I. Project Activities and Findings

The Learning How to Learn Science (LLS) project was funded to carry out research on student learning in college (algebra-based) physics and to see whether significant improvement could be obtained in the way students in a large lecture class (150-200 students) gain a deeper understanding of science and how to learn it. We understood from previous research that student expectations play a major role in how students interpret the goals of a class, both the nature of the knowledge to be learned and what they have to do to learn it. The population for college physics consists largely of biology and health science majors whose experience with science classes tend to be dominated by the mastery of large bodies of new vocabulary and factual knowledge. We hypothesized that physics was an excellent place for students to learn modeling, organization and coherence of knowledge, the development of intuition, and the use of mathematics as an aid to thinking and reasoning (rather than just calculating).

Through a triangulation of in-class behaviors, artifacts, and individual out-of-class interviews, we demonstrated that students' expectations of what is appropriate knowledge-building behavior can vary dramatically from context to context and can create serious problems for the student in the class. We also demonstrated that changing the educational environment, even within traditional staffing and timing limitations, can dramatically improve students' willingness to undertake learning behaviors that favor sense-making and understanding.

The Learning to Learn Science Environment:
A Research Laboratory for Studying College Physics

In traditional college physics classes, the real work of student learning and knowledge construction is frequently hidden from the instructor: it occurs outside of the classroom, when students work by themselves. Students are typically passive in lecture. Recitations turn into mini-lectures led by untrained TAs in response to a few sparse student questions, and laboratories are "cookbook" – students follow detailed protocols and there is rarely any discussion, even when students work in pairs.

In the LLS project, the college physics learning environment was modified to serve as a laboratory to observe students' knowledge building and to explore the extent to which it was possible to influence their approach to learning. Much of their learning took place in the following activities where it could be observed with video data collection:

Laboratory: Traditional labs were replaced by *Scientific Community Labs* (SCL) developed as part of a dissertation (available on the web). Labs were held for periods of two hours with 20-24 students and one TA. The goal was to help students understand the construction of knowledge through measurement and analysis. Instead of being given pre-set-up apparatus and a detailed lab manual, students were given a half-page instruction sheet containing a one-sentence question that could be answered by making measurements. The students' task was to design an experiment using available equipment, make measurements, analyze the results, and present them to the class. Experiments were kept simple so as to make designing and carrying out the experiment feasible. Students worked in groups of four, wrote group reports and were evaluated on their thoughtfulness, persuasiveness, understanding of measurement concepts, and their understanding of how they could improve their experiment. There was considerable interaction and discussion among the students and with the TA.

Tutorial: Instead of a TA-led recitation, students worked through worksheet-based group-learning activities based on the model developed at the University of Washington and ones developed at the University of Maryland for a previous NSF-supported project. These tutorials were originally designed to produce strong conceptual gains and have been demonstrated to succeed in this goal, but our previous research indicated that they did not help with the development of better epistemological attitudes associated with the class. We modified ("epistemologized") these tutorials to emphasize the reconciliation of everyday, intuitive thinking and experience with formal scientific thinking and to encourage explicit epistemological discussions about the learning process. Trained facilitators wandered the room, listened, asked questions, and checked results.

Course Center Problem Solving:, The homework was modified to require more thought. Assignments included no "plug-and-chug" problems, but included complex problems, explanations, essays, estimations, and situations where there was not a single clear answer. (These are described in detail in Redish's book, *Teaching Physics*, available on the web at http://www2.physics.umd.edu/~redish/Book/04.pdf.) Since homework problems were not solved in recitation, students were offered an open lab-style room where they could come to work together on the homework and ask TAs for help. The room layout was chosen to encourage collaboration and to discourage TAs from lecturing. TAs were encouraged to guide the students with hints and questions rather than to give answers.

Lecture: Although there were 100-170 students in a lecture, the lecturer regularly held interactive demonstrations in which the students filled in worksheets, predicting and discussing the results of demonstrations. These worksheets were based on the Interactive Lecture Demonstrations of Sokoloff and Thornton, which had been demonstrated to lead to strong conceptual gains. We modified ("epistemologized") these to place a stronger emphasis on intuition building and to focus on reasoning rather than on results. In the final two years of the project, the students used wireless remote answering devices to respond to the questions. These techniques resulted in some lectures in which there was considerable discussion.

Data Collection

Artifacts: Weekly homework, lab reports, and exams were scanned for approximately 500 students throughout the four years of the project.

Video data: Student activities in authentic learning settings were videotaped. The project produced approximately 400 hours of videotape of students participating in tutorials, approximately 500 hours of videotape of students participating in laboratories, and approximately 50 hours of students working in Course Center to solve homework problems.

Survey data: All students taking the project class took surveys at the beginning and end of the first term and at the beginning of the second term. Surveys included a mechanics conceptual survey (either the FCI or FMCE) and an attitudes/expectations survey (a combination of the Maryland Physics Expectations (MPEX) Survey and the Epistemological Beliefs Assessment for Physics Science (EBAPS) Survey).

Interview data: Approximately 30 hours of one-hour semi-structured interviews were collected from volunteers at the beginning and end of the first and second terms. As a result of observations of the video data of students working in tutorials, a student with particularly interesting epistemological orientation was sought out and volunteered to provide 6 hours of interviews as a case study.

Findings of the LLS Project

1. It is possible to achieve significant gains on the Maryland Physics Expectations (MPEX) survey in a large lecture class without sacrificing conceptual gains.

The Maryland Physics Expectations (MPEX) survey was developed to probe student attitudes towards what they expected to do and learn in their physics course. Subsequent pre-post testing in dozens of first semester university physics courses with thousands of students in large classes all around the country produced an extremely robust result: students in large lecture classes scored worse after a semester of instruction than before, even in those classes with some active engagement components that produced substantial conceptual gains. (Fig. 1(a)) The only classes to produce gains on some MPEX components were Workshop Physics and two high school classes that focused on meta-learning issues.

As a result of the reformed instruction developed in LLS described above, we were able to obtain a dramatic improvement (fig 1b). These gains were obtained without sacrificing the conceptual gains that had been achieved by the previous (un-epistemologized) versions of the materials on which our reforms were based. Standard conceptual instruments (FCI, FMCE) showed very strong gains from this instruction. These are shown in figure 2, combined with the results of a previous study that focused on conceptual learning. The figure displays a histogram of the fraction of the possible gain for a "class," i.e., a section of the course run by a single professor. Each section typically included 75-175 students and had a uniform instructional method. The traditional classes showed a wide spread with a mean fractional gain (g) of about 0.20. Classes taught with a one-hour research-based active-learning intervention per week had less dispersion and a mean g of 0.34. The class from the LLS project (labeled "metalearning") has been averaging a g of about 0.47. This demonstrates that epistemological development did not come at the expense of conceptual learning.

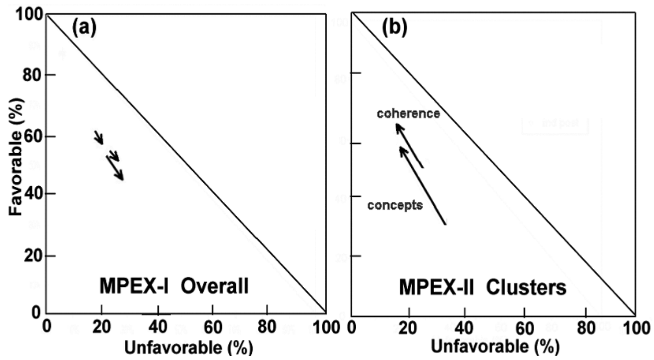

Fig.1

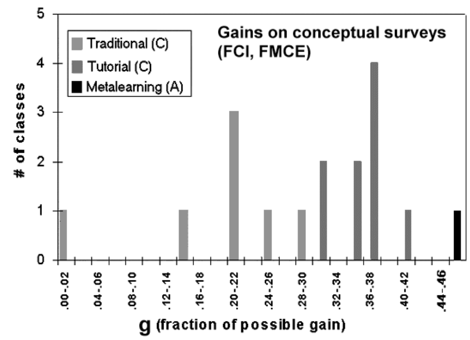

Fig. 2

Fig. 1: MPEX results. (a) summary results for 3 large classes (~500 students each) at 3 large research universities.[57] These losses are typical of large-class university physics. (b) MPEX –II cluster gains in large-class LLS college physics (2002).

Figure 2: Fraction of possible gain achieved by classes in introductory physics taught traditionally (light gray), with recitation replaced by active-learning research-based tutorials (dark gray), and for the epistemologically oriented LLS class (black)

2. Students in a traditional "cookbook" physics laboratory tend to activate unproductive authority-driven epistemological resources, whereas in more open-ended inquiry-based laboratory settings they tend to activate more constructive epistemological resources.

In the spring of 2001 we videotaped students working in traditional laboratories. These laboratories are strongly guided by detailed instructions in a comprehensive lab manual, prepared by Physics Department faculty. When the student behavior and discourse in these labs is analyzed from the point of view of source of knowledge used, we find that students access knowledge almost solely from authority (the manual, the textbook, the TA). There is almost no construction of knowledge, coherence building, or sense making. Data taken from the equipment was treated in an authoritative way, as "the right answer (unless we made a mistake)." The lessons about the nature of measurement (need for repeated measurements, range of variation, limitations on repeatability, etc.) were ignored and calculations of averages and standard deviations built into the lesson were performed without any thought or understanding of why those calculations were done.

To try to overcome the barrenness of student epistemological response in this environment, some TAs were given the flexibility to vary the lab structure. When the lab manual was taken away and students only given the task and the equipment, they responded by accessing much richer sources of knowledge including social (group) construction and sense making.

As a result of these observations, we decided to undertake modifications of the laboratory not originally planned as part of the project and created the Scientific Community Labs (SCL) described above. These laboratories present the students with a task and equipment but no protocol. Students have to build an understanding of how a measurement can answer a question. The lab's social interactions are explicitly structured and the lab tasks are designed to help foster understanding of the nature of measurement.

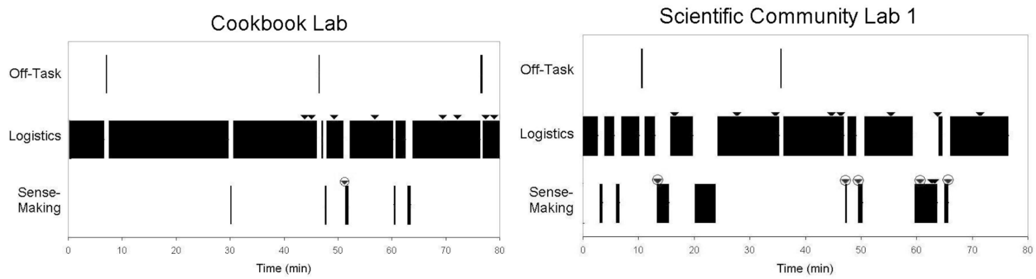

Fig. 3: Discourse analysis of a traditional "cookbook" lab and a scientific community lab showing a track of the time when group discourse was off-task, engaged in logistics, or focused on sense-making. Metacognitive statements are marked by small triangles. Metacognitive statements that are productive in changing the mode are circled. These results are typical.

When traditional protocol-based laboratories are replaced by our SCL, a discourse analysis of student interactions shows dramatic increases in the fraction of time spent in sense-making behavior (see fig. 3) and in the effectiveness of metacognitive statements in moving students into sense-making mode. (For results from the LLS project, see papers and talks at http://www.physics.umd.edu/perg/role/rolepandt.htm.)

3. Students" epistemological stances ("frames") can vary from one instructional environment to another and can affect what they take away from that instruction, including their conceptual learning.

From our video observations of student interactions in both tutorial and laboratory environments, it was clear that students brought different assumptions as to how knowledge was to be obtained to each environment. Furthermore, different students brought different assumptions and felt that it was appropriate to use different epistemological resources. Simply putting them together in a group environment was not sufficient to change these epistemological stances.

In the tutorial environment, inappropriate student expectations concerning the nature of knowledge and knowledge generation appeared to be a significant cause of difficulty and student resistance.

In reviewing our tapes of student work in tutorials, one student seemed to present a particularly clear example of this syndrome, insisting on formal reasoning and actively suppressing the rational sense-making arguments put forward by another member of her group. We approached this student and she volunteered to undergo a series of six hours of interviews after the conclusion of the class. In these interviews we explored her reasoning and problem solving. She clearly demonstrated the ability to reason physically and to apply sense-making arguments to physical problems when they were presented outside the context of the class.

This case study provides a clean example of the context dependence of student epistemologies. A paper on this study was published in the American Journal of Physics. It provides strong support for the resource model of student epistemologies described below.

4. In solving reasonably complex physics problems (e.g., that involve both conceptual and quantitative components), students tend to access a coherent set of reasoning and problem solving tools ("moves") that they deem appropriate for the task that they identify as a local goal. The (tacit) choice to engage in one of these coherent activities ("epistemic games") limits the student's repertoire of tools and may lead to serious difficulty.

As a result of the class environment, students in the LLS class became accustomed to working in groups and spending extended amounts of time — as much as 1-2 hours — solving and making sense of a single problem. The videotapes of students working together in the Course Center and tutorials indicated that students" functional epistemologies (what they deemed was the nature of the knowledge they were constructing and the tools appropriate to construct it) played a powerful role in determining how they approached problem solving and the use of mathematics in physics.

For his dissertation, Jonathan Tuminaro studied students working on problems in the course center and tutorials. He observed that students often used a limited repertoire of tools and reasoning on a part of a problem for extended periods of time. We refer to these coherent knowledge-creating activities as "epistemic games." (Note that our epistemic games are ethnographically descriptive rather than normative.)

We identified six epistemic games that described most student problem-solving behavior observed in approximately 50 hours of Course Center videotapes: Mapping Meaning to Mathematics, Mapping Mathematics to Meaning, Physical Mechanism, Pictorial Analysis, Recursive Plug-and-Chug, and Transliteration to Mathematics.

Students made an, often tacit, choice of which games to play. We refer to this process as "epistemological framing." Sometimes, inappropriate epistemological framing led the students to play the wrong epistemic game and resulted in what would typically appear to an instructor to be bizarre behavior. The language of games and frames allows us to frame hypotheses that makes this behavior seem much more plausible and natural.

Training and Development

Five graduate students and three postdoctoral associates in physics have been associated with the project. All have been trained in educational research skills including: semi-structured and demonstration interviews, survey development, and discourse analysis. The training activities included a seminar class in cognitive theory of education, a seminar in research methods in education research, and regular group meetings in which the junior staff presented and critiqued each other"s work. In addition, both students and postdocs attend a regular weekly seminar in which local and visiting specialist present current research topics. Two of the students have completed dissertations. One has gone on to a visiting faculty position in Sweden, the other to a law firm. One of the postdocs (Lising) has gone on to a faculty position at Towson University. The other two remain at Maryland and have been promoted to Assistant Research Professor (Scherr) and Assistant Research Scientist (Elby).

Although the project was a research and not a development project, the results of our research and associated curriculum modifications led to our writing a proposal to develop materials. This proposal was submitted to the NSF/CCLI competition and was awarded in the Spring of 2005 for the development of epistemological tutorials and a training environment for learning to use them. (A. Elby, PI)

II. Contributions

a. Contributions within Discipline

Our primary discipline is physics education research, a discipline-based interdisciplinary activity carrying out education research with and for teachers of physics at the high school, college, and university level. The type of contributions that further the discipline include publishing papers in journals, books, and conference proceedings, and presenting the results of our research at general conferences of physics teachers, at specialized research conferences, at summer schools, and at research seminars and physics department colloquia.

During the calendar years 2001-2005, the members of the research team for this project reported on their work in the following venues:

-- American Association of Physics Teachers (AAPT) National Meetings:

8 invited talks, 27 contributed talks, 1 workshop

-- Regional AAPT meetings:

3 invited talks

-- Other National and International Physics Meetings

13 invited talks, 2 invited workshops

-- National Education Meetings (AERA, NARST, and regional meetings)

9 invited talks, 2, workshops, 1 extended poster session (5 posters)

-- Seminars and Colloquia at Education Schools and Departments

2 seminars, 1 extended lecture series and workshop

-- Colloquia at Physics Departments

2 seminars, 18 colloquia (seminars are directed at a single research group, colloquia to an entire department)

Presentations included:

At the national AAPT meeting in Rochester, NY in August 2001

A. Elby and L. Lising, "The importance of epistemological considerations in fostering conceptual development" (invited)

E. Redish, R. Lippmann, and L. Lising, "Improving Student Expectations in a Large Lecture Class" (contributed)

R. Lippmann, E. Redish, and L. Lising, "I"m fine with having to think as long as I still get an "A": What students in a modified physics class think about learning" (contributed)

L. Lising, E. Redish, and R. Lippmann, "Analyzing Student Discourse from an Epistemological Perspective – What Can We Learn?" (contributed)

At the AAPT national meeting in Philadelphia, PA in January 2002

R. Scherr, "Coordinating theoretical models of student reasoning with evidence: An example from special relativity" (invited)

D. Hammer and E. Redish, "Design Implications of a Resources-Based Perspective on Student Knowledge and Reasoning" (contributed)

A. Elby and R. Scherr, "Bringing Epistemological Considerations to Tutorial Design" (contributed)

L. Lising and R. Lippmann, " Bringing Epistemological Considerations to Interactive Lecture Demonstrations" (contributed)

R. Lippmann , E. Redish , L. Rana , L. Lising , and A. Elby, "Designing Laboratories to Focus on Epistemology and Measurement" (contributed)

At the AAPT national meeting in Boise, ID, August 2002

J. Tuminaro, "A Framework for Describing Common Mathematical Errors Students Make in Introductory Physics" (contributed)

R.E. Scherr, A. Elby, and S. M. Snowman, "Epistemological considerations in analogical modeling laboratories" (contributed)

R.E. Scherr, "Modeling student reasoning in physics: An example from special relativity" (poster)

R.E. Scherr and M. C. Wittmann, "The challenge of listening: The effect of researcher agenda on data collection and interpretation" (poster)

M. C. Wittmann and R.E. Scherr, "Epistemology mediating conceptual knowledge: Constraints on data accessible from interviews" (poster)

At the AAPT national meeting in Austin, TX, January 2003

R.E. Scherr, "Questioning the questions: Playing with constraints in physics education research" (invited)

R.E. Scherr and M. C. Wittmann, "The challenge of listening: Selective attention in clinical interviews" (invited)

M. C. Wittmann and R.E. Scherr, "Epistemology mediating conceptual knowledge: Constraints on data accessible from interviews" (invited)

N. Gillespie, M. C. Wittmann and R.E. Scherr, "The negotiation of relevance: student inference in clinical interviews" (invited)

T. McCaskey, A. Elby, R. Lippmann, and E. F. Redish, The MPEX 2: Modification of a survey instrument (contributed)

J. Tuminaro and E. F. Redish, A Framework for Understanding the Role of Mathematics in Physics (contributed)

R. Lippmann and E. Redish, Concepts for Building an Understanding of Uncertainty (contributed)

P. Gresser and E. Redish, New Way for Students to Plan and Understand Laboratory Experiments (contributed) (15 minutes)

E. Redish, Influence of the Research Agenda on Data Collection, Analysis, and Interpretation: Part 1 – the clinical interview, (discussant)

A. Elby, B. Birkett, R. Scherr, and E. Redish, Bringing Epistemological Considerations to Your Introductory Physics Course, workshop at AAPT National Meeting, Austin TX, January 12, 2003 (4 hours).

At the AAPT national meeting in Madison, WI, August 2003

J. Tuminaro and E. F. Redish, Understanding Students" Poor Performance on Mathematical Problem Solving in Physics (contributed)

E. F. Redish, T. McCaskey, D. Hammer, A. Elby, and L. Lising, Epistemological gains in a large lecture class (contributed)

R. Hodges, Physicists" Epistemology of Quantum Mechanics (contributed)

T. McCaskey, M. Dancy, and A. Elby, Belief vs. "Scientists" Answers": Effect on Assessment (contributed)

R.E. Scherr., "Gestures as evidence of student thinking in physics" (contributed with poster)

D. Hammer and R.E. Scherr, "An epistemological intervention with big results" (contributed)

At the AAPT national meeting in Miami Beach, FL, January 2004

R. Scherr and J. Tuminaro, Student patterns of knowledge construction (contributed)

T. McCaskey and A. Elby, Belief vs. "Understanding": Why do students "split" on the FCI? (contributed)

J. Tuminaro, E. F. Redish, and R. Scherr, Two kinds of student mathematical errors in physics: A theoretical perspective (contributed)

P. W. Gresser and E. F. Redish, "What Are We Doing Here in This Lab?" (contributed)

At the AAPT national meeting in Sacramento, CA, August 2004

D. A. Hammer, A. Elby, R. Scherr, and E. F. Redish, Resources, Framing, and Transfer (invited) (30 minutes)

A. Elby, T. McCaskey, and E. F. Redish, Cognitive Models Matter for Creating and Interpreting Classroom Measurements (invited) (30 minutes)

Talks at regional AAPT Meetings

E. Redish, Teaching Physics for Other Sciences And Engineering: What Do We Have to Offer? Keynote address, Florida regional AAPT meeting, University of Central Florida, Orlando FL, April 13, 2002. (1 hour)

E. Redish, Our Model of How a Student "Works": Does It Matter for Teaching Physics? Plenary address, joint meeting of Texas Section of the AAPT, the Texas Section of the APS, and Zone 13 of the SPS, Southwest Texas State University, San Marcos, TX, March 8, 2003. (1 hour)

E. Redish, Our Model of How a Student "Works": Does It Matter for Teaching Physics? Banquet talk, Chesapeake Section regional AAPT meeting, Towson University, Baltimore, MD, April 11, 2003. (1 hour)

Talks at Physics Conferences

E. Redish, Thinking About Thinking: Making the Transition from Classical to Quantum Physics, invited talk, Gordon Research Conference on Physics Research and Education: Quantum Mechanics, Hadley, MA, June 9, 2002. (1 hour)

R.E. Scherr and S. Vokos, Properties of student reasoning in special relativity, invited talk, Gordon Conference on Physics Research and Education: Quantum Mechanics, Hadley, MA, June, 2002. (1 hour)

D. Hammer, The Variability of Student Reasoning. Lecture 1: Case studies of children's inquiries, Summer School, "Enrico Fermi" Course CLVI, Italian Physical Society, August, Varenna, Italy, August, 2003. (1 hour)

D. Hammer, The Variability of Student Reasoning. Lecture 2: Transitions, Summer School, "Enrico Fermi" Course CLVI, Italian Physical Society, August, Varenna, Italy, August, 2003. (1 hour)

D. Hammer, The Variability of Student Reasoning. Lecture 3: Manifold cognitive resources, Summer School, "Enrico Fermi" Course CLVI, Italian Physical Society, August, Varenna, Italy, August, 2003. (1 hour)

E. Redish, A Theoretical Framework for Physics Education Research: Modeling student thinking, Summer School, "Enrico Fermi" Course CLVI, Italian Physical Society, August, Varenna, Italy, August, 2003. (3 hours)

L. Lising and A. Elby, The impact of epistemology on learning: A case study from introductory physics, Summer School, "Enrico Fermi" Course CLVI, Italian Physical Society, August, Varenna, Italy, August, 2003 (20 minutes)

R.E. Scherr, Gestures as evidence of student thinking in physics, Summer School, "Enrico Fermi" Course CLVI, Italian Physical Society, August, Varenna, Italy, August, 2003 (20 minutes)

E. Redish, The Future of Physics Education: Building an Applied Science, invited plenary talk, Joint APS/AAPT regional meeting, Berkeley, CA, November 15, 2003. (1 hour)

E. Redish, Research Based Pedagogies: Beyond Content, Part 1: Epistemology, A. Elby, E. F. Redish, and R. E. Scherr, PART 2: Problem Solving, E. F Redish and J. Tuminaro, invited workshop, Ontario Association of Physics Teachers, University of Ontario Institute of Technology, Oshawa, Canada, May 28, 2004. (2 hours)

E. Redish, Changing Student Ways of Knowing: What Should our Students Learn in a Physics Class? E. F. Redish, invited seminar, Ontario Association of Physics Teachers, University of Ontario Institute of Technology, Oshawa, Canada, May 28, 2004. (45 minutes)

E. Redish, Changing Student Ways of Knowing: What Should Our Students Learn in a Physics Class? E. F. Redish, invited seminar, Symposium on physics education: Meeting the challenges of university of physics education, University of Lund, Sweden, June 3, 2004. (50 minutes)

R. L. Kung and E. F. Redish, Alternative Ways of Approaching Student Learning in Physics, invited workshop, Symposium on the Scholarship of Physics Teaching – Looking at Alternative Ways of Teaching Physics, Uppsala University, Sweden, June 1, 2004. (2 hours)

Talks and Sessions at Education Conferences

Hammer, D. (2001). Preparing teachers as diagnosticians—the case of science, invited, AERA

We proposed and had accepted a symposium for presentation at the 2002 Annual Meeting of the American Educational Research Association, titled "Epistemological resources and curriculum reform in introductory physics," with presentations:

D. Hammer, "Epistemological resources and contexts" (contributed)

A. Elby, "The importance of attending to epistemology in curriculum development" (contributed)

L. Lising and A. Elby, "What Jan tells us about student epistemologies" (contributed)

R. Lippmann, "Analyzing student epistemologies during laboratory activities" (contributed)

E. Redish, "Negotiating expectations in a large introductory physics course" (contributed)

E. Redish, Metacognition and instructional design: Theory-driven goals and methods in a large university physics class Edward F. Redish, invited presentation, Ganiel Symposium, Rehovoth, Israel, September 12, 2001 (45 minutes)

E. Redish, Our Model of How a Student "Works": Does It Matter for Teaching Science? Keynote address, Conference on Integrating Science and Mathematics Education Research into Teaching, Orono, ME, June 23, 2002. (1 hour)

R.E. Scherr and M.C. Wittmann, "The challenge of listening: An individual student interview about current flow," Conference on Integrating Science and Mathematics Education Research into Teaching, Orono, ME, June 23, 2002 (contributed with poster)

E. Redish, Developing Student Expectations in Algebra-Based Physics, invited talk, Conference on Integrating Science and Mathematics Education Research into Teaching, Orono, ME, June 23, 2002. (30 minutes)

D. Hammer, Epistemological resources, invited talk, 2003 Meeting of the National Association for Research in Science Teaching.

D. Hammer, Multiple local coherences in student epistemologies, invited talk, 2004 Annual Meeting of the American Educational Research Association.

D. Hammer, Discussant for symposium, "Exploring Issues of Epistemology in Contemporary, Non-majority Communities of Practice." 2004 Annual Meeting of the American Educational Research Association.

E. Redish, Deconstructing problem solving in algebra-based physics, workshop, NARST National Meeting, Dallas, TX, April 5, 2005.

E. Redish, How we think: should a teacher care? banquet talk presented to Chicago Symposium Series, Excellence in Teaching Mathematics and Science: Research and Practice, DePaul University, Chicago, IL, February 4, 2005.

E. Redish, M. Sabella, and R. Lippmann-Kung, Free-range laboratories: can less guidance lead to more engagment and learning? workshop presented to Chicago Symposium Series, Excellence in Teaching Mathematics and Science: Research and Practice, DePaul University, Chicago, IL, February 4, 2005.

E. Redish, How students "work": should a teacher care? plenary talk presented at the Auburn University "Dead Day" Symposium, Auburn, AL, May 4, 2005.

Seminars and Colloquia at Education Departments

E. Redish, Learning About Teaching Physics, a 3 week series of lectures and workshops for math education students, Education School, University of Pavia, Pavia, Italy, May 2-18, 2000. (15 hours)

E. Redish, The Implication of a Cognitive Model for Instructional Design, seminar, University of Maryland School of Education, November 16, 2001 (50 minutes)

D. Hammer, Variability and local coherences of K-16 student reasoning in physics. University of California, Berkeley, Education in Mathematics, Science, and Technology Colloquium. October 4, 2004.

Seminars and Colloquia at Physics Departments

Redish, E., The Science in the Art of Teaching Physics: What do we learn from physics education research? Colloquium, Physics Department, Rutgers University, November 14, 2001.

Redish, E., What can we usefully accomplish in algebra-based physics? Seminar, Physics Department, The Ohio State University, April 23, 2001.

E. Redish, The Science in the Art of Teaching Physics — What Do We Learn from Physics Education Research? colloquium, Physics Department, Rutgers University, New Brunswick NJ, November 14, 2001.

E. Redish, The Hidden Curriculum: What Do We Really Want Our Students to Learn? colloquium, Physics Department, University of Delaware, Dover, DE, May 2, 2001.

Hammer, D. Student resources for learning introductory physics, colloquium, Department of Physics and Astronomy University of Maine, December 7, 2001.

E. Redish, What Can We Usefully Accomplish in Algebra-Based Physics? colloquium, Physics Department, The Ohio State University, Columbus OH, April 23, 2001.

E. Redish, Teaching Physics for Other Sciences and Engineering: What Do We Have to Offer? Physics Club, Yale University, New Haven CT, February 8, 2002.

E. Redish, Rethinking The Algebra-Based Physics Course: Can Physics Offer Something Useful? colloquium, Physics Department, University of Illinois Urbana-Champagne, Champagne IL, March 14, 2002.

E. Redish, The Hidden Curriculum: What Do We Really Want Our Students to Learn? colloquium, Physics Department, McGill University, Montreal, Canada, April 26, 2002.

R. E. Scherr, Modeling student reasoning in physics: An example from special relativity, colloquium, Physics Department, University of Maine, Orono, ME, May 2002.

E. Redish, The Hidden Curriculum: What Do We Really Want Our Students to Learn? colloquium, Physics Department, Kent State University, Kent, Ohio, November 14, 2002.

R. E. Scherr, Modeling student reasoning in physics: An example from special relativity, colloquium, Physics Department, Rochester Institute of Technology, Rochester, NY, October 2002.

R.E. Scherr, Gestures as evidence of student thinking in physics, Physics Education Research Seminar, The Ohio State University, Columbus, OH, March 2003.

D. Hammer, Hearing the science in students" thinking. Planetary Astronomy Lunch Seminar, University of Maryland, College Park, MD, May 5, 2004.

D. Hammer, What is physics education research and who does it? Department of Physics colloquium, University of Maryland, College Park, MD, September 14, 2004.

E. Redish, The Hidden Curriculum: What Do We Really Want Our Students to Learn? colloquium, Virginia Tech, Blacksburg, VA, March 5, 2004

E. Redish, Changing Student Ways of Knowing: What Should Our Students Learn in a Physics Class? colloquium, University of Toronto, Toronto, Canada, May 27, 2004.

E. Redish, Using Math In Physics: How Can We Better Help Our Students Learn To Solve Problems? colloquium, Purdue University, Lafayette, IN, September 23, 2004.

E. Redish, Using Math In Physics: How Can We Better Help Our Students Learn to Solve Problems? colloquium, Washington University, St. Louis, MO, November 17, 2004.

E. Redish, Problem solving and the use of math in physics courses, colloquium, CCNY, New York, NY, March 9, 2005.

b. Contributions to Other Disciplines

Physics education research (PER) is seen in many disciplines of science as the most fully developed of the discipline-based science education research fields. As a leading group in PER, our group members are in considerable demand as presenters and discussants at meetings of other STEM disciplines attempting to vitalize discipline-based education research in their areas. Members of the project have been invited to and participated or presented at 12 meetings of other disciplines including astronomy, geosciences, and university wide centers of teaching and learning. The PI of this project has been invited to serve on the advisory board for CASEE (the Center for the Advancement of Science and Engineering Education) and is a member of the Colloquy in Engineering Education Research team. He has been invited to present talks to the NSF HER/CMPS symposium, to the Board on Science Education, and to the CASEE advisors overviewing physics education research.

Talks and workshops for other disciplines and interdisciplinary meetings

E. Redish, What Can Astronomy Education Learn from Physics Education Research? invited talk, AAPT National meeting, San Diego, CA, January 10, 2001 (30 minutes)

E. Redish, Building a Science of Teaching, Scholarship of Teaching and Learning Seminar, Indiana University, Bloomington IN, February 20, 2001 (90 minutes)

E. Redish, The Scholarship of Teaching: An Example from Physics, invited seminar, Center for Teaching Excellence, University of Maryland, February 12, 2001 (30 minutes)

E. Redish, Astro 101: Rethinking The Goals, invited seminar presented at meeting of Astronomy Department Chairs, Berkeley CA, May 11, 2001.

E. Redish, What Can Astronomy Education Learn from Physics Education Research? invited talk, AAPT National meeting, San Diego, CA, January 10, 2001. (30 minutes)

E. Redish, Overview of Physics Education Research, presenter and discussion leader, Wingspread Conference on Education in the Geosciences, Racine, WI, July 8, 2002.

E. Redish, Discipline-Based Educational Research: A (Theoretical) Physicist"s Perspective, NSF Symposium for the joint EHR/CMPS Advisory Boards, Washington, DC, November 7, 2002. (30 minutes)

E. Redish, Panelist, Peer Review of Education Research Grant Applications Implications, Considerations, and Future Directions, National Academy of Sciences, Washington DC, February 25, 2003.

D. Hammer, Inspirational closing remarks. Towson University, Department of Physics, Astronomy, and Geosciences. Scientific Inquiry Workshop, January 22, 2004.

D. Hammer, Discovery learning and discovery teaching. National Academy of Sciences Board on Science Education, Committee on High School Science Labs, March 29, 2004.

E. F. Redish, Physics Education Research: A Personal Historic Overview, invited talk, meeting of the Advisory Board of the Center for the Advancement of Science and Engineering Education (CASEE), Savannah, GA, October 19, 2004 (50 minutes)

E. Redish, Discipline-Based Science Education Research: The Interplay of Teaching And Research, invited talk, meeting of the Board on Science Education (BOSE) of the National Academy of Sciences, Irvine, CA, December 3, 2004 (30 minutes)

c. Contributions to Human Resource Development

The primary goal of this project is to improve human resource development in science by improving our understanding of the difficulties students (especially students in biology) face in learning science. The project's findings and development of materials (preliminary in this project, to be continued in a CCLI grant that grew out of this research) should directly help to improve human resources in science. During the term of the project, about 750 students took our reformed physics course. These students showed substantially higher gains in traditional measure of success in physics (FCI and MPEX) than do students in traditional courses.

This project also explicitly contributes to human resource development in STEM through the training of graduate students and postdoctoral associates in physics education research. The project supported 3 postdoctoral associates (some part time) and 5 graduate students. Two of the postdoctoral associates remain with us, having been promoted to research track faculty positions. One of the postdoctoral associates got a tenure-track faculty position at Towson University. All three remain active in research and have successfully submitted their own proposals for funding. Two of the graduate students have completed their dissertations and a third is expected to complete his work in the fall of 2005. One of the completed students has a faculty position in the physics department at Uppsalla University; the other has taken a position in a law firm working on patent law.

d. Contributions to Resources for Research and Education

An important contribution that the results from this project are potentially making to the resources for research (and in particular for research in education) is the beginning of the development of a coherent theoretical framework for educational research. This framework relies on a triangulation of results in neuroscience, cognitive science, and behavioral science for its general principles. The framework provides a mid-level set of structures of association and control that can serve as tools for building models of thinking and learning in science education. Although this development is in early stages (and only a few papers have been peer reviewed and published), this structure looks very promising for synthesizing some of the best results from many workers in education and for providing guidance for future research.

The research carried out for this project has led to four new projects:

- for transforming the ideas developed in this project into practice
  (CCLI grant DUE-0341447),
- for extending the research to upper division students
  (DTS grant DUE-0524987),
- for studying TA training and developing TA training materials
  (ROLE grant REC-0529482), and
- for extending and deepening the research results, combining it with K-12 studies to produce a more global understanding of student learning of science
  (ROLE grant REC-0440113).

In addition, we are aware of a number of other research groups who are now carrying out research projects built on our results. These include researchers at the University of Colorado, the University of Maine, the University of New Hampshire, Grand Valley State University, and Loyola Maryount University (Los Angeles).