Physics Education Research and Contexts of Student Learning

> Why do university students exit courses capable of solving difficult analytic problems (e.g., calculate current in a complex circuit), but are unable to explain the same content conceptually (e.g., which light bulb is brighter in such a circuit)?
>
> Why do many of the educational reforms being called for today echo the calls of almost 100 years ago?

Building on the well-established foundations of physics education research that have focused on student cognition, curriculum design and course practices, this research program establishes another perspective from which we may understand student learning in physics – one that emphasizes learning in context. The proposed work investigates the central role of context in the practice of physics education. That is, how and what students learn depends not only on traditionally conceived content but also upon the formation of tasks, class environments, and broader institutional structures in which the content is embedded. Such a perspective begins to explain a host of research questions, such as those listed above, and is directed at understanding sustainable and scalable models of reform in physics education.

This project coordinates research studies on the role of context in student learning at three different levels: the individual, the course, and the department. Because these three contextual levels of educational practice strongly influence one another, they are studied simultaneously to discover the relations among them. While this project spans all three levels, it does not strive to answer all questions within them. Instead, the project focuses on specific sets of questions surrounding common themes: tools, such as the use of computer simulations; practices, such as teaching as a mechanism of learning; and surrounding frames, such as departmental norms and their influence on student learning. Many of these research questions are new in physics (e.g., examining the effects of having students teach others in order to learn) while others augment existing lines of research (e.g., the role of computer simulations in the classroom). Collectively, these investigations provide a framework for understanding each of the individual research studies, which allows us to interpret their results and portability to other environments. Furthermore, their coordinated outcomes will result in meaningful models of context in student learning, which will serve as the foundation for long-term research in this area.

The intellectual merit of this CAREER proposal is to create a deeper understanding of the role of context in learning physics. This essential aspect of education complements existing physics education research, and must be considered to fully and effectively address improvements in student learning of physics. This work will develop our understanding of tools, practices and surrounding frames of physics education at the levels of the student, the classroom, and the institution.

The broader impact of this program will be to improve educational practices at each level and better understand how to make them sustainable and scalable. These efforts will infuse education into broader physics practice, and simultaneously make physics more accessible in other educational realms. Recently, the field of physics education research (PER) has undergone substantial growth.[1] The proposed efforts will develop and promote this relatively new sub-discipline of physics, will build a new research line in PER at the University of Colorado, and will establish a long-term career path. Many of the studies of broader context will also impact educational reform in other disciplines. Finally, this program will reach thousands of students at the University of Colorado and establish models for reaching students at all large-scale research universities.

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I. Introduction

> How might we substantively include context in our models of student learning, course practice, and institutional reform in physics?
>
> What are productive models and practices for sustainable and scalable educational reform?

My research program addresses these related research questions by examining the multiple and intertwined levels of context of student learning. Rather than focus solely on one aspect of student learning (e.g. competence at moving among various representational formats in physics), I research these questions of context, in context. The following research program examines three levels, or frames of context, of education that collectively shape the educational experience in physics: student, course, and departmental practice. While such a program spans a remarkably broad domain, I am not attempting to solve all problems in educational reform at these levels. Rather, the set nine inter-related research and education efforts discussed below are designed to:

- emphasize the great gains we might make in research and reform by considering the broader perspective in which individual efforts exist,
- promote reformed educational practice at the department in a sustainable manner,
- build a new focus area in the doctoral program of the physics department at the University of Colorado, Boulder: physics education research, and
- set a career trajectory for me that will continue well beyond the scope of this CAREER funding

A. BACKGROUND: CALLS TO INCLUDE CONTEXT

As I first started teaching an advanced undergraduate and graduate level course in physics, I noted that a large fraction of my students had passed the introductory courses with high grades, and yet were unable to answer half of the questions correctly on a basic conceptual survey of the field.[2] The same survey issued to students taking the introductory level course yielded results that were even worse; students scored 25% correct upon entering the introductory course and scored 35% correct upon exiting. The most basic concepts covered in these physics courses were not reaching the students.

Of course, this situation is not new and has been reported extensively within the physics community[3,4,5,6,7] and well as by cognitive psychologists.[8] Traditionally taught physics classes fail to impart robust conceptual understanding, even for those students who perform well on class exams. Faculty researchers have found that students can calculate the potential difference in a complicated, abstract circuit diagram, but cannot correctly predict what happens to current, brightness, voltage, and power in a far simpler circuit using more realistic iconography.[9] Findings such as this have spurred researchers to develop new curricula,[10] rearrange course structure,[11,12] and study student learning.[13,14]

To date, discussion of university student learning in physics been largely student and content centered.[6,7] A common goal of these efforts is to design activities that promote conceptual understanding for the large fraction of students who fail to do so in traditional forms of instruction. As thoroughly reviewed by McDermott and Redish (1999)[6] and Redish (2003),[7] researchers have gone to great lengths to create environments supportive of such conceptual development. However, the environments that promote such student learning remain undertheorized. Local culture and context are taken to be implicit or are merely alluded to in these student- and content-centered models of student learning. While the theorists of physics learning have moved toward a more differentiated view of the learner (few would defend the view that students themselves are homogenous), the contexts in which learning occurs are treated more generically. We have yet to provide thorough accounts of how context and the teaching/learning process are interconnected. In order to understand what and how elements of learning environments shape students' understanding, it is necessary to develop a detailed description of context and models of interaction between context and student learning. My research strives to articulate an educationally useful conception of context, and develops, applies and tests models of how context participates in the process of student learning in physics.

In recent years within the physics education research community, context has begun to emerge as topic of discussion – Researchers recognize the necessity for including context and in so doing make implicit calls for a more differentiated understanding of context and of the dynamic relations between learning and context. Redish emphasizes that that the conceptual learning that occurs in a constructivist approach to education[15,16] depends upon context – what he refers to as the context principle.[7] While he demonstrates that different contexts yield differing results for student learning, the definition of context and the relations of context and learning are yet to be explored. diSessa, Hammer and Elby recently have revisited their studies of epistemology and judgment in physics problem solving.[17] They argue for a "context-sensitive activation of finer-grained knowledge elements," (pg. 238) to explain why a student ("J") shifts epistemological stances through the course of clinical interviews given very subtle shifts in problem formation. They conclude, "that 'beliefs'… seemed unable to carry the burden of explaining J's behaviors. Instead we offered the idea of 'judgment in context' . . . " (pg. 284) These researchers begin to differentiate context by delineating macro-contexts (e.g. physics vs. art) from micro-context (e.g. formation / presentation of a particular problem). Similarly, in discussions of "transfer", researchers examine whether or not students can apply similar procedures and tools for problem solving in different contexts. In examinations of student learning during the course of interviews, Rebello and colleagues develop a model of transfer of conceptual mastery of physics that helps them characterize the dynamics of learning and the mechanisms of transfer.[18] In such investigations, context (both that of the interview and that of the domains of transfer) plays a critical role. The approaches of Redish, of diSessa, Elby and Hammer, and of Rebello and colleagues provide a good point of departure for the present effort to elaborate on the concept of context. While these discussions emphasize students, the present research line strives to make a more detailed examination of what is meant by context and how it shapes and is shaped by student learning.

B. MODELS FOR INCLUSION: *FRAMES OF CONTEXT*

In other fields focusing on student learning, context has played a central role. Socio-cultural researchers of learning in anthropology, education and psychology have a long-standing tradition of emphasizing the social, cultural and context-bound nature of education. My research seeks to bridge the work that emerges from this tradition with the traditions in physics education research described above. My goal is to emphasize the role of context in physics learning by drawing upon research that stresses the situated and embedded nature of learning,[19,20] and the role of local culture and the use of cultural tools that mediate human action.[21,22] This work holds context central to student learning, not as an analytically separate factor, nor as the backdrop against which student learning occurs, but as an integral part of student learning. Students (and other

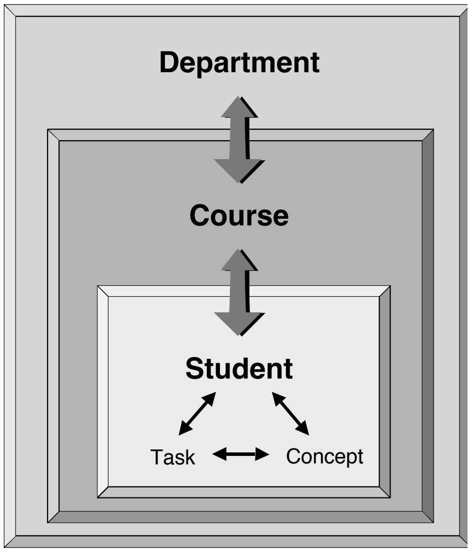

Figure 1: *Frames of Context:* embedded levels of context that shape (and are shaped) by student learning.

educational participants) shape and are shaped by the context in which these educational endeavors occur.

Despite our everyday understanding of the definition of context, such a notion is insufficient for delineating its role in student learning. My approach applies Cole's use of embedded context[21] to identify particular levels of context, or *frames of context*, that are critical to this examination of the educational process.[23] The metaphor of frames of context, or collection of surrounding conditions and lens of focus, is particularly useful in identifying varying levels, or scope, of context to which we attend. Figure 1 illustrates one such example: a student may be working on a task (teaching other students), which is part of a class (introductory physics), which in turn is part of a larger system (the department). Of course these frames of context extend inward and outward: teaching involves particular actions, and the department is part of a university and larger social and economic structure. At the same time, participants belong to multiple frames of context not shown – e.g., students are embedded in other nested frames such as family and personal relations. Notably the system we focus on is simultaneously embedded (our examination of student learning sits within a course) and hierarchical (while students can affect the outcomes of the course, generally the outer layers influence the inner more significantly). At the same time Figure 1 represents a static image, which captures neither the dynamic nature of learning, nor the relational nature of these frames. For this shortcoming, it is important to consider the relational notion of frames of context. Frames of context include the collection of components and the relations among them. Elements of a system are shaped by their relations with other elements, and hence, removing an element from the system to examine its features necessarily reshapes it. Such a conception of embedded nature of learning goes a long way to explain why individuals may be perfectly capable of calculating and comparing prices in a store, but unable to perform equivalent operations on a formal test.[24] So too might we begin to understand that our efforts at educational reform do not sit in isolation – they shape and are shaped by surrounding structures / contexts. My research program builds on this model of frames of context to address the inclusion of context in our understanding of student learning and to promote sustainable and scalable forms of educational practice.

II. Research/ Educational Programs:

A set of nine coordinated research and education efforts are designed to emphasize the broad and inter-related perspectives of frames of context. That is, research on how a student understands various representational formats will depend upon surrounding and surrounded frames of context -- the situation in which the question is asked and the resources present (in addition to a variety of other factors such as personal beliefs and larger-scale influences, like the value of education). This CAREER program outlines three frames of context for investigation of student learning in physics: the micro-level of student actions, the level of course structure, and the broader scale of institutional influences. While particular research activities described below may be located within a given frame of context, my approach emphasizes the relations among these various frames, paying particular attention to the dynamic nature of student learning within and across these levels of inquiry. To facilitate an examination across each of these frames of context of student learning in physics, my research follows particular themes: use of tools, practices, and meta-level regulation and surrounding features. A summary of my proposed research projects and their relations are listed in Figure 2.

Theme Frame of context	i. tools	ii. practices	iii. meta/ surrounding features
a. Individual	Representational competence	Learning by teaching	Student attitudes and beliefs (ABs)
b. Course	Role of simulation in undergraduate courses	Physics 4810: *Teaching and learning in physics*	Secondary adaptation of reforms
c. Department	Faculty use of PER-based materials	Programs in graduate, post-doc, and faculty preparation	Influence of departmental norms on program success

Figure 2: Research programs that make up the CAREER proposal. Programs are organized by frame of context (individual, course, and department) and by theme (tools, practices, and meta-features).

In the following sections each of the research activities is described. While they exist in various states of maturity, they are coordinated in addressing the fundamental research questions of the role of context in student learning and how to create and understand sustainable and scaleable reform. These areas serve as rich veins of research that will thrive during the period of my CAREER program, and continue over the rest of my career.

Each of the research activities below has direct implications for and influence on the teaching practice at the University of Colorado. That is, each research program will result in tools, practices or infrastructure for promoting improved education (locally and ultimately elsewhere). Simultaneously, these research activities will support the development of a new doctoral research line in physics by providing a variety of directed research activities for graduate students in the newly formed Physics Education Research Group at Colorado (PER@C).

The overarching methodological framework for this study is that of a design-experiment, which emphasizes simultaneously engaging in research on learning and education, and transformation of practices that lead to student, course and institutional development.[25,26] Each element, of research and of practice, will be used to inform the other. As such, the findings will be grounded so as to make them relevant to the real practices at universities and portable to other institutions seeking to employ the resulting models and findings. My approach applies a mixture of methods, using both quantitative and qualitative analyses to capture both the process of development (generally through qualitative research) and the outcomes (often summarized as quantitative data). Each form of data collection, whether survey instrument, observation, interview, or project-based assessment will be used both formatively, to shape these research projects and summatively, to evaluate outcomes. Throughout the course of this coordinated program there will be tight coupling between research, teaching and education.

A. INDIVIDUAL CONTEXT

1. ***Representational competence*** with educational application*: curricular modification*

> How do students respond to different representational formats (pictorial, mathematical, etc.) in learning physics?

From a socio-cultural perspective, the use of tools (such as language, or representations) characterizes higher order cognition.[27] Tools not only facilitate but shape how we think and act.[27,28] In this research project, we have begun to examine student competence using varying representational tools (e.g. graphs, mathematical formula, pictures, language) to solve physics problems. While experts have been able to effectively use, translate, and coordinate differing representational formats,[29] students often see isomorphic problems as different simply because of representational format.[29,30]

- How does student performance differ by representation?
- Why? For instance, is this a function of the student (as suggested by learning-style research), the environment, or the interplay between student and environment?
- Does student choice of representational format play a role?
- Can students be specifically taught representational competence in physics?

In our recent pilot studies of a large-enrollment algebra-based physics class, students solved isomorphic problems in four different representational formats. We found that there are statistically significant performance differences between isomorphic problems. For example, of 218 students who solved the "same" problem using graphical representation and pictorial representations, 77% solved the graphical problem correctly and 62% solved the pictorial problem correctly. This difference is statistically significant ($p = 0.006$, 2-tailed binomial test). Subsequently, students were given a single problem multiple-choice quiz where they selected the problem format. As a control, part of the class was assigned the follow-up quiz with a random format, allowing a comparison with the group that was provided a choice. Here we found that allowing students to choose which representational form they use increases student performance under some circumstances, and reduces it in others, as shown in Figure 3.[31]

Such preliminary findings are indicative that both representation formats and student ability to select representational formats play a significant role in student achievement. Future work will include: i) refining and broadening the instruments (e.g. to ask questions in a variety of content areas), ii) further validating the questions / student choices by interviews and open-response questions, iii) understanding the influence of the course (a larger frame of context) and the representations used in text, lecture etc., iv) testing in a variety of other environments (the calculus based course, physics for non-majors), v) developing curricular elements which make representation explicit and promote representational competence among the students.

	Verbal	**Math**	**Graphical**	**Pictorial**
Choice	**0.81** **(N = 21)**	**0.90** **(N = 42)**	**0.96** **(N = 28)**	**0.39** **(N = 58)**
Control	**0.32** **(N = 19)** **p = 0.002**	**0.13** **(N = 15)** **p < 0.0001**	**0.53** **(N = 17)** **p = 0.0004**	**0.83** **(N = 18)** **p = 0.0012**

Figure 3: Student performance on isomorphic problems in differing representational formats. One group (choice) selected format, the other (control) was randomly assigned problem format.

These activities will comprise the bulk of a doctoral thesis for one of my graduate advisees and occur over a 3 year time-span. Year 1: instrument design, validation, and broadening with baseline data on student performance; Year 2: develop and pilot work on curricular modifications in two or three content areas (e.g. mechanics and optics); Year 3: revised curricula to support representational competence, finalized instrument and analysis.

2. ***Learning by teaching*** with educational application: *student practice, e.g homework*

Why is teaching such an effective mode of learning?

While it is colloquially understood that people learn well by teaching material (anecdotally it is easy to get faculty to admit that they do not understand material until they teach it), few studies in physics have researched the relations between teaching and the associated learning for the person teaching. Nonetheless, a variety of curricular reforms recognize the value of teaching and do emphasize collaboration.[9,10,32 ,33,34,35] Papert's early work emphasized the role of teaching -- fourth grade students made computer software to teach third grade students about fractions.[36] He demonstrated that the fourth graders understood fractions better than their counterparts who engaged in more traditional forms of instruction.

- Do students learn better by teaching concepts? Under what conditions?
- How do students reorient their beliefs about knowledge in order to teach?
- What models of cognition and context support the approach of teaching to learn?

My prior work demonstrated that a course that heavily incorporates the activity of teaching physics promotes students' conceptual development in the domain.[2] In this course, half the students were given the task of teaching younger students, the other half were assigned traditional homework for the same amount of time. Those teaching performed better on conceptual tests of this material; however, these data are too few to make definitive judgments. The next steps of this study are two-fold: experimental and theoretical.
<u>Experimental:</u> study student learning from teaching vs. other forms of educational practice (homework, lab etc) for the same time on task in a variety of differing environments.
<u>Theoretical</u>: Begin to describe why teaching is so effective as a learning tool. Such work would build on the ideas of contextual constructivism in physics,[23] of developing students' epistemology,[17] and of epistemological framing.[37] The context in which one teaches, how someone perceives knowledge, and what resources an individual uses to frame his perception of a task all shape a person's approach to understanding that task.

In the second year of this project, a class on teaching and learning physics (established during the first year and described more below) will be used as a test-bed for assessing student learning from the practice of teaching (using controls as described above). Identifying and developing theoretical models will shape studies in future years, which would include infusing micro-teaching opportunities into the lecture and recitation sections of the large-scale introductory physics courses and following graduate students engaged in teaching opportunities described in sections below. Through carefully designed studies such as those outlined above, we will be able to determine at what point in a student's mastery of material, it is appropriate for a student to consider teaching as a mechanism to concretize his or her own understanding.

3. ***Attitudes and beliefs*** with educational application to: *course structure and evaluation*

How do student attitudes and beliefs shape learning in courses?

In addition to the traditional content within any course, there are extensive sets of attitudes and beliefs about science we teach to our students. The way we conduct our classes send messages about how, why, and by whom science is learned. Such meta-messages have been referred to as the "hidden curriculum."[7] As offered in traditionally taught courses, some of the hidden curriculum is beneficial (e.g., the message that science is a coherent representation of the world) while other aspects are detrimental (e.g., the notion that women cannot be strong scientists). While decades of physics education research have reformed classroom practices to improve student mastery of conceptual domains,[6,7] these same class environments are found *not* to improve student attitudes and beliefs (ABs). In fact, normally, students are found to regress from more expert-like beliefs to more novice beliefs over the course of a semester.[7,38] In our findings and those of prior researchers, it is notable that such regression of students' ABs are seen even for courses where reform pedagogy is used and improved conceptual gains are observed.

- How do student ABs relate to their performance and retention in a physics course?
- What course practices shape and are shaped by student ABs?

Our recent studies of student ABs indicate that ABs are correlated with student's choice of discipline and retention. Using a recently designed and preliminarily validated instrument,[39] we have found that the percentage of physics majors in a course is correlated with the average student response to questions about the personal relevance of physics.[40] ABs also correlate with retention within individual courses. Sample data are shown in Figure 4. Additionally, in our pilot studies we have observed correlations between student conceptual mastery of physics and their attitudes and beliefs. Those students who perform better in the course also have more favorable ABs, and those students doing worse also have less favorable ABs (that regress over a term).[40] Note that these results show clear connections, but they do not establish the nature of the relationship among student ABs, performance and retention, which will be a subject of study in the current work.

University Environment	**Favorable Pre-Test Score (%) (uncertainty; n)**
UNC Calc-based Phys I (FCI 0.35) (mostly majors)	**71 (5%, n=41)**
CU Calc-based Phys I (FCI 0.6) (mostly engineers)	**63 (2%, n=174)**
UNC Alg-based Phys I (FCI 0.13) (who stayed enrolled) **Students who started**	**61 (5%, n=36)** **49 (4%, n=78)**
CU Non-Science Major Physics I	**44 (4%, n=77)**
CU Non-Science Major Physics II	**61 (n=34)**

Figure 4: Student favorable responses in AB survey category, Reality Personal View, issued at the beginning of term for a variety of different courses**.**

The next steps of this study will be to make modifications in the evaluation instrument that probes student ABs and to conduct full statistical analysis of large sample results. Based on these results, we will change some of the questions and delineation of the factor groups (categories of ABs) to improve consistency of the instrument. We will collect data on student attitudes and beliefs in a variety of course environments (the suite of introductory and advanced physics courses), in one-on-one and group interviews, and correlate these ABs with other student characteristics (e.g. traditional demographics) and measures of student learning (such as conceptual mastery[41]). Particular emphasis will be placed on tracking student ABs in environments that overlap with the other projects described in this CAREER proposal. Thereby, we may begin to observe the synergistic effects of these programs (layered frames of context). Through formative and summative evaluation we will be able to understand the process of shifts in ABs and the relations of these shifts with student achievement. Over the long term we will examine their role in student choice in future major and career. In particular, we will focus on ABs for student populations that are traditionally under-represented in the sciences and how these affect decisions for these populations who differentially switch out of STEM disciplines.[42] Of course, the goal is to find what factors can be most effective at recruiting and retaining such students in careers in the physical sciences.

This research will be conducted in collaboration with other faculty in the PER@C research program (Prof. Wieman) and conducted primarily by a lead graduate student (under my supervision) in the Physics Education Research Group at CU.

Outcomes (Individual Level): Build a model of student learning in the most localized layer of context: tools, practices, and meta-cognitive skills that shape and are shaped by student learning. At the same time these projects explicitly support education by improving course tools and practices with the expectation that these lead to improved student mastery, attitudes and beliefs, and retention in the sciences.

B. COURSE CONTEXT

1. *Applying differing tools* with educational application: *new course tools*

> How might we productively leverage the opportunities provided by the availability of new technologies?

Over the last decade there has been an increase in the use of computer simulations to support student learning in physics.[43,44,45] With the enhanced capabilities of computers, their ubiquity in the classroom, and the knowledge of how to engage students around particular ideas in physics, a variety of computer tools have been found to promote student understanding in the classroom.[46,47,48] In this line of research into context of class practices that foster student learning I examine:

- What are the necessary features of these computer simulations to serve as educational tools?
- How might these new tools be productively applied in a variety of educational environments?
- Where do these tools enhance traditional forms of educational practice? Where do they add value? Where are they limited in applicability?

The proposed work will build on an extensive foundation developed by the Physics Education Technology (PhET) project at the University of Colorado.[49] The PhET team has created over three dozen computer simulations in physics around four particular design features. 1) The simulation designs and goals are based on educational research. 2) The coding is done by high-level software professionals (partly supported by a private foundation) working closely as part of a team with disciplinary experts and physics education researchers; this team enables the development of simulations involving quite technically sophisticated software, graphics, and interfaces. Such development makes these simulations appealing to use, while they model a wide range of physical behaviors and allow users to manipulate a wide variety of variables to encourage open-ended exploration. 3) The range of expertise working on the PhET team enables a rapid cycle through coding, testing with students, and refinement to optimize effectiveness and user-friendliness. 4) The sophisticated software creates simulations that embody predictive visual models of expert scientists, allowing many interesting but relatively advanced concepts to become widely accessible.

Research on these simulations will reveal the conditions of their use that promotes student learning individually, in groups, and in class environments. The PhET team has conducted pilot studies of the use of these simulations; however they will be carried out in more detail with the support of the CAREER program. These studies include: 1) asking a student a brief physics question on material that they have not seen before and allowing them to play with a simulation with no guidance before answering, 2) video-taped interviews in which students worked with a simulation for 0.5-1 hours while thinking out loud, 3) simulations used in lecture followed by short multiple-choice questions, 4) student surveys as to how useful to their learning they found simulations to be both in the context of lectures and homework, 5) studies in which simulations were used as direct replacements or supplements to traditional labs, 6) observations of students working in groups to use simulations to answer homework problems.

In a pilot study in which computer simulations replaced real lab equipment in the circuits laboratory of an introductory physics course, we observed that students using the virtual lab learned relevant circuit concepts better than students who had engaged in the same laboratory using real equipment.[50] (See Figure 5.) By continuing studies of student use of these simulations, through clinical interviews, observations, and video analysis we will begin to ascertain why students perform better using these simulations. Further research will focus on areas listed above as well as design and study of curricula that effectively engage students from all backgrounds with the simulations and associated physics. As part of the PhET project, under the support of the CAREER grant, a graduate research assistant will lead the studies of simulation effectiveness (described above) and develop (or modify existing) curricula to study the real and contextually productive application of these computer simulations.

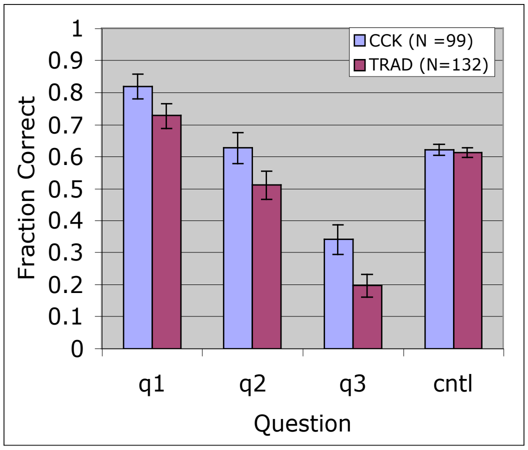

Figure 5: Student final exam performance for groups that had used simulations (CCK) or real equipment (TRAD) during a circuits laboratory. q1 –3: three conceptual questions on circuits (ave CCK = .593 and ave. TRAD = 0.476; p< 0.001). cntl: the remaining 26 questions of the final (no statistical difference for CCK and TRAD groups).

2. ***Education research and physics*** with educational application: *new courses / programs*

> How might we include the questions of PER into the educational practices of physics? What are the effects of such inclusion on student mastery of physics? What are the effects on the broader scale – the department, and institutional factors?

Based on work previously supported by the NSF,[2,23] I will develop a new service-learning program in the physics department at the University of Colorado. The central element of this program will be a new course in physics education reform and physics education research for advanced undergraduate and graduate students: *Teaching and Learning Physics*. The class builds upon a successful model developed in my work at the University of California, San Diego.[2,23, 51] The structure of the course includes three central components: study of pedagogical issues (cognitive, psychological, educational), study of physics content, and practical experience teaching in the community (both in Boulder area and within the University). Each of these components is designed to complement the others by providing a differing perspective on the same area of inquiry. For example, the same week that students read about studies that document individuals' difficulties with the electric field, the students study the concept itself, and teach it to others. This model has been demonstrated to increase student mastery of physics, proficiency at teaching, and the likelihood that students engage in future teaching experiences.[51] As occurred in the prior implementation, it is anticipated that this set of activities will attract students to physics from all demographic backgrounds, increase the number of physics majors enrolling in teacher education, improve student achievement in other courses, and build strong and sustainable ties between the university and community partners.

As a research venue, this course will be a core of the study of student learning in context and of the study of scaling and sustaining educational reforms. It will be in this course that the studies of learning-by-teaching will occur, as described above. Data on students' performance in physics, education research and teaching will be collected through interviews, project work, and pre- and post-test evaluation. At the same time, because this course has been offered previously (and continues) at a similarly large scale research institution, comparative analysis of this secondary implementation of the program will provide insight into the portability of this model of educational practice. Data on institutional response (interviews, documentation of institutional support, long-term outcomes for students and department) will be collected and compared. Furthermore, this course serves as a bridge between studies of the individual and studies of institutional response, the frames of context described in Figure 1. Research surrounding this course will be conducted directly by the PI who will offer the course, and ultimately by a post-doctoral fellow supported by this CAREER grant.

3. ***Study of secondary implementations*** with educational application: *adapting reforms*

> While the physics education research community has developed many "proven" reforms, their replication is not well studied. What are the necessary elements of adopting proven educational reforms?

Many of the calls for educational reform,[5,7,52] echo the calls from early last century.[53] This is not to say that we have not made progress. Research on how people learn has led to the development of science teaching methods that have been shown to be more successful than traditional practices.[5,6,7] As a result of these calls and dedicated education research, a variety of very useful curricula and practices have been developed.[6,7] To date, however, there have been few studies of what it means to replicate these known reforms. In addition to studying the core elements of a given educational reform (for example *Tutorials in Introductory Physics*[10]), we must study the critical elements of the context in which these tools will be used.

With the support of the NSF's CCLI Adaptation and Implementation program, we will be implementing several of these known reforms in our introductory calculus-based physics sequence.[54] As such, it provides an excellent opportunity to study the effects of secondary implementation and the fidelity of replication of educational reforms. With the support of the CAREER program a graduate researcher will be able to compare the features of successful implementation of *Tutorials in Introductory Physics* at the University of Colorado with their implementation at the University of Washington. Areas of investigation will include:

- Assessment of the fidelity of the curricula -- are the curricular materials identical or need they be modified?
- What characteristics of the course, students, and surrounding departmental structure promote or inhibit the adoption of Tutorials?
- Do students learn the same material as at UW?
- Are there complementary or competing effects from other educational reforms being implemented (such as *Peer Instruction*[9])?

The onset of the CAREER program will coincide with the end of the first year of the year CCLI grant. As such, the first rounds of adoption of Tutorials will have occurred. For the following year (the first year of the CAREER project), we will run comparative studies of student achievement on conceptual surveys, attitudes and beliefs instrument (ABs), and surrounding structure (e.g. coupling of Tutorials with the course). The second and third years will be spent refining the implementation and examining the effort to create a sustainable change. Because the CCLI program has proposed a model of hand-off of these reforms to other departmental faculty, studying the process by which this succeeds or fails will determine the necessary conditions for successful implementation of such reforms.

Outcomes (Course Level): Build a model of educational practices: use of tools, particular course practices, and approaches to implementing known educational reforms. Such research efforts will: support the research-based inclusion of computer simulations in a wide variety of environments, create bridges between education and traditionally conceived domain of physics, and implement a variety of educational reforms in the introductory physics sequence.

C. DEPARTMENTAL CONTEXT

1. *Faculty awareness and use of PER* with educational application: *improved faculty practice*

> How much do faculty know about research based reforms in physics teaching?
> What tools might be used to increase faculty awareness and use of these materials and practices?

As discussed above, a variety of educational reforms have been proven effective, but have failed to become broadly adopted by the college and university teaching communities. In addition to the context of implementation (the course), the surrounding departmental structure plays a significant role.[55,56,57] Particularly, it appears as though faculty lack awareness of these materials and support for using them locally. To study these issues and their relations to other frames of context of student learning, I anticipate participating as a research member in two projects focused on the issues of faculty awareness of and facility at using physics education research-based materials.

The first project, led by Professors Charles Henderson (Western Michigan State University) and Melissa Dancy (University of North Carolina at Charlotte), strives to understand faculty knowledge about, attitudes towards and use of innovative instructional materials in introductory physics courses (both calculus and algebra based sequences). The project will include a survey of faculty practices, interviews of select faculty and observations of their practices. It will provide baseline data of faculty practices from which we may understand the context of current educational reform and address the development of future reforms. The second project, led by researchers Dr. Matthew Schneps and Professor Phil Sadler (Harvard-Smithsonian Center for Astrophysics) seeks to increase faculty awareness of research based reforms and practices by building on their well-known, NSF-funded "Private Universe Project" for K12 teacher development. The program applies the same methodology of using video as a tool to alert faculty to research in STEM learning, to provide visual models for instruction, and to promote community among those seeking to change instruction in higher education.

The CAREER sponsored investigations of faculty awareness of research-based reforms will use data collected in these two programs to understand the context for sustainable inclusion of educational practices listed in prior sections. These data augment the studies secondary implementations (section II.B3) in order to develop a more complete and coherent model of implementing sustainable reforms. This line of research will begin in collaboration with these two programs during years one and two of the CAREER program and become the subject of more focused attention during years three to five. Case studies of faculty using particular reforms, comparative analysis with local implementations of these same reforms (discussed in section II.B), and analysis of aggregate data of the use of these reforms by faculty across the nation will provide material to triangulate an understanding of faculty awareness, and use of educational reforms in physics.

*2. **Seeding faculty change*** with educational application: *improved faculty practice*

> What mechanisms might we introduce to support the development of future faculty in physics education?
> Can these same programs be used to promote the reform of current faculty practices*?*

Over the last decade departments of physics have been increasing their attention to educational practice.[1,58] At the same time the demands on the faculty and the hosting physics departments for conducting traditional research compete with these increasing demands for educational practice –research remains to be the main focus at large-scale, PhD-granting institutions.[56,57] In this broader frame of context (the departmental level), I examine two programs designed to support the development of future faculty and to promote the inclusion of research-based educational practices in the physics department.

The first program, a departmentally-based Preparing Future Faculty (PFF) program, includes graduate students and postdocs in bi-weekly seminars and mentored teaching opportunities.[59,60,61] The program is designed to simultaneously support the development of these future faculty in teaching and educational practice, and to support the introduction of educational reforms in the department. As part of the PFF program, graduate students and postdocs will be encouraged to participate in education and outreach opportunities, including service to the lower division physics courses. Participants will select a track of involvement that will include: participating in regular meetings, engaging in micro-teaching opportunities, presenting on topics of interest, teaching in selected university environments, participating in reform of the undergraduate sequence, and ultimately (as occurred in prior instantiations of this model), taking over the program. By participating over several years under the guidance of the PI and faculty mentors, students will gain the expertise to run the program.[19]

The second program is a model of postdoctoral fellowship in physics education research. In collaboration with Professor Carl Wieman (University of Colorado, Boulder), we seek to develop and study a new model of simultaneously supporting reform of departmental practice, and the preparation of future physics education research faculty. The Senior Teaching Fellow model is based on the use of recent graduates with discipline-based Ph.D. level training who have decided to pursue a career in teaching or education research. The Senior Teaching Fellow (STF) works in partnership with the faculty who are introducing educational reforms (such as those listed in section II.B) to develop course goals, implement the desired transformations, carry out assessments, and carefully archive all the course materials for subsequent reuse. STFs will receive ongoing training in the relevant research on learning and discipline-based educational research by the PI and professional research partners. Our hypothesis is that after the STF and the partnering faculty member have taught a course together to carry out a given transformation and carefully preserve the materials in a user-friendly form, it is then practical for the same or a different individual faculty member to teach the transformed course in subsequent terms without undue effort. Our pilot work has provided some support for this hypothesis, but much more work is needed to establish its validity. After completing most of the transformation of one course, the STF will then move on to team with a new faculty member in the transformation of a second course. Part of the design study is to find what conditions (or contexts) are necessary to ensure that it is easier for subsequent teachers to successfully teach the course in the transformed approach than for them to revert back to the more traditional, but less well documented and supported approach.

While the CAREER project will not provide the funds to run these two programs, a postdoctoral fellow will be hired during the later portions of this grant to analyze the effects of these programs. Data will collected to research the effects at the individual, course, and departmental levels. These data include: measuring conceptual development of students participating in reformed classes, assessing individual graduate and post-doctoral evaluations and shifts in attitudes and abilities, tracking shifts in attitudes and practices of faculty participating in these programs, documenting shifting classroom practices, and departmental response.

3. *Examination of top-down influences* with educational application: *departmental awareness*

> What are the effects of departmental norms on educational practice?
> What are the relations among these various frames of context of student learning?

Departmental norms and practices play a significant role in shaping those reforms and research projects described above. Simultaneously, it is anticipated that these activities will shape the departmental norms and practices. In this segment of the study, I study the dynamics and relational nature of departmental practice, course reforms, and individual student learning – the interplay among these frames of context. For instance, it is generally recognized that from perspective of nested frames of context (Figure 1), the system is generally hierarchical- -- the outer influences the inner more than visa versa.[21] It is worthy of documenting the prevailing norms and how they influence the more local frames of context[58] -- Are faculty rewarded or discouraged from participating in educational reforms? How might these messages influence graduate student / future faculty perception of the role of the department? At the same time, localized reforms have been shown to influence broader culture. For example, the introduction of new personal response systems (individual infra-red responders) used in *Peer Instruction*[9] in one course in introductory physics has spread throughout the department and now across the university. The practice has become so widespread that the use of these tools has been recently studied by researchers in the Department of Communication.[62]

In the latter portions of this CAREER grant, in coordination with partnering researchers and the supported post-doctoral fellow, I will document the institutional practices which shape and are shaped by the particular research programs and reforms described above. Data will include documenting the materials used for faculty evaluation of teaching practice, level of departmental financial support for educational reforms, and the widespread adoption (or lack thereof) of some of these practices.

Outcomes (Departmental Level): model of relations among individual, course, and surrounding structures. Models for realistic reorganization of educational practice to support course reforms at the departmental level without a significant shift in resources (faculty time or funding). Proof-of-concept of research-based approaches to improve education at a broad level.

III. Timeline:

The timing of each of these projects is discussed above in the description of the research and summarized below in Figure 6.

	Individual			**Course**			**Department**		
	Representational Competence	Learning by Teaching	Attitudes & Beliefs	Role of Simulations	Teaching & Learning	Course Reforms (ABs)	Faculty Use of PER	Future Faculty	Departmental Norms
Year 1	Gr		Gr	Gr	PI / Gr	PI / Gr	Collab	Collab	
Year 2	Gr	PI	Gr	Gr	PI	Gr	Collab	PI	
Year 3	Gr	PI	Gr	Gr	PI	Gr	PI	PI	PI/ PD
Year 4		PD		PD	PD		PI	PI/ PD	PI/PD
Year 5		PD		PD	PD			PI/PD	PI/PD

Figure 6: CAREER Project Timeline: Project managed by graduate student (Gr), Postdoc (PD) under supervision of PI, jointly run (PI/Gr) or directly run by the PI, or part of a larger collaboration (Collab).

IV. Integration of Research, Education, and Departmental Practices:

Because these research projects follow a design experiment methodology and because the research projects themselves focus on education, there is necessarily a tight coupling with educational practice, as described throughout section II. These coordinated research studies are designed also to foster the development of the newly formed Physics Education Research Group at Colorado (PER@C). As one of the leading faculty members of the research group, this CAREER grant will support both my professional development and the graduate doctoral emphasis in PER in the physics department. With the anticipated continued growth of the new PER@C group, the University of Colorado is poised to become one of the major research centers in physics education in the United States. At the end of our first year, four faculty, five graduate students, and one post-doc contribute to the research program at CU. With the support of the CAREER, our efforts will continue to grow and we will be able to support graduate students and post-doctoral fellows who are now applying to join the CU program.

V. Prior Work:

In one line of NSF supported research (NSF - PFSMETE # 9809496, $153,000 8/1/99 - 7/31/2001), I developed and studied programs (a new class, graduate program and a study of postdocs) that blended physics, education, and community partnership. Published work has appeared in the *Journal of College Science Teaching,*[2] the *International Journal of Science Education*[23] and the *Journal of the Scholarship of Learning and Teaching.*[51] In another of NSF-supported project (NSF - IERI# 0090294, $118,496 1/1/01 - 12/31/01), I examined the structure of educational systems and studied principles and mechanisms for sustaining and scaling educational reforms, leading to talks and reviewed publications in the *Proceedings of the Physics Education Research Conference*.[61,63] Beginning summer of 2004, I anticipate becoming PI on an NSF Course Curriculum and Laboratory Improvement, Adaptation and Implementation grant (proposal DUE-0410744)[54] which will support the transformation of practices in one of the introductory calculus-based physics courses described in section II.B3.

VI. Advisory Committee:

In addition to the support of the physics department and members of the Physics Education Research Group at the University of Colorado, three senior faculty will serve as mentors in faculty development.

Carl Wieman, Distinguished Professor of Physics at the University of Colorado and the only winner of both a Nobel Prize and the NSF Director's award for Teaching Scholars. He is widely recognized for his talents and commitment to education. He is a University of Colorado Presidential Teaching Scholar. He serves on several National Academy boards including the Board on Physics and Astronomy and the Board on Science Education (which he chairs). He directs the physics education technology project (PhET) at the University of Colorado and is a co-PI on an NSF supported STEM-TP grant, Transforming Science and Mathematics Teacher Preparation

Michael Cole, University Professor, University of California. Professor, Departments of Communication and Psychology University of California, San Diego. Prof. Cole is recognized as an international leader in the field of cultural psychology. He has pioneered work in his studies of student learning and its relations to cultural systems. He is a Fellow of the National Academy of Education and the American Academy of Arts and Sciences.

Andrea diSessa, Chancellor's Professor of Education, University of California, Berkeley. He is the director of the Boxer Computer Environment Project and worked extensively pioneering the use of computers in education. He has written extensively about student learning in physics. Andrea diSessa is a member of the National Academy of Education.

Finally, because I am an active member of the physics education research community (organizing sessions, workshops, and meetings of the AAPT and PERC), I have a large network of faculty with whom I shall consult on these varying research projects. This group includes but is not limited to: David Hammer, Lillian McDermott, Sanjay Rebello, Edward Redish and others.

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University of Colorado, Boulder

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