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Learning How to Learn Science: Physics for bioscience majors

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Physics for Bioscience Majors

A Proposal Submitted to the National Science Foundation
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Project Summary

The impact of technology on the workplace has been dramatic. Large numbers of workers use the fruits of science every day, and, as the advance of science continues with no letup in sight, these workers must advance with it, learning new tools and techniques. Yet much of our instruction in science has changed only superficially, especially at the college level where most technical professionals receive the bulk of their scientific training. The issue “What is it that our students really need to learn today and for their future careers?” is rarely discussed in the delivery of large-lecture service courses, even when those courses are being reformed.

For those students who are going on to work in biology or in health care delivery, a good understanding of the underlying ideas is vital. In the next 20-50 years, the biological professions will be increasingly reliant on an understanding of physical and chemical mechanisms and on ever-more sophisticated probes into those mechanisms. Today, however, many biology majors are strong in biology and chemistry but weak in physics and mathematics. This can be limiting and even dangerous. Researchers who don’t understand the way their instruments work cannot use them creatively and effectively. Technologists who don’t understand the motivation for safety protocols are more likely to ignore them under stress.

At present, traditional instruction in the algebra-based physics class taught for these students is less effective and less well studied than the calculus-based class, where considerable reform has taken place. A reformed physics class could play a significant role in helping students in the biosciences learn to understand scientific thinking; but to address these issues, explicit instruction in “meta-learning” is needed. This includes metacognition, epistemologies, expectations, and the construction of broad and powerful mental models – learning that goes beyond content and helps students understand what it means to learn science and how to learn it effectively.

Over the past fifteen years, research has demonstrated the importance of meta-learning in the teaching of science and mathematics. But almost all of the effort has been on pre-college small-class environments. There has been little or no development of approaches that are appropriate for the large classes in which algebra-based physics is taught, little work on how to measure the students’ development in meta-learning, and little understanding of how meta-learning skills can be affected by instructional activities in large classes.

In this project, a cross-disciplinary team of the University of Maryland Physics Education Research Group (UMd PERG), working with an advisory team of biologists and biology-oriented education specialists proposes to

- carry out basic research in science learning among college-level bioscience students,
- study student learning of fundamental issues in thinking about science,
- modify current best-practices learning environments to make them effective tools for teaching meta-learning in a large-lecture environment; and
- develop survey tools that will permit the documentation and evaluation of the state of student meta-learning attitudes and skills in large classes.

Our work is strongly guided by a theoretical frame we draw from cognitive science, neuroscience, and education researchers. The critical insight of this theoretical frame is that knowledge is comprised of resources and that reasoning largely entails the selection and coordination of these resources. It is thus essential to study and address how students conduct that selection and coordination. This is the focus of our research: How do students select and coordinate their cognitive resources? And how can instruction help students develop more sophisticated beliefs and strategies for learning?

The proposed project builds on a decade of work done by the UMd PERG in studying student meta-learning in high-school and calculus-based university physics classes. We will develop learning environments based on best-practice curricula that have been demonstrated to be a cost effective way of improving student concept learning in large lecture classes. Our preliminary attempts to reconfigure these environments to focus on meta-learning using insights developed from our theoretical model of student resources suggest the possibility of dramatic improvements in student attitudes, approaches to learning, and growth in understanding basic concepts. Finally, we will adapt instruments that we have developed to allow us to document and evaluate the state of student meta-learning in science in large classes.

The graduate students and postdocs who will work on this project will have the opportunity to integrate their physics and educational research and become the badly needed next generation of educational researchers bridging education and the scientific disciplines.

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1. Introduction and Overview

The impact of technology on the workplace has been dramatic. Across a range of established and emerging industries, large numbers of workers use the fruits of science every day, and, as the advance of science continues with no letup in sight, these workers must advance with it, learning new tools and techniques. Yet much of our instruction in science has changed only superficially, especially at the college level where most technical professionals receive the bulk of their scientific training. The issue "What is it that our students really need to learn today and for their future careers?" is rarely discussed in the delivery of large-lecture service courses, even when those courses are being reformed.

Two years ago, Bruce Alberts, President of the National Academy of Sciences and a leading research biologist, discussed the preparation of the next generation of biologists in an article in *Cell.* In it, he said

> *[T]he students of today will carry out most of their research in a post-genome sequencing era, when most of the advances in molecular biology will come from successfully dissecting complicated in-vitro systems….Here, a deep understanding of the key constraints on the system posed by thermodynamic and kinetic factors, as well as an ability to use new developments in chemistry and physics as appropriate tools, will often be vital for success.*
>
> *From my point of view, the education that we are offering today to young biologists in our colleges and universities is in need of a major rethinking….Most important for the future of our field, the departmental structures at most universities seem to have thus far prevented any major rethinking of what preparation in mathematics, in physics, and what preparation in chemistry is most appropriate for either the research biologists or the medical doctors who will be working 10 or 20 years from now. The result is a major mismatch between what today's students who are interested in biology should be learning and the actual course offerings that are available to them*. [Al]

In this project, a cross-disciplinary team of the University of Maryland Physics Education Research Group (UMd PERG), working with an advisory team of biologists and biology-oriented education specialists proposes to

- carry out basic research in science learning among college-level bioscience students,
- study student learning of fundamental issues in thinking about science,
- develop new learning environments that can be used in a large-lecture college or university environment for teaching physics to biology majors and pre-meds; and
- develop survey tools that will permit the documentation and evaluation of the state of student meta-learning attitudes and skills in large classes, and enable us to understand the character of the population of biology students compared to engineers and other scientists.

The central premises of this proposal are (1) that physics can play a significant role in helping students in the biosciences learn to understand scientific thinking; and (2) that to address these issues, explicit instruction in "meta-learning" is needed. By *meta-learning* we mean metacognition, epistemologies, expectations, and the construction of broad and powerful mental models – learning that goes beyond content and helps students understand the nature of scientific thought.

The UMd-PERG is a group of education researchers in the Physics Department and in the Education School who have been carrying out research and development in student learning for about a decade. Our research has focused on three areas: (1) understanding the role played in science learning by student meta-learning, especially epistemologies; (2) developing classroom materials and environments that foster the learning of concepts and students' epistemologies; and (3) evaluating different learning environments on a large scale, studying both concept learning and expectations. We have collected data from over 6000 students at more than two-dozen colleges and universities. (See section #4.)

Our work is strongly guided by a theoretical frame we draw from an alignment of ideas from cognitive science [Bad] [No1], neuroscience [Sh2] [No2], and education research. [dS] [dSS] The critical insight of this theoretical frame is that knowledge is comprised of productive resources and that reasoning largely entails the selection and coordination of these resources. Learning in physics, on this view, involves learning to manipulate and reorganize existing resources. It is thus essential to study and address how students conduct that selection and coordination. This is the focus of our research: How do students select and coordinate their cognitive resources? What do they know about learning ("meta-learning")? And how can instruction address this knowledge? In short, how can instruction, as a direct objective, help students develop more sophisticated beliefs and strategies for learning?

In this project, we will be developing learning environments based on best-practice curricula, including *Tutorials in Introductory Physics*,[McD4] *Group Problem Solving*,[He] and *Interactive Lecture Demonstrations*.[Sok1] These environments have been demonstrated to be a cost effective way of improving student concept learning in large lecture classes.[Red3] [McD3] [Sok3] We will adapt them to focus on achieving meta-learning goals. Preliminary results (described below) indicate that this can be done without a loss in concept learning. Finally, we will adapt existing instruments that we have developed [Red4] to allow us to document and evaluate the state of student meta-learning in science in large classes. (See section #5A-(3).)

2. Motivation

In this section, we make the case that the project is important and significant. In outline:

- As a result of the growth of technology, students in the biological and health sciences need a more solid science education than ever before.
- Traditional instruction in the algebra-based physics class taught for these students is less well-studied than the calculus-based class for engineers, where considerable reform has taken place.
- Physics can be one of the best classes in which students can learn about the nature of science.
- Building life-long learning skills in science requires a focus on meta-learning.

Over the past fifteen years, a considerable amount of work has demonstrated the importance of meta-learning in the teaching of science and mathematics. [Sch1] [Sch2] [Chi] [Gu] [WhG] [Res] [Wh2]. But almost all of the effort has been on pre-college small-class environments. There has been little or no development of approaches that are appropriate for the large classes in which algebra-based physics is taught, little work on how to measure the students' development in meta-learning, and little understanding of how meta-learning skills can be affected by instructional activities in large classes. In the remainder of the proposal we will describe how this situation can be improved and why we are the right group to do it.

Students in medicine and the biosciences need more solid science education than ever before.

For those students who are going on to work with technology in biology or in health care delivery, a good understanding of the underlying ideas is vital. Research in the biosciences is becoming increasingly technology driven and increasingly based on a good knowledge of physics. Today's bioscience students will use complex instruments based on sophisticated physics, such as fMRI scanners or mass spectrometers. They must have some idea how their tools work in order to understand what the tools can do and under what situations the tools can be expected to mislead or fail. Furthermore, as the scientific underpinnings of biology become increasingly strong, an understanding of the fundamental physics constraining the biology becomes increasingly important. Harold Varmus, director of NIH, stresses the importance of physics in the coming developments in biology.[V]

In the next 20-50 years, the biological professions including health-care will be increasingly reliant on an understanding of physical and chemical mechanisms and on ever-more sophisticated probes into those mechanisms. Today, however, many biology majors are strong in biology and chemistry but weak in physics and mathematics. This can be limiting and even dangerous. Researchers who don't understand the way their instruments work cannot use them creatively and effectively. Technologists who don't understand the motivation for safety protocols are more likely to ignore them under stress.[1]

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[1] Last year, workers at a Japanese nuclear power plant violated protocols and safety regulations "in order to transport uranium more easily" and wound up producing a near critical mass. The resulting radiation injured hundreds and caused the death of two workers.[ABC]

The building of solid scientific understanding is also of great importance for health-care workers. Recent studies of the health care system document the immense cost of medical errors.[K] Some of these problems can be solved by systemic changes (such as not having medical residents on shift for 36 consecutive hours).[Bo] But some errors come from the fact that many people in the health care system do not understand what they are doing. Although protocols and checking are necessary and helpful, human beings are not cogs in production machinery. It is almost impossible to create effective procedures that protect against all error. First, human beings are prone to error, especially when they may not be aware which errors are irrelevant and which critical. Second, human beings have free will. Given any protocol, if the people supposed to carry it out do not understand the reason for it, they may well choose to ignore even the most stringently imposed protocols "in order to make their jobs easier." An essential component of a well-functioning system is workers who understand what they are doing and why.[2]

Traditional instructional methods in algebra-based physics are ineffective and have lagged behind the developments in the calculus-based physics course.

A number of circumstances make it particularly important to analyze, understand, and improve the effectiveness of algebra-based physics, the physics course most commonly taken by pre-med and bioscience students. In the last decade, a large body of research on calculus-based physics for engineers has demonstrated that the traditional approach is ineffective in providing either conceptual learning or improvement in student understanding of the nature of science and science learning.[McD2] We expect that the algebra-based physics class typically taken by bioscience students is even less effective for biologists than the traditional calculus-based physics class is for engineers. First, the algebra-based physics population differs from the engineers. They tend to have less skill in mathematics and less hands-on experience with equipment. Second, the courses in which these students are prepared are largely a legacy from a time when biologists didn't need to know much physics and one goal of a physics course for training medical students was to keep weak memorizers out of medical school.

With the increasing role of physics and the pace of change in the biological professions, it is essential that physics education go beyond facts and procedures. More than helping students understand established ideas, science instruction must help them understand how those ideas, and further ideas we cannot anticipate, come to be. Students must be prepared to contend with ambiguities, to make sound judgments about what to accept and what to question, to reconsider past assumptions and adapt to new discoveries. In short, they must learn how to learn. Science instruction at the university level tends to ignore these issues, hoping that they will somehow spontaneously spring into being through coverage of traditional content. This appears to work for a small minority of students after many years of combined undergraduate and graduate training. Our goal is to learn how to help more students develop meta-learning skills by paying attention to these issues and developing curriculum to deal with them explicitly

Physics can be one of the best places to learn about scientific thinking.

A physics class can be one of the best places for students to learn how to think about scientific thinking. Physics deals with universal issues that apply to all matter and energy. Physics focuses on fundamental laws and in finding the simplicities around which to organize one's thinking about complex real-world situations. Physics is the ideal place to learn how to apply mathematics to help organize one's thinking about the physical world. Physics is also an excellent place to learn about the character and nature of measurement. Understanding difficulties with simple measurements such as length or temperature can help students understand what kinds of issues arise in more complex measurements.

But perhaps the most compelling reason for bioscientists to study physics is that physics presents a tractable example of learning about coherence. The spontaneous reasoning of non-physics-trained individuals about the real world tends to be *ad hoc* – limited to specific narrow phenomena, inconsistent, and ungeneralizable: "knowledge in pieces."[dS1] Physics focuses on building consistent and coherent theories of phenomena, and

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[2] Studies of surgical errors indicate that errors occur when surgeons fail to maintain a global mental model of the structures involved. [Gan]

at the introductory level, they are sufficiently large to illustrate the principle, but come in sufficiently small chunks for students to be able to take the point (Newtonian mechanics, electrostatics, kinetic theory,…). We have developed methods that have been demonstrated to be effective for helping students learn to take a more coherent view of scientific knowledge [Ham4] and we will build on them.

Building lifelong learning and understanding requires a focus on meta-learning

Physics education research has built a strong knowledge base on student difficulties and concept development, especially in calculus-based physics.[Br] [McD2] This has led to the development of a large number of research-based curriculum materials that have been explicitly demonstrated to improve student learning of concepts and understanding of the physics.[Red3] [Red2] This is only a part of the story, however. We really want students to become scientific thinkers and to be able to be creative problem solvers and lifelong learners. What are the components of this? Local cognitive components have been well researched, but there has been only a small amount of work on the global ones – synthesizing and building appropriately structured long-term understanding and functionality.[Ham1] [Sch1] [Chi1]

The situation for teaching science in algebra-based physics classes for bioscience students is challenging.

1. Few students have had any classes that focused on metacognitive development.
2. Many students are preparing for standardized examinations such as the MCAT, so many topics have to be "covered" in a short period of time.[3]
3. Most algebra-based physics is taught in large classes so the types of educational activities that can be created are highly constrained.
4. Evaluating meta-learning gains for large numbers of students cannot be done using interviews, detailed observation of in-class behavior, or analysis of extended written activities or tests.
5. Most physics faculty and graduate teaching assistants are not trained in modern instructional methodologies and neither time nor funding is available to remedy this situation.

In particular, because of current large class sizes and high student/faculty ratios, it would be prohibitively expensive to implement classes which mock up the scientific process by creating groups and having students carry out inquiry investigations as part of a class/community exploration activity.[4]

3. The Theoretical Frame

Physics education research has been dominated for the past two decades by studies of student misconceptions and difficulties. The former are more specifically defined as stable cognitive structures; the latter notion is theoretically non-committal; but both are concerned with understanding aspects of students' knowledge and reasoning that present obstacles to learning.

While this work is valuable in that it helps sensitize instructors to common errors their students may make, as views of student knowledge and reasoning, misconceptions and difficulties are limited in two important respects. First, they provide no account of productive resources students have for advancing in their understanding. Second, descriptions of student difficulties provide no analysis of underlying mechanism, while the perspective of misconceptions cannot explain the contextual sensitivities of student reasoning [Sm] [Ham1], such as the empirical fact that questions seen as equivalent by experts, posed in different ways, can evoke different responses from the same student. [St]

In order to provide ourselves with the theoretical terminology in which to discuss issues of student thinking, we turn to neuroscience, cognitive science, and more phenomenological education theories built on careful

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[3] In the early 1990s, the MCAT was revised to emphasize depth more and breadth less. A teacher covering only topics tested by the MCAT could go through the material at a much slower rate than is currently typical in physics for bioscientists courses, and an emphasis on metacognitive learning is likely to produce improved MCAT scores.

[4] Such classes can be highly successful in improving both student meta-learning skills and content knowledge. Two examples of classes of this type are the CPU project at SDSU (for pre-service teachers)[Go] and the ThinkerTools project (for middle-school students).[Wh2]

observation of student behavior and reasoning. Although there are many such models, there are common threads and fairly broad agreement on some of the basic features.

Basic Ideas of Thinking and Learning

In studying students' thinking and learning, as with any experimentally based science, a theoretical frame is an essential component for making sense of observations and proposing new experiments. As educational researchers, we demand a theoretical frame with a strong tie to the direct observation of authentic real-world (ecological) student behavior. As physicists, we demand a theoretical frame that plausibly arises out of underlying physical structures, even if, at the present state of knowledge, all the details cannot yet be filled in.[Tha]

Recent developments in education theory and recent research in cognitive science and neuroscience have begun to combine to create an understanding of the structure of human thinking that satisfies these conditions.[Bad] [By1] [Fu] [Sq] [Ga] [Chu] [Co2] Necessarily (and appropriately), most research in cognitive neuroscience has focused on the simplest possible (but still difficult) issues: what is the nature of working memory, how does learning take place in terms of real biological structures, etc. Although people have developed a variety of models, there is reasonable agreement on the core elements and structures. A representation is shown in figure 3.

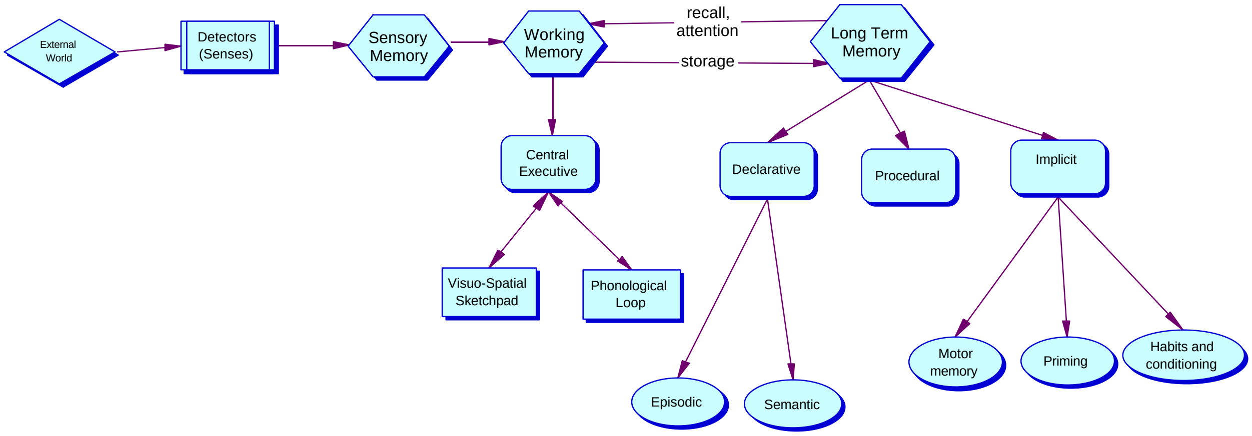

Fig. 3: A modern model of human memory structure. Adapted from [Bad] and [Sq].

For our considerations, a small number of elements of this model stressed by Joaquin Fuster, Alan Baddely, and Tim Shallice are important.

- All memory is essentially associative and is facilitated or created by modifications of synaptic connections between neurons.[Fu]
- Memory can exist in at least three states of activation: inactive, primed, and active.[Fu]
- Elements stored in long-term memory are recalled into working memory for processing.[Bad]
- An executive component of working memory negotiates the choice of what to bring from long-term memory in response to novel situations (contention scheduling).[No2] [Sh1] [Sh2]

These features have been demonstrated by the observation of patients with brain damage, by the behavior of intentionally lesioned animals, and by direct neural recording from animal brains.[Chu] [Sq] [Ga]

Cognitive resources

These precepts from neuroscience align with several ideas from cognitive science and education research regarding forms and levels of hierarchy in cognitive structure. This alignment supports a general theoretical frame for understanding cognition that underlies our thinking in this project about metacognition.

At its core, this theoretical frame describes student knowledge as comprised of cognitive resources, in various forms and levels of hierarchy [Ru] [No1] [dS] [dSS] [Mi]. Within each level is a heterarchical collection of resources, which are primed, activated, and deactivated depending on context and metacognitive control.

At the lower level of this structure are conceptual "primitives," primitive in the sense that they are indivisible to the user. One form of primitive is the "phenomenological primitive" diSessa has described. [dS] For example, asked to explain why it is hotter in the summer than in the winter, many students will respond that it is because the earth is closer to the sun. Educators often attribute this response to a faulty conception students have formed, by which the earth moves in a highly eccentric ellipse around the sun, and in some cases this may be the case. DiSessa's account allows an alternative interpretation: Asked the question, students conduct a quick search among the resources they have in their knowledge that may apply, and one of the first they tend to find is the notion that getting closer to a source increases the intensity of its effect: *Closer means stronger*. As a primitive, *Closer means stronger* is a resource productively activated to understand a number of phenomena. Students' tendency to explain seasons in terms of proximity to the sun may be understood as a faulty activation of this resource, which in itself is neither correct nor incorrect. Other resources students have available would be more productive, such as for understanding greater strength arising from more direct incidence. DiSessa has described a range of these primitives, and there are certainly many more.

These structures are "primitive" in the sense that they are indivisible to the user: Ask a student why it feels hotter closer to the fire, and from the student's perspective there is nothing else to say. At a higher level of cognitive structure we may identify collections of primitives that tend activate in patterns. These we may consider as concepts or "schemas"; at another level we may see "mental models." The details of this analysis are not essential to our proposal, nor have they been resolved.

What is essential is the central and well-established insight is that reasoning about any particular question entails a selection, tacit or explicit, from a collection of resources, whether primitive or schema or mental model. All of these resources are useful in some contexts, or they would not exist as resources; reasoning involves selecting those that are useful in the given situation. Learning physics, on this view, largely entails a reorganization of existing resources. For this reason, it is critical that educators attend to how students select from and coordinate their cognitive resources, and this falls under the topic of metacognition.

Meta-learning and organizational structures

The activation of students' knowledge related to the physical behavior of the world is controlled by executive functions (which are also patterns of association). A variety of different kinds of executive structures can be identified including:

1. metacognition (including self-knowledge and assessment and control decisions) [Sch2]
2. epistemology (how students think they know what they know) [Ham1]
3. expectations (what students think is appropriate for a physics course) [Red4]
4. mental models (a coherent organizational structure providing executive functions of access and guiding activation) [Fr2]
5. metarepresentational competence (ability to create and use a variety of representations to organize and activate sets of resources) [Fri]

Since these exert powerful control over how students learn and how they respond to educational environments, we refer to them as *meta-learning structures* (MLS). A critical component of our use of the learning framework is to maintain awareness of the context dependence of the student response and to consider existing student knowledge as the *resources* from which students build their new knowledge.

4. Previous Work by Our Team

The group who will carry out this project consists of 3 senior personnel, 2 postdocs and 4 graduate students to be hired for the project, and an interdisciplinary advisory team. The senior personnel are E. F. Redish, Professor of Physics (PD and PI), David Hammer, Professor of Education and Physics (co-PI), and Andy Elby, Research Associate in Physics. Redish has had 30 years experience teaching physics. For the past 15 years he has been working on various aspects of physics education including development of software and educational materials, educational research, and educational evaluation and assessment. He has been a leader in strengthening the role of education research within physics and in building links to the education community. David Hammer is a graduate of the Berkeley SESAME program who is a specialist in student epistemologies. He recently joined the faculty at the University of Maryland as an Associate Professor in Physics and Education and as head of the Science Teaching Center in the College of Education. Andy Elby is a recent PhD in Physics from Berkeley who worked with diSessa, White, and Frederiksen on education. He is a PFSMETE Fellow and has been teaching high school physics part time in Virginia. He is the author of a two volume problem-solving guide for introductory physics and is presently under contract to John Wiley & Sons to produce a major new textbook in introductory physics.

The previous work of the senior project members is described below, followed by a description of the advisory panel.

A. Results from Redish's Prior NSF Support

In the past six years, the PD for this grant, E. F. Redish, has been involved in five NSF grants: Three resulted in research, tools, and materials that are of particular relevance for this project.

1. Redish was PD of a three-year grant *Student Expectations in University Physics* (RED-9355849, $405,000, 8/17/94-8/16/97). This grant resulted in the creation of the MPEX survey.[Red2] [Red4] The results of this grant facilitates the development of the survey instrument that is described below under “Attitudes and Expectations”.

2. Redish was co-PI of the multi-university project, *Activity-Based Physics*, with P. Cooney, P. Laws, R. Thornton, and D. Sokoloff. (DUE-9455561, $196,990 5/1/95-4/30/98). The Maryland component of this project resulted in the creation of instructional materials described in the section “Curriculum Development and Evaluation” below. The materials developed are available on the web at [UMd1] [UMd2] and are scheduled to be published by John Wiley & Sons.

3. Redish was co-PI on an ILI grant *Computer-assisted Laboratories and Tutorials* DUE-9550890 ($105,000, 8/1/95-7/31/97). This grant helped to set up computer facilities for a two tutorial rooms and two laboratories. The results of the research enabled by this grant is reported on in [Red3]. These computer classrooms will be used in the curriculum development described in sections 4-(3) and 5-(2).

4. Most recently, Redish has been PD of a three-year grant *A New Model Course in Quantum Mechanics for Scientists and Engineers*, DUE-9652877 ($305,126, 9/1/97-8/31/00). This grant is exploring the difficulties engineering students have with beginning quantum physics and is developing materials (tutorials and problems) that help students get over these difficulties. (This project functions in conjunction with a FIPSE grant that supports addition materials development.) The results of this research have been presented at AAPT[5] conferences in 12 contributed talks and in invited talks in the US, China, and Italy. Six papers describing the results of the research are in various stages of preparation. A preliminary CD with the materials developed for this and the FIPSE grant was pressed last January. The materials will be finalized this summer. We have a tentative agreement with John Wiley & Sons to publish the materials.

5. Redish also was co-PI on an NSF grant with John Rigden (AIP) to organize the *International Conference on Undergraduate Physics Education*, DUE-9628652 ($65,000) in 1996. This conference was held at the University of Maryland just before a national AAPT summer meeting. It was attended by approximately 300 people from 26 countries and led to the publication of a 1200 page two volume proceedings.[Red1] The descriptions of the sample classes given at this conference have also been put up on the AAPT website as a community resource [http://www.psrc-online.org/classrooms/papers.html]. Group discussions at this conference led to the creation of the annual Physics Education Research Conference held after each AAPT summer meeting (the fourth one will be held in Guelph this August) and to the creation of the Physics Education Research Supple-

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[5] The American Association of Physics Teachers is the primary national organization of high-school and college physics teachers. They have approximately 12,000 members and have national meetings twice a year.

ment to the AJP, a 64 page annual archival journal presenting physics education research for physics faculty (the second issue will appear this July). (See [http://www.physics.umd.edu/perg/pers] for more information.)

Attitudes and Expectations

The UMd-PERG research on attitudes and expectations grew out of the dissertation work of David Hammer. In this work, Hammer investigated the views of a small number of students in a calculus-based physics course about the nature of the physics knowledge.[Ham] He found that most of the students had attitudes about the nature of physics and how one approaches problems that were counterproductive to helping them develop a strong understanding of physics or expert problem-solving skills. He classified their beliefs along three dimensions: independence/authority, coherence/pieces, and concepts/equations. In order to probe the distribution of these attitudes in large calculus-based physics classes, the UMd-PERG under Redish's guidance developed the Maryland Physics Expectations (MPEX) survey, a set of 34 statements that students are asked to agree or disagree with.[Red4] These probe the Hammer dimensions and two more: a physics-reality link, and a math-physics link. (See Table 1.)

	Favorable	***Unfavorable***
Independence	Learns independently, believes in their own need to evaluate and understand	Takes what is given by authorities (teacher, text) without evaluation
Coherence	Believes physics needs to be considered as a connected, consistent framework	Believes physics can be treated as separated facts or "pieces"
Concepts	Stresses understanding of the underlying ideas and concepts	Focuses on memorizing and using formulas
Reality link	Believes ideas learned in physics are useful in a wide variety of real-world contexts	Believes ideas learned in physics are unrelated to experiences outside the classroom
Math link	Considers mathematics as a convenient way of representing physical phenomena	Views the physics and the math as independent with no strong relationship between them

Table 1: The expectation variables probed by the MPEX.

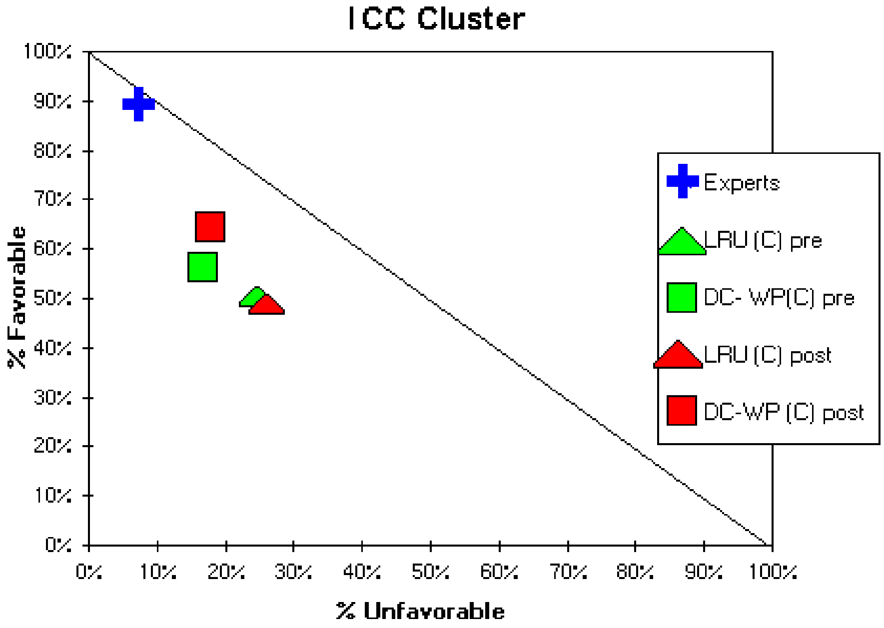

Fig. 1: Average results of the MPEX survey on the Independence / Coherence / Concepts variables described in Table 1. The survey was given at the beginning and end of the first semester of introductory calculus-based physics at Dickinson College (Workshop Physics [WP]) and three large research universities [LRU] traditional).

We presented our survey to a group of expert physics instructors and asked them to choose the answers they would like their students to give. The experts agreed on the polarity (whether the students should agree or disagree) of the responses approximately 90% of the time. We refer to a student opinion that agrees with the expert polarity as *favorable* and to one that disagrees as *unfavorable*.

We have now delivered the MPEX to more than 6000 students in calculus-based physics at about two-dozen institutions of a variety of types. Results show systematic differences among populations and distinct effects from differing styles of classes and instructors. We find that the course structure can affect the direction of shift, and that most traditionally courses produce shifts in the unfavorable direction. We plot the number of students agreeing with the expert view along the ordinate and the number disagreeing with the expert view along the abscissa. We refer to the result as an *agree-disagree plot*. In figure 1, we present the results on the Hammer sub-variables at the beginning and end of the first semester of engineering mechanics. Groups of 500 students at 3 large research universities showed a 1-sigma deterioration. The only university group we found that improved was a Workshop Physics class at Dickinson College.[La1] This class is small (N ~ 30) with a carefully constructed, research-based group-learning studio environment that uses a discovery learning model with powerful computer-assisted data-acquisition tools.

Curriculum Development and Evaluation

Edward Redish (PD) has been involved with the development of curricular materials with three previous NSF grants (listed above). Two sets were designed to enhance concept learning in calculus-based class in large lecture environments: (1) a set of non-plug-and-chug *Thinking Problems in Physics* appropriate for homework assignments and group problems solving (including Fermi estimation problems) and (2) a set of *Mathematical Tutorials in Introductory Physics*. These tutorials are in the mode developed by the University of Washington [McD4], but they use computer-assisted data-acquisition and focus on issues of relating mathematics and physics. Both materials are available on the internet.[UMd1] [UMd2] The experience creating these tutorials facilitates the materials development proposed in sections 5-(1) and 5-(2).

Redish has also had experience with large-scale data collection for evaluation, comparing the concept learning in calculus-based physics in four different instructional environments at 14 colleges and universities.[Sau] [Sau1] [Red3] The expectations grant also involved large scale data collection at multiple universities.[Red4]

B. Results from Hammer’s (co-PI) Previous Work

David Hammer has not had previous NSF support (though a grant with E. van Zee is pending), but much of the project grows out of his work. In particular, he has developed a course for teaching meta-learning skills to non-scientists using physics. Our experience with this course will be a source of insights and ideas.

Teaching How to Learn Physics

A supplementary context for this study will be a course titled *How to Learn Physics* (HTLP), which one of us (Hammer) has been developing and teaching for non-scientists over the past several years. The primary agenda of this course is the development of student beliefs about knowledge, reasoning, and learning in introductory physics, and for this reason it provides a rich laboratory for the study of student epistemologies and their evolution. Meta-learning issues are stressed throughout. The course description explicitly states: “Many students believe learning physics means taking in information – facts and formulas and problem solving methods – and committing it to memory. But, for Einstein and others,[6] learning physics means *refining one's everyday thinking*. And that means, first, becoming *aware* of one's everyday thinking. They may not always think of what they're doing this way, but students who succeed at learning physics know this instinctively: Learning physics is as much learning about yourself, about how and what you know and see and think, as it is finding out new things about the physical world.”

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[6] “The whole of science is nothing more than a refinement of everyday thinking.” [E]

Because HTLP is a small course, it allows experimentation with alternative approaches more freely than will the large-lecture algebra-based physics course. Some of our work will focus on trying to scale-up experiences in HTLP to the larger course. (Textbook materials for this course are in preparation.[Ham4])

An anecdotal experience from this course gives an example of analyzing the physics-learning situation in terms of epistemological resources. A student in HTLP described herself as artistically inclined but incapable of scientific thinking. Roughly halfway through the course she came to an office hour for help. Asked to reflect on why she had answered a particular physics question as she had, she responded “That's like asking 'why did I put purple on my canvas?'” Having made this connection, she made others as well, until she characterized her difficulty learning physics by analogy to her thinking about interpersonal relationships. She described herself as having “lots of tools” for analyzing her relationships, “sort of a file cabinet full of ideas,” and similarly for thinking about her art. She characterized her difficulty with physics as not having assembled a comparable set of tools. The conversation marked a turning point in her work in the course; we consider it an example of a student's having drawn her own epistemological analogy, helping her apply a set of productive epistemological resources she had developed in another context to her work in introductory physics.

C. Results from Elby’s Previous Work

Metacognitive Tutorials

One of the best-tested curricular innovations for the large lecture environment is *Tutorials in Introductory Physics,* developed by the University of Washington Physics Education Group (UW PEG). [McD4] Instead of watching TAs modeling problem solving, students work in groups of 3 or 4 on carefully designed worksheets. In these worksheets, students are led to make predictions and compare various lines of reasoning in order to build an understanding of basic concepts. TAs serve as “facilitators” rather than as lecturers. Help with textbook problems is available in extended office hours. In addition to a lecturer, this model requires approximately one facilitator per 15 students one contact hour per week, but they can be graduate students or peers, as they receive explicit training for 1-2 hours per week. The training is targeted to first helping them understand the physics (many don’t), second, to helping them learn to understand common student naïve conceptions, and third, to helping them learn to facilitate by asking guided questions and leaving the students to work out most of the difficulties among themselves. The details of the method are described in numerous references documenting the development of specific tutorials. (See for example, [McD3].) These have independently been verified to be highly effective for concept learning, even in secondary implementations.[Red3] However, these tutorials, while effective in their objectives, do not successfully address the meta-learning goals of this project. Pre-post MPEX results indicate tutorial students deteriorate amounts comparable to traditional students.[Red4]

In his class at Thomas Jefferson High School in Virginia, Andy Elby [E2] developed an instructional strategy based on the Tutorial environment that applies a resources-based view of student knowledge and focuses on epistemological development. In one example, the context for a lesson was Newton’s 3rd law. As part of the lesson, Elby posed to students the following question:

> *A truck rams into a parked car, which has half the mass of the truck. Intuitively, which is larger during the collision: the force exerted by the truck on the car, or the force exerted by the car on the truck?*

That most students responded that the truck exerts a larger force on the car than the car exerts on the truck is not surprising; this is a commonly recognized “misconception.” Elby then posed another question:

> *Suppose the truck has mass 1000 kg and the car has mass 500 kg. During the collision, suppose the truck loses 5 m/s of speed. Keeping in mind that the car is half as heavy as the truck, how much speed does the car gain during the collision? Visualize the situation, and trust your instincts*

This time, most of the students answered correctly; and by working through follow-up questions, they came to the conclusion that their “instincts” agree with Newton’s 3rd law. Elby identified students’ correct answer to this question as reflecting their “raw intuition” that “the car reacts twice as much during the collision,” and he lead them to the idea that they could “refine” this raw intuition in one of (at least) two ways. Elby identified the notion that “the car reacts twice as much” as a resource from which students could build their understanding. Depending on how they used this resource, how in Elby's terms they “refined” it, the idea could contribute to a Newtonian understanding or it could pose a difficulty for that understanding. In this way, what Elby loosely characterized as a “raw intuition” provided the raw material for students in building their understanding. Like a subroutine for a programmer, the intuition itself is neither correct nor incorrect; it becomes correct or incorrect in its use.

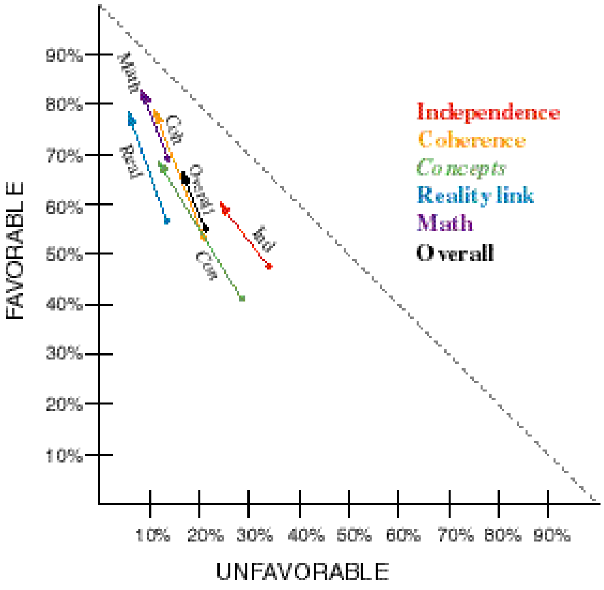

Fig. 2: MPEX gains in Elby’s meta-learning high school physics class.

What this meant in class for Elby was an instructional strategy explicitly designed to help students refine their intuition toward a coherent understanding. He guided them to see the consequences of the two alternatives: If they apply their “car reacts twice as much” intuition to the concept of force, their reasoning leads to a contradiction with Newton's Third Law; if they apply it to the concept of acceleration, their reasoning is consistent with Newton's Laws.

Elby created a number of lessons based on modifications of the Tutorial model, continually focusing on metacognition, asking the students to express and evaluate their intuitions. Elby gave his class the MPEX as a pre/post test and obtained spectacular gains on every cognitive category, the best gains ever recorded. These are shown in figure 2.[7]

D. The Adivisory Panel

The advisory panel will play a critical role in the project. They will provide relevant expertise, input, and criticism. We have chosen to have a significant number of our biology experts on site so that they will be able to meet with us on a regular basis, be on call to answer specific questions, and be available to observe and comment on classes. We also hope to build a strong link among the three on-campus units involved: physics, education, and biology.

The External Advisory Panel consists of six individuals:

- Marco Colombini, Professor, Biology, U.of Maryland
- Spencer Benson, Assoc. Prof., Cell Biology & Molecular Genetics, U. of Maryland
- James Byrnes, Prof., Human Development, U. of Maryland
- Paul Feltovich, Assoc. Prof., Dept. of Medical Educ., S. Illinois U. Medical School.
- John Frederiksen, Educational Testing Service
- Ann Hildebrand Kindfield, Educational Designs Unlimited

M. Colombini is a biophysicist studying membrane transport phenomena. He has taught upper-division biophysics and has a strong interest in training biological researchers. S. Benson is a biologist carrying out research on bacterial evolution and membrane structure. He has been a campus leader on interdisciplinary courses and innovative education. J. Byrnes is and education researcher with a strong interest in the implica-

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[7] Conceptual gains as measured by the fractional pre-post gain on the FCI were also among the highest ever recorded – 0.88,

tions of cognitive science and neuroscience for education.[By][By1] His book on neuroscience and education is about to appear.[By2] P. Feltovich is an education researcher and director of the Cognitive Sciences Division of the Department of Medical Education at S. Illinois University Medical School. J. Frederiksen is a cognitive scientist and a specialist in the development of metacognitive skills in K-12 students. A. Kindfield is a biology education researcher and a graduate of Berkeley's SESAME program. Since this proposal involves input and advice from a highly interdisciplinary team, short bios are included for members of the panel.

5. The Proposed Project

A. Basic Research

A major component of this project is basic research in cognitive education. The focus of our research is studying the components of students' meta-knowledge about science and developing instructional environments to improve those components appropriate for the university. We will do this in the context of the large algebra-based physics class for bioscience students.

(1) The Structure of Epistemological Reasoning

The fundamental components of student conceptual knowledge in physics have been studied and in part identified.[dS] The components of students epistemological knowledge, the elements from which they construct their expectations about knowledge and knowing, have been much less studied. Existing studies of student epistemologies (see [Hof] for review) have presumed a consistency in student "beliefs," leading to views analogous to those of misconceptions and subject to the same concerns: They cannot explain contextual sensitivities of epistemological reasoning, and they provide no account of productive resources from which students may construct more sophisticated beliefs.

We propose to identify structures in students' epistemological reasoning and learn how to build those structures as resources into lessons for helping students develop stronger meta-learning skills. The lessons will be built on best-practice large-lecture curriculum tools – Tutorials, Group Problem Solving, and Interactive Lecture Demonstrations. These are environments in which our preliminary work (discussed above and below) has suggested that modifications can lead to improved meta-learning skills (MLS).

(2) Social Construction of Physical Models

There is, by now, considerable evidence that group discussion and explaining their thinking out loud, helps students build up MLS.[Chi] [Fr2] [Sch1] In a large-lecture environment, the financial support is rarely available to provide the teacher-led small group discussions and the strong formative feedback directly from the instructor used in these references.

In the typical large-lecture framework there is one resource available for small class interaction: the section. Almost all large lecture algebra-based physics classes have a laboratory or a recitation or both run in small sections of 25-30 students by teaching assistants (often graduate students). Many, including the classes at Maryland, have both. An interesting possibility is to use student epistemological resources associated with social learning environments to attempt to foster student MLS. In the development section below, we propose to create a group-learning environment in which students solve complex-rich biologically-relevant physics problems in small groups (N=3-4), analyze their solution using a knowledge/concept map visualization tool (e.g., *Inspiration*™), and finally, negotiate a common solution and knowledge map among the groups in a full class discussion (N=25-30). (The classroom environment is described in more detail under development below.)

As this environment is being developed, we will observe and videotape some of these sections, and analyze the discourse from the point of view of epistemological and meta-learning resources in order to determine what tasks and activities are most effective in improving student MLS.

(3) Creation of a Survey Instrument and Data Collection

In our previous NSF-supported work, we developed a measuring and analysis tool that is highly relevant to the present project: the MPEX. Preliminary results indicate that the MPEX is particularly useful in distinguishing populations with different attitudes and expectations. A result with particular relevance to the population in the proposed project was found by a group of investigators at the University of Ghent, Belgium. They translated the MPEX into Flemish and delivered it to 600 first year college students. They found substantial differences between their engineering and biology students.[L] A recent study we made of historically black and women's colleges also showed interesting differences between populations. Students at HBCUs scored comparably to students at large state universities. Students at selective women's colleges scored higher on the pre-MPEX than any other population previously tested. [Hod]

Hammer, Redish, and Elby will create a new survey that combines the best features of the MPEX and EBAPS surveys which were designed for different populations (engineers in calculus-based physics and high-school students respectively) and that makes use of what has been learned from our epistemological resources research. We will adapt the spreadsheets constructing for analyzing the MPEX survey and generating AD plots for the cluster variables. The new survey will be calibrated against the MPEX and validated with student interviews. We will use our survey to collect extensive data on bioscience and premedical students meta-learning skills, both at Maryland and at associated universities.[8]

B. Development

In this project we propose to build on existing best-practice tools, developed through extensive research to help students in large-lecture classes learn concepts and problem-solving skills. These methods have been thoroughly tested and shown to have a powerful effect on student learning. In their present form, however, tests using the MPEX suggest that they do not lead to improvement in students' MLS; indeed, they seem to be associated with the same deteriorations shown for traditional instruction. Preliminary attempts by Elby and Redish (described below) suggest that these learning environments can have a powerful positive effect on student MLS. We will be explicitly working with three instructional tools designed for enhancing student content learning in physics: Tutorials,[McD4] Group Problem Solving,[He] and Interactive Lecture Demonstrations.[Sok1] In addition, we will be extending our collection of Thinking Problems in Physics [UMd1] to include problems specifically relevant to biology students.

(1) Metacognitive Tutorials

As a part of our research and development, we will explicitly adapt and extend Elby's approach using our theoretical frame in order to produce a series of modified tutorials for use in the algebra-based physics class. The students will be tested pre and post both for concept learning and for epistemological gains.

(2) Group Problem Solving Tools

Group-problem solving (GPS) is a method developed by Pat and Ken Heller at the University of Minnesota.[He] In this method, recitation sessions remain as problem-solving sessions, but instead of having students watch TAs answer questions or solve sample problems at the board, the students work in groups of 3-4 on complex problems. These problems are more authentic than a typical end-of-the-chapter physics problem, having a real-world context, sometimes include extraneous information, and sometimes have insufficient information. They are designed to be too difficult for any single student in the class to solve alone in the given time period (10-15 minutes). These environments are also effective in improving student conceptual knowledge, but have little effect on their expectations.[Sau]

Phenomenologically, there is substantial evidence that working with explicit knowledge structures helps students build a more coherent view of scientific knowledge.[Ey] [Chi] There is also explicit evidence that expressing their views helps students improve their recall of knowledge. [Wal]

Following up on some anecdotal evidence of Mary Nakleh with teaching introductory chemistry at Purdue, [Na] we propose to introduce a group- problem-solving concept-map (GPS/CM) activity. Although we have some concerns about the applications of concept maps as either a probe of a student's knowledge or as an indi-

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[8] We have strong contacts with many physics departments around the country through our former students and postdocs and through our many collaborators. We will be able to get data from many sources as we have in our previous studies.[Red3] [Sau]

vidual exercise, we feel it could have considerable promise as a way of metacognitively focusing a group discussion on the elements of their process of problem solving using dramatic visual representations. We will have students solve a context-rich problem in groups, then create a map of what they used and how using a computer idea-visualization tool such as *Inspiration* ä. (This product is strongly Windows compliant so has a very small learning curve. Figure 3 on page 5 was prepared using it.)

After the group has negotiated a problem-associated concept map among themselves, the groups will go to the blackboard and put up their problem solutions and concept maps. The class will then compare and discuss both the methods of solutions and the proposed maps. We expect that the negotiation of a community map for individual problems will help students focus on the structure of their thinking and the relationships between the elements of their knowledge.

We will videotape and analyze the discourse in some of these classes from the point of view of understanding the epistemological resources the students are using. The effect of the intervention will be evaluated by comparing the responses students in the test class and in a control class give to a common examination problem.

(3) Epistemologically Enhanced Interactive Lecture Demonstrations

Interactive lecture demonstrations (ILDs) are an instructional method developed by David Sokoloff and Ron Thornton to improve concept development in a large lecture environment. In this method, education research on student difficulties is used to focus on critical places where students' common naïve conceptions hamper their understanding of physics. A series of very simple demonstrations are prepared (usually using computer-assisted data-acquisition). Students receive two identical worksheets asking what will happen in each of the demonstrations. For each demonstration the lecturer first walks through the demonstration without starting the computer. He then asks the student to sketch or describe on the first of their sheets (the *prediction* sheet) their prediction for what will happen. They then discuss their predictions with their neighbors for two minutes. There is then a brief class discussion comparing different predictions. The demonstrator then does the experiment and discusses with the students why some of the proposed answers didn't work. The students copy the result onto their second worksheet (the *results* sheet). At the end of the series of demonstrations, the students hand in their predictions sheets and keep the result sheets for further study. The worksheets are published together with extensive instructions for the teacher.[Sok1] Evaluations of concept learning show substantial gains using this technique.[Sok3]

In the fall of 1998, E. F. Redish used ILDs for the second time in his algebra-based physics class of 165 students. The first time he had used them, student response was good and conceptual learning improved somewhat. The second time he used them, he focused on shifting student expectations. Typically, students in this class think physics is about knowing the right answer instead of about the process of understanding reasoning and evaluating arguments. Getting students to respond to a question in a large lecture is like pulling teeth (especially after someone in the front row has given what they think is the "right" answer). Many are afraid to give a wrong answer and look foolish to their friends or to the teacher. With an effort, one can bring the number of respondents up to about 10% (10-15 students).

In the context of the ILD, Redish expanded the scope of the discussion substantially. He specifically focused the students' attention on generating answers, not just the right ones. After the correct answer was given (usually by the first student raising a hand in the front row), he asked for "creative" answers – "something your friend or roommate who isn't taking this class might say." This freed the students from the burden of possibly giving the wrong answer. Often, he asked other students (sometimes the one who gave the correct answer) to try to defend one or more of the wrong answers. This had the impact of shifting the students' understanding of what was going on – shifting the emphasis from "finding the correct answer" to considering the possible space of answers and figuring out how you know which is correct. This shift had a dramatic and unexpected result. Many more of the students were willing to participate. Nearly 25% of the students became involved in discussions (~40 students) and this change in the lecture continued throughout the class – even when an ILD was not being done.

As part of the research in this project, we will document what is happening in this environment using brief interviews with selected students immediately after lecture, longer expectation interviews with volunteers at the beginning and end of the semester, and the pre-post survey. We will be able to have enough separate sections so that at least one class will only have this intervention and otherwise will receive traditional instruction.

(4) Relevant Problem Collection

There is considerable research evidence to support the idea that students learn better if the problems they solve are authentic – seen as real-world and relevant to the students' interests.[Br] We need problems in physics taking place in a biological environment that are "context rich" and have the possibility of supporting rich and stimulating discussions about epistemology and knowledge organization. There are many sources of good physics problems in biology environments, such as [Ah] [Li] and [Pe]. We will develop a carefully chosen set of approximately 50 problems (so about 1-2 per week are available for homework and/or group discussion) of this degree of interest and richness. These problems will be collected and distributed on our web site.

C. Evaluation and Testing

The Instructional Context

The context in which the research and development for this project will be done is the algebra-based physics course at the University of Maryland. This is taught as a 2-semester course to about 1000 students, 500 in each course in each semester. Typically, a class of 500 students is divided into 3-5 classes, each taught by a different faculty member. Each faculty member has complete responsibility for his or her class within the constraints of textbook and content. This offers us considerable opportunity for finding controls. A class includes the following instructional content: (1) three 50-minute lectures per week, (2) one three-hour recitation/lab period consisting of 1 hour of recitation followed by 2 hours of lab, and (3) weekly homework assigned, collected, and graded. TAs typically solve homework problems in recitation and answer questions and a different faculty member handles laboratories independently of the other parts of the course.

Recent developments in research-based curriculum reform offer an exciting opportunity. The Activity-Based Physics group is developing a project for John Wiley & Sons known as *The Physics Suite*. This includes a popular textbook [Hal] rewritten to include strong input from physics education research and research-based active learning elements including: tutorials [McD4], laboratories [Sok2], interactive lecture demonstrations [Sok1], workshop classes [La], and a teacher's guide [Red5]. These materials integrate modern computer data gathering and modeling tools. They provide "best practices" environments that lend themselves well to meta-learning adaptations. This has two implications. First, as a participant in *The Physics Suite* development project, we will test our modifications in one class, with the classes of other professors as controls. Second, our modified materials will have an obvious publication venue.

D. Dissemination

An important goal of this project is raising the visibility of the issues associated with meta-learning in the community of post-secondary physics teachers. In part, the project is structured to provide the large-scale quantitative data that will be convincing to this group. The PIs have strong connections to the AAPT, the largest organization dedicated to physics teaching in the world. Dissemination and communication will be carried out through presentations and workshops at AAPT meetings, through invited workshops and seminars at college and university physics departments, and through publication of papers describing the research. The impact of our results will be increased through publication of meta-learning oriented materials, making it feasible for non-researchers to implement the methods we create.

We will also have an impact on increasing the research capacity of the field by training discipline-based education specialists. We have had excellent success in attracting outstanding students to education from physics and in placing those students in faculty positions within physics departments. In the past 5 years, we have helped train 3 NSF-PFSMETE fellows, a Spencer Foundation Postdoctoral Fellow, and 4 physics PhD students with education dissertations. Three of our PhDs have tenure track positions in physics departments and the fourth is completing his first year of a prestigious postdoc in physics at the University of Washington.

References Cited

Note that many of the papers and dissertations produced by the Maryland PERG are available on the WWW and URLs are provided.

[ABC] ABC News.com, “N-probe intensifies,” February 20, 2000. [http://www,abcnews.go.com/sections/world/DailyNews/napannuke991004.html].

[Ah] B. K. Ahlborn, *How Animals Make Use of Physics* (Springer Verlag, to be published).

[Al] B. Alberts, “The cell as a collection of protein machines: Preparing the next generation of molecular biologists,” Cell 92**,** 291-294(1998).

[Bad] A. Baddeley, *Human Memory: Theory and Practice, Revised Edition* (Allyn & Bacon, 1998).

[Bao] L. Bao, *Dynamics of Student Modeling: A Theory, Algorithms, and Application to Quantum Mechanics*, Ph.D. dissertation, University of Maryland, December 1999.

[Bo] M. S. Bogner, Ed., *Human Error in Medicine* (Lawrence Erlbaum Associates, 1994), especially H. Van Cott, “Human errors: Their causes and reduction,” 53-65; N. Moray, “Error reduction as a systems problem,” 67-91.

[Br] J. D. Bransford, A. L. Brown, and R. R. Cocking, Eds., *How People Learn: Brain, Mind, Experience, and School* (National Academy Press, Washington DC, 1999).

[By] J.P. Byrnes, *Cognitive Development and Learning in Instructional Contexts* (Allyn and Bacon, 1996).

[By1] J. P. Byrnes and N. A. Fox, “The educational relevance of research in cognitive neuroscience,” Ed. Psych. Rev. 10:3, 297-342 (1998).

[By2] J. P. Byrnes, *Minds, Brains, and Education: Understanding the Psychological and Educational Relevance of Neuroscientific Research* (Guilford Press, in press).

[Cha] R. Chabay and B. Sherwood, *Electric and Magnetic Interactions* (John Wiley and Sons, 1995)

[Chi] M. T. H. Chi, N. de Leeuw, M-H Chiu, and C. laVancher, “Eliciting self-explanations improves understanding,” Cog. Sci. 18, 439-477 (1994).

[Chi1] M. T. H. Chi, J. D. Slotta, and N. de Leeuw, “From things to processes: A theory of conceptual change for learning science concepts,” Learning and Instruction 4, 27-43 (1994); J. D. Slotta and M. T. H. Chi, “How physics novices can overcome robust misconceptions through ontology training,” LRDC preprint.

[Chu] P. S. Churchland and T. J. Sejwnowski, *The Computational Brain* (MIT Press, 1993).

[Co1] A. Collins and W. Ferguson, “Epistemic forms and epistemic games: Structures and strategies to guide inquiry,” Educ. Psychologist 28:1, 25-42 (1993).

[Co2] A. Collins and E. E. Smith, Eds., *Readings in Cognitive Science: A Perspective for Psychology and Artificial Intelligence* (Morgan Kauffman, 1988).

[dS] A. diSessa, “Toward an Epistemology of Physics,” Cognition and Instruction 10, 105-225(1993).

[dS1] A. diSessa, “Knowledge in Pieces,” in *Constructivism in the Computer Age*, G. Forman and P. Pufall (eds.), 49-70 (Lawrence Erlbaum, 1988).

[dSS] A. A. diSessa and B. L. Sherin, “What changes in conceptual change?” Int. J. Sci. Educ. 20(10) 1155-1191 (1998).

[E] A. Einstein, “Physics and Reality,” J. of the Franklin Institute 221 (1936)

[E1] A. Elby, “Another reason that physics students learn by rote,” Phys. Ed. Res. Suppl. to the Am. J. Phys. 67 S52-S57 (1999).

[E2] A. Elby, “Helping physics students learn how to learn,” submitted to Phys. Ed. Res. Suppl. to the Am. J. Phys.

[Ey] B. Eylon and F. Reif, “Effects of knowledge organization on task performance,” Cognition and Instruction 1, 5-44 (1984).

[Fr1] J. R. Frederiksen and B. Y. White, “Teaching and learning generic modeling and reasoning skills,” Interactive Learning Environments 5, 33-51(1998).

[Fr2] J. R. Frederiksen, B. Y. White, and J. Gutwill, “Dynamic mental models in learning sciences: The importance of constructing derivational linkages among models,” J. Res. Sci. Teaching 36(7) 806-836 (1999).

[Fri] J. S. Friedman and A. diSessa, “What students should know about technology: The case of scientific visualization,” J. Sci. Ed. and Techn. 8(3), 175-195 (1999).

[Fu] J. M. Fuster, *Memory in the Cerebral Cortex: An Empirical Approach to Neural Networks in the Human and Nonhuman Primate* (MIT Press, 1999).

[Ga] M. S. Gazzaniga, R. B. Ivry, and G. R. Mangun, *Cognitive Neuroscience* (W.W. Norton, 1998).

[Gan] W. Gantert, F. Tendick, S. Bhoyrul, D. Tyrrell, Y. Fujino, S. Rangel, M.G. Patti, and L.W. Way, “Error Analysis in Laparoscopic Surgery,” in M. Bogner, et al., (eds.), Proc. SPIE Conference 3262 on Surgical-Assist Systems, San Jose, CA, pp. 74-77 (1998).

[Go] Fred Goldberg, San Diego State University, private communication.

[Gu] R. F. Gunstone, “The importance of specific science content in the enhancement of metecognition,” in *The Content of Science*, P. Fensham, R. Gunstone, and R. White, Eds. (Falmer Press, 1994) 131-146.

[Hal] D. Halliday, R. Resnick, and J. Walker, *Fundamentals of Physics, 6th Ed.* (John Wiley & Sons, 2001).

[Ham] D. Hammer, *Defying common sense: Epistemological beliefs in an introductory physics course*, PhD Thesis, U. of California, Berkeley (1991).

[Ham1] D. Hammer, “More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research,”, Am. J. Phys. 64, 1316-1325 (1996). [http://www2.physics.umd.edu/~davidham/AJPmultpersp.html]

[Ham2] D. Hammer, “Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions?” Journal of the Learning Sciences 5, 97-127(1996).

[Ham3] D. Hammer and A.Elby, “On the form of a personal epistemology,” in B. K. Hofer, & P. R. Pintrich, Eds., *Personal Epistemolgy: The Psychology of Beliefs about Knowledge and Knowing* (Erlbaum, in press).

[Ham4] D. Hammer, *How to Learn Physics*, in preparation.

[He] P. Heller, R. Keith and S. Anderson, “Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving,” Am. J. Phys. 60, 627-636 (1992); P. Heller and M. Hollabaugh, “Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups,” Am. J. Phys. 60, 637-644 (1992).

[Hod] AK Hodari, B Hufnagel and J Saul, “Student cognitive expectations in non-traditional settings,” AAPT Announcer 29, 78 (Winter 1999).

[Hof] B. K.Hofer, and P. R. Pintrich, , “The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning,” Rev. Ed. Res. 67 (1), 88-140 (1997).

[K] L. T. Kohn, J. M. Corrigan, and M. S. Donaldson, Eds., *To Err is Human: Building a Safer Health System* (National Academy Press, 2000).

[L] J. Lenaerts, University of Ghent, Belgium, private communication.

[La] P. Laws, *Workshop Physics Activity Guide* (John Wiley & Sons, 1997).

[La1] P. Laws, “Millikan lecture 1996: Promoting active learning based on physics education research in introductory physics courses,” Am. J. Phys. 65, 14-21 (1997).

[Li] H. Lin, “Fundamentals of zoological scaling,” Am. J. Phys. 50(1), 72-81 (1982).

[McD1] L.C. McDermott, “Millikan Lecture 1990: What we teach and what is learned — Closing the gap,” Am. J. Phys. 59, 301-315 (1991).

[McD2] L.C. McDermott and E. F. Redish, “Resource Letter Per-1: Physics Education Research,” Am. J. Phys. 67, 755-767 (1999). [http://www.physics.umd.edu/rgroups/ripe/papers/rlpre.pdf]

[McD3] L.C. McDermott, P.S. Shaffer, and M.D. Somers, “Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwoods's machine,” Am. J. Phys. 62, 46-55 (1994).

[McD4] L. C. McDermott, P. S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics* (Prentice Hall, 1998).

[Mi] J. Minstrell, “Facets of students' knowledge and relevant instruction,” In: *Research in Physics Learning: Theoretical Issues and Empirical Studies, Proceedings of an International Workshop*, Bremen, Germany, March 4-8, 1991, edited by R. Duit, F. Goldberg, and H. Niedderer (IPN, Kiel Germany, 1992) 110-128.

[Na] M. Nakleh, Department of Chemistry, Purdue University, private communication.

[No1] D. Norman, “Some observations on mental models”, in Derdre Gentner and Albert L. Stevens, Eds., *Mental Models* (Lawrence Erlbaum Associates, 1983).pp. 7-14.

[No2] D. Norman and T. Shallice, “Attention to action: Willed and automatic control of behavior,” in *Consciousness and Self-Regulation, Vol. 4*, G. E. Schwartz and D. Shapiro, eds. (Plenum Press, 1986).

[Pe] C. J. Pennycuick, *Newton Rules Biology: A Physical Approach to Biological Problems* (Oxford U. Press, 1992).

[Red1] E. F. Redish and J. Rigden, Eds. *The Changing Role of Physics Departments in Modern Universities: Proceedings of the International Conference on Undergraduate Physics Education (ICUPE),* College Park, MD, July 31-Aug. 3, 1996, AIP Conf. Proc. 399 (American Institute of Physics, Woodbury NY, 1997) 1200 pages (2 vols.).

[Red2] E. F. Redish and R. N. Steinberg, "Teaching physics: Figuring out what works," Physics Today 52, 24-30 (January 1999). [http://www.physics.umd.edu/rgroups/ripe/papers/PT/pt.htm]

[Red3] E. F. Redish, J. M. Saul, and R. N. Steinberg, "On the effectiveness of active-engagement microcomputer-based laboratories," Am. J. Phys. 65, 45-54 (1997). [http://www.physics.umd.edu/rgroups/ripe/papers/mbl/mbl1.html]

[Red4] E. F. Redish, J. M. Saul, and R. N. Steinberg, "Student expectations in introductory physics," Am. J. Phys. 66, 212-224 (1998). [*http://www.physics.umd.edu/rgroups/ripe/papers/expects/expects1.htm*]

[Red5] E. F. Redish, *Teaching Physics with the Physics Suite* (John Wiley & Sons, 2001) estimated.

[Res] L. Resnick, *Education and Learning to Think* (National Academy Press, 1987).

[Ru] D. E. Rumelhart, "Schemata: The building blocks of cognition," in *Comprehension and Teaching: Research Reviews* (International Reading Association, 1981) 3-26.

[Sa] M. Sabella, *Using the context of physics problem solving to evaluate the coherence of student knowledge*, PhD thesis, University of Maryland, 1999.

[Sau] J. Saul, *Beyond Problem Solving: Evaluating Introductory Physics Courses Through the Hidden Curriculum*, PhD thesis, University of Maryland, 1998.

[Sau1] J. Saul and E. F. Redish, "Evaluation of the Workshop Physics Dissemination Project," U. of Md. Physics Education Research Group preprint, April, 1998.

[Sch1] A. Schoenfeld, *Mathematical Problem Solving* (Academic Press, Inc., 1985).

[Sch2] A. Schoenfeld, "Metacognitive and epistemological issues in mathematical understanding," in E. A. Silver, Ed., *Teaching and Learning Mathematical Problem Solving: Multiple Research Perspectives* (Lawrence Erlbaum, 1985)

[Sh1] T. Shallice, *From Neuropsychology to Mental Structure* (Cambridge U. Press, 1988).

[Sh2] T. Shallice and P. Burgess, "The domain of supervisory processes and the temporal organization of behavior," in *The Prefrontal Cortex: Executive and Cognitive Functions*, A. C. Roberts, T. W. Robbins, and L. Weiskrantz, eds. (Oxford U. Press, 1998).

[Sm] J. Smith; A. diSessa and J. Roschelle, "Misconceptions reconceived: A constructivist analysis of knowledge in transition," J. Learning Sci. 3(2), 115-163 (1993/1994).

[Sok1] D. R. Sokoloff and R. K. Thornton, *Interactive Lecture Demonstrations* (John Wiley & Sons, 2001).

[Sok2] D. R. Sokoloff, R. K. Thornton, and P. W. Laws, *RealTime Physics: Active Learning Laboratories* (John Wiley & Sons, 1999).

[Sok3] D. R. Sokoloff and R. K. Thornton, "Using interactive lecture demonstrations to create an active learning environment," Phys.Teach. 35, 340-347 (1997).

[Sq] L. R. Squire and E. R. Kandel, *Memory: From Mind to Molecules* (Scientific American Library, 1999).

[St] R. N. Steinberg and M. S. Sabella, "Performance on multiple-choice diagnostics and complementary exam problems," Phys. Teach. 35(3), 150-155 (1997).

[Th] B. Thacker, U. Ganiel, and D. Boys, “Macroscopic phenomena and microscopic processes: Student understanding of transients in direct current electric circuits,” Phys. Ed. Res. Suppl. to the Am. J. Phys. 67, S25-S31 (1999).

[Tha] Paul Thagard, *Mind: Introduction to Cognitive Sciences* (MIT Press, 1998).

[V] H. Varmus, “The impact of physics on biology and medicine,” *APS News* (August/September 1999) 8.

[UMd1] University of Maryland Physics Education Research Group, *Thinking Problems in Physics* [http://www.physics.umd.edu/perg/abp/think/]; *Univeristy of Maryland Fermi Problems*, [http://www.physics.umd.edu/perg/fermi.html];*Alternative Homework Assignments* [http://www.physics.umd.edu/perg/abp/aha].

[UMd2] University of Maryland Physics Education Research Group, *Mathematical Tutorials in Introductory Physics* [http://www.physics.umd.edu/perg/abp/abptutorials/] (password: ‘pergTUTS’) to be published by John Wiley & Sons.

[Wal] D. S. Wallace, S. W. C. West, A. Ware, D. F. Dansereau, “The effect of knowledge maps that incorporate gestalt principles of learning,” J. Exp. Educ. 67(1) 5-16 (1998).

[Wh1] B. Y. White, “Intermediate causal models: A missing link for successful science education?” in *Adv. in Instr. Psych., Vol. 4,* R. Glaser (ed.) 177-252 (Lawrence Erlbaum Assoc., Hillsdale NJ, 1993).

[Wh2] B. Y. White and J. R. Frederiksen, “Metacognitive facilitation: An approach to making scientific inquiry accessible to all,” in J. Minstrell and E. van Zee, Eds., *Teaching in the Inquiry-Based Science Classroom* (AAAS, 2000), to be published.

[WhG] R. White and R. Gunstone, *Probing Understanding* (The Falmer Press, 1992).

[Wit] M. Wittmann, *Making sense of how students come to an understanding of physics: An example from mechanical waves*, Ph.D. thesis, University of Maryland, 1998.