Strengthening Undergraduate and Graduate STEM Education

Research and Science Education Subcommittee
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Chairman Lipinski, Ranking Member Ehlers, and distinguished members of the Subcommittee on Research and Science Education,

Education is society's fundamental form of investment in its future.

As a result, we are now deciding among a variety of possible futures for our nation.

- Will we depend on other countries for technological innovation? Or for essential technological infrastructure, such as energy?
- Will our children grow up to be leading innovators and scientists?
- Will *all* students have access to college in a time when, more than ever before, a college degree is required for even entry-level positions? Will the *average* student?
- Will our school systems continue to mimic the educational systems that were designed for a different era, or will new models of education emerge?
- Will we have the basic human capital to ensure a quality of life for all, and to address our continued growth in consumption? Will our future be secure?

Current indicators are pessimistic for our country, on just about all accounts.

A critical, perhaps *the* critical linchpin in our educational system is in Higher Education, and STEM education in particular.

I applaud the Committee on holding these hearings and its continued investigation into the state of affairs in STEM education at all levels.

The focus of this testimony will be predominantly on the nature of undergraduate STEM education. My esteemed colleagues will be discussing the role of graduate education. However, much of what is stated here also applies to our graduate programs, and I explicitly address the linkages among our many educational levels.

I make 3 points in this testimony:

1) Through a scientific approach to science education, educational researchers in STEM have developed substantial research-based knowledge. Research has demonstrated that traditional models of classroom-based education are no longer appropriate and that new models that engage students in learning experiences are critical. Further, we now know what to do to improve individual learning, engagement, access, and retention of students in courses. We also know that these improved and effective educational experiences are not widespread. And we know that we are missing critical research on sustaining and scaling these educational reforms.

2) The challenges to our STEM educational endeavors are complex and intertwined, and so, too, should be our solutions. So far, higher education has been separated from national discussions regarding educational reform. It is time to focus on integrated approaches that reach across disciplines and across levels of our educational system to provide us with solutions that address our broad national challenge and do so in a scalable, sustainable, and cost-effective manner.

3) Given the magnitude of our educational challenges in STEM, we need far more resources than the Federal Government can supply – but we do need the Federal Government to become the catalyst for other kinds of investment. We need the investment of the American citizenry and the University system. We need to engage STEM faculty and researchers in educational innovation and change. Seed-funding from the Federal Government can stimulate the involvement of the populace and unlock $100's B in latent infrastructure of the higher educational system, thereby providing some hope of addressing the Grand Challenge that faces us.

<u>1. We know which educational practices work, but they are not widely implemented.</u>

In recent decades researchers within STEM disciplines, informed by research in the learning sciences, education, psychology and other social science arenas, have productively focused attention on how students learn, conditions that support (or inhibit) student learning, what defines meaningful learning, and how to authentically assess student learning in STEM disciplines. Numerous reports and testimonies document this shift in understanding of teaching and learning. We must move away from teacher-centered and passive-student pedagogy to a student-centered, inquiry oriented, discipline-based model of pedagogy that is research-based and research-validated. We have documented the failures of our traditional educational system on: student mastery of foundational concepts, problem-solving skills, views about the nature of science, interest, engagement, and retention.

Through careful research, we have documented the sorts of educational practices that lead to substantial learning gains. For example, as part of the Colorado Learning Assistant model (described below), we have carefully implemented two key educational reforms in the introductory physics sequence at the University of Colorado:

Tutorials in Introductory Physics, perhaps the most thoroughly researched educational reform at the introductory college level in our nation, and *Peer Instruction*, one of the most widespread educational reforms in introductory college physics. Both educational approaches shift from the instructor-centered to the student-centered, from dissemination of information to student construction of understanding, from rote algorithmic processing to student argumentation that is supported by and develops robust conceptual understanding. As a result of implementing these new educational practices, we now consistently document student learning gains that are two to three times what they used to be, and two to three times the national average for traditional educational experiences. Researchers within STEM departments are leading the way in similar, but isolated transformations around the country, and such results are found nationally in all STEM disciplines that make scholarly inquiry into the nature of student learning.

Because of a new scientific approach to education, STEM departments are establishing measurable learning goals for undergraduate education, tools for course transformation to address these goals, and evaluation instruments and metrics for assessing these achievements. Faculty are measuring not just rote algorithmic processing, but deep problem solving skills, conceptual mastery, beliefs about the nature of science, and beliefs about the nature of learning science. Researchers are identifying mechanisms for addressing the historical disparity in access, inclusion, and achievement between majority and minority students, and between male and female students. The involvement of researchers within STEM disciplines who focus on STEM education is critical in attending to disciplinary and departmental specifics. As a result of this scholarly approach, there are a variety of examples of educational practice that address the lack of achievement, poor retention and the gender and racial gaps in STEM education at the university level. Discussed below, we find that the most successful programs, and those that are likely to be sustained, are those that integrate across the many of the challenges that face us, those challenges identified in NRC's *Rising Above the Gathering Storm* report and those challenges that the America COMPETES Act seeks to address.

While effective practices of educational reform in undergraduate STEM have existed for decades, and data on their success have been widely accessible and cited, the reforms themselves are not widespread. This limited adoption is not because of a lack of effort on the part of the developers. For example, my colleagues at the University of Washington who authored the *Tutorials in Introductory Physics* have been running workshops on their curricula for the last decade. *Peer Instruction*'s developer, Eric Mazur of Harvard, has given over 300 talks about *Peer Instruction* and 18,700 copies of his book *Peer Instruction* have been shipped—including 12,700 free copies. This represents approximately one free copy for each of the roughly 13,000 physics faculty employed in all four-year and two-year colleges in the U.S. Despite the best efforts of educational innovators across the country, practices have not changed dramatically. Current research studies from a variety of sources suggest that we lack a model of educational change that is sufficient. We cannot simply put good ideas out there and expect them to be used. We cannot simply mandate their adoption. We cannot expect these innovations to diffuse on their own. In recent reviews of over 400 studies of change in undergraduate STEM education, we have found that most change initiatives do not cite or build on prior approaches, most are not based on research, and most are not effective or sustained.[1] As a recent synthesis of a National Academies workshop on STEM education concludes, "the greatest gains in STEM education are likely to come from the development of strategies to encourage faculty and administrators to implement proven instructional strategies".[2] The conclusion calls for the development of "models for implementation, dissemination, and institutionalization for STEM reforms where the relative roles of evidence-based research on teaching, leadership, workloads, rewards, and so on are clearly delineated." In short, as of yet, our nation's universities are not taking a scholarly and scientific approach to promoting change in STEM education on a broad scale. These studies and others suggest that successful change efforts:

- identify a coherent vision of change and communication of that vision;
- attend to multiple scales of reform (focusing on individual faculty development and reward, along with departmental, institutional, and disciplinary community engagement);
- recognize that educational reforms must be adapted and transformed (at least modestly) to attend to local circumstances;
- focus on the university department as a key unit of change;
- and evaluate the change process and use evaluation to improve programmatic approaches.

Such findings provide us with tools and suggestions as we shape calls for reform and criteria for funding models of educational transformation. However, more research is needed, both on how educational innovations are locally adapted and models of scaling educational reform.

2. Education is a complex and integrated system; this structure is an opportunity for leveraging change.

The same features that challenge us to improve our educational system provide us opportunities to solve these challenges. Because components of our educational system are coupled with each other, we can effect change in the entire system by carefully seeding change at critical junctures. Higher education is a critical and often overlooked juncture. Policy makers, industry leaders, scientists and much of the broader populace are educated at universities. Universities are the institutions where we recruit and prepare our future teachers and where current teachers return for professional development. Universities are where disciplines are defined, modified, and practiced. Universities are (and should be) the destination for our nation's youth beyond high schools or community colleges.

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[1] Henderson, Beach, and Finkelstein. Facilitating Change in STEM Education. See: http://www.stemreform.org or http://www.wmich.edu/science/facilitating-change/

[2] Fairweather (2008). P26. http://www7.nationalacademies.org/bose/Fairweather_CommissionedPaper.pdf

Because universities serve such a broad constituency and possess such intellectual, social, and political capital, we can strategically leverage their roles to promote lasting, national-scale change in STEM education. Universities house the STEM researchers, STEM education researchers, and educators. Universities house and develop this knowledge and we can foster the necessary integration of these historically different areas of scholarship to promote educational transformation and institutional change. This approach requires that we implement change in which disciplinary content is brought together with educational research and educational practice. The model programs that are most successful – whether they are directed at increasing the number and quality of disciplinary majors or increasing access, at awareness and expertise in science among the general public, or at improving the number and quality of K20 STEM teachers – bring together stakeholders and expertise from disciplinary, pedagogical, and educational research domains. In addition to housing the resources necessary to improve undergraduate STEM, scalable, adaptable models of educational reform exist within universities that simultaneously address the multiple goals and challenges of the broader STEM education system.

Successful research-based programs at the University of Colorado at Boulder (and others across the nation) demonstrate that we can increase student learning and engagement, include more students, engage STEM faculty in educational change, recruit more and better STEM teachers, and do so in a sustainable, scaleable, and cost-effective manner.

The Colorado Learning Assistant (LA) model,[3] directed by my colleague, Professor Otero, is a nationally replicated model for simultaneously improving undergraduate learning, recruiting talented STEM majors into careers in K-12 teaching, engaging STEM research faculty in educational transformation, and scientifically investigating these efforts. The model is designed to work in any discipline and currently runs in nine science, mathematics, and engineering departments at the University of Colorado at Boulder. The key to this approach is the experiential learning process, in which talented undergraduates (LAs) facilitate course transformation and thereby learn themselves. LAs lead learning teams of other undergraduate students, encouraging them to articulate and defend their ideas, engage with inquiry-based activities, and analyze real scientific data—activities that have been shown to improve student learning and retention. LAs also work with disciplinary faculty to refine course materials and instruction-based on student assessment data. To help LAs with this process, they take a pedagogical course, which encourages them to reflect on, evaluate, and investigate different teaching practices. Central to the Colorado LA model is its role in promoting institutional change. The LA model addresses the needs of multiple stakeholders including STEM and education faculty, undergraduate students, K-12 teachers, and university administrators and is flexible to accommodate small-scale to large-scale innovations.

These shifts have doubled and even tripled undergraduate learning gains for students in our introductory physics courses. At the same time Learning Assistants

[3] Colorado Learning Assistant Program, see: http://stem.colorado.edu

learn content (performing more similarly to our elite graduate students on measures of conceptual mastery), perform better in their upper division courses, and demonstrate more sophisticated views on the nature of education and teaching. As a result of the LA program, we have more than doubled the number of physics and chemistry majors getting certified in these hard-to-staff subject areas. The program also positively impacts graduate students (who are departmentally assigned Teaching Assistants) and future graduate students – the bulk of LAs go on to graduate school and carry their mastery of content and pedagogy with them. As such, the LA program directly addresses the concerns National Research Council's *Rising Above the Gathering Storm* recommendations: 1) more and better teachers and 3) educating our best and brightest in STEM education. Furthermore this program develops STEM departmental culture and promotes the positive and instrumental role that STEM faculty can play in education. Because it is a high impact, cost-effective, and easily adapted model of institutional transformation, the program has spread to institutions throughout the country with the support and the endorsement of professional organizations such as American Physical Society and the Association of Public and Land-grant Universities, discussed below.

The Science Education Initiative[4] (SEI) program led by Nobel Laureate Carl Wieman provides another model for simultaneously achieving two critical steps towards more effective STEM education. First, these programs are improving STEM courses at both the University of Colorado and the University of British Columbia. More importantly, however, this model focuses on shifting departmental culture. The program is designed to secure departmental-level commitment (and to provide substantial resources) to established, well-defined learning goals for students, rigorous assessment of learning, and implementation and testing of improved teaching methods for each of its core undergraduate courses. Two key features of this approach include widespread discussion (and ultimate consensus) among the faculty of a department, and employment of department-based science education specialists, who bring expertise within the STEM discipline, knowledge of education research within the disciplines, and are familiar with proven educational approaches and evaluation techniques. The SEI partners faculty with each other, and with the educational specialist to draw on what is known in the field and make locally relevant and meaningful changes based on research. The goal of the SEI is to implement course- and department- level transformations that become a part of a department's institutionalized practice. Initial results demonstrate the potential of such a model: the bulk of faculty in several participating departments at two major research institutions have engaged in SEI activities; it has fostered a better understanding of practices that help students learn and has conducted fundamental research in STEM education; and the SEI has positively impacted tens of thousands of students in its four year history.

University-Community Partnership Models in Informal Science Education:
Increasing attention is now being paid to the breadth of educational opportunities that exist for our students, to the great deal of learning that happens outside of formal school

[4] Science Education Initiative, see http://www.colorado.edu/sei

hours, and to the opportunities for partnerships between universities and local communities that can be leveraged inexpensively to be productive for all levels of education. The recent National Academy of Education study, *Time for Learning*,[5] recognizes the importance of out-of-school time for K12. Meanwhile, professional societies and universities have been calling for more opportunities for undergraduate research, real-world internships, service learning, and experiential-based learning programs. Partnering universities with community-based K12 programs provides a key opportunity for universities to educate undergraduates in innovative ways, while simultaneously addressing challenges of under-represented and under-supported students in STEM at all levels. We already have replicable models of university-community partnerships that bridge the historic divides between the university system and host communities, and the public broadly. A long-standing program, initiated at the University of California system, UC Links,[6] serves as a key model that has spread internationally with minimal funding or fanfare. As part of undergraduate education, students engage in a practicum course where they put their university, school-based learning into practice in local community center activities designed to improve the education, access, and identity of students in local areas, especially students from poor and under-represented populations. Project-based STEM activities are central to these activities, which have been shown to increase interest in teaching careers, increase children's performance, *and* increase college student performance and retention. Our own application of this program, Partnerships in Informal Science Education in the Community[7] has improved undergraduate and graduate students': mastery of content; interest, understanding, and acuity in teaching; awareness of the diversity and challenges in our local communities; and abilities to communicate with the public about science in everyday language. These programs are also shown to improve the communities in which they are embedded. They provide children with an increased understanding, interest, and ability in STEM; they promote community agency and ability to engage in STEM educational programs; they support the development of community leaders and professional development of teachers. All partners benefit by leveraging local resources in a cost effective, sustainable, and scalable fashion.

These are a subset of the models of institutional support of STEM education that reach beyond the narrow vision of making improvements to specific courses. As a result of coordinating a broad-scale agenda, these programs address the integrated challenges in STEM education, and bring together supportive stakeholders at key levels. A variety of other models apply similar principles, which include but are certainly not limited to recent testimonies before this committee on the Center for Integration of Teaching and Learning (CIRTL) and K12 Engineering education (programs at Tufts, Purdue, VaTech, and Clemson), and the NSF GK12 and MSP programs (when well implemented, as per findings of recent studies[8]), and Peer Led Team Learning programs that are spreading from chemistry to other disciplines.

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[5] *Time for Learning*, http://naeducation.org/Time_for_Learning_White_Paper.pdf
[6] UC Links, http://uclinks.berkeley.edu
[7] Partnership in Informal Science Education in the Community, http://spot.colorado.edu/~mayhew/PISEC/
[8] Change and Sustainability in Higher Education, http://cashe.mspnet.org/

I do not advocate a one-size-fits-all model of institutional change, but rather emphasize the programmatic characteristics, and key features that emerge from these successful programs. These features are consistent with and build upon effective change models listed in section 1:

Establishment and Articulation of Goals for undergraduate STEM education. While broad goals have been established nationally (to provide access, inclusion, excellence in STEM disciplines), these must be realized in a localized fashion. Programs must clearly establish their goals, and mechanisms for achieving those goals. A significant, positive, and dramatic shift has been to focus on these goals and outcomes rather than on strictly mandating process (like seat-time or credit-hours for students). ABET[9] 2000 provides a key example of this successful shift, as does the European approach in the Bologna Process[10] to coordinate efforts in Higher Education.

Programs based on valued scholarship. Making a scholarship of our educational practices supports the use of effective research-based programs in locally meaningful ways. The explicit inclusion of disciplinary-based educational researchers (within university STEM departments), in partnership with educators and community members, is a particularly effective mode of bringing about scholarly change. The STEM fields, especially in departments at research institutions, should measure and value their educational pursuits to the same extent that they measure and value their research pursuits.

Participation and support of stakeholders at a variety of levels. Distributed expertise is needed to stimulate improved undergraduate instruction. Successful programs bring together students, faculty, administrators and often community members in creating sustained programs. Again, disciplinary-based education researchers provide a new model and instrumental resource for leading such change. At the same time, key reward structures are required to insure inclusion and enthusiasm of appropriate stakeholders at all levels.

Departments as are key levers of change. A variety of institutional structures can be employed in the transformation of undergraduate education. A key unit of change will be individual courses in STEM education, but to sustain these changes requires broader thinking. It is faculty, departmental and institutional culture, vision, policies, and structures that ultimately sustain the new practices in undergraduate STEM education.

Evaluation that provides formative (and corrective) assessment of programs will ensure relevance and evidence of success. These evaluations must be aligned with the identified goals at each level of the intended transformation (learning goals for the students, faculty engagement, sustained institutional transformation, and scaling of programs nationally).

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[9] ABET 2000, http://www.abet.org/
[10] Bologna Process, http://www.bologna2009benelux.org

3. Who is at the table and how do we act to improve undergraduate STEM Education?

Because our educational problems are not isolated, our solutions need to be integrated. We must act across scales of the educational system, from individual students and faculty to departments, institutions, and disciplinary societies, from K12 teachers to districts and states. Again models of programs from the prior sections provide key insights into factors that enable quality transformation of undergraduate education in STEM, dramatically increase the number of majors, and significantly enlarge the pool and quality of STEM teachers.

National societies have played important roles in addressing these integrated problems and associated solutions. Physics provides a good example. With its internationally recognized Physics Teacher Education Coalition,[11] the American Physical Society (APS), in collaboration with the Am. Association of Physics Teachers (AAPT) and the Am. Institute of Physics, has acted on its main educational mission – increasing the number and quality of physics teachers. APS's second educational mission, doubling the number of physics majors, is intimately coupled with its mission to improve teacher education at all levels. The disciplinary societies also recognize the key role that discipline-based education research plays. Starting in the 1970's faculty in physics started offering PhDs to physicists for work in education research; in the 90's APS endorsed physics education research within departments, supporting the creation of this sub-discipline. APS and AAPT have been empowering departments to engage in the educational research and reform to simultaneously recruit and prepare more teachers and to recruit more students into the major. The University of Colorado at Boulder is a prime example of this approach; without the physics education research group our students would not be learning as much. APS and AAPT have been a key supporters in building this discipline-based education research group and the field more broadly.

More recently, and following APS model, the Association of Public and Land-grant Universities has launched it's Science and Mathematics Teacher Imperative.[12] Representing one of the largest coalitions of university presidents, chancellors, and provosts in the U.S., this organization brings together 121institutions that are committed to doubling the number of high quality physics and chemistry teachers. They are part of the Educate to Innovate solution in K12. They recognize the critical role that Universities play in national-scale educational change in both undergraduate education and teacher recruitment and preparation. This organization is moving universities to improve undergraduate STEM education by identifying effective models and practices, enacting and applying research on educational change, and creating value for institutional participation in these broad-scale challenges.

These are the seeds of change.

These are efforts that are beginning to *unlock the latent potential of universities to address the integrated challenges that face us in STEM education* at all levels. By leveraging significant and targeted Federal funding (in the $1B's) we can engage the

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[11] American Physical Society's, Physics Teacher Education Coalition, http://www.ptec.org

[12] Association of Public and Land-grant Universities, Science and Math Teacher Imperative, http://teacher-imperative.org

resources ($100B's) that reside, largely inert, in our university system to improve STEM education. Universities are established as institutions of Higher Education; faculty are hired and given salary to simultaneously develop new knowledge and to share this knowledge with the public – through education. Recent studies demonstrate that faculty are committed to education – they spend tremendous time and resources on their teaching pursuits. We need to ensure that these faculty practices are aligned with our understanding of student learning. We need to establish institutional resources that support faculty engagement in meaningful educational experiences. And, we need to shift institutional reward structures, modestly, to support this scholarly approach to STEM education.

Long term and Federal support are critical.

The National Science Foundation (NSF) provides an excellent model in providing both funding and prestige (imprimatur) to effect change. NSF can allow scientists, engineers, mathematicians and educators alike to engage in STEM education research and reform.

How might NSF and other Federal agencies take steps to enhance the value (prestige) for the essential levers of change?

At a small but critical scale, programs that bring key individuals to the table, that engage scientists in the *scholarly* pursuit of education, are vital. In my own field, the story of success can be traced, in part, to key individuals who have received essential NSF support, which has provided needed prestige and funding. In the NSF Distinguished Teaching Scholars (DTS) program, faculty are recognized for their commitment to scholarship in traditional areas of science *and* science education. Other NSF programs achieve similar goals, CAREER, PFSMETE, GRF's, simultaneously provide a cache and financial resources for basic research and innovation in education. These award winners bring about change in education. My own work in education was started with a PFSMETE. Later, a CAREER award provided essential infrastructure to support our research group, now one of the largest of its kind. This type of funding has allowed me and other scholars to engage in fundamental education research and reform – that high risk, high reward research that is the hallmark of American innovation.

Because NSF applies a scholarly review to education funding, it emphasizes a scholarship of educational research, reform, and practice. NSF supports a scientific approach to conducting STEM education research and reform, and supports and rewards individual scholars with its high status reputation. Other agencies should adopt such review procedures. Key NSF programs, in addition to those listed above (DTS, CAREER, PFSMETE, GRFs), have supported individuals in the development of educational research in STEM and associated reforms. These include but are not limited to CCLI, REESE, DR-K12, education efforts within STEM directorates, and Noyce. However, due to lack of funding high quality, innovative programs, some that review well and draw on and contribute to educational research are often not supported. With funding rates of ~10% in some areas, quality programs, those that contribute to our educational solution, are not getting funded. These programs, and others that allow for both research and reform at multiple levels (such as MSP, and potentially Noyce) should be supported more substantially. Further, excellent programs like Noyce are too limited to allow for creativity in models for preparing and supporting teachers. While I recommend the continuation of such funding, I also recommend that flexibility be increased so that educational researchers can develop and test new models of teacher preparation and the intimately linked roles of undergraduate STEM education.

Meanwhile sustained Federal support is a characteristic of other Federal Departments that should be adopted by the NSF. As noted in *Gathering Storm*, US infrastructure suffers from a "recurring pattern of abundant short-term thinking and insufficient long-term investment" (p25) A critical challenge of NSF is the intermittent funding. However other Federal programs, such as the Department of Energy, have recognized the essential role of sustained funding of innovation. This Committee can examine the potential for providing continuing funding for programs that are proving successful and still require external support. Another area of needed focus for NSF is to allow for larger-scale programmatic efforts - While individual faculty and researchers may seed change, larger units are essential to sustained and scaled transformation. Funding for larger scale programs such as departmental and institutional level transformation are needed. Small examples, such as NSF's Innovation through Institutional Integration, are a start. This funding is helping support the institutionalization of the educational reforms in STEM at the University of Colorado at Boulder.

Of course the scale of challenge that faces our nation demands a yet larger scale response, with more funding. What is needed is a cultural shift – within science, technology, engineering and math:

- for STEM departments to take up the mantle of educational reform and assume leading roles in STEM education challenges across all levels,
- for institutions to integrate efforts across STEM disciplines and teacher education programs,
- for professional organizations and societies to assume leadership in endorsing, enabling, and connecting efforts across the nation in reform,

and for this Committee to catalyze and to endorse both in name and in action (funding) these key stakeholders in improving STEM education at the undergraduate and at all levels. We know this approach can work; it has been demonstrated at a small number of institutions, such at my own, the University of Colorado.

This cultural shift in supporting STEM education may sound ephemeral, but it can be the result of a Grand Challenge, where all Americans realize their identity and agency in STEM education reform. As such, we can return to our roots as a Democracy based on an educated citizenry.

Thank you for your dedication to this critical issue.