A physics department's role in preparing physics teachers: The Colorado learning assistant model

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In response to substantial evidence that many U.S. students are inadequately prepared in science and mathematics, we have developed an effective and adaptable model that improves the education of all students in introductory physics and increases the numbers of talented physics majors becoming certified to teach physics. We report on the Colorado Learning Assistant model and discuss its effectiveness at a large research university. Since its inception in 2003, we have increased the pool of well-qualified K–12 physics teachers by a factor of approximately three, engaged scientists significantly in the recruiting and preparation of future teachers, and improved the introductory physics sequence so that students' learning gains are typically double the traditional average.

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I. INTRODUCTION: THE U.S. EDUCATIONAL CONTEXT

Physics majors are typically not recruited or adequately prepared to teach high school physics. One needs only to look at reports,[1] international[2,3] and national[4] studies, and research on student learning[5] for evidence. Two out of three U.S. high school physics teachers have neither a major nor a minor in physics,[6] and there are no subject matter specialties that have a greater shortage of teachers than mathematics, chemistry, and physics.[7] Many undergraduates are not learning the foundational content in the sciences,[8,9] and average composite SAT/ACT scores of students who enter teaching are far below scores of those who go into engineering, research, science, and other related fields.[10] The effects may be dramatic. For example, only 29% of U.S. eighth grade students scored at or above proficient on the National Assessment of Educational Progress in 2005.[11] What is worse is that only 18% of U.S. high school seniors scored at or above proficient.[11] With few exceptions, universities and research universities in particular, are producing very few physics teachers.[12] And some universities are sending the message, usually implicit but often explicit, that such a career is not a goal worthy of talented students.[13]

Recently, the National Academies listed four priority recommendations for ensuring American competitiveness in the 21st century. The first recommendation, in priority order, is to "increase America's talent pool by vastly improving K–12 science and mathematics education."[1] Who will prepare the teachers? Physics teacher preparation cannot be solely the responsibility of schools of education.[14] Studies point to content knowledge as one of the main factors that is positively correlated with teacher quality.[15] Yet, those directly responsible for undergraduate physics content, physics faculty members, are rarely involved in teacher preparation.

II. THE COLORADO LEARNING ASSISTANT MODEL

At the University of Colorado at Boulder (CU Boulder), we have developed an model that engages both physics faculty and education faculty in addressing the national challenges in science education. Talented undergraduate physics majors are hired as *learning assistants* (LAs) to assist interested faculty in redesigning their large-enrollment introductory physics courses so that students have more opportunities to articulate and defend their ideas and interact with one another. In our redesigned courses, we employ findings of research on student learning, utilize nationally validated assessment instruments, and implement research-based and research-validated curricula that are inquiry oriented and interactive.[16] To this end, we have implemented *Peer Instruction*[17] in lectures and *Tutorials in Introductory Physics*[18] in recitations. These innovations have been demonstrated to improve student understanding of the foundational concepts in introductory physics.[8,9]

The Learning Assistant program in physics is part of a larger campus-wide effort[19] to transform science, technology, engineering, and mathematics (STEM) education at CU Boulder and has now been implemented in nine science and mathematics departments. The program uses undergraduate courses as a mechanism to achieve four goals:

(1) improve the education of all science and mathematics students through transformed undergraduate education and improved K-12 teacher education;
(2) recruit more future science and math teachers;
(3) engage science faculty more in the preparation of future teachers and discipline-based educational research; and
(4) transform science departmental cultures to value research-based teaching as a legitimate activity for professors and our students.

These four synergistic goals are illustrated in Fig. 1. *Undergraduate Course Transformation* is highlighted because it also serves as the central mechanism by which the other three goals are achieved within the Learning Assistant model.

Since the inception of the program in Fall 2003 through the most current data analysis (Spring 2010), we have transformed over 35 undergraduate mathematics and science courses using LAs with the participation of over 48 science

Fig. 1. Synergistic goals of the Colorado Learning Assistant program.

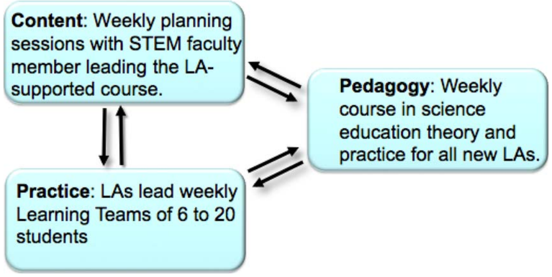

Fig. 2. The LA experience triad for developing pedagogical content knowledge.

and mathematics faculty members including two Nobel Laureates and several National Academy members. More than 15 physics faculty members have been involved in transforming a course or in sustaining previous transformations.[19] The program impacts roughly 2000 introductory physics students per year and is still growing. Recent efforts are focusing on the transformation of upper-division courses.[20,21]

The LAs are instrumental in initiating and sustaining course transformation by taking active roles in facilitating small-group interaction both in large-enrollment lecture sections and in interactive recitation sections. Because the LAs also make up a pool from which we recruit new K–12 teachers, our efforts in course transformation are tightly coupled with our efforts to recruit and prepare future K–12 science teachers.

Each semester, the physics department typically hires 18 LAs from a pool of roughly 60 applicants. These LAs predominantly support transformations in the introductory calculus-based physics sequence for majors and engineers but have also supported transformations in nonmajor introductory courses such as Light and Color, Sound and Music, and Physics of Everyday Life, and upper-division courses such as Electricity and Magnetism. In the Introductory Physics I and II courses, faculty members work with both undergraduate LAs and graduate teaching assistants (TAs) on a weekly basis to prepare them to implement research-based approaches to teaching and to assess the effectiveness of these instructional interventions. Participating faculty members also work with each other to provide support and advice for implementing various innovations, trying out new ideas, and discussing their research findings regarding the course transformations.[22] Some of these research results are presented in Sec. III.

LAs engage in three major activities each week, which support all aspects of course transformation (see Fig. 2). The LAs in each department meet weekly with the instructor of the class to plan for the upcoming week, reflect on the previous week, and examine student assessment data in these courses. LAs from all the participating STEM departments attend a course in the School of Education, *Mathematics and Science Education*, which complements their teaching experiences. In this course, the LAs reflect on their teaching practices, evaluate the transformations of courses, share experiences across STEM disciplines, and investigate relevant educational literature. In addition to weekly meetings with instructors and attending the Education seminar, LAs assume one or two main roles to support changes in lecture-based courses. First, LAs lead learning teams (sometimes in recitation sections) in which students work collaboratively to make sense of physical problems posed in curriculum activities (see Fig. 3). Second, LAs work within the large lecture setting where they facilitate group interactions by helping students engage in debates, arguments, and forming consensus around conceptual questions that are posed roughly every 20 min of lecture typically through personal response systems (clickers) used to poll the class.

Through the collective experiences of teaching as a LA, instructional planning with a physics faculty member, and reflecting on their teaching and the scholarship of teaching and learning, LAs integrate their understanding of content, pedagogy, and practice, or what Shulman[23] calls *pedagogical content knowledge*, which has been shown to be a critical characteristic of effective teachers. Putnam and Borko[24] described why pedagogical training is more beneficial when it is situated in practice—teachers have the opportunity to try out and revise pedagogical techniques by implementing them with real students. Eylon and Bagno demonstrated the effects of situating physics-specific teacher professional development in practice.[25] This reflective practice is a feature of the LA program because LAs take their Math and Science Education course during the first semester in which they serve as LAs. Those LAs who decide to seriously investigate K–12 teaching as a possible career option are encouraged to continue as LAs for a second and third semester. Those who commit to becoming teachers and are admitted to our CU-Teach teacher certification program are eligible for NSF-funded Noyce Teaching Fellowships.[26]

There are several elements that distinguish the Learning Assistant program from other programs that use undergraduates as teaching assistants. First, although course transformation is a key element of the LA program, the target population of the program is the LAs themselves. The LA program is an *experiential learning program*; the learning is embod-

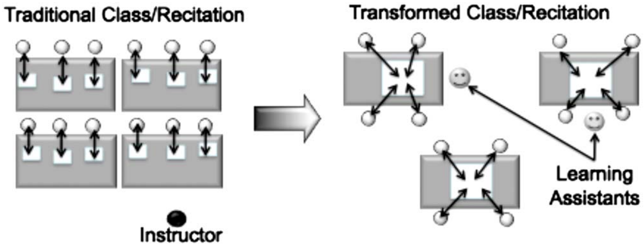

Fig. 3. Traditional versus transformed educational environment for recitation sections. The new recitation environment depicts one LA and one TA working together with students in lieu of a TA working problems solo at the chalkboard. (Lectures are still held in a 350 seat hall.)

ied in the *experience* of serving as an LA. Second, the LA program serves as a K–12 teacher recruitment program. Throughout the LA experience, LAs learn about the complexity of the problems involved in public science education and their potential roles in generating solutions to these problems. Although only approximately 12% of LAs are actually recruited to K–12 teaching careers, the program is valuable to all students as they move into careers as research scientists and college professors or into industry and have opportunities to improve science education more broadly.

III. RESULTS OF THE LA PROGRAM

The LA program has been successful at increasing the number and quality of future physics teachers, improving student understanding of basic content knowledge in physics, and engaging research faculty in course transformation and teacher recruitment.

A. Impact of the LA program on teacher recruitment

Since its inception in Fall 2003 through Spring 2010, 186 LAs positions have been filled in the physics department (120 individual LAs, 66 for more than one semester), and 123 positions have been filled in the astronomy department (82 individual LAs, 41 for more than one semester); 40 physics LAs were female (80 male) and 45 astronomy LAs were female (37 male). Of the 120 individual LAs in physics, 68 were physics, engineering physics, or astrophysics majors, and 45 were other STEM majors (such as mechanical engineering, aerospace engineering, and math); among the remaining seven, four had undeclared majors at the time that they served as LAs, and three were finance or communications. In astronomy, 27 of the 82 individual LAs were astronomy majors, three were physics majors, 17 were other STEM majors, and six had undeclared majors. The remaining 29 LAs hired in astronomy were majors such as economics, international affairs, finance, and political science. The large number of nonscience majors in astronomy should be expected because some of our astronomy course transformations take place in courses for nonscience majors, which is one of the places from which LAs are recruited. In some cases, students changed their majors to STEM majors as a result of participating in the LA program. For example, a political science major who served as a LA in astronomy changed her major to biochemistry, became certified to teach secondary science, and is now teaching science in a local high needs school district. The average grade point average of physics majors was 3.6 (the department's average is 3.0) and 3.2 for astronomy majors. Nine physics and seven astronomy/astrophysics majors have been recruited to teacher certification programs.

The impact of the LA program is demonstrated by a comparison of the total enrollments of physics/astrophysics majors in teacher certification programs in the entire state of Colorado to those at CU Boulder since LAs began graduating from teacher certification programs. In AY 2004/2005, the state of Colorado had only five undergraduate physics majors enrolled in teacher certification programs (out of almost 11000 certification students at 18 colleges and universities).[27] For comparison, in AY 2007/2008, CU Boulder's enrollment of physics/astrophysics majors in certification programs was 13. As of Fall 2009, ten physics/astrophysics majors that were former LAs were teaching in U.S. schools (mostly in Colorado), and an additional six was enrolled in teacher certification programs. Before the LA program began recruiting, CU Boulder had an average of less than one physics/astrophysics major per year enrolled in our teacher certification programs.

Most of the LAs who decided to become teachers report that they had not previously explored teaching as a career until participating as LAs. Our surveys of LAs indicate that one of the factors influential in helping students to consider teaching has been the encouragement and support of participating STEM faculty members.[13] Another frequently reported reason for deciding to become a teacher is the recognition of teaching as an intellectually challenging endeavor. A typical LA (Physics, Fall 2004) stated,

> "It would have been weird at first when I first started [to consider teaching].… But now [the LA program] is really affecting the way a lot of us think.… So now it's kind of a normal thing to hear. Oh yeah, I'm thinking about K–12.… It's not out of the ordinary, whereas a couple years ago it would have been strange for me to hear that."

B. Impact of the LA program on physics content knowledge

Students learn more physics as a result of the course transformations supported by the LA program. In this section, we present sample results from our introductory calculus-based physics courses where most physics LAs are employed. These classes are large (500–600 students) with three lectures per week, implementing *Peer Instruction*[17] and now including the *Tutorials in Introductory Physics*.[18] The LA program in physics was established due to one faculty member's (Pollock) intention to implement the *Tutorials* after visiting the Physics Education Group at the University of Washington. At that time, the LA program was being piloted in four departments and Pollock took advantage of this opportunity to use undergraduate LAs alongside graduate TAs. We therefore have no course transformation data that isolate the use of LAs (or TAs) from our implementation of the *Tutorials*. This type of isolation would be difficult because the *Tutorials* require a higher teacher to student ratio, which was made possible at CU Boulder through the LA program. We do not argue that LAs are more effective than graduate TAs when the *Tutorials* are used. In the following, we demonstrate the value that the LA experience has on the LAs themselves and on faculty using LAs.

Each semester, we assess student achievement in the transformed courses using conceptual content surveys (in addition to traditional measures). Specifically, we use the Force and Motion Conceptual Evaluation[28] (FMCE) in the first semester and the Brief Electricity and Magnetism Assessment[29] (BEMA) in the second semester. Figure 4 shows BEMA results for all of the students enrolled in second semester introductory physics. The data demonstrate that LA-transformed courses result in greater learning gains for students and, in even greater learning gains, for students who participated as LAs. The histogram shows pre- and post-test scores for the fraction of a 600-student class within each range. The average pretest score for this term was 27%, the post-test was 59% (which corresponds to a normalized learning gain of $(\langle\text{post}\rangle - \langle\text{pre}\rangle)/(100\% - \langle\text{pre}\rangle) = 0.44$). For com-

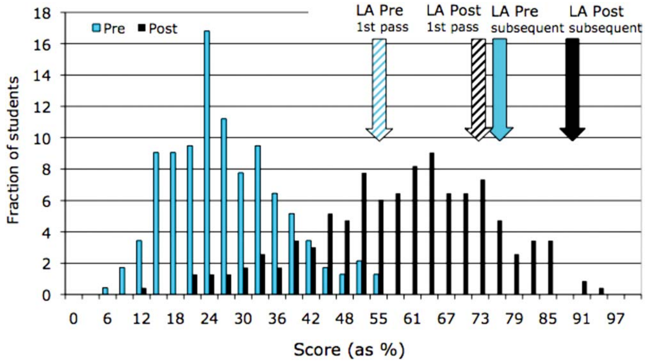

Fig. 4. Pre/postscores on the BEMA instrument for enrolled students compared to LAs. Histogram bars show data for students enrolled ($N=232$) in a representative term of Calculus-based Physics 2 (Spring 2005). Hashed arrows indicate LA pre/postscores the first semester LAs were used ($N=6$). Solid arrows indicate LA pre/postscores ($N=6$) from the following semester.

parison, a recent national study[31] shows that typical post-test scores in traditionally taught courses at peer institutions are around or below 45% (and normalized gains of 0.15–0.3). The dashed arrows in Fig. 4 show the BEMA pre- and post-test scores for LAs during the first semester that LAs were used in the physics department. All of these LAs had taken a non-transformed introductory electricity and magnetism course preceding their service as an LA. The solid arrows near the top of Fig. 4 show the average BEMA pre- and post-test scores for LAs in the first semester for which all LAs were recruited from transformed classes. That is, most of the LAs from the subsequent semesters had taken an introductory course that was transformed using LAs. The average normalized learning gains for all students in the transformed courses have consistently ranged from 33% to 45%. The normalized learning gains for the LAs averages just below 50%, with their average post-test score exceeding the average incoming physics graduate-TA's starting score.

The data in Fig. 5 show the scores of students enrolled in upper-division Electricity and Magnetism. The bin labeled F04-F05 is the average BEMA score for students who were enrolled in upper-division E&M in the three consecutive semesters from Fall 2004 through Fall 2005 ($N=71$). None of these students had enrolled in an introductory physics course that was transformed using LAs. The three bins labeled S06-S07 represent the average BEMA scores for three different groups of students who were enrolled in upper-division E&M during the next three semesters from Spring 2006 through Spring 2007: (1) those who had a traditional introductory experience with no LAs ($N=18$), (2) those who did take an introductory course that was transformed using LAs ($N=36$), and (3) students who had been LAs themselves ($N=6$). The scores of the students who did not take a transformed course are comparable in both F04/05 and S06/07. The students who had taken a transformed introductory E&M course scored significantly higher than those who did not, and the LAs scored even higher. These data suggest that the LA program produces students who are better prepared for graduate school and for teaching careers and that the LA experience greatly enhances students' content knowledge.[30] Note that although some students from each group in Fig. 5 have taken the BEMA multiple times, the average change from post-freshman score to post-junior score (after taking the BEMA for a second time following upper-division E&M) is zero.[30] Also, repeated testing of individuals on the BEMA shows no impact on their scores.[30]

In addition to increased content gains, LAs show strong evidence of attitudinal gains. The Colorado Learning Attitudes about Science Survey[32] (CLASS) is a research-based instrument intended to measure students' attitudes and beliefs about physics and about learning physics. As is the case with the Maryland Physics Expectations Survey[33] and other instruments of this type, students' attitudes and expectations about physics tend to degrade over a single semester.[33] The arrows in Fig. 6 show results from a recent semester. First semester physics students showed large negative shifts in their overall views about physics and in their personal interest as measured by the CLASS, consistent with national findings.[33] The second semester course showed smaller negative shifts (possibly due to a combination of instructor and selection effects). Both of these courses were transformed and show high levels of conceptual learning. The LAs started with much more expertlike views and high personal interest, both of which increased greatly throughout a semester of serving as LAs.

Although there is a contribution from selection effects associated with the LA data shown in Fig. 6, students who are serving as LAs shift in a dramatically favorable manner during the semester. These students make up the pool from which we are recruiting future K–12 teachers and exit the LA experience with more favorable beliefs about science, greater interest in science, and greater mastery of the content than their peers.

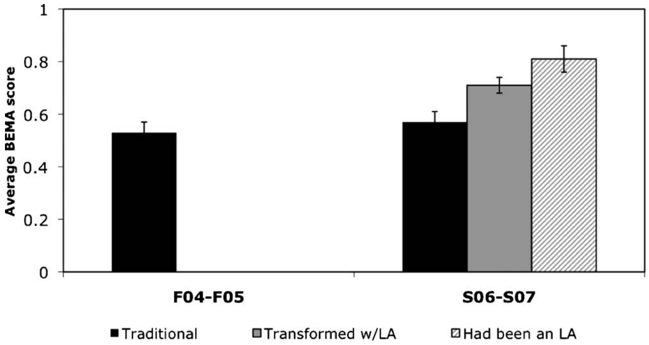

Fig. 5. BEMA scores of physics majors after taking upper-division Electricity and Magnetism, binned by semester and freshman (Physics II) background.

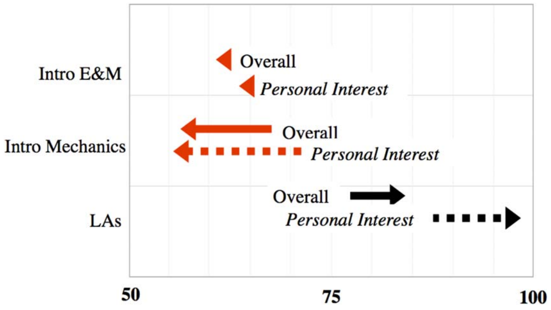

Fig. 6. Shifts by non-LA and LA students in attitudes about learning physics and in their interest in physics over one semester. The horizontal axis represents percent favorable scores on the CLASS instrument. The LA scores are an average for the LAs in both courses combined.

C. Impact of the LA program on faculty

As a result of transforming courses and working with LAs, participating faculty members have started to focus on educational issues that they had not considered previously. Faculty members report increased attention to student learning. All of the 11 faculty who were involved in the LA program from 2003–2005 were interviewed and reported that collaborative student work is essential, and LAs are instrumental to change. One typical faculty member noted,

> "I've taught [this course] a million times. I could do it in my sleep without preparing a lesson. But [now] I'm spending a lot of time preparing lessons for [students], trying to think 'OK, first of all, what is the main concept that I'm trying to get across here? What is it I want them to go away knowing?, which I have to admit I haven't spent a lot of time in the past thinking about."

This statement was drawn from the group of 11 faculty members who are now perceived by students as caring about student learning and supporting their decisions to become K–12 teachers.

Impacts on faculty are also observed in the scaling of the program at CU Boulder. Increasingly, faculty members are working together to implement the LA program in the physics department as well as in other departments. Faculty members seek out one another for support and meet weekly in informal "Discipline-Based Educational Research"[34] meetings to discuss their teaching and the use of LAs and to present data from their assessments and evaluations of their transformations.

The Learning Assistant model does not stop at the introductory level. Faculty members who teach upper-division courses are increasingly drawing on LAs to help them transform their courses, including third semester Introductory Physics[35] and upper-level Electricity and Magnetism[36] and Quantum Mechanics. In these environments, faculty members work with LAs (typically second- or third-time LAs or Noyce Fellows) to make research-based transformations to their courses. Typically, educational research regarding the efficacy of the transformation is conducted by the lead faculty member, a Noyce Fellow, and sometimes a postdoctoral scholar. In these contexts, LAs assume varying roles, all with the common theme of supporting educational practices that are known to improve student understanding.

IV. SCALING THE LA PROGRAM

We have studied the scaling of the program by examining the use of LA-supported *Tutorials in Introductory Physics* over a 6-year span, covering 15 different implementations of the tutorials by 15 faculty members.[22] We observe that it is possible to demonstrate strong and consistent learning gains for different faculty members. Table I summarizes the overall measures of students' conceptual learning gains in first semester courses. Although the listed courses span nearly the entire range of learning gains documented for interactive courses elsewhere,[9] all courses with the LA-supported tutorials led to learning gains higher than any classes that had traditional recitation experiences. All except two of the courses listed in Table I were taught by different instructors. Semesters F03 and S04 were taught by the same instructor, a faculty member who also engaged in physics education research. All of the other faculty members who taught the courses listed in Table I range from somewhat to vaguely familiar with physics education research.

Table I. Normalized gain on the FMCE for first semester Introductory Physics taught by different instructors.

Semester	Recitation	N (matched)	Average post-test score	Normalized gain $\langle g\rangle$
F01	Traditional	265	52	0.25
F03	Tutorials	400	81 (FCI data)	0.63
S04	Tutorials	335	74	0.64
F04	Workbooks[a]	302	69	0.54
S05	Traditional	213	58	0.42
F05	Traditional	293	58	0.39
S06	Tutorials	278	60	0.45
F06	Tutorials	331	67	0.51
S07	Tutorials	363	62	0.46
F07	Tutorials	336	69	0.54

[a] Students worked in small groups on problems in a workbook that came with their text. No LAs were used (Ref. 37).

The data suggest that the transformations are transferable among faculty members at CU Boulder, even among faculty members who have little or no experience with physics education research. This finding suggests that such LA-supported tutorials are transferable to faculty at other institutions.

The development of an LA program in physics departments at other institutions requires the commitment of dedicated faculty and administration within the department. Currently, at least five universities in the U.S. are funded to emulate the Colorado LA program as a part of their work with the Nationwide Physics Teacher Education Coalition.[38] Many other institutions are also emulating the Colorado LA model. Although the Colorado LA program is a campus-wide program spanning nine departments, other institutions have successfully developed and managed LA programs in the physics department alone.[39] Successful LA programs have started in the physics department with a buy-in from the department chair and a handful of interested faculty members.

Departments considering implementing an LA program need to identify sources of financial and pedagogical support for the undergraduates who will be enrolling. Implementation of an LA program requires funding of a few thousand dollars per LA per year.[40] An alternative to this cost is to provide course credit in a service-learning model,[41] where LAs receive course credit for time spent supporting course transformation. Although pedagogical support for LAs may be challenging, it is a critical component of the program. LAs must be supported both in weekly content preparation such as the tutorial preparation we have discussed and in their acquisition and implementation of pedagogical techniques through a forum such as the Mathematics and Science Education course. We encourage physics departments to partner with their Schools of Education to offer such a specialize course and have sample course materials available for those interested.

V. SUSTAINING SUCCESSFUL LA PROGRAMS

Can the Learning Assistant model be sustained? Is it possible to scale this model without significant external funding? We believe so. Currently, 85% of our LAs are funded by our administration and private donations, although these are temporary funds and the university is working toward stable institutional funding.

At CU Boulder, the Learning Assistant program is university-wide and benefits from such scale. We bring together a variety of interested faculty members, department heads, deans, and senior administrators, each of whom has a stake in and benefits from increasing the number of high-quality teachers, improving our undergraduate courses, and increasing the number of math and science majors. Because teacher recruitment and preparation are tied to the improved education for all students through the transformation of undergraduate courses, many members of the university community have a vested interest in the success of the Colorado LA program. CU Boulder recently received funding to replicate the University of Texas at Austin's successful UTeach certification program.[35] The new CU-Teach certification program utilizes the Colorado LA program as one of two methods for recruiting students to careers in teaching.

With the commitment of physics departments to the enhanced education of all students and to the recruitment and preparation of future teachers, we can collectively enhance the status of education both for the students considering teaching careers and for the faculty teaching these students. As scientists, we can take action to address the critical shortfall of science teachers by improving our undergraduate programs and engaging more substantively in evidence-based solutions in education and teacher preparation.

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