in the context of a study of advanced algorithms. In this perspective, the algorithms presented contribute to enhancing the skill and overall interest in the field of computer science. For instance, one can compare compilation techniques with algorithms to natural language parsing, and one can relate logical reasoning to pattern matching and search. The second issue addresses an important pitfall in the design of an AI course syllabus: the need to identify and eliminate concepts traditionally covered in older offerings that are either no longer relevant or are incorporated in other core computer science courses. Two such examples are: the coverage of basic graph searching techniques; and the teaching of Lisp/Prolog. The ACM-IEEE curriculum recommends the coverage of basic graph searching techniques in the second introductory computer science course as well as in one of the discrete mathematics courses. The teaching of Lisp/Prolog, traditionally relegated to the introductory AI course is now covered in the core computer science curriculum in either the introductory course itself, or as a part of the programming language concepts course, or in a separate course on programming paradigms. At Swarthmore College, students learn Scheme (a derivative of Lisp) in CS 20 the first serious introduction to programming and use it again in the programming language course CS 43. Bryn Mawr College offers a separate, sophomore-level, course titled, Programming Paradigms (CS 246), that introduces Lisp and Prolog. In fact, this course forms a pre-requisite for the AI course [8]. Consequently, our AI course does not need to dwell on teaching the Lisp language, but can focus on the fundamental questions of AI itself. The third issue is in reaction to the misconception that AI is a collection of unrelated subfields which arises when an AI course is presented from the historical perspective (as is adopted by most AI text books [1]). We as educators must emphasize the field's common problems and standard techniques for attacking them. The agent approach enables all the components of intelligence to be gathered together toward a unified goal: building a rational, competent agent.

3.2.2 An *Embedded* Agent-Centric Approach

The agent-centric approach is based on a study of agents having varying levels of capabilities [14]. The syllabus is centered around the idea of constructing environments with agent programs running in them. All concepts are studied in this context. It provides a natural link to the laboratory exercises as well as giving the student a feeling of accomplishment—the agents they design actually do something. It also facilitates a criteria for measuring the success and failure of the agent and thereby the underlying algorithms and technology. Currently, there is only one recent text that takes this approach [15]. The text provides simple implementations of some of the standard tools as well as a host of small utilities to enhance experimentation and understanding. This proposal is to extend this approach one step further to an *embedded* agent-centered approach. The proposed approach involves the actual physical construction of agents that are embedded in the real world as opposed to being part of a simulated environment.

The embedded approach shifts the focus of building agents from a simulated environment to a more realistic physical embodiment of agents in the form of robots. This adds a dimension of complexity as well as excitement to the laboratory component of the AI course. The complexity has to do with additional demands of learning robot building techniques. At the same time, it also leads the students to an important conclusion about scalability: the real world is very different from a simulated world, which has been a long standing criticism of many well-known AI techniques. The complexity of robot building is easily overcome these days by the introduction of kits that are easy to assemble. Additionally, they are lightweight, inexpensive to maintain, programmable through the standard interfaces provided on most personal computers, and yet, offer sufficient extensibility to create and experiment with a wide range of agent behaviors.

The goal of the proposed project is to introduce the embedded, agent-centric approach in the introductory AI course at both colleges. The laboratory for the course would be conducted in *closed*, supervised, sessions. Students would engage in constructing several physical agents exhibiting simple to more complex behaviors as the semester progresses. Such an approach has also been called *evolutionary artificial intelligence* [12].

3.2.3 Useful Side Effects

The proposal intensifies the role that an AI course can play in the overall computer science curriculum in several important ways. Typical undergraduate computer science curricula focus mostly on the development and analysis of algorithms. Thus, indirectly, the emphasis is on software development. This creates a void in that the students may never experience the underlying hardware of the computers they utilize. Students are required to take a core course on computer organization and perhaps an elective on computer architecture. However, even in these courses, there is minimal exposure to actual physical hardware components. Construction of physical agents intrinsically involves the handling of controller boards (microcomputers in themselves), interfacing of sensors to these boards, and, more importantly, dealing with the physical connection between a computer and the controller board (via a serial port). Developing software to control the behavior of physical robots also involves working under constrained resources (especially with respect to speed and memory) imposed by the robot control board. This provides a direct exposure to the time as well as the space complexity of algorithms. Yet another link that can be emphasized via the laboratory exercises is that between the algorithms embodied in the agents and their equivalence as a whole to an automaton. Additionally, the programming of simple behaviors is essentially no different than the programming of simple problems as studied by students in introductory computer science courses. We intend to explore the use of simple robots in enhancing the pedagogy of these other courses.

3.2.4 Potential Beyond the Current Scope

We have designed the development plan so that our experiences can be easily duplicated at other institutions. We will restrict ourselves to the use of standard equipment, interfaces, and software that is freely available. The key outcome of this project is expected to be a laboratory manual which is specifically tailored towards the use of robotic agents in the context of an AI course at an undergraduate level. This is not unlike similar laboratory manuals now available for several introductory computer science courses. While the need for development of closed laboratory materials for introductory courses has been identified, to our knowledge, similar material is not available for upper-level computer science courses. It is expected that this project will help remedy this. The resulting laboratory and any associated materials will be made publicly available to faculty members at other institutions (See Section 3.5, Dissemination and Evaluation).

3.3 Equipment

The goal of this proposal is to equip two identical robotics laboratories for teaching AI, one at Swarthmore and one at Bryn Mawr. To this end there are three types of equipment being requested: robot building kits, computers for programming the robots, and a more complex off-the-shelf robot to demonstrate higher-level behaviors.

Through the experience gained by the PI in teaching CS 91, the Building Intelligent Robots course, the optimal team size for constructing robots seems to be two or three students. Since upper-level computer science classes at Swarthmore and Bryn Mawr typically have less than 20 students, the proposal calls for nine robot building stations (i.e. a kit and a computer) in each institution's laboratory. With nine stations each, we will be able to accomodate 18 students working in pairs, and have room for up to 27 students working in threes. This should be ample space for quite some time. Note that an extra robot kit has been requested for each institution for the PI and Co-PI's use in demonstrating techniques to the students, bringing the total number kits requested to 20.

The Lego robot building kits have been well tested by the PI in her research laboratory as well as by the students in the current CS 91 course. These kits are inexpensive, extensible, infinitely adaptable, and most importantly are very accessible to the students. Kits of this kind have also been used for the last five years at MIT for its extrememely popular Robot Design Competition [2], conceived as a way to get engineering students excited about a design project. There are several options for which controller board to include in the kit; from simplest to most complex they are the Mini board, the Handy board, and the 6.270 board (all designed by the MIT instructors of the design competition). For the CS 91 course we have used the Mini board [10] which is easy for the students to master, but has a very limited 2K of program memory. The Mini board can be tethered to a computer, allowing the program to reside off-board and thus side stepping the memory limitations. The Handy board [9] is the newest controller, and it incorporates most of the more advanced features of the 6.270 board, such as a larger memory and an on-board battery, but in a much more compact and simplified form. Since the Handy board has more features than the Mini board and is approximately the same price we have chosen to include the Handy board as the controller in the robot building kits.

The programming environment for the control boards can run on either DOS or Unix platforms. Since low-end DOS machines are more affordable we have requested nine Pentium-based personal computers for each insititution's laboratory, with one of these being a laptop. Having a laptop will enable us to occaisionally take our robots out of the laboratory and into other kinds of real-world environments, in addition it is necessary for the final request described below.

With these nine robot building stations, consisting of a Lego building kit complete with sensors, motors, and controller and a dedicated computer for writing, testing, and debugging their programs, students taking the Artificial Intelligence class will be able to build a simple but complete robot from start to finish. Much insight into how intelligent behavior is created can be gained by this endeavor.

Yet, there will be a number higher-level planning behaviors that will be beyond the capabilities of these simple robots. For this reason, we have also requested one of the most affordable off the shelf robots, the Pioneer 1 from Active Media, which is equipped with a bank of sonar sensors for mapping the environment and can be equipped with a gripper attachment. This robot is able to carry a payload of 10 lbs, allowing a laptop to be placed directly on board. With this more sophisticated robot, we can demonstrate the full range of Artificial Intelligence agent capabilities as well as provide a platform for more advanced student research. In recent years at each meeting of the American Association of Artificial Intelligence there has been a robot competition [13, 16] where teams of students spend several months preparing control programs for a variety of tasks. The Pioneer 1 would give Swarthmore and Bryn Mawr students the opportunity to enter these kinds of competitions for the first time.

3.4 Faculty expertise

The PI (Meeden) has taught a course titled, Building Intelligent Robots (CS 91) at Swarthmore College which served as a testbed for the kinds of equipment that have been requested. The PI's research interests include using machine learning techniques such as genetic algorithms, neural networks, and reinforcement learning to adapt the control programs of physical robots. The PI's dissertation [11] described a series of learning experiments with a robot called Carbot aimed to better understand how planning abilities could develop from successful reactive behaviors. The PI is co-chairing the international workshop ROBOLEARN-96 [5], in association with FLAIRS-96, on learning for autonomous robots. The PI was a lecturer on the topic of teaching machine learning methods in the NSF sponsored Summer Faculty Enhancement Workshop on Teaching Undergraduate AI held in the summer of 1995. The PI has submitted the paper, *Integrating Robot Building into the Undergraduate Computer Science Curriculum*, to the special track on AI Education at the upcoming FLAIRS-96.

The Co-PI (Kumar) was a participant in the summer 1994 NSF sponsored Summer Faculty Enhancement Workshop on Teaching Undergraduate AI. In summer 1995, the Co-PI was a lecturer and a host of the same workshop. The Co-PI has also presented a paper at the only American Association of Artificial Intelligence (AAAI) sponsored Symposium on Improving the Instruction of Introductory AI courses held in New Orleans in Fall 1994. The Co-PI was subsequently nominated to ACM SIGART's editorial board for featuring articles related to the teaching of AI. Since then, the Co-PI has edited a special issue of the SIGART Bulletin on AI Education, and featured other writings on the same topic in the SIGART Bulletin. He will continue to be the column editor for SIGART for the duration of the proposed project. The Co-PI is also the coordinator of a Special Track on AI Education at the Florida AI Research Symposium to be held in May 1996. As mentioned earlier, the Co-PI is also actively involved in research in AI in the areas of BDI architectures, knowledge representation, reasoning, sharing, planning, and acting. The Co-PI was also recently nominated to the program committee of the 1996 conference on principles of Knowledge Representation and Reasoning (KR '96).

3.5 Dissemination and Evaluation

The overall effectiveness of this project will be determined by the successful integration of robot building into the laboratory component of the two courses on Artificial Intelligence. We will produce a laboratory manual describing techniques for assembling robots and using them in various assignments. We will base the evaluation on (1) the students' feedback, (2) the students' performance on examination questions directed at laboratory assignments, and (3) the effect of introducing robots into our undergraduate research program. The plan for disseminating the results of this project are via several channels shown below.

SIGART Column: As mentioned earlier, the Co-PI is a contributing editor on the topic of AI Education for the ACM SIGART Bulletin. Ongoing results will be reported regularly through this medium.

Conferences: The Co-PI is also actively involved with the organization of tracks and symposia on the topic of AI Education. All results will also be disseminated through these meetings. We will also make similar efforts to submit results to ACM SIGCSE conferences.

Summer Training Workshops: Both the PI and Co-PI have participated in summer faculty enhancement workshops on teaching undergraduate AI. Both will also continue to lecture in the future offerings of the workshops (as long as the project at Temple is active). These will form a natural platform for providing results from our project.

WWW: Both schools have world-wide web (WWW) servers that provide information on educational as well as research activities. Each course in session is conducted through a "dynamic class handout" on the WWW which is used by all students enrolled in the course. This information is also accessible to the internet community at large. Up to date information about the project would be available online through this medium.

AI Repositories: Currently Temple University maintains an extensive WWW repository of pedagogical information related to the teaching of undergraduate AI [3, 6]. Our materials will also be accessible through this repository. Also, under development is a similar repository of educational materials on the WWW server at AAAI. We will include the results of our project there as well.

References

[1] Eugene Charniak and Drew McDermott. *An Introduction to Artificial Intelligence.* Addison Wesley, 1985.

[2] Matt Domsch. Mit 6.270 lego robot design competition. World Wide Web, URL is http://www/mit/edu:8001/courses/6.270/home.html.

[3] Giorgio P. Ingargiola and Judith Wilson. Introductory AI Course as Observed on the WWW. *ACM SIGART Bulletin*, 6(3):2–6, July 1995.

[4] Marti A. Hearst. Preface: Improving Instruction of Introductory Artificial Intelligence. In *Working Notes of the 1994 AAAI Fall Symposium on Improving the Instruction of Introductory Artificial Intelligence*, pages 1–4. AAAI Technical report, November 1994.

[5] Henry Hexmoor and Lisa Meeden. Robolearn-96, an international workshop on learning for autonomous robots. World Wide Web, URL is http://www.cs.buffalo.edu/ hexmoor/robolearn96.html.

[6] Giorgio P. Ingargiola, Nathan Hoskin, Robert Aiken, Rajeev Dubey, Judith Wilson, Mary-Angela Papalaskari, Margaret Christensen, and Roger Webster. A Repository that Supports Teaching and Cooperation in the Introductory AI Course. *ACM SIGCSE Bulletin: Proceedings of the Twenty-Fifth Symposium*, 26(1):36–40, March 1994.

[7] Deepak Kumar and Marti A. Hearst, editors. *ACM SIGART Bulletin: Special Issue on Artificial Intelligence Education*, volume 6. ACM Press, April 1995.

[8] Deepak Kumar and Richard Wyatt. Undergraduate AI and its Non-imperative Prerequisite. *ACM SIGART Bulletin: Special Issue on Artificial Intelligence Education*, 6(2):11–13, April 1995.

[9] Fred Martin. The handy board. World Wide Web, URL is http://lcs.www.media.mit.edu:80/groups/el/Projects/handy-board/.

[10] Fred Martin. Mini board 2.0 technical reference. MIT Media Lab, Cambridge MA, 1994.

[11] Lisa A. Meeden. *Towards planning: Incremental investigations into adaptive robot control*. PhD thesis, Indiana University, 1994.

[12] Nils J. Nilsson. Evolutionary Artificial Intelligence. *ACM SIGART Bulletin: Special Issue on Artificial Intelligence Education*, 6(2):22–23, April 1995.

[13] I. Nourbakhsh, S. Morse, C. Becker, M. Balabanovic, E. Gat, R. Simmons, S. Goodridge, P. Harsh, C. Hinkle, K. Jung, and D. Van Vactor. The winning robots from the 1993 robot competition. *AI Magazine*, 14(4):51–62, 1993.

[14] Stuart Russell and Peter Norvig. A Modern, Agent-Oriented Approach to Introductory Artificial Intelligence. *ACM SIGART Bulletin: Special Issue on Artificial Intelligence Education*, 6(2):24–26, April 1995.

[15] Stuart Russell and Peter Norvig. *Artificial Intelligence: A Modern Approach*. Prentice Hall, Englewood Cliffs, NJ, 1995.

[16] Reid Simmons. The 1994 AAAI robot competition and exhibition. *AI Magazine*, 16(2):19–30, 1994.

[17] S. Rebacca Thomas. A Consideration of Some Approaches to Course Organization. *ACM SIGART Bulletin: Special Issue on Artificial Intelligence Education*, 6(2):27–28, April 1995.

[18] Allen Tucker, editor. *Computing Curricula 1991: Report of the ACM/IEEE-CS Joint Curriculum Task Force*. ACM Inc., 1991.

4 Appendices

4.1 Major equipment

4.1.1 Major Equipment at Swarthmore College

The Computer Science Program holds the following equipment which is available for undergraduate use:

- A Sun-based laboratory comprised of seven Sun ELCs upgraded from Sun Sparc 3's on 6/17/92 for a cost of $15,200 and one Sun Sparc 4 purchased on 6/18/95 for $4520. This laboratory is reserved for students taking upper-level computer science courses.
- A PC-based robotics research laboratory containing two NCI 386 DX/40 machines purchased on 2/23/95 for $2056. In addition, there is the following equipment: 5 Mini board robot controllers purchased on 1/17/95 for $475.00; and 5 Lego 4.5 volt resource sets for $1030. This laboratory is primarily used for the PI's research but has also been employed by students.

4.1.2 Major Equipment at Bryn Mawr College

The computer science program at Bryn Mawr College falls under the administrative purview of the Department of Mathematics. The following equipment is used by both computer science and mathematics students:

- An Apple Macintosh-based laboratory comprised of 14 PowerPC Model 6100 computers, purchased in summer 1994 for a total price of $28,000.00. All the computers have ethernet connections to the campus network. The laboratory is also equipped with a SONY overhead projection system. Another SONY projection system, one Apple Macintosh Centris and a Dell P75 PC are part of a media equipped class room. The total cost of the two projection systems and the two computers was approximately $38,000. All of this equipment was purchased between Spring 1993 and Spring 1995.
- A SUN Sparc 10/51 server that supports all upper-level computer science courses as well as undergraduate and faculty research. It was purchased in October 1993 for a price of $18,000.
- A SUN Sparc IPX workstation purchased in August 1992 for a price of $15,000. This workstations is primarily used for research by faculty and students in Mathematics.
- An X Terminal Laboratory consisting of 10 color X Terminals. Four of these are Hewlett Packard Aptrex terminals purchased in August 1994 at a price of $8000, and six are HDS-FX-17c purchased in August 1995 at a price of $12000.00. All computer science courses beyond the introductory (CS 1) use this as a platform for laboratory assignments.

- A laboratory with 6 Dell 486 PC's purchased in summer 1994 for the price of $21,000. This laboratory is time-shared with Physics, Mathematics, and Computer Science Students. The proposed purchase of new PCs will replace these and add to this pool.

4.2 Course descriptions

CS 63 Artificial Intelligence (at Swarthmore College). The unifying theme of this course is the concept of an intelligent agent. Based on this perspective, the problem of Artificial Intelligence is seen as that of describing and building agents that receive perceptions from an environment and perform appropriate actions based on them. This course will examine many different methods for implementing this mapping from perceptions to actions including: production systems, reactive planners, logical planners, and neural networks. We will use Lisp to program various agent and environment models. Lab work required. (Currently offered in the spring semester every other year. The expected enrollment is 15 students/offering, and the course is one of the options for fulfilling an upper level requirement for majors and concentrators.)

CS 91 Building Intelligent Robots (at Swarthmore College). This course addresses the problem of controlling robots that will operate in dynamic, unpredictable environments. In laboratory sessions, students will work in groups to build small, lego-based mobile robots and to program them to perform a variety of simple tasks such as obstacle avoidance and light following. In lecture/discussion sessions, students will examine the major paradigms of robot control through readings with and emphasis on adaptive approaches. (This semester was the first time this course was offered, but we plan to offer it every other year. At present, enrollment is capped at 15 students because of limited equipment, although over 25 students registered for the course. This course is one of the options for fulfilling an upper level requirement for majors and concentrators.)

CS 372 Artificial Intelligence (at Bryn Mawr College). A study of how to program computers to behave in ways normally attributed to human "intelligence." Topics include: heuristic *vs* algorithmic programming; cognitive simulation *vs* machine intelligence; problem solving; inference; natural language understanding; scene analysis; learning; and decision making. These are illustrated by programs from literature and programming assignments in appropriate programming languages (Common Lisp and Prolog). (Currently offered in the fall semester of every even numbered year. It is expected to be offered in the Fall semester of every year. The expected enrollment is 15 students/offering, and the course is required for all students pursuing an independent major, recommended for minors and concentrators.)

4.3 Recent Undergraduate Student Research Talks and Reports

4.3.1 At Swarthmore College

1. Phil Brandenberger: **Parallelizing Compilation with Dynamic Storage Allocation**. Seminar paper, Spring 1994.

2. Ivan MofoKeng: **Exploring Communication and Computation Patterns of Large-scale Image Convolutions on Parallel Architectures**. Seminar paper, Spring 1994.

3. Guy Haskin: Implementation of Parallel Algorithms on a SIMD Architecture. Seminar paper, Spring 1994.

4. Sam Erlichman: **A Classifier System that Learns to Play Tic-Tac-Toe**. A semester long research project completed as a one-credit course, Fall 1994.

5. Dave Sobel: **The Chinese Room and Connectionism**. Seminar paper, Spring 1995.

6. Margret Patterson: **An Introduction to Computer Science via Sorting: A Curriculum Plan**. Seminar paper, Spring 1995.

7. Goeff Noer: **Unix Network Daemons: Less Evil Than You Might Think**. Seminar paper, Spring 1995.

8. Jonathon Feinstein: **Data Visualization for the General User**. Seminar paper, Spring 1995.

4.3.2 At Bryn Mawr College

1. Farhannah Akikwala and Susanna Schroeder: **Algorithm Animation: Visualizing Sorting**. A summer Research Project sponsored by a grant from the Howard Hughes Medical Instititute, Summer 1994.

2. Amy S. Biermann: **Parallel Implementation and Optimization of the Minimax Algorithm with $\alpha--\beta$ Cutoffs in the context of the game Othello**. Honors Thesis, Spring 1995.

3. Niklaus Swoboda: **Graphical User Interfaces for AI Architectures**. A Summer Research Project sponsored by a grant from the Howard Hughes Medical Institute, Summer 1995.

4. Sarah Hacker: **Visual Programming**. A Summer Research Project sponsored by a grant from the Howard Hughes Medical Institute, Summer 1995.

5. Niklaus Swoboda: **Default Logics in Belief-Desire-Intention Architectures**. Honors Thesis (under progress), expected Spring 1996.

5 Biographical sketches

Biographical Sketch of PI

Lisa Meeden

Computer Science Program
Swarthmore College
Swarthmore, PA 19081
meeden@cs.swarthmore.edu
(610) 328-8565

Education

Ph.D. Computer Science, Minor: Cognitive Science, Indiana University, Bloomington, Indiana, 1994.
M.S. Computer Science, Indiana University, Bloomington, Indiana, 1990.
B.A. Mathematics, Grinnell College, Grinnell, Iowa, 1985.

Employment

Asst. Professor, Computer Science Program, Swarthmore College
(September 1994–present).

Courses Taught

CS 10, Great Ideas in Computer Science; CS 20, Structure and Interpretation of Computer Programs; CS 35, Fundamental Structures of Computer Science; CS 41, Data Structures and Analysis of Algorithms; CS 63, Artificial Intelligence; CS 91, Building Intelligent Robots.

Recent Professional Activities

Workshop Co-Chair for ROBOLEARN-96, an international workshop on learning for autonomous robots, FLAIRS-96, May 1996.
Lecturer in the NSF Summer Faculty Enhancement Workshop on Teaching Undergraduate AI, Summer 1995.
Reviewer for *Cognitive Science*, *IEEE Journal on Systems, Man, and Cybernetics*, and *1995 International Joint Conference on Artificial Intelligence.*

Recent Publications Relevant to this Proposal

1. Meeden, L. (submitted). Integrating Robot Building into the Undergraduate Computer Science Curriculum. Submitted to the FLAIRS-96, Special Track on AI Education.

2. Meeden, L. (1996, in press). An incremental approach to developing intelligent neural network controllers for robots. *IEEE Journal on Systems, Man, and Cybernetics.*

3. Meeden, L., McGraw, G., & Blank, D. (1993). Emergence of control and planning in an autonomous vehicle. In the Proceedings of the *Fifteenth Annual Meeting of the Cognitive Science Society* (pp. 735–740). Hillsdale, NJ: Lawrence Erlbaum Associates.

Recent Invited Lectures

1. Integrating reaction and deliberation: Using learned strategies to bootstrap planning. *Villanova University Computer Science Colloquium Series*, Villanova University, PA, October, 1995.

2. A connectionist approach to building plans from the ground up. *Spring Colloquium Series*, Computer Science Department, Indiana University, Bloomington, IN, March, 1995.

3. Incremental investigations into adaptive robot control. *Bryn Mawr and Haverford Colleges Mathematics and Computer Science Colloquium Series*, Bryn Mawr College, PA, February, 1995.

4. Emergence of control in an autonomous robot. *Neural Networks and Vision Seminar*, Cognitive Science Department, Brown University, Providence, Rhode Island, October, 1993.

5. A robot that learns through connectionist reinforcement training. *Workshop on Learning and Adaptation in Robots and Situated Agents*, Santa Fe Institute, Santa Fe, New Mexico, May, 1993.

Recent Collaborators:

Research Collaborator: Deepak Kumar, Bryn Mawr College.
Research Collaborator: Paul Grobstein, Bryn Mawr College.
Undergraduate Research Advisees: Andrew Brown (class of 1997), Sam Erlichman (class of 1995), Ben Vigoda (class of 1996), Sam Weiler (class of 1996).

Biographical Sketch of Co-PI

Deepak Kumar

Department of Mathematics
Park Science Building
Bryn Mawr College
Bryn Mawr, PA 19010
dkumar@cc.brynmawr.edu
(610) 526-7485

Education

Ph.D. in Computer Science, State University of New York at Buffalo, 1994.
M.S. in Computer Science, State University of New York at Buffalo, 1988.
M.Sc. (Tech.) in Instrumentation, Birla Institute of Technology and Science, Pilani, India, 1983.

Employment

Asst. Professor, Department of Mathematics & Computer Science, Bryn Mawr College (September 1993–present).

Courses Taught

CS 110, Introduction to Computer Science; CS 206, Data Structures; CS 245, Programming Language Concepts; CS 246, Programming Paradigms; CS 372, Artificial Intelligence.

Recent Professional Activities

Program Committee Member, KR-96 (Principles of Knowledge Representation and Reasoning), November 1996.
Track Chair, Special Track on AI Education, FLAIRS-96, May 1996.
Contributing Editor on AI Education, ACM SIGART Bulletin.
Lecturer in the NSF Summer Faculty Enhancement Workshop on Teaching Undergraduate AI, Summer 1995.
Guest Lecturer on Computational Intelligence, Brain and Behavior Summer Institute (A Science Outreach Program for Philadelphia Area School Teachers), Summer 1995.
Minitrack Coordinator, Track on Emerging Paradigms for Intelligent Systems, HICSS-28 (Hawaii International Conference on System Sciences), January 1996.
Reviewer for ACM SIGCSE, HICSS, FLAIRS, GWIC, Journal of Experimental and Theoretical Artificial Intelligence, Portugese Conference on Artificial Intelligence.
Responsible for creating and co-ordinating a new undergraduate Computer Science Program in conjunction with Haverford College (1993–present).

Recent Publications Relevant to this Proposal

1. Editor (with Marti Hearst), ACM SIGART Bulletin Special Issue on AI Education, Volume 6, Number 2, April 1995.

2. with Richard Wyatt: "Undergraduate AI and it's Non-Imperative Prerequisite", Proceedings of the AAAI 1994 Fall Symposium on Improving Instruction of Introductory Artificial Intelligence, Marti Hearst (editor), New Orleans, November 1994, AAAI Press. Also, in ACM SIGART Bulletin Special Issue on AI Education (edited by Deepek Kumar and Marti Hearst), Volume 6, Number 2, April 1995.

Other Recent Significant Publications

1. "The SNePS BDI Architecture" in The Journal of Decision Support Systems, Elsevier Science Publishers The Netherlands), forthcoming in 1995.

2. with Stuart C. Shapiro: "Acting in Service of Inference (and *vice versa*)", Florida Artificial Intelligence Research Symposium (FLAIRS 94), May, 1994.

3. with Stuart C. Shapiro: "The OK BDI Architecture", in International Journal on Artificial Intelligence Tools, volume 3, number 3, World Scientific Publishing, 1994.

4. with Stuart C. Shapiro: "Deductive Efficiency, Belief Revision, and Acting" in JETAI —*Journal of Experimental and Theoretical Artificial Intelligence*, volume 5, numbers 2 & 3, 1993, Taylor & Francis (London).

5. with Hans Chalupsky: Guest Editor, JETAI —*Journal of Experimental and Theoretical Artificial Intelligence*, volume 5, numbers 2 & 3, Special Issue on Propositional Knowledge Representation, Taylor & Francis (London), 1993.

6. Editor, "Current Trends in SNePS —Semantic Network Processing System," Lecture Notes in AI, Volume 437, Springer-Verlag, 1990.

Recent Collaborators:

Ph.D. Advisor: Stuart C. Shapiro, State University of New York at Buffalo.
Research Collaborator: Lisa Meeden, Swarthmore College.
External Member of Ph.D. Committee: Libby Levison, The University of Pennsylvania (Ph.D. in progress), Michael Hart, Temple University (Ph.D. in progress).
Undergraduate Research Advisees: Farhannah Akikwala (Bryn Mawr College class of 1995), Susanna Schroeder (Bryn Mawr College class of 1995), Amy S. Biermann (Bryn Mawr College class of 1995), Niklaus Swoboda (Haverford College class of 1996), Jyotsna Advani (Bryn Mawr College class of 1996), Sandeep Poonen (Haverford College class of 1996), Sarah Hacker (Bryn Mawr College class of 1997).

6 Proposed Budget

ILI-IP DETAILED BUDGET (EQUIPMENT LIST)

Item	How Many	Unit Price (list)	Unit Price (discounted)	Total Cost (discounted)
Lego Robot Building Kit (Includes 9 volt resource set, temperature, light, touch sensors lamps, assembled Handy Board controller)	20	550		11,000
Active Media Pioneer 1 Robot (on board MC68HC11 controller, two-wheeled two independent DC, motors, 7 sonar and 2 IR sensors, gripper, software includes 3-D, mapping, 2-D simulator, and utilities)	2	3245	3115	6,360
Shipping Costs:	2	50		100
Dell P75 PC (Intel Pentium-based 75MHz with 16 Mb RAM, 0.5Gb disk, with 3-year limited warranty.)	16		2,108	33,728
486 Laptop	2		2,900	5,800
Shipping Costs:	18	50		900
Total Project Cost:				57,888
Non-NSF contribution:				28,944
NSF Request:				28,944

BUDGET JUSTIFICATION

Lego does not offer educational discounts. Active Media's discounted price is for each subsequent unit after the first. Thus, the total price for two Pioneer 1's is \$3245 + \$3115 = \$6360. Unit prices for the PCs and Laptops are already discounted prices. Technical justifications for each item are presented in more detail in Section 3.3 above.