Connecting Learning and Education for a Knowledge Society

Task Force on Innovation in Learning and Education
National Science Foundation

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The pace, scale, and complexity of our knowledge-intensive society rely on human capacity to learn and innovate continuously. The learning and education enterprise, supported and pushed by advances in computing technology[1], is at a moment of unprecedented opportunity:

- Advances in the science of learning are informing the science and practice of education. New and evolving pathways to innovation through the integration of the science of learning and the science of education require deep, persistent, and explicit connections between the learning and education communities.

- Fundamental knowledge about learning, e.g., its neural basis, psychological theories of knowing, and biologically-inspired learning algorithms, is informing the development of learning technologies for use in education, as well as the design of "smart" technologies with autonomous learning capabilities of the human brain.

- Advances in computing technologies now allow us to conduct investigations in learning and education on a larger scale and in much more complex contexts than were ever previously possible. At one extreme, machine learning algorithms are making possible new discoveries about learning by the human brain; and at another, the Web is itself a serendipitous distributed dynamic learning laboratory, available anytime anywhere by anyone with access to the Internet.

- The very nature of how science and engineering are conducted has been transformed by computing technologies. Continued innovation in STEM teaching should capitalize widely on this transformation. We can now harness diverse resources—e.g., authentic and realistic data, digital telescopes, immersive environments, mobile and portable devices, modeling and

[1] By "computing technology," we mean not just computing artifacts such as hardware, software, digital data, networks, and devices, but also computing abstractions (aka "computational thinking") such as algorithms, data structures, languages, methods, models, processes, and protocols.

simulation resources, sensor networks, remote instruments—that can transform STEM learning as effectively as they have transformed science and engineering themselves.

- Computing technologies are deeply entwined in our lives, especially so for young learners and teachers entering the profession. Students expect teachers to be adept with these technologies and to fully exploit the technologies' capabilities in their pedagogy. Teacher preparation programs that update their curriculum to incorporate the use of technology can help keep the learning and education enterprise modern.

The potential for bringing learning and education innovations to scale through technology has never been greater.

An Administration priority on K-12 STEM education provides NSF with a unique and timely opportunity to take a collaborative leadership role. Through our investments in research in learning, education, and computing, we are particularly suited for deepening and strengthening connections between advances in learning and the ways in which we educate, and for connecting advances in computing to the way we conduct research in learning and education and to the way we educate. Moreover, the Administration's priority for data-driven policymaking relies increasingly on the outcomes of the research and education we fund, from published results in scholarly journals to NSF-sponsored third-party studies, to systematic assessments of our educational programs.

In Section 1 we present a framework (Figure 1) for depicting the learning and education enterprise. We describe the cycles of activities and their interconnections; emphasize the cross-cutting roles of research, development, and evaluation; and highlight the foundational role of technology in learning and education. In Section 2, we make some general remarks about the framework, and in Section 3, we make some preliminary observations about the learning, education, and scientific communities based on the discussions we had in developing the framework.

1. A Learning and Education Framework

Figure 1 depicts the connections in the learning and education enterprise: fundamental knowledge and innovation in learning informs the research and practice of education, and conversely, knowledge and experience gained from education practice continue to raise relevant questions that push forward the frontiers of fundamental knowledge about learning. The framework is a stylized, theoretical model, not necessarily an ideal, in that it allows us to name and discuss the enterprise's components and their relationships, without intending to prescribe any one specific path to improving education, or to preclude other innovations for improving education. It deliberately and necessarily goes beyond the learning and education activities NSF supports.

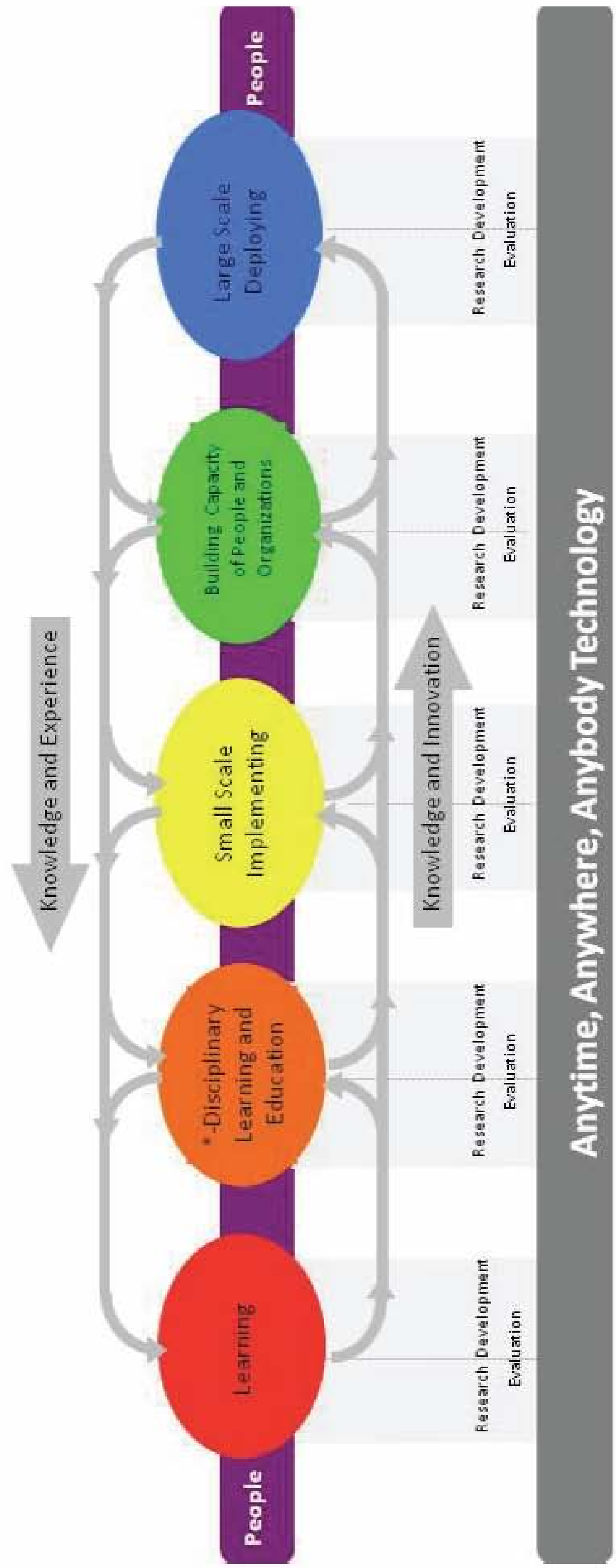

Figure 1. A Learning and Education Framework

Working through Figure 1:

- **Learning** refers to the understanding of learning by humans, other animals, and machines. This activity encompasses multiple dimensions and levels of abstraction of learning: from cells to brain systems, from cognition to behavior, and by individuals, groups, and organizations. It addresses such basic questions as: How does the human vision system learn to detect edges? Is the understanding of infinity innate or learned?
- *-**Disciplinary Learning and Education** refers to understanding learning within a single or across multiple disciplines to inform the way we educate[2]. For example, in teaching mathematics, how can we exploit the fact that human mathematical competence emerges from two different systems: an innate "number sense", e.g., used in understanding the concept of "greater than", and a learned symbolic representational system, e.g., used in learning calculus [HMF08]? Or perhaps this distinction in our brain is irrelevant for teaching mathematics? At another level, how can teacher preparation programs exploit evidence that suggest there is a specialized "mathematical knowledge for teaching" that may be more important than advanced disciplinary knowledge in mathematics [HRB05, BB00]? *-Disciplinary Learning and Education also encompasses research about learning processes/skills within specific subject matter topics which are relevant for teaching and learning of topics in other disciplines. For example, how are the spatial skills important in understanding concepts in geometry also important (or not) for understanding molecular configurations in chemistry, and for understanding time and space in geologic phenomena?
- **Small Scale Implementing** refers to implementing techniques, models, resources, and/or technologies on a small scale, e.g., with a few students and teachers locally, in one or a handful of classrooms, museums, schools, or school districts. This activity includes stress-testing prototypes, to learn about their potential for supporting learning and to gain insights for their re-design. The initial trials of "cognitive tutors"[3] to support students' algebra learning are an example. This activity also includes organized outreach efforts in the scientific disciplines that may apply results of educational research, for example the Centers for Ocean Science Education Excellence. Small Scale Implementing includes efforts that explicitly build on learning and educational research and lay the foundations for expanding the *educational* capabilities of the nation. Through this activity, we gain an understanding of which elements of a technique, model, resource, or technology are critical for learning, and as appropriate, use this knowledge to inform efficacy studies.
- **Building Capacity of People and Organizations** entails the development of human and institutional capital to develop, test, adapt, and implement innovations and frontier work in

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[2] In computer science, the asterisk (*) is used as a wildcard to stand for any and all possible matches. Hence, here it stands for single-disciplinary, inter-disciplinary, cross-disciplinary, and multi-disciplinary learning and education.

[3] Cognitive Tutors grew out of a line of research that has had over 30 years of funding from ONR, NSF (CISE, SBE, EHR), and other agencies. These learning systems are based on the cognition research of John Anderson and the AI principles of Herbert Simon at Carnegie Mellon University, and continue in the current work of the Pittsburgh Science of Learning Center.

education. Within this category are efforts to disseminate more broadly successful results of Small Scale Implementing to affect a wider community, with the goals of changing individual institutions through widespread education of educators, administrators, and organizations. Such changes also prepare institutions for learning and research innovations. The Building Capacity activity also allows the preparation of test sites to be used in large-scale implementation and effectiveness studies.

- **Large Scale Deploying** refers to the use of a technique, model, resource, and/or technology at the state or national scale, usually based on decisions made by policymakers, informed by researchers (e.g., in learning and education), practitioners (e.g., teachers), and other stakeholders (e.g., parents). This activity is more than replication at large scale, because organizations, communities, and institutions also need to be able to identify key elements of a technique, model, or technology that are essential for their context, and most likely to address the learning and education needs of their setting, based on findings and experiences of others. Here is where the learning and education enterprise itself is potentially transformed. For example, the proposed Common Core State Standards Initiative in Mathematics has this transformative potential.

The "Cycles of Learning and Education" drawn as ovals and arrows in Figure 1 depict the five major activities (described above) and their interconnections. The arrows show how the feed-forward flow of **Knowledge and Innovation** gained from one activity affects all others; conversely, the feedback flow of further **Knowledge and Experience** from one activity to all others shows this whole enterprise is continuously changing and improving. For example, a K-12 curriculum in a specific discipline, say mathematics, should ideally be based on an understanding of how a child's understandings of particular concepts develop and build over the years. Children come to school with significant experience and understanding of numbers, and learning progressions can illustrate how that understanding provides the foundation for curricular emphasis on arithmetic in the elementary years, algebra concepts in middle school, and the underpinnings of calculus and statistics in high school. An example in the opposite direction is when the large-scale deployment of a particular learning technology can raise new fundamental and challenging questions for the learning research community to address. For example, is the use of e-books in a science class more effective than standard textbooks? More subtly, is it more effective when the target audience is already facile with similar device technology and accustomed to non-linear thinking (via exploratory search a la the Web)?[4] And, is effectiveness topic- and context-specific? As another example of the feed-forward/feedback interconnections, MIT educators successfully developed and deployed an online laboratory facility for remote experimentation to be used in undergraduate engineering courses. Making the facility available to high school students required design and development of a

[4] Not only does a new technology raise a new learning question (and vice versa), but even though a question may have been answered before, our environment continually changes (in this case, children's facility with computing technology), and so the answer may change.

new user interface and of appropriate curriculum materials, in addition to professional development workshops for teachers [L07].

Each of these activities, from Learning to Large-Scale Deployment, rests upon the pillars of **Research, Development, and Evaluation**. For example, we explore fundamental questions about learning as part of Research underlying Learning, and we conduct state and national assessments of students that are often used as part of Evaluation underlying Large Scale Deployment. These pillars highlight two points: research, development, and evaluation underlie *each* activity in the Cycles of Learning and Education; and *evaluation* is such an important part of research and development that we choose to make it explicit. The types of evaluation done differ across the activities and depend on the nature and scale of the activity itself. Evaluation in learning and educational research assesses factors such as the quality and rigor of the research, the diffusion of ideas, citations, and uptake by practitioners. Evaluation of a large scale implementation of a new science curriculum measures outcomes such as students' science test scores as a way of gauging effect sizes in comparison to a control condition.

The RD&E done to support each activity produces both new Knowledge and Innovations in learning and education techniques, models, resources, and/or technology. Knowledge is also gained from the Experience acquired from engaging in each activity. Knowledge in both cases can also be a result of extracting relevant information from massive amounts of collected data: from the obvious, such as a national assessment of student performance, to the futuristic, such as the Army's systematic real-time data capture during the use of advanced gaming strategies for preparing soldiers to perform high-level tasks. Computational analysis of large data sets creates not only new knowledge in the science of learning and education, but also new ways to assess the efficacy of new learning and teaching methods and new ways to evaluate student learning.

Technology is a foundation that evolves and advances, providing inspiration and opportunity for new learning and education cycles. Looking to the future, advances in computing technology will change the very nature of the learning and education enterprise. With the potential to deliver information to anyone anywhere anytime, the rigid boundaries of classroom learning and the organizational structures of today can blur and perhaps re-emerge in unimagined new configurations. Children already can learn about the stars of our universe from their bedroom; they can participate in biodiversity studies using their cellphones to take pictures of wildlife on their weekend hikes; and they can control a robot on Mars from their local science museum. Advances in computing technology means anybody—from the young to old, rich to poor, able to disabled, literate to illiterate, urban to rural—can more easily and continuously learn new skills and gain new knowledge during the course of an entire lifetime.

Finally, we come to the role of **People** in the learning and education enterprise. People are the inputs and outputs of the entire learning and education enterprise. Human capital is needed to invent, design, study, carry out, and participate in the activities, and to act as a bridge between activities. The products of the learning and education cycles are ideally a society of learned citizens and a well-educated and trained workforce. Future generations of scientists across multiple disciplines, educators, and practitioners will do the research and development and produce the innovations needed for our knowledge-based society to meet the demands of the complex, global challenges we currently face.

2. Remarks on the Framework

The framework is not a staged pipeline of activities. A simplistic view of the learning and education enterprise would be: do basic research in learning; develop educational materials, curricula, and learning technologies; test prototypes on a small scale; disseminate more broadly; scale up by deploying nationally; evaluate and assess. Such a linear model suggests a research-development-test-deploy-evaluate process. We rejected this model: first, because there should be feed-forward and feedback from each activity to others, possibly skipping "stages"; and second, because as noted, research, development, and evaluation are done during each activity. Our model of a cycle of cycles captures dynamism, fluidity, and evolution.

This framework is general enough to support all types of learning and education activities: informal to formal, professional degree programs to research degree programs, general-purpose to discipline-specific or population-specific programs. It is general enough to support the learning and education of all age groups, from pre-school to adult.

An agency's program or project may fall under multiple activities and/or categories. The framework gives us a vocabulary and a way to ask relevant questions such as:

- How does the organization of my agency support the feed-forward and feedback loops necessary for information and learning to flow between and among the various programs?
- Which activities, from Learning to Large-Scale Deploying, do my agency's programs focus on or span?
- How does my program build on fundamental knowledge about learning?
- How does my program build on advances in computing technology?
- Is it the intent of my program to build capacity of STEM teachers or STEM researchers? Is the focus on a particular discipline or not?
- What evaluation method is appropriate for my program, given where it fits in the framework? How is my program contributing to developing new methodologies for evaluation and assessment?
- What knowledge and experience gained from my program can provide feedback for other programs, including those funded by other agencies?
- For what target population is my program aimed?

NSF as well as other agencies support workforce development programs. We make this explicit in the framework's reference to **People**. We consider "Workforce" as a subcategory of People, in contrast to the general public. Programs that provide direct support for undergraduate and graduate students, post-doctoral fellowships, and faculty to carry out *-disciplinary science and engineering research would fit under Workforce Similarly, institutional support that builds capacity for scientific research, but that is not focused on improving the transfer or translation of educational research knowledge, would fit under Workforce. In contrast, programs specifically designed to expand or build *educational capacity*, e.g., those that support stipends for students or teachers to further their teaching education and credentials, might be categorized under Small Scale Implementing and/or Building Capacity.

3. Observations

Based on the discussions leading up to and the interpretation of our framework, we make some general observations about the learning, education, and scientific communities.

1. There are disconnects between the learning sciences and the education sciences, between the education sciences and the discipline-specific educational activities, and between the learning sciences and discipline-specific educational activities. What we understand about learning does not always inform the way we teach a particular discipline. Specifically, distribution of learning and education research findings is often fulfilled by publishing in the relevant academic journals, but this method of distribution often does not transfer or translate the knowledge/information in ways that make it usable for those who are designing and implementing STEM education programs practices. Libarkin, Asghar, Clark, Elkins, and Stokes [LACES09] give a concrete example of this isolation among relevant communities: they show for the first issues in 2008, none of the papers in the *Journal of Geoscience Education* and none of the papers in *the Journal of Chemical Education* cite any paper published in the *Journal of the Learning Sciences*, the premier journal in learning and cognitive sciences.

2. There is a disconnect between advances in computing, especially cyberinfrastructure, and those who provide STEM instruction. Scientists in academia are often responsible for teaching undergraduates and may be involved in K-12 education efforts. Even those familiar with cyberinfrastructure may not know how to use it effectively for educational purposes.

3. What is considered “wisdom of practice” is not always taken as potentially problematic and examined rigorously in research. There are some counterexamples, but long-standing views such as “students cannot think abstractly before about age 13”, or “young children can’t learn complex ideas” still prevail in the design of instruction and curriculum.

4. There is an under-exploited opportunity to integrate neuroscience research about brain function and behavior with research in the science of learning pertaining to perception, action, and cognition.

Postscript

Please send comments on this document to Dr. Joan Ferrini-Mundy (jferrini@nsf.gov). The appropriate citation for this document is: “Connecting Learning and Education for a Knowledge Society,” Task Force on Innovation in Learning and Education, National Science Foundation, unofficial document, draft, January 30, 2010.

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