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Since its inception, scientific inquiry has been based on the materials, tools, and equipment that scientists procure and develop for their research. Increasingly, computing and computer-controlled instrumentation is the foundation of modern scientific work. Beginning in the 1980s with microcomputer-based laboratories (MBLs), schools have introduced such equipment. This new technology, however, has often been employed in the fashion of much school science laboratory work, where students perform measurement-confirmation “experiments” rather than deep inquiry-based investigations.

Over the last 10 years, the use of classroom robotics has become prevalent across the K–12 grade levels. In contrast to “school science,” much of this robotics work does exhibit the characteristics of inquiry-based science: students are highly engaged as they frame problems, experiment, debug problems, and pursue solutions. Why is classroom robotics successful in inspiring students to take charge of their work, while classroom science has trouble getting students’ attention?

Central to answering this question is recognizing the type of inquiry performed by students in science classes. For more than 40 years, science educators have advocated an inquiry-based approach to science. More recent work has refined this idea, characterizing teacher practice and student work more deeply, and studying classroom activity by asking: who poses the questions, who designs the procedures, who interprets the data, and who takes the next steps? To the extent that agency is in the hands of students, school classrooms can reflect the nature of science that is close to our conceptions of actual scientific practice.

Providing capable, extensible, and inviting technology to teachers and students is also key. The PI is co-developer of several widely used robotics technologies, including the now-ubiquitous LEGO Mindstorms system. For this project, I propose both using and extending research technology—the Handy Cricket microcontroller—with the goal of characterizing and then providing materials that can be readily assimilated into authentic inquiry-based work by teachers and students.

The project includes research and development components. From a research standpoint, I will investigate how beginning and practicing middle-school science teachers perform their own inquiry-based science experiments, reflect on and make sense of their own experiences, and then bring these approaches to their students. From a development standpoint, the project will (1) create deep linkages between computing science and middle school science content (including sensing, measurement, time), and (2) create improved technology for widespread classroom use.

The PI will collaborate closely with faculty and staff of our Graduate School of Education, and will co-teach sections of the Science Methods courses required of the student-teachers in its program. These individuals and other teachers who participate in project professional development workshops will be invited to participate in classroom trials using project materials and approaches. The development plan includes an international component, extending the PI’s previous collaborations with leading educator/researchers in Ireland and Germany.

The project’s intellectual merit stems from its goal of understanding and promoting authentic science inquiry by teachers and students, and creating deep connections between computing and middle school science. Its potential for broader impact is based on its practical, classroom-based approach, which will ensure materials and pedagogical strategies that can be employed widely.
1. INTRODUCTION

Beginning in the early 20th century and furthered in Sputnik-era reforms, science educators have argued for students to be engaged in inquiry-based science learning (Dewey, 1910; Schwab, 1962). This continues to be recognized in key policy documents such as the National Science Education Standards, which urges that scientific literacy be achieved through “a new way of teaching and learning about science that reflects how science itself is done, emphasizing inquiry as a way of achieving knowledge and understanding” (National Research Council, 1996, pp. ix).

Indeed, the NRC and a large body of science education researchers recognize that inquiry-based learning is pivotal in science education. Rather than focusing strictly on students’ acquisition of information, “students should develop an understanding of what science is, what science is not, what science can and cannot do, and how science contributes to culture” (NRC, 1996, p. 21). Furthermore, “without understanding the values and assumptions of the knowledge and the processes by which the knowledge is created, the learner can do little more than construct an image of science consisting of isolated ‘facts.’” (Schwartz et al., 2004).

Historically, high school science laboratories were assumed to provide students with inquiry-based experiences (Spears & Zollman, 1977), but modern definitions of inquiry allow us to better interpret student work in the laboratory environment and its impact on science learning and students’ conceptions of the nature of science. In many cases, science labs are a contrived experience in which students follow recorded procedures to obtain results that are already known—so-called “confirmation experiments” (McComas, 1997). While these labs may help students develop basic process skills, they do little to allow students to pursue creative problem-solving, and encourage a portrayal of science as facts that are revealed only when the prescribed scientific method is followed (Pizzini et al., 1991).

In contrast, over the last ten years we have witnessed an explosion of enthusiasm and learning with classroom robotics. Classroom robotics is widely recognized as being highly engaging and valuable in cultivating students’ design and problem-solving abilities (e.g., Martin et al., 2000; Sklar et al., 2003; Miglino et al., 1999; Bers et al., 2002). Why has classroom robotics been so successful in capturing the imagination of teachers, parents, and students alike, yet many classroom science activities seem formulaic by comparison? There is a cluster of reasons that explains the success of educational robotics, and can be brought to bear on transforming classroom science:

- **Teacher-supported, student-directed work.** In many classrooms and most informal learning environments that use classroom robotics, teachers support students in significant design- and inquiry-rich work. Educators agree that students must be given the opportunity to think creatively, make mistakes, and solve problems (Lough and Fett, 2002).

- **Authentic problem-solving with immediate, real-world feedback.** In the classroom, the task that the robot must perform becomes quite real, and students get continuous feedback as to how well their designs are working. The robots become more than models—they embody students’ ideas and aspirations, and their success or failure becomes a powerful and authentic challenge to students (Martin et al., in press).
• Technology as a design ingredient. When children build robots, they are using an array of interacting modern technologies, combining computer programming, sensing devices, actuators, and building components. This is far more intellectually exciting, challenging, and pedagogically valuable than use of older design technology materials, such as slotted sticks, light bulbs, and wire.

For my career development plan, I propose a longitudinal research program that takes what we have learned about classroom robotics and applies it to science learning. There is a huge opportunity to transform teachers and children’s notions of scientific inquiry, the process of science, and the nature of scientific knowledge with (1) the use of contemporary computing technology and (2) an approach that recognizes the value of letting students and teachers invent their own experiments and carry out their own scientific investigations.

There are several components to this program. First is teacher professional development, both pre-service and in-service. Teachers serve as both content experts and intellectual models for their students; before we can expect any significant change in how science is presented to students, we need to offer teachers a chance to themselves experience science in a different way. To carry out this portion of the work, I will partner with UMass Lowell’s Graduate School of Education and co-teach science philosophy and methods courses for pre- and in-service teachers. These teachers will become part of the research in two ways: (1) their own learning will be an object of study, and (2) interested teachers will be recruited to bring the ideas of this project into their own classrooms, and their students’ learning will be studied. I will also recruit teachers to join summer professional development workshops and subsequently bring the ideas into practice in their own classrooms.

The second phase of the program will commence with the first cohort of teachers who complete coursework or a summer development program. These teachers will creatively adapt project materials and methods in their own classrooms. This work will be carried out in a range of classrooms from various school districts. In addition to in-depth, case studies of selected teachers and students, I will employ a quasi-experimental method to characterize changes in students’ learning across project and non-project classrooms.

In parallel with this learning research, project technology will be developed. We already have extensive experience using our core technology, the Cricket (previously developed by the PI as technical director of NSF grant EIA-9616444) in robotics education, and in recent work, we have used the Cricket for inquiry-based science experiments with teachers (Martin and Greenwood, in preparation). This technology will be refined, improved, and evolved based on teachers’ and students’ work over the course of the program. Indeed, I am particularly interested in how computing technology can serve as a motivating and empowering design medium in the hands of teachers and students. One research objective of this project is to produce a classroom technology system, along with strategies, assessments, and practical example of its use, that can demonstrably be used widely in schools. This approach was successful employed in my prior work, which led to the widely used LEGO Mindstorms Robotics Invention System (Martin, 2000).

In following sections, I present further rationale for the research and a statement of the key research questions that will guide the work. This is followed by a practical discussion of how the research will be conducted, including work with teachers, students, and other colleagues, and a description of the data that will be collected. Next is a discussion of project technology and a
sample of teacher work that has already been piloted. The last sections describe the educational plan, project management, and my prior work in the field.

2. RATIONALE

Building on the introductory discussion, this work draws inspiration from Norm Lederman’s extensive work on scientific inquiry (SI) and the nature of science (NOS), and how science teaching needs to change to address modern views of these central ideas. As he declares, “In short, understandings of the NOS and scientific inquiry are believed to be critical and essential components of the modern day battle cry of ‘scientific literacy’” (Lederman, 1998).

Lederman’s cogent discussions have built consensus on the actual meaning of science inquiry and the nature of science. Science inquiry “extends beyond the mere development of process skills such as observing, inferring, classifying, predicting, measuring, questioning, interpreting and analyzing data. Scientific inquiry includes the traditional science processes, but also refers to the combining of these processes with scientific knowledge, scientific reasoning and critical thinking to develop scientific knowledge.” He contrasts this with the popular and “distorted” notion of the “scientific method,” which can be criticized as “an algorithm that students are expected to memorize, recite, and follow as a recipe for success” (Lederman, 1998).

While its precise meaning of the “nature of science” has been in flux over decades of thought, Lederman defines its essential meaning to include the principles that “scientific knowledge is tentative (subject to change), empirically-based (based on and/or derived from observations of the natural world), subjective (theory-laden), necessarily involves human inference, imagination, and creativity (involves the invention of explanations), and is socially and culturally embedded.” (Lederman, 1998).

Lederman has demonstrated that these notions should be considered as cognitive pedagogical goals, rather than as indirect affective outcomes. This is to say that our contemporary views of SI and NOS should be taught, not simply left to emerge from any particular set of classroom activities: “If K-12 students are expected to develop more adequate conceptions of the NOS and scientific inquiry, then, as any cognitive objective, this outcome should be planned for, explicitly taught, and assessed” (Lederman, 1998). Other work confirms that students’ conceptions of the nature of science, even after a year of project-based work, do not change significantly when explicit discussion of NOS is not integrated with hands-on activities (Moss et al., 2001).

Recent work demonstrates the value of providing teachers with a multi-faceted learning program that includes internship with practicing scientists, readings, discussions, and reflection. In the work reported by (Schwartz et al., 2004), teachers are paired with practicing university scientists as apprentices and use these direct observations and experiences of the scientific practice to reflect on the nature of science:

None of the interns thought their activities within the research setting directly impacted their NOS views. Most reported learning techniques and content. … What the research setting did provide, however, was an authentic context for reflection: a real research setting with which to apply and revise one’s knowledge of NOS. This was viewed as the most beneficial aspect of the research portion of the course relative to NOS learning. (pp. 632, original emphasis.)

Existing work on teacher professional development has demonstrates the value of this integrated approach to teacher learning (e.g., Butler, 2004). Here, I propose that with the advent
of digital technology in the classroom, we can accomplish the equivalent of the internship with a scientist in teachers’ and students’ own classrooms, by providing an authentic context for learners’ design work, and deliberative instruction that includes periods for discussion and reflection.

**Process Experiences.** This and other work makes it clear that process experiences are crucial. For teachers, they are necessary for their own personal enjoyment of science, and furthermore so that they can facilitate similar experiences for their students. For students, process knowledge is also essential, so they can experience the excitement that scientists do when they make discoveries and connect ideas together, and to give them a basis for understanding the nature of science, both personally and at an abstract level. Only by actually “doing science” can a teachers and students start to perceive of themselves as scientists. A significant reason why children are “turned off” to science is because it is presented a large set of known facts, giving the impression that all the discovery was done in the past, or at best, is done by other people. So students perceive science as the task of learning contemporary explanations and models, rather than as the process of constructing these understandings. Students never get to experience the excitement that comes from figuring out how things work first-hand.

**Role of technology and computation in science.** Increasing, computing is an essential part of the conduct of science. Computers are used to control instrumentation, record data, and analyze data. Beginning the 1980s with microcomputer-based laboratories (MBLs) and continuing into the present with hand-held “probeware,” science educators have introduced computing into science classrooms. These technologies have proven value. Students who use probeware to collect and analyze data score significantly higher on the NAEP science scale (National Assessment of Educational Progress, 2002).

Nevertheless, much of the classroom use of these materials is in the same fashion as school science laboratories in general. Students follow cookbook-style instructions, performing confirmation experiments where the expected results are known in advance. Clearly, some benefit does result from this work, but the true potential of these advanced materials is not being realized. Part of the research program proposed here is to characterize and understand the usage patterns of existing computing technology in school science. How is computing made a part of science in existing schools? What types of inquiry do students perform as they use these materials? How do teachers support students’ inquiry? What is the background and prior experiences of teachers that are supporting more self-directed, advanced inquiry in their students?

**Design of instrumentation and experimentation.** Central to scientific practice, in its ancient, historical, and modern forms, is the design of an experiment and the development of the apparatus for carrying it out. Yet this is often lacking from science as it is practiced in school. Even when students perform experiments, it is usually with a closed set of materials that have been provided to them, with all of the potential variables so tightly controlled there is little to do but replay a mechanical procedure. In this project, research will focus on supporting teachers and students in designing, debugging, and carrying out their own experiments, looking closely at cognitive skills and reasoning processes they engage while doing so. I hypothesize that the more constrained computing materials might actually hinder students and teachers from inventing their
Personal connection to science. Any biography of a well-known scientist reveals that scientists are deeply connected to the questions and ideas they are studying, often to the point of obsession. Scientists take a problem or question and make it their own. Yet children and teachers rarely experience scientific knowledge in this way. To the contrary, knowledge is presented as a fait accompli, already discovered and fully researched by the great minds of the past. Even if hands-on experiments are conducted as part of a curriculum module, at the end of exercise, the accepted-as-correct model is presented to students.

Several factors contribute to the lack of connection that many students and teachers feel to science. Despite recommendations that science should be taught as “what is known does not stand separate from how it is known” (Massachusetts Science and Technology/Engineering Curriculum Framework, 2001, pp. 5), many curricula focus on teaching existing scientific models and “facts,” rather than the process by which they were developed. Experimentation in classrooms is often constructed to reproduce known results (“confirmation experiments”). Ultimately, students and teachers are not often asked to develop their own experiments to investigate questions that they personally care about.

In this project, teachers will be encouraged to think about questions of their own, and use project technology to help them explore their questions. Our existing work in this area, using data collection technology with student-teachers, shows great promise; teachers created experiments to measure the efficacy of wet-suits, study an attic’s insulation performance after a home improvement project, and determine which family member takes the hottest baths. These and other examples are presented further in the Sample Projects section later in this proposal. In each of these cases, the teacher’s project became an authentic inquiry, because the individual actually cared about the result.

This work has been facilitated by taking the science out of the classroom and into the real world, and by encouraging teachers to “think outside of the box”—that is, conceive of a project other than demonstrating a scientific principle with which they are already familiar. We expect the sample principle to apply when working with children.

3. RESEARCH QUESTIONS

This study is primarily concerned with teachers’ learning and the resulting choices they make when implementing activities with their students. The research questions that underpin this work include the following:

1. Does the use of Cricket technology enhance teachers’ awareness of the messiness of the inquiry process? E.g., how do they anticipate, respond to and account for unexpected data?

2. Given teachers’ own understanding of inquiry and the explicit teaching of the nature of science, how do they implement Cricket technology projects in their classroom? How does the mode of implementation influence middle school students’ interest in and understanding of the nature of science?
3. When they are acting as students, what scientific concepts are examined by the teacher-participants through the use of this technology? Then, as they implement activities in their classrooms, what concepts do their students explore using the Cricket? Further, how does student understanding of these concepts vary as a function of prior instruction?

The project’s intellectual merit stems from its goal of understanding, promoting, and supporting authentic science inquiry by teachers and students, and creating deep connections between computing and middle school science. Ultimately, this work has the goal of developing teachers and students who perceive themselves as scientists and can be objectively measured to exhibit the habits of mind—curiosity, skepticism, creativity, logic, and rigor—that characterize practicing scientists.

Its potential for broader impact is based on its practical, classroom-based approach, which will ensure materials and pedagogical strategies that can be employed widely. The PI’s past technologies have had a significant impact on students’ learning in the area of engineering and classroom robotics; the opportunity here is to similarly transform school science.

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Figure 1: Program Overview

4. RESEARCH PROGRAM

The project’s core research activities will be based on professional development for teachers and follow-on implementation of project activities by these teachers in their own classrooms. Research will be conducted on teachers’ learning and changes in student learning as a result of project activities. Additionally, I will work directly with students of a partner middle school in the city of Lowell, gaining first-hand knowledge of students’ interests and abilities. An international dimension to the project is planned, as well as on-line teaching and on-going professional development meetings.

The program in organized into three strands, as illustrated in Figure 1. Strand 1 is the core work, which centers on teachers’ learning, teachers’ subsequent implementation work in their own classroom, and student learning. Strand 2 is a small pilot project that the PI will conduct directly with middle school students. Strand 3 is the project’s international component.

4.1. Strand 1: Core Research and Implementation

Graduate School of Education Students. Students of three different courses offered by UMass Lowell’s Graduate School of Education (GSE) will be involved in the research program. Students of these courses are both in-service and pre-service teachers, and all of the courses include aspects of the history, nature, and philosophy of science. Each of the courses will be revised to include a class project that is based on teachers designing and carrying out an
experiment of their own conception using project technology. This module has already been piloted in the Science for Secondary Science Teachers course, and will be used as the basis for the design of the other courses. The courses are:

- **Science for Secondary Science Teachers (UML 04.525).** This is one of four required science education in the M.Ed. program in Curriculum and Instruction for Science. Students of this course are typically half pre-service and half in-service teachers, and typically have an undergraduate degree in a science or engineering field.

- **Elementary Science Methods (UML 02.563).** This is a specialization course in the M.Ed. program in Curriculum and Instruction for Elementary grades. Students of this course are typically pre-service, and usually do not have a significant undergraduate background in science.

- **Research into Learning in Science – Online Course (UML 04.674).** This is one of 5 courses offered (of which 4 are required) in the NSF-funded joint program between UMass Lowell and UMass Amherst in M.Ed. in Curriculum and Instruction with Concentration, taught online (ESI-0243536, “Science Education Online,” $1.2M). Students of this course are typically in-service teachers with several years of teaching experience. The program draws students regionally and across the country. Partnering with the GSE in teaching this course will allow us to focus on technology support for teachers’ sharing of ideas. This is discussed further in the Technology section.

Upon completion of these courses, students who are in-service teachers will be invited to participate in the research project. These teachers will join a project team that meets monthly and implements project ideas and technology in their classrooms. Based on their own interests, classroom constraints and opportunities, and curriculum, teachers will contribute their own expertise in pedagogical design as they develop modules for their own students.

**Summer Professional Development Workshops.** In addition to working with in-service graduate students, I will offer 1-week intensive summer workshops to interested area teachers in conjunction with the GSE and the state Department of Education. These teachers will be become part of the pool of teachers from which classroom research collaborations will be formed.

**4.2. Strand 2: Bartlett Middle School Students**

The PI will personally conduct science inquiry workshops, using project technology with middle school students as part of an after-school program in the New Bartlett School, a city-wide PK–8 Professional Development school adjacent to the university campus in Lowell. UMass Lowell has a collaborative research relationship with the Bartlett school, and UML faculty are encouraged to pursue research there. The school is representative of Lowell’s public school system, which has significant Hispanic (22%) and Asian (29%) populations. Over 60% of its students are classified as low income, and over 40% of its students have a non-English first language.

The objective of this portion of the project is to enable the PI to gain direct experience introducing middle school students to project ideas, learn from the students’ creative appropriation of project materials, and demonstrate the efficacy of our materials and approach
with a higher-needs population. This portion of the project will be conducted for the first 2 years by the PI, and will be continued by undergraduates from the Computer Science department in subsequent years.

4.3. Strand 3: International Collaborations

The project will benefit from collaborations with research groups located in Germany and Ireland with whom the PI has existing, multi-year research relationships.

In Germany, I will work with Prof. Dr. Heidi Schelhowe’s Digital Interactive Media In Education (DIMEB) team, an interdisciplinary group of computer scientists, educators, and designers at the University of Bremen. In the past, I have contributed to Schelhowe’s work in educational robotics and gender equity in technology and science. For this project, I will conduct an annual workshop that brings DIMEB researchers and students together with public school teachers from the city of Bremen, introducing project themes and technology. Dr. Schelhowe will support implementation work with the teachers and her researchers.

In Ireland, I will collaborate with Dr. Deirdre Butler, a Lecturer at St. Patrick’s College, and Clifford Brown, who is project coordinator for the Diaego Liberties Learning Initiative. I co-advised Dr. Butler during her PhD dissertation work from 2000–2004, which focused on the development of teachers’ attitudes and approaches they integrated educational robotics into their primary school classrooms. Mr. Brown was one of these project teachers and presently coordinates the introduction of innovative technology into a network of 10 primary and 5 secondary schools in an economically disadvantaged area of Dublin. Dr. Butler is the faculty advisor to this Diaego Liberties project.

Arranged by Dr. Butler and Mr. Brown, I will visit Ireland annually to work with secondary teachers in the Diaego Liberties project. As noted in Mr. Brown’s collaboration letter, his teachers are already using the PI’s version of the Cricket technology. With my assistance, their work will focus on inquiry-based approaches to science learning.

4.4. Focus on Middle School Science

While coursework will be conducted with teachers at grade levels 1–12, implementation and subsequent research activities will focus on upper elementary and middle school students. There are two key reasons for this: technology and approach. The Cricket materials are designed to be easy to use (and we expect them to become more straightforward as technology work processes), but they still require some degree of abstraction. Essentially, teachers and students will use them to capture data that are later analyzed. This is perhaps too advanced for early elementary work—though, if I encounter primary teachers who are enthusiastic about trying project ideas with their students, I will encourage their efforts.

When teachers bring project materials into their own classrooms, they will be encouraged to adapt them to the content already in their curriculum as they think best. Because of the more specialized content requirements of high school science, middle school is likely the ideal context for both of access to the technology and support for a style of work that emphasizes science process and inquiry skills.

5. DATA COLLECTION AND EVALUATION

This section presents the strategy for collecting and analyzing data on teachers’ and students’ learning over the lifetime of the project. I will use a combination of data collection approaches, including in-depth interviews, open-ended responses and Likert-type pre- and post-
questionnaires. The research design in classrooms will be quasi-experimental. In the following discussion, I illustrate the approach that will be used for each of the three research questions upon which the project is based. These approaches will be refined over the course of the project.

**Question 1—Explores inquiry in teachers’ formal thinking and experiential learning.** At the beginning of coursework, teachers will be given a set of open-ended questions (based upon the methodology and instrumentation used by Hewson and Hewson, 1989) that asks them to represent their understanding of inquiry. Teachers will then engage in the main body of coursework, including their experimental project using Cricket technology. They will be required to keep a journal describing their process. At the end of the course, they present their work, and I will compare their statements and approach with their initial responses. Also, teachers will reflect upon their learning. Finally, I will conduct representative interviews with teachers.

**Question 2—Examines the mode of classroom project implementation and student interest.** In monthly project meetings, I will discuss implementation plans with teachers. I will observe classrooms directly at least 3 times and document procedures used. A quasi-experimental design will be used to measure school students’ interest in science and understanding of the nature of science. Students in classroom using Cricket technology as well as comparable control group classrooms will be given pre- and post- Likert-scale questionnaires. Also, teachers will recommend a representative sample of students for in-depth interviews of their experiences.

**Question 3—Identifying science concepts in teachers’ and students’ work.** Teachers will log the concepts they perceive as involved in project work; this will be supplemented with interviews. In the classroom, teachers will document their observations of their students’ work. Additionally, students will prepare written statements that reflect their understanding of the science ideas that were involved in their work. Teachers and students will be asked to prepare tentative explanations for the phenomena they have observed. Students’ statements will be analyzed using concept maps.

6. **TECHNOLOGY**

The project will employ custom-designed microprocessor technology, along with desktop and internet-based software applications developed by the PI and his team. *A key research goal of the work is to closely examine the relationship between properties of these digital materials and the nature and content of the scientific inquiry they foster by their users (teachers and children).* Because of this, technology will be designed and adapted in an iterative fashion with close attention paid to its ongoing usage in practice.

6.1. **The Handy Cricket**

Figure 2 shows the Handy Cricket, a tiny microprocessor board optimized for science projects involving control activities and data collection. As technical director of NSF grant EIA-9616444 (“Collaborative Research on Learning Technologies: Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Instruments,” January 1, 1997 to December 31, 2000, $880,658), I co-designed the Handy Cricket. Building upon this prior work, it will serve as the technology foundation for this research.
The Handy Cricket and programming interface. The Handy Cricket is about 2” square in size.

The Cricket has a set of properties that make it suitable for use by teachers and students. First, it is small, inexpensive (production cost: less than $20 each) and inviting. Teachers and students alike are attracted to its name, hand-held size, and its “beep” when you turn it on. Also, many users have commented that they like the fact that the electronics are exposed. Teachers report that students perceive that they are using a real piece of technology, not just a toy.

As an essential part of its use, teachers and students program the Cricket to perform the functions that they desire. This many include periodic sampling of sensor data, waiting for events and triggering output actions, and communicating data with other Crickets. Because they must be programmed, even in a simple way, before they are used, teachers and students gain a sense of control, because they literally are telling the device what they would like it to do. The programming activity gains meaning because it is an end to serve the goal of communicating your objective to the Cricket.

Relative simplicity of Cricket technology encourages students to be creative in how it is used. For example, using a light sensor may be used to record ambient light levels, or set up opposite a flashlight to function as a break-beam motion detector. A temperature sensor may be used to record temperature readings or to trigger an alarm if the temperature crosses a predetermined threshold.

In the project, we plan for a 1-to-1 (or higher) ratio between Crickets and learners (teachers or students). This is essential because we plan for learners to bring Crickets out of the classroom and into their lives. As the direct cost of a Cricket is about $20 (they are built by a contract fabricator located in Phoenix, AZ) this is feasible both in a research context and in subsequent dissemination.

6.2. Other Commercial Systems

The objective over the course of the research is to develop technology that fosters genuine, inquiry-based science. In addition to the Handy Cricket, the research will include the use of leading commercial science technology, such as Vernier and Pasco sensors, and Onset “Hobo” data collectors. These technologies will be evaluated along with our own to gain an honest appraisal of how the technology affects learners’ thinking and usage patterns.
We note that the advanced systems of Vernier and Pasco may tend to be used more frequently in high school than middle school. Why this is so is worth understanding. Also, we would like to characterize the type of experimental work that is fostered by the commercial systems—are teachers and students more likely to follow planned experiments specified in curricular material that accompanies the materials? If so, why?

6.3. Internet-Based Collaboration Tools

In addition to the hardware tools, the project will include development of improved software environments. As schools are increasingly networked, and we can assume that any given desktop or laptop computer is connected to the internet, I am particularly interested in software tools that can support joint learning. The existing Handy Cricket software allows individual learners to interact with the Cricket on their desk, but does not facilitate sharing of questions, raw data, or interpreted conclusions. As part of this research, my team will develop new, internet-based software that lets users both interact with their Crickets and other learners.

This internet-based software will be especially valuable for use by teachers in the online science course, but will be employed for all teachers, and students, involved in the project.

6.4. Interaction Between Technology and Science

There are two particular research foci with respect to the use of technology for science inquiry. First, we will to encourage a view of technology as a configurable, flexible media, rather than as a set of single-purpose devices. To the extend that learners perceive the technology as a material that unifies their thinking and builds confidence, it is successful.

Secondly, the research will focus on ideas introduced by the technology that directly impact the nature of science. For example, how accurate are sensors? When does it matter? Do they need to be calibrated, and if so, how does one do that? Along these lines, what is it like to work with real-world, noisy data? Can outlying data points be discarded? When? What is actually being measured by the sensor? How can you build confidence in your experimental apparatus and trust that the data it has reported reflects reality? All of these questions become part of computational science projects in a powerful way. Observations and interactions with students and teachers will pay attention to these and other aspects of how technology affects science thinking.

7. SAMPLE PROJECTS

As mentioned, inquiry-based activities using the Handy Cricket have been prototyped for the last 3 years in the Science for Secondary Science Teachers course (Martin and Greenwood, in preparation). Students of the class (pre-service and in-service teachers) were provided with Crickets, temperature sensors, and ambient light sensors and asked to develop and carry out an experiment that would allow them to formulate a scientific hypothesis.

The assignment produced a surprising range of work. The teachers often chose to explore a question or phenomenon that was of close personal interest. For example, one teacher had recently completed a home improvement project in which she insulated the attic of her house. She was curious as to its heat retention properties, and developed an experiment to compare it to the attic of her garage, which was similar in construction but was uninsulated. Another teacher who was a diving enthusiast designed an experiment to compare the heat retention performance of several different models of wet suits that he owned. Others attempted to resolve household disputes, such as whose room is the hottest (it was summertime) and who takes the hottest bath.
The teachers exhibited a wide range of sophistication with respect to their experimental design. One teacher was interested in his own perceptions when using a heating pad on his back. After he had the pad on for a while, it seemed to no longer get sufficiently hot. He postulated that this might be a matter of his own sensory perception rather than an external phenomenon (e.g., a malfunction of the heating pad). His experiment included sampling of the temperature of his skin along with a correlated record of his own sensory perceptions.

Others had naïve experimental designs. The teacher who attempted to resolve the “who takes the hottest bath” question produced graphs that she described as showing water temperature versus time. Yet near the end of her formal presentation, she revealed that her Cricket apparatus was measuring the air temperature of the bathroom near the tub, rather than the water temperature itself. She had taken the assumption that the two would be so closely correlated that she could use the air temperature reading as a measurement of the water temperature. It may indeed have been the case that the two had a tight correlation, but most of us believed this could not be simply assumed.

Another teacher was interested in the question, “Why does my soda sometimes seem really cold and sometimes not?” Unlike the teacher with the heating pad question, this teacher did not consider the perceptual dimension of the question; she was focused on objective measurements of her refrigerator’s performance. In her enthusiasm to experiment with all sorts of variables, she carried out a protocol that was hardly controlled. Essentially she just used the refrigerator as she normally would, using the Cricket to record its temperature while keeping a log of activity. Despite the relative lack of experimental design, she settled an old question: Are parents justified in chastising their children for standing in front of the refrigerator with the door open? It turns out that holding the door open for a while does not produce a significant loss of coldness in the refrigerator—when the door is closed and the fridge has kicked on, it will quickly lower the internal air temperature. Instead, the act that really makes a refrigerator work hard is depositing a bunch of room temperature food into it! (It’s hard to avoid that.) Despite the lack of clear experimental design, this conclusion was clearly supported by her data. In retrospect, this result seems fairly obvious—if one has an understanding of heat transfer and thermal mass.

There are several themes common to each of these projects. Teachers had to creatively adapt the technology to their own ideas. In some cases, this was straightforward; e.g., the Cricket plus its temperature sensor could simply be placed into the refrigerator, and the only question is where does one put it. In other cases, some sort of experimental apparatus had to be developed. The teacher doing the wet-suit experiment devised a method for protecting the Cricket from water exposure, and the teacher with the heating pad experiment invented a method for shielding the temperature sensor itself from the direct heat of the pad so that it could accurately measure his skin temperature.

Teachers often chose to explore something of personal interest, rather than performing a test of a more abstract “scientific phenomenon.” This was not exclusively the case; some of the teachers’ projects were in this more abstract category. But we noticed a significant difference in engagement between the two. The teachers who had selected a more complex, personally meaningful research question were typically more enthusiastic and animated when presenting their work, and generally had done a more thorough job. We think this correlation is not accidental.

Ultimately, each of the projects centered on a data set that the teachers had collected, and the narrative that they developed around it. The key task in the work was interpreting the data in a way that was plausibly consistent with reality—first convincing oneself of the validity of the
explanation, and then presenting it to others. This often involved surprising subtlety. In one project, a teacher was trying to determine how the use of the washing machine affected basement temperature. In one of her experimental runs, the Cricket recorded exactly the same temperature in a few hundred samples over an 8-hour period. She wasn’t sure if this was indeed the case or an equipment malfunction (since it seemed so improbable). Because the washing machine was not in operation that day, and neither she nor her children had gone down to the basement during the sample period, she decided it was correct data. In this as well as many other instances, the matching of experimental measurement to physical reality was complex.

Another important observation is that the real world is often much more interesting than the classroom world. All of the experiments discussed here feel very different, yet they all have to do with temperature measurements! We saw this lovely diversity of projects in part because the teachers could bring the Crickets into their lives. One of the challenges in this research program is to carry forward this engagement and enthusiasm as the materials move into a classroom setting. Part of the solution will involve teacher creativity, in developing meaningful classroom contexts, but also, exploring the possibility of middle school students bringing Crickets home and conducting experiments in their own households. This would have the added benefit of allowing parents to participate in their children’s work.

8. EDUCATION PLAN

The research program itself is based on joint work between my home department, Computer Science, and the Graduate School of Education. I will be contributing to three courses offered by the GSE, and GSE faculty and staff will be contributing to this research endeavor. Graduate students supported by the project will come from both departments, and undergraduates from Computer Science who are involved in technology development efforts will also participate in learning research activities.

As part of my longer-term objectives as a faculty at UMass Lowell, I plan the development of a new graduate/upper-level undergraduate course in Digital Media in Learning in this work plan. This course will bring together students from the Computer Science department, Graduate School of Education, and other departments across campus (e.g., Art and Regional Economic and Social Development) and will include readings, discussions, and an implementation or research project in its syllabus. It will be an introduction to the field of interactive media from a constructivist standpoint.

This project will also result in publication of design narratives that describe teachers’ and students’ work with project materials. This will occur both in an on-line format, using the internet collaboration tools that will be established for the project, as well as conventional print media.

As part of the collaboration with the Bartlett school, I will recruit Computer Science undergraduates to participate in after-school teaching with area middle school students. This will be valuable for both groups. I will seek support from local companies to provide stipends to encourage this activity.

In addition to academic publications and presentations, I anticipate significant adoption of program materials, both domestically and internationally. I will work with our commercial ventures and intellectual property licensing office to facilitate effective technology transfer from the academic to commercial realms, including both open-source and licensed designs. My past work has been quite successful in practice, and I expect this to be the same.
9. PROJECT ORGANIZATION AND MANAGEMENT

This career development plan includes resources to support two graduate researchers, one to focus on technical design (from the Computer Science department) and one to focus on learning research (from the Graduate School of Education). An undergraduate assistant will be recruited from Computer Science to contribute hardware, software, and web design expertise.

This work will be carried out in close collaboration with the Graduate School of Education. In particular, Prof. Anita Greenwood will be a close advisor to the work. Dr. Greenwood’s research area is science education, and she is a co-PI on the previously mentioned Science Education Online program. Dr. Greenwood and I will co-advice a graduate student from the GSE.

In addition, the GSE, headed by Dean Donald Pierson, will lend its full support to this work. This will include facilitating collaborations with the Bartlett PK–8 school, area schools and teachers, and its own faculty.

Dr. Alex Ballantyne, an adjunct faculty at the GSE, will participate in the work. Dr. Ballantyne has an industrial background in using computers for experimentation, is presently teaching high school physics, and is completing his doctoral work in education. He will assist the project in implementing project activities in his own classroom as well as supporting the group of teachers who becomes involved in the research program.

The international team (Prof. Dr. Heidi Schelhowe, Dr. Deirdre Butler, and Mr. Clifford Brown) will conduct activities in parallel with the work I lead in the United States. In addition to developing this related work, these faculty will act in an advisory role to the project.

The table on the following page summarizes the project’s major teaching, research, and design milestones. Each year, a cohort of teachers from GSE courses and summer professional development programs will join the project to conduct research in their own classrooms. This is indicated in the “data collection” row as cohort 1’s students (Yr 1), cohort 1–2’s students (Yr 2), etc. I anticipate that each year some teachers will join and others will leave; in the budget plan, I requests funds to support a total of 4 teachers in year 1, 8 in year 2, 12 in year 3, and 16 in each of years 4 and 5.

The teaching row appears to grow arithmetically across the years, but I do not anticipate teaching all of the courses in all of the years. As I will be co-teaching them each time that I am directly involved, I anticipate that GSE faculty will continue with the Cricket modules and teacher research activities (supported by the project graduate student) in years that I am not co-teaching a particular course. The Digital Media and Learning course will begin in year 4.

10. SUMMARY OF PRIOR WORK

The PI is an internationally recognized leader in classroom robotics technology. While a graduate student in Dr. Seymour Papert’s group at the MIT Media Laboratory, he laid the foundation for the LEGO Mindstorms Robotics Invention System, which was launched by the LEGO Group in 1998 and became a worldwide phenomenon (Martin et al., 2000). As part of his PhD dissertation, he developed the Handy Board robotics controller, and released its design with an open-source license; the technology is now in use in hundreds of high schools, colleges, and universities worldwide (Martin, 1994; Martin, 2001). As technical director on the NSF-supported project “Collaborative Research on Learning Technologies: Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Instruments,” he co-created the Handy Cricket. This work resulted in several publications, including (Resnick et al., 2000; Martin et al., 2000; Martin et al., 2000b), and forms the foundation for this career development proposal.
<table>
<thead>
<tr>
<th>Year 1 (06-07)</th>
<th>Year 2 (07-08)</th>
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<td>• Science for Secondary (525, cohort 2)</td>
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<td>• Bartlett Middle School</td>
<td>• Elementary Science (563, cohort 2)</td>
<td>• Elementary Science (563, cohort 3)</td>
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<td>• Summer PD workshop</td>
<td>• Research into Learning (online – 674, cohort 3)</td>
<td>• Summer PD workshop</td>
<td>• Research into Learning (online – 674, cohort 4)</td>
<td>• Research into Learning (online – 674, cohort 5)</td>
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<tr>
<td>Data Collection</td>
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<td>• teachers in 3 courses</td>
<td>• teachers in 3 courses</td>
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<td>• Bartlett students</td>
<td>• Cohort 1’s students</td>
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<tr>
<td>Technology Development</td>
<td>• re-engineer for reliability &amp; lower cost</td>
<td>• improve programming env based on feedback</td>
<td>• use Crickets with remote teachers</td>
<td>• re-engineer for lower cost w/new features</td>
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<tr>
<td>• port desktop app to internet</td>
<td>• implement new HW features based on feedback</td>
<td>• test new sensors</td>
<td>• organize online material based on contributed work</td>
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<td>• set up internet collaboration tech</td>
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<td>• techn to share work</td>
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<td>Research Foci</td>
<td>• teacher inquiry</td>
<td>• sensing, data, and analysis</td>
<td>• supporting teachers in bringing ideas to classroom</td>
<td>• integration of results and dissemination</td>
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<tr>
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<td>• sci content with project tools</td>
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REFERENCES CITED


