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Task Force on Cyberlearning and Workforce Development

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A REPORT OF THE NATIONAL SCIENCE FOUNDATION ADVISORY COMMITTEE FOR CYBERINFRASTRUCTURE

TASK FORCE ON CYBERLEARNING AND WORKFORCE DEVELOPMENT

Although this report was prepared by the Cyberlearning and Workforce Development (CLWD) Task Force, commissioned by the National Science Foundation (NSF) Advisory Committee on Cyberinfrastructure, all opinions, findings, and recommendations expressed within it are those of the CLWD Task Force and do not necessarily reflect the views of the NSF.

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National Science Foundation Charge to the CLWD Task Force

The workforce for the 21st century must be cyberinfrastructure (CI) savvy if it is to be competitive in the international marketplace. Education is no longer K-12, but rather a lifelong endeavor effecting not only future scientists and engineers but also the general citizenry. CI serves a dual role in learning and workforce development. First, our next generation of scientists and engineers must be prepared to incorporate the tools of CI within the context of interdisciplinary research, which requires learning new methods to observe, acquire, manipulate, and store data. Second, the general population must be effectively trained; individuals who experience opportunities to work with and learn through networked environments learn new ways of doing old things or new ways of doing new things, both essential in an increasingly competitive world. The charge to the group comes directly from Chapter 5 of the NSF's Cyberinfrastructure Vision for 21st Century Discovery [1] that identified the following goals in the area of workforce development:

- Foster the broad deployment and utilization of CI-enabled learning and research environments.
- Support the development of new skills and professions needed for full realization of CI-enabled opportunities.
- Promote broad participation of underserved groups, communities, and institutions, both as creators and users of CI.
- Stimulate new developments and continual improvements of CI-enabled learning and research environments.
- Facilitate CI-enabled lifelong learning opportunities ranging from the enhancement of public understanding of science to meeting the needs of the workforce seeking continuing professional development.
- Support programs that encourage faculty who exemplify the role of teacher-scholars through outstanding research, excellent education and the integration of education and research in computational science and computational science curriculum development.
- Support the development of programs that connect K-14 students and educators with the types of computational thinking and computational tools that are being facilitated by CI.

Executive Summary and Core Recommendations

In light of the transition into the global, knowledge-based economy driven by information technology (IT) and innovation, the nation faces a critical need for a competent and creative workforce in science, technology, engineering and mathematics (STEM). The need is particularly strong in computational and data-intensive science and engineering (CDS&E) fields and in the skillful use of cyberinfrastructure (CI) for knowledge creation and learning.

On one hand we see the computational transformation of research and development in engineering and the sciences; on the other the emergence of the Cyberlearning and Workforce Development (CLWD) Task Force's vision—of a Continuous Collaborative Computational Cloud (C^4). C^4 is described in this report and intended to capture the pervasive and ubiquitous Internet-based interactive devices, data sources, and users coming to dominate not only the practice of research and education, but also virtually all areas of human endeavor. Computational tools have profoundly transformed much more than researchers' scientific understanding—they have provided a new set of analytical approaches to research problems and methods for addressing their challenges. These powerful forces must be harnessed to optimize their positive impact on education. Cyberinfrastructure has the potential to transform science curricula and pedagogy at all levels of education by providing tools that can facilitate the learning process at any age level, and in any setting, formal or informal. To inspire and motivate the next generation workforce—the Net Generation— interdisciplinary computational approaches, including computer science, CDS&E, informatics, and computational science must be introduced into the K-20 curriculum in ways that build deep understanding and stimulate further exploration. At the undergraduate level, interdisciplinary computational approaches have essential roles both as separate content areas and incorporated into existing math and science (including social and behavioral sciences) curriculum. These interdisciplinary computational approaches, including computer science, have to be presented as more than just programming. What has been termed "computational thinking" represents a perspective, an approach, and a set of problem-solving tools that complement those provided by mathematics and scientific logic, and that should be considered essential to students' education and professional preparation, regardless of discipline.

The CLWD Task Force's core recommendations anticipate and are largely based upon the emergence of C^4, which is central to the call for interdisciplinary computational approaches and CDS&E research and education. C^4 services will provide the context and environment within which people will prepare for professional careers, and as part of that vision C^4 presupposes a more prevalent facility for computational thinking. The promotion, encouragement, funding, and sustaining of resources, tools, virtual organizations, and efforts to build-out C^4 for education, learning, broadening participation, and general workforce development purposes is the urgent business of the NSF.

The confluence of CDS&E, computer science, interdisciplinary computational approaches, cognitive and learning sciences, and rapid developments of a pervasive C^4 environment portend a sweeping transformation of the classroom, grades, course structures, learning, pedagogy, and all else that constitute our current educational system. This is both astonishing and exciting, and encompasses aspects that combine new and old. It incorporates learning approaches that have served primates since their first appearance on the evolutionary landscape to the most recent developments in the learning sciences. In fact, it has the promise of scaling the Socratic method of engaging critical thinking skills—as well as best practices of teaching and learning since Socrates—to the general population, and perhaps most important, restoring "play" to a place of prominence in the learning process.

The recommendations in this report come at a time ripe for harvesting an expanding field of rapidly emerging opportunities. California and likely Texas will soon abandon the use of printed textbooks to electronic textbooks exclusively for their K-12 systems primarily for cost savings, and many other states will soon follow for the same reason. This seemingly small, incremental change can become radical change in the near future if the linear concept of the "textbook" is dropped for that of a personalized, dynamic, interactive, playful, and learner-actuated social learning environment that is enabled by a C^4 cyberinfrastructure.

The potential transformation of science, engineering, learning, and the educational system comes at a time of changed and changing demographics in our schools, colleges, universities, and the nation at large; as well as rapid developments by many across the globe. There remains the long-standing issue in STEM of the underrepresentation of women, persons with disabilities and minorities. Science and engineering need the diversity of perspective and additional brainpower provided by these groups to spur innovation. Furthermore, bluntly stated, the nation cannot meet its STEM workforce requirements without them. Full participation in the nation's STEM workforce is essential if as a nation we are to remain a primary driver of the rapid advancement of STEM, and concurrently the knowledge-based, global economy. Broadening participation in STEM is particularly urgent because of the rapid growth of underrepresented minorities, the fastest growing populations in our nation. We are impeding half of the nation's reservoir of talent by allowing barriers to remain for women, particularly women of color. Our current scientific and economic leadership is at risk and unsustainable until full participation is achieved.

The nation cannot continue to be competitive scientifically, intellectually, and economically unless we take effective action on this issue. We can accomplish full participation using the power of the new tools and resources of CI, particularly C^4. Used effectively, CI can motivate and properly prepare the members of any group to be part of the next generation of undergraduate and graduate students, post-docs, and professorate—a generation better prepared and more capable than any prior generation. Furthermore, it can help renew the hope and promise of education as the means of inclusion for those that have been traditionally largely left out of the world of STEM work.

There is still much work needed, and many opportunities to exploit, such as the pedagogically substantive educational repurposing of the many existing "digitized" science and engineering research efforts and resources of CI and cyberscience. Also, a consensus must be reached regarding CDS&E and computational thinking curriculum, and regarding the strategic investments necessary for building out C^4, described in the next section. There is presently a tremendous opportunity for the NSF within the agency and at least equally important as a leader and team member in some spheres of activity and influence, of a truly collaborative enterprise with the shared responsibility and effort of other federal agencies, state and local government entities, industry, and non-profit associations. The NSF can expect to accomplish its potential for intellectual development of science and engineering and societal impact only within such a team effort. With CI providing the playing field, science and engineering research and education are now very much team sports.

The NSF's Advisory Committee on Cyberinfrastructure (ACCI) CLWD Task Force has addressed the critical changes, improvements, and in some cases, paradigm shifts in education and training content, processes, and approaches that are needed to build and sustain a U.S. workforce in view of the rapidly evolving global economy, particularly within the context of an evolving CI that presents both solutions and new challenges. For the nation to be competitive and meet the anticipated workforce demands, optimal uses of cyberlearning—learning mediated by computational devices and CI—must continue to be researched and developed, to make advancements in exploiting ongoing developments in resources, tools, and their applications to learning, its content, delivery, and pedagogy.

This work must encompass—in addition to cyberinfrastructure and cyberscience—advances in cognition and learning, as these developments and our understandings of them continue to grow and, in turn, influence technological developments. Cyberscience and technology are providing an impressive array of new tools that transform the relationship between individuals and information, and go far beyond access and what is usually referred to as "e-learning" today. These tools and resources include greater intelligent interactivity with content and with other people, the ability to use multiple data representations and work with complexity, and manipulation and simulation of real and virtual phenomena—tools that are integral to our concept of cyberlearning.

The nation needs the talents of all its citizens, calling for significantly greater representation from women, persons with disabilities, and minorities for our nation to have a workforce to support global industries and businesses. Global enterprises are increasingly prepared to locate operations wherever the properly trained workforce and the optimal economic environment exists. In an increasingly interdependent world—and due to the tensions caused by economic exploitation and extreme differentials in wealth and resource allocations—it is in the economic, political, and social interest of our nation that all peoples both here and around the world participate in the emerging technology-enabled workforce. Global scientific, economic, and educational advancements should help raise the standard of living for all, and, hopefully promote better understanding across groups, nations, and regions of the world.

Given rapid global developments and domestic economic health, we cannot simply continue to tap the "best and brightest" from other countries to meet the shortfalls in our home workforce. Cultivating the so-called best and brightest from home or abroad is insufficient to meet the sheer quantity of workers required. Nor can we afford to ignore the opportunity to employ C^4 to help prepare the very workforce it necessitates. Cyberlearning brings with it the power to individualize the learning path for each and for all and allow individual paths to knowledge in ways that traditional learning does not. Properly nurtured, C^4 can transform our educational systems, including higher education, to provide the educational resources necessary to build a broad, diverse, domestic workforce. At the same time, those educational resources and the intellectual excitement and economic prosperity they foster can enable us to attract and retain domestic and foreign talent. This environment can also support international research and educational collaborations benefiting our nation and the global community.

A deeper understanding of conditions that optimize cyberlearning will allow pervasive CI to contribute meaningful and effective solutions (and elucidate remaining challenges) to building the needed workforce, eliminating underrepresentation in STEM in our nation, and attracting and retaining top talent from abroad. At the same time, it is imperative that the rapidly evolving knowledge and skills to support the evolving workforce and effective pathways to content acquisition be identified, clearly defined, and updated. This will require a process for adapting education to new technologies that can respond far more quickly than current systems, processes, and organizations. Pedagogical guidance based on a strong foundation of learning research requires significant and continuous partnerships among the learning sciences, domain research science, technology, and education communities at all levels.

For our university campuses to continue to lead in learning advancements and to transform themselves and the larger educational systems there are particular concerns that must be investigated and addressed for the formal campus as well as informal settings. Social networks and other outcomes of a pervasive CI will further integrate the formal and informal learning environments to meet people's professional and personal needs and desires. Integration of learning environments creates tremendous opportunities to respond to the changing demands of academia, industry, government, and our society; particularly given the life-threatening and life-sustaining political decisions before our citizenry at this crucial moment for life on our planet.

The vision for C^4 both enables and responds to the many calls for a much-needed transformation of our education and learning systems, including higher education. This paradigm-shifting transformation is blurring the distinction between formal and informal education, and provides a learning system from pre-K to Gray to meet the continuous learning demands of the Net Generation workforce. C^4 cyberinfrastructure tools and resources will be able to maintain currency in the education system, and by new emergent capabilities continually evolve as people interact with them. It will provide a learning system much more in line with natural and innate learning processes, more interactive, pedagogically Socratic, engaging, adaptive, and easily accessible for just-in-time learning.

We note two possible approaches to addressing the challenge of this transformation: revolutionary (paradigmatic shifts and systemic structural reform) and evolutionary (such as adding data mining courses to computational science education or simply transferring textbook organized content into digital textbooks). Both can be pursued simultaneously but we posit that the nature of the challenge we face demands an emphasis on the revolutionary approaches, to stimulate systemic change in educational institutions that will make them capable of responding to rapidly changing technology skills and knowledge at a pace necessary for a competitive workforce.
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Core Recommendations

The NSF is in an ideal position to foster this systemic transformation directly through cross-cutting programs and indirectly through influence, authentic collaboration, and teamwork with other agencies, organizations, and entities at the national, state, and local level. To address the question of how the NSF might best facilitate this re-alignment, *we recommend that the NSF invest in efforts seeking a deeper understanding of learning and research mechanisms and organizations in a C^4 era,* providing funding for programs with the prospect for a significantly greater systemic impact on science and engineering education and learning pedagogy, tools, and resources.

Perhaps the most crucial recommendation in this report though, is that the NSF structure its programs foundation-wide to encourage bold revolutionary proposals that build in the communication models and learning approaches of the future Internet and target fully the generations whose lifestyles assume it; exploiting and transforming CI-enabled STEM research advancements, tools, and resources for cyberlearning and workforce development purposes.

A key aspect of the revolutionary approach that we associate with C^4 is to adopt the Internet architecture *ab initio* rather than using it to augment existing programs, materials or curriculum. We offer a vision of:

> Systemic change through interdisciplinary cross-institutional, international programs educating the Net Generation of scientists and engineers using and developing C^4, catalyzed by the changes these technologies are bringing to our understanding of the science of learning.

Our recommendations are presented at two levels: 1) Core Recommendations at the policy level, abstracted from and reflecting the core ideas behind the work of the CLWD Task Force and included in the Executive Summary of this report, and 2) more complete recommendations of the CLWD Task Force Committees, provided as more specific, programmatic, action-oriented recommendations, which are organized by Committee and appear in the body of the full report.

It is essential that the NSF takes a leadership role and get about the business of encouraging and fostering the conceptualization, development, and use of C^4, the vision at the base of all CLWD recommendations. To that end, the CLWD Task Force respectfully offers the additional recommendations that follow.

Regarding Cyberlearning toward Workforce Development

> <u>We recommend</u> the promotion and sustained support of a new cross-disciplinary community that will perform not only the transformative research called for in recent reports, but also the work of translating the research for use by increasingly varied research, development, and implementation communities, with particular attention to the needs of women, minorities, and persons with disabilities.
>
> NSF leadership to bring this about should include the development of a systemic strategy for encouraging the cumulative outcomes from this work, including the integration of CI-enabled research advancements, tools, and resources and of the inclusion of proper assessment instrumentation into cyberlearning software.
>
> This research and development community should significantly increase the degree to which all groups participate in STEM education, research, and the workforce, while transforming the CI tools and resources in innovative ways based on increased understanding of effective STEM education practices for diverse audiences, from pre-K to Gray.

We recommend involvement of research, education, and industry in a functional, robust, and sustained process for addressing two critical challenges of systemic change: (1) developing models for educational system organization and processes that can respond quickly and appropriately to rapidly changing technologies; and (2) defining the skills and knowledge essential to support a strong national and internationally connected economy and workforce.

Critical to this discussion will be the expertise and research perspectives of learning scientists, including cognitive scientists, educational, developmental, and social psychologists, social scientists and education researchers who can support the work of customizing cyberlearning resources in support of the newly defined content for all audiences, helping to ensure that evidence-based strategies for optimizing the learning environment of underrepresented groups can be generalized to the entire population.

The transformative nature of this recommendation arises from the need to create, in a timely fashion, a new generative interdisciplinary thinking that can take full advantage of advances in the disciplines, particularly those directly related to cyberlearning, merging the knowledge and insights of two communities that are in rapid but separate evolution: the technological and the cognitive, the latter providing neuro-cognitive and learning research expertise.

Regarding K-14, Training, Informal Science Education, and Lifelong Learning

We recommend an NSF focus on lifelong learning and professional development. Students and workers need skills and competencies that are evolving rapidly, reflecting the latest scientific and technological advances, fueling the need building C^4 resources and tools and repurposing CI-enabled research advancements, tools, and resources for lifelong learning. Lifelong learning in a rapidly changing technology-based society challenges the NSF to create and support bridges among various governmental agencies, educational institutions, and industry.

The NSF should focus particular attention on updating preparation and continual professional development of the myriad educators required for diverse audiences of all ages. Educators need support and training to be more "technologically agile" with their teaching and mentoring of students. Professional development opportunities and resources for teachers to help them understand and adopt new pedagogical approaches using new technology, and to keep them abreast of new developments and how to incorporate them in their teaching, all need to be a part of the educational application of C^4.

We recommend support for research in cyberlearning. The NSF should devote significant resources to research and development in cyberlearning, exploring meaningful metrics for assessing the needs and progress of all learners by the learner, educator, and others, and the learning impacts of cyberlearning resources and opportunities. A solid body of professional research evidence and development work is needed before cyberlearning tools can be effectively implemented across the learning spectrum, maximizing positive impacts while minimizing unintended consequences.

We recommend that the NSF coordinate with other agencies and departments to develop models for reconstructed educational systems. Educating, training, and updating the workforce in an environment of rapidly evolving technologies will require transforming educational systems from unwieldy, staid, and outdated institutions into nimble, responsive, visionary learning entities that can anticipate, adapt, and personalize educational content, presentation, and approaches to rapidly changing science, technology, and CI-enabled learning methods and resources in C^4.

We recommend that the NSF support research on methods for attracting and retaining a diverse STEM workforce. The NSF should invest in research that investigates approaches and methods for using cyberlearning tools and media to stimulate interest in STEM studies and career pathways for diverse learners at all stages of career development and pursuit, within and outside of formal educational channels.

We recommend that the NSF structure funding programs to support interdisciplinary teams engaged in the architecture and implementation of instrumented cyberlearning platforms that are open, scalable, flexible, and sustainable. This should include organizational scientists who consider implementation contexts, and learning scientists who attend to the social aspects of design. Such efforts will foster community, advance cyberlearning technologies, and build upon open and sustainable CI. In this context, the NSF should examine its portfolio carefully for potential candidate platforms for cyberlearning. It should identify people or groups and particular domains of science, and associated research tools and resources, doing transformative and innovative work in education and broadening participation that could benefit from interdisciplinary approaches. These can provide fruitful starting points for future cyberlearning research and development efforts.

We recommend support for cyberlearning resources. Investigate the efficient and effective repurposing of research data, tools, and resources for learning purposes, and investigate learning data, resource platforms, and metadata for efficient access by diverse audiences and purposes. NSF programs should support interdisciplinary teams engaged in the transformation for learning of research resources and tools, and in the architecture and implementation of instrumented cyberlearning platforms that are open, scalable, flexible, and sustainable. The NSF should also support the cumulative development and aggregation of research and lessons learned in these efforts.

We recommend that the NSF promote modeling and simulation, use of multiple representations, quantitative reasoning, and parallel methods across disciplines and throughout the lifelong learning process. These computational thinking skills support deeper understanding of science and engineering and relevant preparation and renewal of students and workers, particularly those currently underrepresented in STEM. They also promote problem-solving approaches to learning and working that stimulate innovation. The NSF should be particularly aware of the ways in which properly constructed and instrumented 'learning-games' within virtual learning communities can contribute to this effort.

Regarding Bridging Campuses into CI for Cyberlearning and Workforce Development

We recommend the creation of Cyberinfrastructure Institutes (CII) of academic, industry, nonprofit, and government partners working together to develop sustainable cyberlearning, broadening participation, interdisciplinary computational and data intensive science and engineering curricula as well as computational thinking programs and campus infrastructure in support of research and education. The campus infrastructure would include the shared hiring and training of staff and faculty and the sharing of knowledge to build and maintain the workforce of skilled programmers, systems staff, and user support staff needed to sustain the national CI enterprise including supercomputing resources, and provide a pathway for skilled practitioners for U.S. academia, industry, and government. The NSF should create an Engineering Research Center (ERC)-like program to fund a coordinated network of multiple Cyberlearning and Workforce Development Institutes (CWDI) located regionally across the nation. Each Institute could specialize in an important aspect related to cyberlearning with lead Institutes to coordinate the activities and maintain focus on the vision and grand challenge problems being addressed.

We recommend the development of a comprehensive, cogent, and accessible CI architecture to support cyberlearning and workforce development nationwide, and the incorporation and repurposing of CI-enabled STEM research tools and resources for educational purposes. To accomplish this, the NSF should convene and maintain a broad-based advisory group to establish the vision and requirements, and both nurture and facilitate the recommended actions described in this document.

Regarding Broadening Participation

We recommend that the NSF strengthen and bolster its national leadership in broadening participation toward the elimination of underrepresentation of women, persons with disabilities, and minorities. Leadership starts within the agency from the Director and Assistant Directors emphasizing the importance of solving this problem, monitoring and reporting on progress, and reinforcing or creating agency-wide requirements and programs, such as targeted broadening participation programs and a separate proposal review criteria for broadening participation. It will further require a team effort of authentic interagency, state, and local government, and industry collaborations with shared responsibilities and goals, as well as the promotion of effective practices and strategies. This is an area where C^4 can be put to great use, facilitating the intergovernmental, policy, and programmatic collaborations as it facilitates meaningful collaborations for scientific research and education. C^4 can also be a strong enabler of broadening participation by making generally available remote resources, tools, and expertise to and from underrepresented researchers, educators, students, and institutions. Such efforts can re-invigorate the hope and expectation that education and learning will help heal the great divides of our nation. The aim—to broaden participation to encompass the full diversity of our nation's talent—is critical to meeting the demand for a globally competitive STEM workforce.

We recommend meaningfully involving Minority-Serving Institutions (MSIs) by enhancing their capacity as efficient and effective mechanisms for significantly engaging underrepresented minorities in STEM. MSIs need support to build their research, education, and student retention and advancement capacity. MSIs could particularly benefit from virtual collaborations and the repurposing for teaching and learning of CI-enabled science and engineering research tools and resources; provided such efforts reflect the specific educational and cultural needs of the students served. MSIs will require additional support and capacity building, including human and technological infrastructure, to fully exploit their potential and the potential of C^4 and cyberlearning for eliminating the underrepresentation of African, Hispanic, and Native Americans. Toward that end, it would be fruitful to consider them not only as individual institutions, but also as communities of institutions.

We recommend establishing a Hispanic-Serving Institutions Program (HSIP) and augmenting two important NSF programs that have been extremely important to their respective target institutions—the Historically Black Colleges and Universities Undergraduate Program (HBCU-UP) and the Tribal Colleges and Universities Program (TCUP). The establishment of a Hispanic-Serving Institutions Program (HSIP) was mandated in the original and supported in the America COMPETES Reauthorization Act of 2010. These programs should be implemented as cross-cutting programs throughout the NSF, similar to the ADVANCE program. In addition to more general cross-disciplinary efforts, this would enable the NSF Directorates to focus more specific efforts toward elimination of underrepresentation within a discipline or set of related disciplines. The recent evaluation of the HBCU-UP program supports the effectiveness of this program and approach.

We recommend that CI tools and resources be investigated, developed, and implemented for the express purpose of advancing the elimination of underrepresentation in STEM and growing and broadening the STEM workforce and participation in STEM.

Recommendation Development, Supporting Information, and Structure

The recommendations of the CLWD Task Force were developed with the careful consideration of input from the cyberlearning community, which took place during workshops, conference calls, and in the form of white papers. The CLWD Task Force was organized into five Committees to provide clear focus on priorities within cyberlearning and workforce development. This report is organized around and based on the work of those five Committees, which are:

Continuous Collaborative Computational Cloud (C^4) in Higher Education
Cyberlearning
K-14, Training, Informal Science Education, and Lifelong Learning
Campus Bridging and Education
Broadening Participation and Cyberinfrastructure

The core recommendations in this Executive Summary were abstracted from the work of the CLWD Task Force Committees. More specific, programmatic, additional recommendations from each of the Committees are included in their respective sections of this report, including additional information to enable the NSF to take action to secure a strong, competitive workforce and advance cyberlearning research, development, and implementation, an area much needed for the evolving knowledge-based economy.

Introduction

We have reached an extremely interesting and exciting crossroad in the history of human knowledge creation. Rapidly evolving information and communication technologies are expanding the range of possibilities for innovation and discovery in all areas of human endeavor, particularly those that fall most directly within the purview of the NSF, including the physical and social sciences, mathematics, and engineering. This expansion of possibilities is accelerating beyond the capacity of our current education systems to effectively respond, leaving us without the collective intellectual resources necessary to move from the possible to the real on a scale that can drive not just knowledge creation for its own sake, but also economic, health, and social advancements on a global scale.

This paradigm shift in knowledge creation calls for and in fact is enabling a parallel shift in the dominant model of knowledge transfer—our education systems. The current systems are based on the standardized production of a mass of students with a common set of educational skills and knowledge. Recognition of a crisis in our educational systems, rather than leading to a search for innovative solutions, has led to a reinforcement and emphasis on standardized curricula and testing models. Standardization was once useful when the economy was largely based upon mass production systems in which workers could be viewed as a type of mechanism that could be designed and trained to continuously repeat a rigid set of operations over the entire course of their employment. This is no longer the case.

The set of skills needed to identify and exploit new and emerging opportunities for knowledge creation and practical application cannot be captured by a standardized curriculum, at least not a curriculum in the traditional sense. Education must move in the same direction as the new knowledge economy—producing graduates able to respond to new challenges and opportunities as they arise, having the capacity to move fluidly from problem-space to problem-space with a mastery of a basic set of problem-solving tools to which new tools can be added and from which obsolete tools discarded. The good news is that we have an idea of what the future workforce will look like; the question is how long will it take us to get there?

This report presents a set of challenges to which the NSF must take a leadership role if we as a nation are to effectively respond. The NSF must engage the general science communities, particularly the CDS&E communities, but also the social and cognitive sciences, all of which will be essential for the research and development of the tools, resources, and effective policies and practices for realizing the paradigm shift in learning and education systems that is absolutely required to support a continually and rapidly evolving workforce.

This paradigm shift must encompass pre-service preparation to in-service professional development, re-education of the talented displaced worker in a volatile economy adjusting to continual innovation, and the engagement of an intelligent citizenry able to make scientifically informed decisions on matters of potentially critical impact on the status of the planet as a congenial host of life as we know it. The NSF must act decisively to take leadership not only because of its mandate and responsibility to develop the nation's STEM workforce, but because the opportunity presents itself for the NSF to achieve all of its key goals: "to provide an integrated strategy to advance the frontiers of knowledge, cultivate a world-class, broadly inclusive science and engineering workforce and expand the scientific literacy of all citizens" [2] with one skillfully administered set of initiatives to fully exploit the opportunities afforded by CI.

The creation of educational and learning systems based upon incorporating and utilizing the very tools and technologies that are motivating the call for new systems suggests an interesting feedback loop in which the tools of knowledge creation, learning, and practical application form continually evolving synergies that generate possible futures impossible to visualize. However, the possibilities are laden with the excitement of discovery and science and engineering in action to the benefit of humankind and social justice. We call upon the NSF to serve as catalyst.

Chapter One 1

Continuous Collaborative Computational Cloud (C^4) in Higher Education

Several recent reports [3] discuss undergraduate and especially graduate education in the areas termed "computational thinking,"[4] "modeling and simulation," [5, 6] "computational science and education" [7-9] and more recently "computational and data-enabled science and engineering" (CDS&E) [10-13]. These reports build on a substantial body of experience and analysis [5, 6, 14-29]. The CLWD Cyberinfrastructure Workforce Development and Higher Education: Computational and Data-Intensive Science and Engineering Committee did not spend much time on these important and well-understood subjects, focusing instead on two main topics as part of the overall charge to the CLWD Task Force:

The barriers facing students and professionals exploring computational fields.

How to engage the next generation—the Net Generation[30]—using methodologies that have proven to be effective in exploiting the unique potential of the Internet, instead of simply adapting older approaches such as PowerPoint and printed textbooks to the Internet.

Motivating Issues

Figure 1 illustrates the organization of our discussion, and also introduces the Continuous Collaborative Computational Cloud (C^4), which we define as the ubiquitous "Internet of things" supplying data to and driven by information from services in the cloud. C^4 is a massive pervasive always-on information aether linking networks, sensors, personal systems (smart phones, laptops, pads, pods, and players), repositories, servers, and supercomputers. C^4 provides each individual user personalized knowledge on demand and the global user community a medium whereby human creativity, collaboration, and communication are being unleashed to new heights. This concept represents what we believe may well be the underpinnings of future cyber-enabled education, and accordingly underlies the CLWD Task Force's recommendations. We build on current efforts at interdisciplinary education approaches (computer science/informatics plus applications) while addressing the motivating issues that may require changes in current educational practices. We also note some broad points, including the importance of building and supporting communities that are fostering innovative changes in education. These recommendations are both timely and crucial because while the NSF has had an enormous impact on research, it has had a relatively modest impact on education, even though education is essential to the health of science in this country.d a relatively modest impact on education, even though education is essential to the health of science in this country.

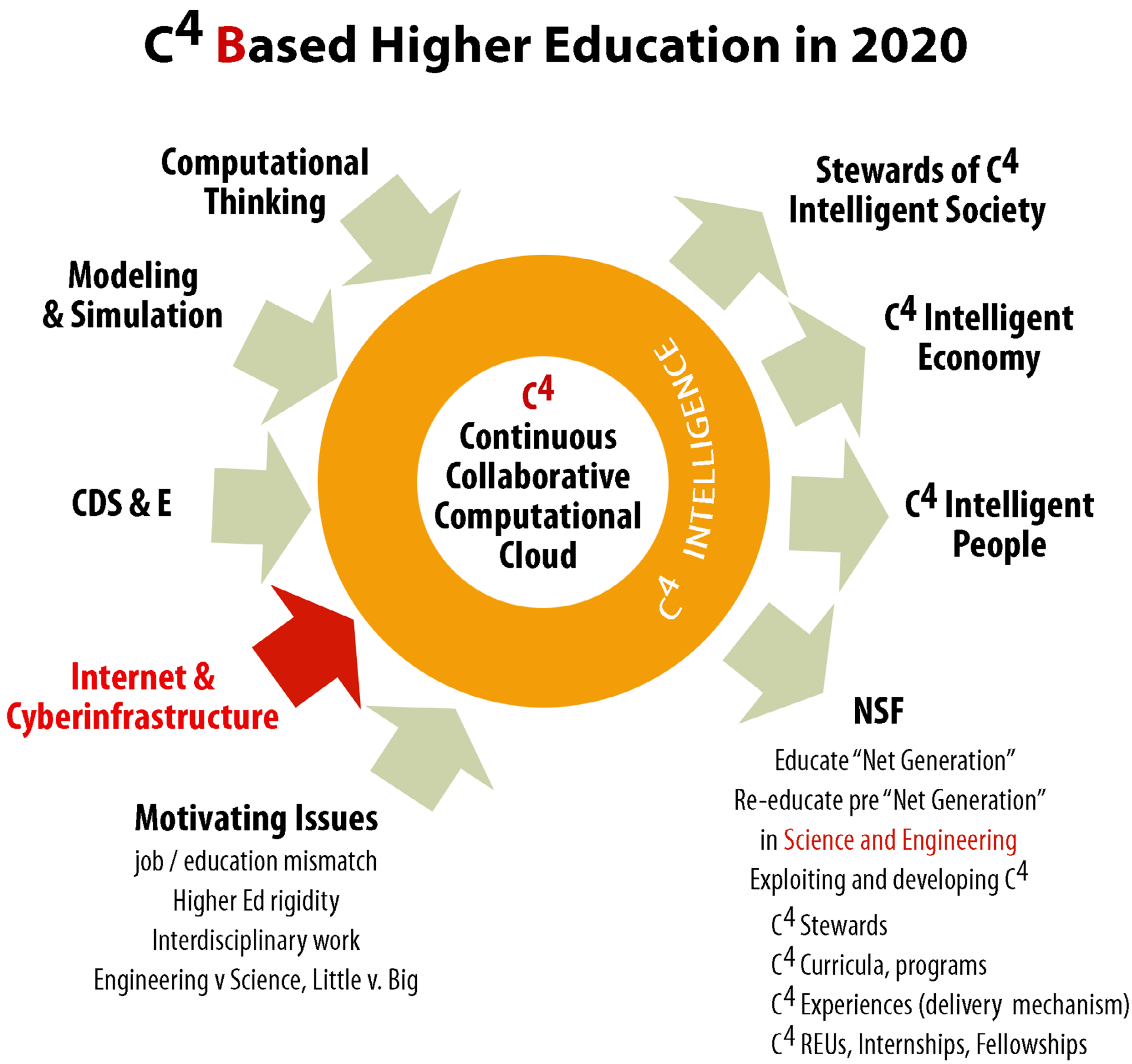

Figure 1: The Motivating Issues, Driving Ideas and Technologies Constituting Higher Education for a Net Generation Workforce

Mismatch between workforce needs and education

At present there is a mismatch between curricula and the workforce needs of employers. Concordingly, there is mismatch between the preparation of teachers, and especially K-12 teachers, both in the education they are receiving and the curricula they are taught to teach. All too often, new hires require several months of additional training because the curricula they encountered in college did not provide them with the experiences or the type of problems requiring multiple scales of resources as would be faced in a modern enterprise. As a result and for the most part, their students are not learning advanced, modern computing concepts. At present, and perhaps for the first time, companies are experiencing a shortage of computational scientists. It is becoming clear that traditional computer science (CS) courses may not be providing the right approach to learning new technologies. Specifically, there is substantial evidence suggesting that technologies such as high performance computing (HPC) are more effectively learned through research experiences accompanied by "spot" or "just in time" training, than by present CS classes. There is also anecdotal evidence suggesting that mid- and senior-level managers typically do not understand computational approaches, and that this lack of understanding hampers industry's modernization. Similar lack of awareness and understanding among senior administrators characterize public pre-college educational leadership from the school district to the state levels.

While certain NSF programs such as Grant Opportunities for Academic Liaison with Industry (GOALI) have had some impact on university-industry interactions, they are the exceptions. The extreme levels of international competition today and in the immediate future clearly underscore the strategic importance of increasing the level of support for interdisciplinary and academic-industrial partnerships that will lead to greater overlap between the skills and knowledge industry needs, and those that academic institutions are providing. The next generation workforce would be better served if there were more interdisciplinary education and interdisciplinary research within the university hierarchy. The NSF has encouraged interdisciplinary research endeavors, but these are rarely incorporated into universities' hierarchies. There are still numerous challenges within academia to accepting multidisciplinary fields and education programs involving computation, one of them being the rapid development of CS technologies and the obsolescence of existing technologies that it causes.

Most significant for research programs, interdisciplinary work is hampered by a lack of understanding by colleagues and university administrators of the computational aspects of a given interdisciplinary project. Without a widespread understanding of the importance of computation in supporting the research objectives of modern interdisciplinary projects, it is extremely difficult to marshal the institutional support and resources needed to implement a productive interdisciplinary research program.

Effective understanding begins with education programs, but we are far from providing effective interdisciplinary higher education programs in our institutions. Firstly, too often faculty are not, or do not feel, prepared to teach interdisciplinary subjects because they do not view themselves as expert in all of the associated disciplines. In part this is just an academic tradition that has not changed with the times. Yet it also reflects a need for appropriate interdisciplinary examples and modules in which the instructor, while a non-expert, is conversant enough with the core concepts to feel comfortable with the examples. Clearly we need more incentives for faculty and universities to make the needed changes. For example, more support should be directed at exploring the use of distance or innovative online learning systems with wide selection of supported teaching modules.

One way of nurturing interdisciplinary education would be to establish a standard for interdisciplinary education programming throughout higher education. If everyone spoke the same language, then interdisciplinary group projects for undergraduates could become the norm. Furthermore, students in all disciplines participating in interdisciplinary projects should complete more math and CS courses with practical labs to prepare them for more active involvement in the development and use of C^4 applications. Teaching computational thinking should be expanded beyond computer science and other STEM majors, providing all students with the tools necessary for interdisciplinary work.

Lack of emphasis at the NSF in engineering compared to science

As a general issue, the NSF does not provide sufficient support for engineering programs, compared with the sciences. Engineering is by its very nature an interdisciplinary enterprise, and should be a focus for much more research and education support to more effectively exploit CI-enabled possibilities. Likewise, there should be more joint classes involving engineers and science and math majors.

The rigidity of higher education institutions and outdated requirements in the curriculum

Higher education is dominated by a culture of conservatism within which it is difficult to modify traditional course requirements to allow interdisciplinary or computational classes. Adding to the problem, many CS faculty stress teaching the fundamentals of CS, as they have been traditionally understood, even to science and engineering majors. This latter group needs to experience the application of CS within disciplines for the materials to have any meaning to them, and are particularly interested in the latest computational tools being used in their professions. The CS faculty, in turn, often view "applications" as too applied, and dismiss "emerging technologies" as transitory and faddish.

While graduate science and engineering research augmented by CI is well accepted, there is no generally accepted definition of computational thinking or computational and data-enabled science and engineering from which core curricula and knowledge could be determined. For example, the role of computational thinking for disciplines outside of CS would be quite different, possibly with less orientation on objects and more on the scientific problem-solving paradigm. Likewise, the role for the IEEE curriculum in distributed and parallel computing is unclear, with scientists and engineers still having to struggle with the low-level programming required rather than on how best to solve a problem "in parallel."

Challenges of data-intensive science

The role of data as both object and tool of research is growing rapidly and cannot be overstated. The explosive growth of data sets and their applicability for new research are not sufficiently reflected in similar growth and development of education programs to prepare students to address emerging data challenges. Training data scientists [11] is growing in importance, as is the demand for data mining expertise. The need for data sharing systems is generating even more new challenges.

The relative roles in data-related education of computer science, statistics, bioinformatics, and application areas that use data must be better defined. It appears that the NSF's Office of Cyberinfrastructure has focused too much on big science, ignoring the "long tail" of "modest-sized" science and engineering which will soon emerge to become the dominant "consumer" of CI.

Future Directions of Computational Science

Computational science and engineering (CSE) is a multidisciplinary combination of techniques, tools, and knowledge first developed in the 1970s and 1980s at research laboratories to solve scientific and engineering problems through computer simulations. Because realistic and complex problems typically do not have straightforward analytical solutions, they are often ignored in traditional education. Indeed, educators interested in including modern computation into their courses continually observe that despite advances in teaching and research, computational science remains absent from typical undergraduate programs, such as AJPed and Microsoft CSE [31-33], with some physics educators going so far as to declare that "we're teaching the same things we taught 50 years ago"[34]. Just as traditional science education requires the understanding of experimental and analytic techniques, modern science also requires the understanding of computational tools.

Various schools have taken first steps to develop programs in Computational ``X'' or ``X'' Informatics, where ``X'' is a traditional discipline such as biology, physics, or mathematics. A Computational X education consists of a multidisciplinary combination of X, computer science, and applied math, and thereby has a broader viewpoint than normally found in the X discipline. Because many of the CX programs teach a common set of computational tools, a CX education is often similar to one in CSE [35]. However, even though science educators are widely incorporating computers to enhance science education, the computation is often presented as a "black box" whose inner workings need not be understood; significantly more knowledge about the "black box" of computation will be needed to function in the future computational Cloud. Indeed, both CSE and CX undergraduate curricula often contain a rather equal balance of computer science, applied math, and X. While a narrow focus is to be expected in graduate education, a balanced one, such as that provided by CX, appears more appropriate for undergraduates and better prepares them for C^4.

A systemic change in college-level curricula is needed in which science and computation are better integrated, and thereby provide better preparation of students and improved learning. While practitioners in the 1980s were content to have students wait until graduate school to learn what is inside the computational black box, there is now a broadly held view that this is one symptom of a set of problems in undergraduate science education that need immediate attention:

Science education throughout the disciplines has yet to recognize that science has undergone a transformation in which computation has become an essential foundation, and that it has become as crucial to understand computation as mathematics. Students are not being prepared for this paradigm change.

Science curricula must incorporate more computation both as stand-alone courses and as part of scientific problem solving within the disciplinary courses in order to meet the demands graduates will encounter when entering the workforce.

New multidisciplinary curricula with real-world computational problems are needed within the disciplines and within CS; traditional CS curricula are not addressing the real-world needs of scientists and engineers.

Having students learn CS and math within the context of solving a disciplinary problem is a more effective and more efficient pedagogy than learning all three subjects separately and out of context.

New curricular materials that integrate computation with science are needed.

Students need exposure to cross-disciplinary research including computation.

Individuals have already done excellent work, with some published and placed in the National Science Digital Library (NSDL). However, a long-term and supported online repository for curriculum sharing and information dissemination is needed.

Teaching a multidisciplinary field such as CX is challenging. Institutions are usually composed of departments in the established disciplines, and they often resist decreasing the number of their courses to make room for computational courses, or having other departments teach their specialty. Additionally, faculty may not be or feel knowledgeable enough in other disciplines to teach them, or may not have experience in teaching a multidisciplinary course that requires a blended approach.

We note that the C^4 vision inherently advocates the need to enhance and extend CS and computational X. C^4 explicitly specifies some of the technologies that CS should use as it teaches and conducts interdisciplinary research incorporating simulation and its use. However we should not forget an important lesson of the limited success of CS as an independent discipline in many institutions. CS or Computational X need not be separate entities at universities and professional societies, but rather they are an approach to science and teaching that can be incorporated into existing disciplines as they recognize the paradigm shift that computation has brought to science.

Socrates Anticipates the Importance of the Internet and Participatory Learning

As relayed in a story from Socrates through Plato, the Egyptian God Theuth—the inventor of written language—has just told the Egyptian King Thamus that textbooks will be a great boon to education allowing rapid and universal access to information. Thamus' response was:

> "(textbooks) are an aid not to memory, but to reminiscence, and you give your disciples not truth, but only the semblance of truth; they will be hearers of many things and will have learned nothing; they will appear to be omniscient and will generally know nothing; they will be tiresome company, having the show of wisdom without the reality." (Phaedrus, 275a)

Socrates' concern about approaching life by reading about it rather than experiencing it for oneself when applied to learning requires full engagement with a subject or problem, but with the engagement managed and directed by a mentor who understands how humans learn. As the first "constructionist," Socrates knew that real learning involved the process of incorporating what one experienced with one's own internal models, which he also correctly recognized as dependent on the interaction of different kinds of memory. In the context of modern neuroscience, this is a process we now call memory consolidation. Socrates' concern about textbooks was that they did not support this kind of integration.

Theuth's advocacy of written textbooks, on the other hand, relates to another core problem in education, which is scalability: a small number of people with knowledge wanting to use that knowledge to influence a much larger number of people. Textbooks and especially the printing press in some sense solved the technical scalability problem, however, at a clear cost to real learning in the Socratic sense. Nowhere perhaps is that more evident than in cramming for a science class and then basically forgetting even the fundamental concepts a few days later. In modern educational structure, all too often it isn't until the second or third year of graduate school that the kind of educational experience valued by Socrates is possible—and then, of course, given scalability problems it is only for a small subsection of our population.

It is a thesis of this report that properly used, C^4 can for the first time scale real "Socratic" learning from pre-K through graduate school. Accordingly, for the first time in history, a technology is available that is cheap and flexible enough to be adapted to how we as primates really learn, and that can, in principle, provide a Socratic style educational experience even to first graders. The rigid and linear textbook-based educational technology we have been using for nearly 2000 years has had such a profound influence on how we approach education, and how we organize our educational institutions, that it will take a sustained effort to realign our approach to education made possible by the technologies we are now developing. Accordingly, we recommend that the NSF restructure its programs foundation-wide to encourage bold revolutionary proposals that maximize the talent and opportunities available today, and harness the tremendous resources developed through past and current NSF support. Proposals that leverage C^4 will provide the platform for research and education at a new level in the U.S., particularly with NSF leadership guiding other agencies in similar and joint endeavors.

A major change in the nation's approach to education will not come easily, but the NSF is in an ideal position to help foster it. While it is prudent to make the change to C^4-based education gradually, this is a disruptive technology that requires more than just a modification of what we have now to a new digital format. While we see this happening now with textbook publishers, we envision truly interactive and executable "texts" using the Cloud and networks to obtain their full functionality and their Socratic structure, something not yet possible.

Broad Discussion of Possible Approaches

In discussing possible approaches the Committee noted that in general "money talks," as for example with the NSF Integrative Graduate Education and Research Traineeship (IGERT) program and the DOE Computational Science Fellowships, both of which advocate strong research and multidisciplinary components for graduate education. We also noted the Virtual School of Computational Science and Engineering[36] and virtual summer schools as ways of incorporating the emerging CI into the structure of higher education. An investment from the NSF in programs related to C^4 will advance NSF objectives for workforce development and strengthen educational systems nationwide.

Regarding the types of changes that are needed to incorporate the developing CI into the training of future work-forces, we observed that some changes are evolutionary, such as adding data mining courses to computational science education, while others are revolutionary, such as replacing face-to-face lectures. While both types of changes can be pursued simultaneously, we recommend that the NSF focus on revolutionary changes because they have the potential to lead to much greater payoffs. C^4, A key aspect of the revolutionary approach, adopts the Internet architecture and the connection of education to employment as the basic structure upon which we build education, rather than just using the Internet to augment existing programs and hoping that our graduates will adapt the education we give them to the needs of the workforce."

C^4 is the pervasive environment of the Internet and other emerging technologies that has already started to impact society and the economy through the mobile and Internet tsunami of smart phones and commercially driven Web2.0 infrastructure. It must be harnessed to drive education to a new level by supporting systemic change through interdisciplinary cross-institutional, international programs educating the next generation—the Net Generation—of scientists and engineers.

As well as considering fundamental changes to methodology, the Committee examined some of the activities that address the motivating issues and the lessons from state-of-the-art work in computational thinking [4], modeling and simulation [5, 6], and computational and data-enabled science and engineering [7-13]. We recommend an organizational structure based on programs that support interdisciplinary experiences aimed at educating the next generation of scientists and engineers, and that possesses the following attributes:

Research

Research support is needed for developing and implementing methods and technologies suggested by C^4.

The C^4 environment provides opportunities for effective exploitation within a growing range of research applications. Research is needed to better understand this emerging research problem-space and the cognitive requirements (e.g. computational thinking) for effectively exploiting it.

Learning

Curriculum tools and systems (e.g. virtual worlds) should be built around C^4 concepts that exploit emerging technologies including mobile phone applications such as Twitter for research and education.

C^4-enabled curricula should be developed that integrate computational and data-enabled science and engineering, computational thinking, CI, and cyberlearning into all aspects of curriculum.

Partnerships and fellowships should be established with industry, international organizations, and national centers (government labs—efforts like NEON), including cross-institutional programs.

Community Building

A community of C^4-savvy learners and teachers should be promoted and nurtured. This community will drive the development and implementation of innovative C^4 learning tools and systems with the right support from the NSF and the C^4 research and development community.

NSF Programs

A cyberlearning institute for current and prospective NSF grantees should be established for disseminating technology applications that effect change in the classroom.

The NSF's Cluster (Cloud) Exploratory (CluE) program should be continued, if it has demonstrated success.

In the section on "motivating issues" we noted that the NSF has inevitably had much greater impact on research than education, including funding. The NSF will only have a significant impact on education when it makes a more significant financial and programmatic investment, or focuses on an area of great educational opportunity. The NSF's OCI should be encouraged to take a leadership position in both research and education, offsetting its current (and mistaken) image as "just an infrastructure" organization. Concurrently, the NSF must develop a coherent approach to educational program evaluation; the C^4 initiative requires a consistent holistic monitoring and assessment approach that would be appropriate for tracking and evaluating the complex and dynamic learner-driven processes that C^4 enables. Proposals for educational activities are often reviewed inconsistently because no clear consensus has been established for determining which among several approaches is the most promising.

<u>We recommend</u> that the NSF develop and fund a suite of new interdisciplinary programs that integrate research, education, and the exploitation of emerging and transformative technologies (e.g. cyberlearning), in collaboration with industry whenever possible. This should be for undergraduate, graduate, and continuing education. The new programs should include these features:

Emphasis on computational and data-enabled science and engineering
Integration of research and education
Study of social aspects of large-scale distributed research
Collaboration with cognitive scientists
Development of new curricula
Research across big/little science, social sciences, engineering, computer science

The above remarks lead us to expand upon the revolutionary aspects of the C^4 concept.

C^4 for Society and Research

Ubiquitous high bandwidth connectivity, even in rural and remote areas (using for example power-efficient micro data centers the size of shoe boxes), will likely characterize most of the U.S. if not the world in the relatively near future.

During the last ten years we have created a technological infrastructure that has fundamentally transformed our lives. Immense volumes of data are being captured continually by instruments and sensors used by scientists, engineers, the military, and large corporations, in areas that include Web search, bioinformatics, drug discovery, nano-engineering, e-commerce, and social networks. These data require yet-to-be-discovered mining algorithms to cope with the unprecedented and essentially unimaginable scale.

At the individual level, the Internet changed the way we communicate, work, travel, and are entertained. By the year 2020, most students will have been born in this century; will live a computer-based, social network existence; and will have difficulty understanding how their parents survived without it. Some of the features of C^4 discussed in this document are motivated by the experiences of Whyville [37], an online virtual learning world that has attracted almost seven million children to voluntarily play math-and-science-based exploration games[38]—an example of how technology is changing education, even for our youngest citizens. Despite clear examples such as this, we still think of using traditional methods and tools to teach the next generation of scientists and engineers, when in fact we need to plan now how to empower succeeding generations with enabling technologies for lifelong learning and interdisciplinary collaboration. Computing is the driving force at the center of the social network phenomenon. Therefore we must leverage this trend and push the envelope toward creating the learning infrastructure of the future.

Today the computational Cloud is a set of uncoordinated systems that people can access only after explicitly connecting to obtain a service. In contrast, we envision that the Cloud in 2020 will be such an important part of our lives, as a much larger, more encompassing, constant experience, that we coined the term "Continuous Collaborative Computational Cloud" or C^4, to capture the essence of that experience. Given the impetus of the social network phenomenon, we believe that in 2020 the C^4 experience will go well beyond our present notions about Internet-centric experience. Although we cannot predict precisely the communicative, interactive, and computational forms manifesting through C^4 that will rise to dominance, we hope that a reasonable criterion of successful C^4 will be its degree of non-intrusiveness and transparency.

C^4 Implications for Education

We have identified above some of the directions technology is leading us and have proposed a vision captured through C^4. We are living in technology-driven disruptive times that offer an historical opportunity to articulate and drive a fundamental reorganization in the process of the creation and intergenerational transmission of knowledge. The pace of change in technology has multiple features that need to be linked and harnessed. We currently have significant potential to expand and utilize cyberlearning and education to exploit powerful new computing technologies—not just the artifacts (hardware, software, networks, devices) but also the abstractions such as algorithms, models, processes, data structures, and protocols. New opportunities to advance learning and education have been and are under development such as Web technologies, which enable the sharing, accessing, and publishing of online content and software from around the world. Our new and emerging immersive learning environment also includes networked content (accessing huge data sets, color visualizations, interactive applications) that is no longer limited to books, filmstrips, videos and other traditional learning media. Rich learning environments have prompted the California and Texas state wide text selection committees to pursue plans to eventually eliminate textbooks. Furthermore, young learners who are already immersed in the world of computing technologies are putting new demands on our teacher preparation programs to prepare teachers that can exploit the possibilities offered by new technologies. The C^4 implications for education address the following key issues:

> C^4 both uses the communication mechanisms preferred by the Net Generation and it also enables the customized participatory learning paths preferred by best pedagogical practice.
>
> There is a growing mismatch between workforce needs and the educational ecosystem that includes institutions, students, curricula, and teachers. The mismatch is particularly serious for K-16 teachers, who need adequate training and experience (research or industry internships) in order to gain the competence needed to address current and future workforce issues. This is the key concept that education in 2020 must match both the learners of 2020 and the jobs to which they aspire.
>
> The technology of C^4 offers new ways of interacting, including various forms of virtual worlds and the complete replacement of printed material by online environments. Distance learning must move beyond talking heads and PowerPoint projected across the globe, although even this would be an improvement over many of today's educational approaches.

Somewhat independently of the interaction technologies of cyberlearning are the possibilities afforded by the world of gaming, namely the extensive use of simulation and realistic data analysis for education. While this is an old idea, as Justin Rattner of Intel explained in his SC09 conference keynote[39], processor and Internet communication performance now make this an entirely achievable goal, projecting that complete adoption of this principle can be achieved by 2020. The Virtual Reality Markup Language (VRML) failed in 2000 not because it was a bad idea but because ten years ago CPU and net performance could not support it.

C⁴ Education Vision for Interaction

We noted above that we expect today's social networking and virtual organizations to continue to evolve and define new C⁴ interaction modes that must be explored to ensure our educational systems can relate to the Net Generation. Indeed these new ways of interacting will define cyberlearning as the default approach to education, and we identify some possibilities below. We do not predict that Twitter, Facebook, or even advertising would monetize the Internet. Our examples therefore cannot pass for predictions, but merely possible capabilities that might define learner-learner and learner-teacher interactions in 2020.

Future devices may be capable of hosting complete computer representations of individuals, including 3D models of the face and other body parts, a data repository containing professional experiences, capabilities, preferences, areas of expertise, learning styles, preferred ways of communication, disabilities, and other attributes that could "stand in" as the individual's "digital persona," having "walk-in" digital meeting rooms to engage in conversations with the digital personae of other people using similar devices.

The digital meeting room of the future will likely operate conference tables (table avatars, or "tabatars") where digital personae will be instantly recognized. Tabatars will have deep knowledge about the conference topic, the expected outcomes, and geographical and cultural settings of the participants, their time constraints, and other information. Tabatars will use this information to deliver collaboration experiences with real-time language translation and contextual awareness so that people anywhere in the world could participate.

Today, students and educators think of their mobile devices mostly as a means to socialize and get entertainment. We believe that educators and students in 2020 will exploit advanced means of communication, interaction, and data gathering made possible by devices permanently connected to the Cloud on a 24/7 basis. Cyberlearning in 2020 will not be constrained to the classroom or laboratory experiences, because students will use robots, sensors, and smart devices to enter active volcanoes, explore the depths of the oceans, or a crowded and polluted metropolis to gather data and conduct science and social experiments never before possible (or even necessary).

C⁴ Education Vision for Content—the Schools in 2020

C⁴ not only implies new interaction models. It also leads to different ways of presenting content from immersive sites to the rampant use of simulation. This section discusses the content and the following section the interaction sites that C⁴ will spawn.

Didactic vs. Inquiry-driven Self learning as a Core Concept

New technologies and changes in the financing of higher education are shifting the control of learning to the learner, which will be more widespread in the future. We will need to have learning systems that are adaptive and responsive to the needs, interests, strengths, and weaknesses of learners as they become even more significant managers of their own education (pull rather than push). In this adaptive approach, expert knowledge is built into digital-based learning systems, and the teacher becomes more of a mentor and resource person who facilitates the learning process but does not necessarily direct it.

Push vs. Pull as a Core Concept

The traditional model of higher education has a professor trying to push knowledge to students. As the future sees students becoming more in charge of their own education, it will see more students trying to pull the knowledge they need from the Cloud. The distinction between synthesized and synthetic data is an example of the difference between the push and pull approaches to education. Synthesized data are generated on-demand in response to a specific question or problem posed by learners as they grapple with specific concepts. Synthetic data, in contrast, were "pre-generated" by educators to illustrate a specific concept, and thus may be just minimally responsive to the immediate needs of the learner. The Internet search engine provides a good example of seeking (pulling) rather than pushing information. The popularity of this model for knowledge sharing speaks for itself.

Digital Environments Arrayed around Content vs. Content Converted to Digital Form

Under the current publishing model, the object is to sell the textbook, with digital attachments providing additional attraction or revenue. Under the new model, digital content in various forms will provide the dominant vehicle for delivery, with the book itself executable, interactive, and including Cloud components. While those in the textbook industry are finally accepting the inevitable use of e-books, much of their movement in this direction has been to place traditional books into digital form, which is far from the potential that exists within C^4. Clearly, there is the need for a new business model for publishing.

Curriculum vs. Games; Storyboards vs. Simulations

Among primates, gaming and play are universal learning activities in which theory and practical application are closely intertwined within an activity framework imbued with emotional rewards. We have yet to effectively apply the full potential of gaming into education, although the tools for designing games with strong learning opportunities are available. Another opportunity afforded by game-based learning is to engage students in virtual careers and real life situations in which they must act based on their knowledge. This is an excellent way to provide a realistic understanding of what specific STEM careers entail, and may help attract underserved groups into computation.

Most current educational gaming offerings are storyboard based, in which all of the visual, text, and audio elements, together with possible interactions and possible screen-to-screen transitions are mapped out and scripted, all of which are tied to a set of learning objectives. In effect, this is "push" technology. One of the core transformations allowed by cybertechnology is the replacement of storyboarded curriculum with models and simulations that allow direct interaction with specific concepts, explored and directed by the learners themselves (pull). The focus of the technology is then on motivating users to explore the underlying science in a realistic way.

STEM/Vocational Education vs. Workforce

It is critically important to maintain a close relationship between workforce needs and STEM/vocational education programming. Links between STEM programs and workforce development needs and opportunities must be continually updated. These programs should enable students to easily transition into targeted certification and other workforce training opportunities.

Intrinsic Interdisciplinary Studies

Much of what is critically important science is intrinsically interdisciplinary and should drive the development of an educational approach built around challenges and problems the solutions to which presuppose an integration of disciplinary perspectives.

Central (Publisher. Author) Generated vs. Stakeholder/User Generated Learning Resources

The opportunity for user/stakeholder-generated content is a consequence of an emphasis on pull and seeking approaches to learning, which requires tools and strategies to facilitate the process. Digital structures should be adaptive and modifiable so that students, teachers, and parents can incorporate ideas and insights as they are identified. Students of all ages can be empowered to design learning games for each other. The socio-technical underpinnings of learning (of which only a small but powerful component is represented by the publishing industry) must be allowed to grow and develop without interference from the demands of publishers, authors, and holders of copyright.

Summative vs. Formative Evaluation

Evaluation remains of primary importance in all education programs. However it is possible to replace periodic (end of chapter, end of year) reporting with continuous reporting as interactions with learning systems provide up to the moment information about the learning status of users. Furthermore, games and simulations allow evaluation efforts to track progress toward specific professional development goals.

C^4 Vision for Learning Environments—the Schools in 2020

Classroom Centric becomes Internet Centric

C^4 is decentralized in space and time, and provides opportunities for immersive learning that is not restricted to the school setting. Learning (as is true in life) occurs any time, anywhere, and is expected never to end.

Isolated Today vs. Cooperative and Competitive in C^4

Education in C^4 is not confined to single, isolated classrooms, or even schools, districts, states, or countries. Instead, it incorporates some degree of cooperation and social interactivity appropriate to the level of the learner. Teachers, parents, and professionals are integrated into this cooperative education model via enhanced communication—just part of the promise and possibility of global access and involvement in a student's education.

Discrete Uncoordinated Records become Continual Persistent Instant Updated Digital Assets
A student's 'learning trace' can be accumulated, maintained, and built upon throughout their educational career (lifetime).

Dynamic Definition of Grades and Learning Levels

As is suggested by the theory of multiple intelligences, children grouped by age will typically span a wide range of levels for a variety of cognitive skills, with the division into verbal and math abilities being just coarse measures. But in the world of C^4 education, students can work from and advance within their current levels (different and multiple) with learning activities adjusting themselves so as to provide scaffolding that is unique to the cognitive skill-set of the individual learner. The concept of "level" in this framework loses its present emphasis, as learning becomes continuous rather than a set of transitions from discrete learning milestone to milestone. Even major transitions such as high school to college may become less meaningful tools for tracking student educational histories. They may still exist due to social aspects, but the educational structure will be more continuous.

Computers in a Laboratory vs. an Integrated Multiplatform Digital Landscape in C^4

Future classrooms should see the integration of all digital devices, be they computers, mobile devices, and others still to be developed. Mobile devices underscore every interaction with the world as a teachable moment. Science research using mobile devices are making scientific inquiry universally and globally accessible, allowing collaborations on a scale never before imagined. The opportunity to engage students and citizens in scientific endeavors is expanding each year, and C^4 provides the platform to support this expanded world of learning and research.

Modality of Electronic Education

While it is extremely important that schools are connected to the Internet, it is even more important that connections are translated into meaningful learning. Broadband connectivity is less important than sophisticated use of Internet connections. To ensure a maximum pull of knowledge, C^4 content must be browser based rather dependent upon customized platforms. Such an emphasis also facilitates more universal and equitable access. At present this is not true for digital books, with the most popular formats for e-books not appropriate for textbooks with equations, tables, and interactive figures. The NSF must support the development of both content and learning environments.

Schools Introducing Technology vs. Schools Adapting to Technology

The market place (consumer) will continue to be the driver for new technology in the foreseeable future. Education will therefore have to keep abreast of C^4 innovations, leveraging technologies and approaches that have been developed for broader more competitive markets.

Concluding Remarks and Recommendations

We are living in disruptive times that offer once-in-a-lifetime opportunities to articulate and drive a fundamental reorganization in STEM education. We believe that the NSF should lead the way and play a significant role in that transformation. In order to meet the challenge, the NSF should introspectively analyze its own programs, articulate a vision for the future, and equally important, articulate processes and metrics to define how to execute on that vision and how to measure the outcomes. While predictions regarding this digital transformation have been around as long as computers have existed, we believe that a primary measure of success will be the extent to which students and the workforce in 2020 look to C^4 for their principal means for lifelong learning. There are several recommendations throughout this section that build upon the establishment of C^4. At the core, we recommend that the NSF support the development of C^4 as well as revolutionary proposals that take advantage of this resource, and that the NSF provide leadership among other agencies to effect significant changes in educational systems that leverage the current and future investments of the NSF.

Chapter Two 2

Cyberlearning

As part of the overall CLWD Task Force charge, the Cyberlearning Committee looked at the knowledge needed to effectively prepare a competent workforce for a society with pervasive Information and Computing Technology (ICT) access. The concluding recommendations address research issues that underlie promising approaches toward the general CLWD Task Force recommendations to the NSF and cover work within the NSF itself in addition to research that the NSF should fund.

The recommendations are directly linked to changes that have taken place in the ways in which society uses ICT for learning and communication, described in the introduction, and are fully consistent with the development of C^4 as described in this report. They reflect an organization of knowledge acquisition and sharing that differs in significant ways from how the NSF has traditionally responded to learning needs. In particular, we want to point out the implications of the broad acceptance, by the NSF and the field in general, that basic research issues underlie some of the problems with present actions and policy. For example, the creation within the NSF of the Science of Learning Centers program responds to this research need, as do the increasing attempts to look at education as a system in need of reform. As a consequence, there is need for the additional expertise of disciplines such as social and organizational sciences, political science, economics, and others that have not traditionally engaged with learning.

Cyberlearning and its Impact on Science and Society

Due to increasingly more sophisticated data collection technology and storage devices and their use by multiple disciplines, science is faced with unprecedented challenges in making sense of a deluge of data, which for the foreseeable future will overwhelm our computational, algorithmic, and machine and human modeling resources. This emerging science, e-science, holds immense promise and is enabled by pervasive CI-networked computing and instrumentation technologies that led to this embarrassment of riches. Cyberinfrastructure presents a challenge to computer science, mathematics, and engineering on the machine and machine-intelligence side, and to education and the learning sciences on the human resources side.

One response to this challenge is to re-vision traditional conceptions of computer-mediated learning by constructing a new view of learning called cyberlearning. Cyberlearning is learning (personal, social, and distributed) that is mediated by a variety of rapidly evolving computational devices, (e.g., computers, smart phones), and CI (e.g., Web, Cloud). In this complex environment, cyberlearning should strive to be coherent across platforms and settings.

Cyberlearning is especially relevant to STEM learning, where it is critical for mediating the learning of computational thinking skills and the effective use of CI, since the challenges and promise of CI will affect learning in all areas (humanities, arts, science, engineering, etc.) and settings (school, workplace, home, public spaces).

In a broader sense, cyberlearning is critical for the use of ubiquitous CI by all knowledge workers and citizens. Cyberlearning is not only about learning to use computers or to think computationally. Social networking has made it clear that the need is much more encompassing, including new modes of collaborating and of learning for the full variety of human experiences mediated by networked computing and communications technologies.

In its traditional form, computer-mediated learning (e.g., e-learning) is already ubiquitous and will continue to rapidly evolve. Learning scientists and designers strive to create a new field of cyberlearning that extends definitions of learning to encompass new ways of incorporating rapidly changing science knowledge within an ever-changing networked technology infrastructure whose impact is slowly being appreciated.

Overarching Priorities as Components for All Recommendations

There are three overarching priorities for the NSF that are integrated with our recommendations. We propose that the NSF programs that support CI, learning, and education consider these priorities beyond our recommendations. These priorities reflect the first recommendation of the 2008 NSF Office of Cyberinfrastructure report, "Fostering Learning in a Networked World" (FLNW)[40] chapter on learning, which states, "Help build a vibrant cyberlearning field by promoting cross-disciplinary communities of cyberlearning researchers and practitioners." The community does not exist now—its creation must be the first task to undertake. The overarching priorities are:

1. The creation and support of a cross-disciplinary community that will perform the research and implementation of the activities proposed by the CLWD Task Force, including strategic considerations and funding of the infrastructure to build and grow that community over time, as the NSF has done with other research communities.

2. The need to make explicit in all instances the targeted audience, learning goals, and metrics to gauge progress—proper assessment instrumentation—by self and by others—embedded in cyberlearning software must be the rule, not the exception.

3. The development of a systemic strategy to encourage the aggregation and cumulative development of outcomes from this work. Mechanisms such as the National Institutes of Health two-stage funding model (i.e., a first phase has the community working on the research roadmap and designing key studies; a second issues a RFP to the field to tackle components of the roadmap) and the MacArthur Foundation Research Networks (http://tinyurl.com/4wnzel) should be explored and adopted.

Themes and Recommendations for the NSF

We have organized our recommendations that follow under three themes that parallel the remaining FLNW learning recommendations, each with a framing context:

Theme 1. Instill a Platform Perspective into the NSF´s Cyberlearning Activities

Theme 2. Emphasize the Transformative Power of ICT for Learning, K to Gray: Seamless Learning, Multiple Pathways to Learning

Theme 3. Adopt Programs and Policies to Promote Open Educational Resources, Including the NSF's Role in Relation to the National Landscape of Federal Agencies

Theme 1: Instill a Platform Perspective into the NSF's Cyberlearning Activities

The 2008 FLNW NSF Cyberlearning Task Force recommended instilling a "platform perspective"—shared, interoperable designs of hardware, software, and services—into the NSF's cyberlearning activities. The CLWD Task Force perceives this approach as generative in catalyzing research in the field of cyberlearning that itself is driven by instrumented data and reflects the fundamental socio-technological changes laid out in this report's executive summary. The creation of cyberlearning research platforms is a focal recommendation as it is seen as a catalyst to facilitate the other major recommendations put forth by the 2008 FLNW report: (1) to help build a vibrant cyberlearning field by promoting cross-disciplinary communities of cyberlearning researchers and practitioners; (2) to emphasize the transformative power of ICT for learning, from K to Gray (kindergarteners to retirees); and (3) to adopt programs and policies to promote open educational resources.

<u>We recommend</u> structuring NSF funding programs to support interdisciplinary teams engaged in the architecture and implementation of instrumented cyberlearning platforms that are open, scalable, flexible, and sustainable, and that bring these tools to broader audiences. Such efforts will foster community, advance cyberlearning technologies, and build upon open and sustainable CI. In this context, the NSF should examine its portfolio carefully for potential candidate platforms that can provide a starting point for future research and development efforts.

Critical challenges to creating an effective platform are *community* (formations of teams that bring multi-disciplinary expertise to bear), *cumulativity* (building on promising innovations from prior technology projects), and sustainability (to ensure that learning materials targeted for the platforms are widely usable and remain so over time). A cyberlearning platform should not only be a *cognitive platform*, one that best supports student learning and teacher effectiveness, but also be a *metacognitive platform,* one that is built to improve through reflection on past performance. The biggest challenge to creating a metacognitive platform is that the platform and its users have access to quality assessment data on learners' progress and critical inputs to that progress, including from teachers.

Reliable diagnosis of student knowledge and learning requires collaboration of cognitive scientists, educational psychologists, psychometricians, and domain scientists (e.g., biologists if the educational technology is targeted at biology). And to assess critical issues of student dispositions, motivations, and identity formation, we also need social psychologists, educators, anthropologists, and designers at the table. Broad contributions from social scientists, educators, user experience designers, and graphical artists are important in the creation of ICT resources that engage students and aid their identity formation as well as help them acquire fundamental knowledge for success in the workforce. The more ICT resources meet these ambitious goals, the higher will be the quality of the data coming from them. A final challenge, which also requires multi-disciplinary input, is educating more stakeholders in sound analysis and interpretation of learning data, toward *educational data literacy*. Such stakeholders range from researchers at the end of the data chain to the teachers, parents, and students at the beginning of the data chain.

From a technical perspective, there are challenges in data stewardship—data collection, storage, dissemination, data reporting and visualization, privacy, support for collaboration around data analysis, and advanced data mining and knowledge discovery. Too often innovative ICT resources for learning are instrumented for data collection after they have been built, if at all. Thus, a fundamental component in the platform perspective is the creation and dissemination of software development and educational technology authoring tools that automatically produce data logging applications. When an educational game, intelligent tutor, or mobile-based collaborative learning tool is developed, it should be able to log user interactions to a database without any added effort. More generally, putting the design, development, and deployment of cyberlearning technologies in more hands through easy-to-use but powerful authoring tools is a major opportunity.

Technical challenges associated with data storage and dissemination are general issues for CI, and apply as well to educational and learning data. Significant research opportunities exist in the area of better data reporting and analysis. Much work is needed in human-computer interaction and design research to customize data reporting for the different needs of stakeholders, including teachers, parents, principals, superintendents, policy makers, researchers, and learners themselves. Better visualizations of learning data are needed, as well as tools for on-line collaborative analysis of data that can benefit from the wisdom of crowds. The state of the art possible in sense-making with interactive data visualizations is illustrated in Hans Rosling's *GapMinder*[41]—we need such tools for educational and learning data.

Instilling such a platform perspective recognizes that software infrastructure is integral to a cyberlearning environment, and reflects that the lessons and processes learned from efforts in the e-science community can serve as guidelines. The effort should therefore, where applicable, leverage and connect to C^4 platforms both from commercial providers and those developed by the community with support from the NSF, such as collaborative and Cloud computing environments for e-science embodied in portals/gateways (e.g. HUB/Zero), toolkits for virtual organizations and Cloud computing (e.g. Globus/Nimbus), and collaborative virtual environments applicable in educational settings (e.g. Social VPNs and educational appliances). A cyberlearning platform effort, however, cannot be limited to infrastructure only, but must involve substantial use by students and teachers right from the start, and therefore use-driven design is critical.

At its core, the platform infrastructure allows simulation, testing, modeling of new ideas, and through an open and flexible architecture, the goal is to foster sharing and reuse of modules and datasets. The infrastructure would include an authoring toolkit(s)/workbench that could automatically provide instrumentation for learning resources, include the ability to allow in vivo experimentation using the platform, and be flexible enough to address the different needs from different users based on their experiences—meshing between what the target audience needs to see and what is available in the data. Processes to deal with policies such as the Family Educational Rights and Privacy Act (FERPA) limitations in teachers sharing data on best practices and providing Web video models need to be defined.

In order to address these challenges, it is important to recognize that the process of architecting such a platform itself should be guided by an expert panel including private industry participation and requires planning by and involvement of a multi-disciplinary community with expertise covering aspects of science of learning, assessment instrumentation, data collection, computing, machine-learning, human-computer interfaces, user experiences engineers, and collaborative environments, thus cutting across NSF Directorates. This requires a strategy that can be broken down into a community road-mapping process for defining the overall big picture and then the development RFPs in relation to research and development for components of the roadmap/plan.

Examples of relevant platforms and instantiations are:

Authoring cyberlearning applications: HUBzero/nanoHUB (http://www.hubzero.org and http://www.nanohub.org respectively) and Molecular Workbench (http://workbench.concord.org) are examples in simulation and modeling. Examples in tutors and dynamic assessment include Cognitive Tutor Authoring Tools (http://ctat.pact.cs.cmu.ed) for Genetics Tutor, Assistment Builder (http://www.assistments.org) for middle school math assistments and PADI (http://padi.sri.com/) for developing assessments. Examples in course content management and authoring include Learner Management Systems, and Lecture Capture, Interactive On-line Text.

Data repositories, reporting, visualization, analysis, and collaboration tools: examples include workflows for scientific and engineering applications (Pegasus, MyExperiment), educational data repositories and analysis tools (DataShop, Diver), collaborative/social networking infrastructure sharing (SocialVPN, http://www.socialvpn.org) and portals that enable impact analyses (such as iKNEER, http://www.ikneer.org/.

Games for education is a topic of current interest, seen as relevant to computational thinking and to providing active social learning experiences in computational and data intensive science and engineering. There has not been so far an emphasis on platforms and engines that are directed solely to school learning, though there is a fast growing number of games and digital products being directed at the school market (for example for learning mathematics or reading) often using engines like Flash and now Unity. Many people working on games for learning have sought platforms and engines that allow for the design of learning across environments such as school, after-school programs, libraries, and museums, as well as homes. There are also a variety of virtual worlds that have been used for designing new forms of learning, worlds like Second Life and Active Worlds.

A variety of game design platforms have been used for both entertainment and non-entertainment purposes (e.g., games for learning, games for health, games for change, etc.) using underlying commercial platforms. Non-entertainment learning games, for example, have been made for the Nintendo DS and Wii. Games that allow for design, such as Little Big Planet, the Sims, and Boom Blox, have been used to build games for learning as well as to teach game design. Systems such as Alice, Scratch, and Gamestar Mechanic have been used to teach game and media design, as well as technical skills and complex thinking. In addition, mobile platforms have been a fertile source of Apps for learning, as well as entertainment.

Recommendations

We recommend that the NSF support a Road-mapping Community Workshop. An immediate term recommendation is to fund the organization of a workshop to map the landscape for an architecture of inter-operating platforms for cyberlearning research and development including e-science in a way that is community-relevant and contributes to the development of C^4. Key charges of the community road mapping process would be to define who builds it and who provides oversight, to determine how to assess its outcomes, and to lay out systemic strategies for cumulativity and sustainability. The workshop should engage both academic and industry partners.

We recommend that the NSF fund the development of funding models that enable cumulativity and sustainability. The applicability of models of funding the development of software that attempt to reconcile fostering innovation and high-risk ideas with continuity, quality control, and sustainability, such as the approach taken within the NSF's Office of Cyberinfrastructure (OCI) Software Institutes program, should be looked into as possible approaches to address these challenges. The funding model should encourage proposers to employ a use-driven design improvement plan that is tied to sustainability.

Theme 2: Emphasize the Transformative Power of ICT for Learning, K to Gray: Seamless Learning and Multiple Pathways to Learning

When considering workforce needs, it becomes imperative to understand and support multiple pathways to acquiring the competencies and knowledge necessary, in particular the mechanisms about emerging job streams and competency requirements. Demographics and the growth of private, for-profit tertiary institutions, in addition to the increased use of community colleges for job retooling, point to communities with whom the NSF has had limited interactions. These communities are nevertheless crucial for maintaining and upgrading skills that need to be continuously upgraded with rapid advances in consumer technology.

When learning can occur anywhere (from formal schooling, to after school, to workplace years later), we need to consider frameworks that explicitly support lifelong and long-term learning, and that embody innovative ways for self-assessment. How can the 30-year-old scientist refer back to the journal paper that used an unusual statistical method that she read a year ago, and connect that to her notes from the statistics class that she took 10 years earlier? We need to support students integrating and aggregating across opportunities for learning over time and over technical platforms such as e-readers. This learning will require new kinds of visualizations (perhaps modeled on mental maps) to track knowledge and learning opportunities over time, to go beyond traditional models of portfolios. This in turn points to the need for frameworks to integrate across multiple instances of learning for just-in-time learning and argumentation.

Pervasive access to CI means that learners can access resources across formal and informal settings. Even today, students probably learn more per hour during their access to Internet resources than they do in their normal school day, because their Internet learning is based on interest, curiosity, and engagement rather than an externally imposed curriculum. Pervasive access built on powerful learning platforms means that the boundaries between formal and informal settings blur—students can build on their home explorations when they get to school, and what they learn at home can be assessed and added to their personal portfolio in school. Once these boundaries are blurred, the similar boundaries of grades and even K-16 can blur, and we can use CI to truly create seamless learning.

To reach this vision of seamless learning, we need change to support the development of a workforce that can use, develop, maintain, and advance CI. The CI workforce needs to be larger than we currently have, and more diverse in its composition so as to design for a national audience. This goal implies a need to broaden participation to draw on groups from whom we have few CI workers today, and increased reliance on CI-savvy human mentors, critical for the inclusion of non-dominant groups. These efforts extend from:

> Encouraging K-16 students to think about e-science as a future career, and to support their K-16 teachers in developing new models and skills.
>
> Providing access to citizens to engage with and learn from the rich scientific data sets available through CI.
>
> Help current workers (including teachers) to re-tool and gain skills and concepts to work within data-enabled science.

In addition, to meet the accelerating growth of needs for the CI workforce, we need a better flow of information between the workforce and the seamless learning opportunities that feed that workforce. Today, a change in workforce needs is informally fed back to educators, and employers get only an indeterminate picture of the interests of students heading their way.

Recommendations

We recommend that the NSF support a Workshop on Cyberlearning Needs. The NSF needs to fund a workshop to articulate the specific cyberlearning needs of different sectors of the CI workforce. While the Math and Physical Science's report on "Data-Enabled Science" [10] includes recommended goals for NSF's Education and Human Resources Directorate, we need actionable needs and a roadmap for achieving those goals. Education developers and researchers need to know what needs are projected for growth from the U.S. Dept of Labor and similar workforce-attuned institutions (e.g., prominent research laboratories in the private and government sectors). The goal would be to span data sharing and projections between e-science and multiple federal agencies and departments, including opportunities to leverage C^4 resources. Before we can estimate the research and development needed for meeting those needs, the community must size, prioritize, and map the knowledge space of CI workspace careers and construct a timetable for meeting those needs. This effort will require understanding the different audiences that are implied by the CI workforce and develop, for each of them, learning goals and metrics for measuring progress toward those goals.

We recommend that the NSF fund efforts to understand how students and teachers currently perceive the learning pathways from K-12 through undergraduate and into the CI workforce. How do students learn about CI opportunities, and what roles do teachers play in helping students imagine their possible future selves as CI workforce contributors? What processes are in place now? What new technical what-if scenario and role-playing designs for envisioning future possible selves in the CI workforce can advance the state of support today? How can we best assess students' acquired relevant knowledge and skills?

We recommend that the NSF fund investigations that seek to understand the cyberlearning practices of current CI workers (e.g., information foraging, social networking), and to develop resources that propagate CI workers' best practices while also creating innovative approaches that will augment the necessary new skills and models within these workers' practices. We cannot effectively and economically take all current CI workers back into classrooms for new learning. These workers certainly already make use of the existing CI to gain new information and develop knowledge. We need to build on learning opportunities within those existing practices to re-tool our current workers, including K-16 teachers. Fulfilling this goal will require research and new tools to support and improve the workflows of teacher's planning, instructional, assessment, and reflective learning practices. New tools and mechanisms will be needed as part of this effort to better enable teachers to tap and build upon the "funds of knowledge" that learners have developed in their broader life experiences.

We recommend that the NSF develop a "sensing network" for tracking CI working and learning. With the instrumented platform described in the previous section, providing effective assessment data, we can accurately track student competencies and interests so as to inform employers about potential hires years into the future. We need a similar flow of information from employers back to the authors of learning resources, to inform them of future needs. The NSF should fund research to develop models of these information flows, and to understand the barriers to successful implementation of mechanisms for supporting such flows. This work entails collaborations with the U.S. Department of Labor and the Business Roundatble since these communities have dramatically different understandings of privacy, information sharing, and quality of predictions. In short, we need to better understand how to reduce friction in the development of the CI workforce by enhancing the fit between supply and demand.

Theme 3: Adopt Programs and Policies to Promote Open Educational Resources, Including the NSF's Role in Relation to the National Landscape of Federal Agencies

The paradigmatic changes that have taken place in the realm of ICT available outside the traditional STEM workforce have forced upon the NSF an emerging attention to the translation of learning research results into practice as a research issue in itself—the concept of implementation research as reflected in medicine, public health, and ecology, among other areas where general scientific concepts and ideas have to be absorbed and adapted to—and by differing local environments. Essentially, management and planning for change should be considered as part of the NSF's mission. This extension has two implications:

> The need to bring to the learning sciences several disciplines that have not been a regular component of education and learning research (such as organizational studies, political science, economics, and complexity sciences) but that are needed to consider the organizational aspects of managing change, and that only the NSF can accomplish.

> The need to develop the interdisciplinary aspects of interagency responsibilities for the process of research-based large-scale improvement of educational practice. In the same way interdisciplinary research requires an investment in collaboration and communication across different idioms, assumptions, and practices, interagency collaboration requires an internal NSF investment into its own process of adaptation.

We view the scientific and modeling challenges of CI and the workforce as providing an integral research theme across the NSF Directorates. We view the phenomena of data deluge management, data modeling, data-enabled sciences, sense-making through interactive data visualization, insight generation, and knowledge communication and learning as core issues for all segments of society. They provide a Grand Challenge for the science and engineering disciplines, the social sciences, the learning and cognitive sciences, and education. The themes of CI and the workforce provide a pressing basis for establishing a research-intensive ARPA-ED initiative centered at the NSF.

Cyberlearning implies dynamic changes in the workplace, including K-16 workplaces where teachers will be both supporting the cyberlearning of the next generation of CI workers and citizens, and engaging in their own cyberlearning. Today, there is a bootstrapping problem that schools of education traditionally do not develop in-service programs that presume pervasive computing access by learners because teacher placements rarely find schools that have such access. So the new teachers are not prepared for the cyberlearning environments that we take for granted will appear within several years, and that are presumed in the National Education Technology Plan [42]. Thus, the recommendations below integrate reflections by the CLWD Task Force on the conditions required for implementing those recommendations.

Recommendations

<u>We recommend</u> that the NSF foster development of platforms for cyberlearning research that enable innovation and implementation of high-risk ideas from the community with processes to ensure continuity, quality control, and sustainability, and use-driven design and improvement. The NSF should consider funding models to support such activity with buy-in from multiple NSF Directorates/offices, as in the NSF's OCI Software Institutes program.

<u>We recommend</u> that the NSF develop a visionary, transformative, outside-of-the-box, cyberlearning NSF-wide working group of program officers who have expertise in, and actively promote:

Modeling and simulation; "science" as opposed to disciplines
Connected teaching
High-risk, high-gain flexibility
Integration across ages
Cumulative community-wide tool development
Common community protocols
Rapid prototyping/ modeling change
Support for learning ecosystems
Different reviewer pools

<u>We recommend</u> that the NSF develops studies that pursue alternative possible futures and considerations of their positive, negative, and unintended consequences. Instances of key topics include: (1) pros and cons of moving the onus of learning to an individual (i.e. increase in inequality as rich-get-richer); (2) balancing individual and societal responsibilities in advancing learning; (3) changes in credentialing—multiple skill competency certificates; degrees no longer serve as the only credential (i.e., the future of universities); (4) data privacy trade-offs in relation to benefits of personalized custom learning resource recommendations and pathways.

<u>We recommend</u> that the NSF support the development of strategies and programs for creating robust networks of organizations for cyberlearning research and development. As part of this effort, the NSF needs to find ways to establish future-facing testbeds that include K-16 organizations and research enterprises that make learning possible by apprenticing "in the future" (i.e., in settings that will become representative in the future) as a means to study processes of change and improvement in cyberlearning. Establishing these partnerships may need to be in public-private partnership given today's educational funding models.

Chapter Three 3

K-14, Training, Informal Science Education, and Lifelong Learning

The CLWD Training, Informal Science Education, and K-14 Education Committee focused on the following critical aspects of science education:

How cyberlearning tools affect skills training and professional development of the current and future workforce.

The impact of cyberlearning on strategies, approaches, and content considerations related to STEM workforce skills and knowledge acquisition outside of formal university curricula.

Inclusion of the considered workforce—those who seek computational and data-intensive STEM knowledge and skills for using and for teaching with and about rapidly evolving technologies and data resources, including HPC.

Within the Committee's consideration of the overall CLWD Task Force's charge was the uses and value of cyberlearning for reaching audiences ranging from K to Gray in both formal and informal learning venues. The Committee considered the capacity of cyberlearning to reach and enable broad audiences to both adapt to and create STEM-related jobs for a region or community's available resources, location, and local talents.

Background

Cyberlearning fundamentally changes the manner in which people seek and obtain knowledge and skills. Knowledge seekers are empowered by CI-based learning that can be personalized to address their individual needs, styles, and level of knowledge. Cyberlearning reduces barriers to learning, proffering its riches to all individuals, regardless of age, gender, race, or cultural differences. In this way, cyberlearning makes current, relevant, equitable, and unbiased education available to all individuals with Internet access. To the extent that it is a persistent medium, the Internet provides substantive support for the lifelong learning pathways that are now essential for the U.S. workforce to play a leadership role in the global economy. At the same time, it has the potential to exacerbate economic inequities that are coupled with poor connectivity. For those connected, all things are possible. The unconnected see increasing distance between their hopes and dreams, and the tools to achieve them. This Committee's discussion and recommendations are predicated on the essential need for universal access to dependable and reasonably broad bandwidth Internet resources and continued access to developing resources such as C^4.

Workforce development can be an effective driver for needed systemic change if thoughtfully planned, designed, and leveraged for sustainability. Jobs offer a powerful incentive to learn, and workforce development must prepare workers for current and emerging jobs. Timely, adaptable, customizable training for problem-solving skills along with rapidly changing STEM workforce skills is critical for sustained economic growth. Workforce development must also foster skills for creativity and innovation, key to creation of new jobs for a thriving, evolving economy.

New program implementation requires well-defined metrics for measuring short-term and long-term progress toward targeted goals. National-scale initiatives will benefit from a shared understanding of metrics among all funding agencies. The NSF has a valuable opportunity to advance this understanding through a process that advises the larger funding community on the scope and scale of appropriate metrics, and the instruments and methods to both collect and analyze those metrics in a consistent manner across projects, programs, and funding agencies.

It will also be important to identify specialized skills and the related metrics that must be tailored to specific needs and situations. The educational communities can best develop formal and informal learning opportunities based on a collection of defined competencies and skills needed for the diverse range of workforce careers. Students of all ages need to learn the skills that will make them marketable in the workplace. A clear articulation of the skills and knowledge for both current and future jobs will facilitate development and delivery of meaningful and effective formal and informal learning materials and opportunities.

The process of metrics definition should involve sociologists, education researchers, Web analytics and technology experts, and others who can contribute to understanding which metrics can be collected through instrumentation within cyberlearning platforms and how. The process of establishing metrics, instruments, and analysis techniques should outline what can be done at present and the level of understanding that today's metrics can provide, as well as necessary preconditions to understand deeper level indicators of impact, sustainability, and success.

Support of workforce development demands of the NSF a holistic and forward-thinking balance of funding priorities among research; hardware/software infrastructure; and development of human capacity to contribute to long-term advancement of discovery and innovation.

Overarching Priorities

NSF Operations

The Committee identified six overarching priorities related to NSF operations, philosophy, or approach considered essential to significantly advancing cyberlearning and workforce development. We propose that the NSF consider these priorities above and beyond our specific recommendations:

1. The NSF should assume long-term engagement with cyberlearning, measuring the success of its initiatives over longer time frames than the two to three years of most funding programs. The NSF should adopt measures to identify the best of the best, through an evaluation of outcomes from funded projects for highlighting those of particular merit among the community.

2. The NSF can significantly enhance community building by connecting people working on related projects to share strategies, challenges, and best practices. Emerging CI and cyberlearning technologies can directly contribute to the process. These investments will help NSF projects avoid duplication of effort and improve the additive and transformative impact of individual projects.

Support for development of a sustainable STEM cyberlearning professional community, mentioned many times in CLWD Task Force meetings and discussions, is contained within this priority.

3. To create sustainable and coordinated initiatives, to avoid duplication of effort, and to identify gaps that need to be addressed by one or more agencies, the NSF should build stronger collaborative links with other agencies (e.g., Department of Education, Department of Energy, National Endowment for the Humanities, Department of Homeland Security, and others). Currently, the Networking and Information Technology Research and Development Program[43] Social and Economic Workforce effort includes 14 agencies; providing evidence that such a collaborative process and structure exists and can be more frequently utilized. All will need to contribute to the STEM workforce development challenge at hand for success to be broad-based and sustained.

4. The NSF should strive to ensure that its own staff clearly understands the potential for cyberlearning to enhance research and education. Cyberlearning changes some of the basic foundational paradigms of how people learn and conduct computational thinking and research. To fully adapt to the change, the NSF should offer regular professional development for its staff.

5. The NSF should establish and announce a policy of promoting access to the Internet as a civil right, working with legislators to make this possible at a national scale. Without equitable universal access, cyberlearning will not achieve its promise and workforce development will fail to reach the last mile, exacerbating the economic and digital divide.

6. The NSF should focus on improved dissemination of findings. By this, we mean that the NSF should develop searchable, complete documentation of NSF research, development, and program outcomes, taking full advantage of the power of shared metadata and browseable links enabled by CI to increase the transformative impact of past NSF investments.

Evolution of Goals and Review Criteria

This Committee identified four overarching priorities related to the evolution of NSF program goals and review criteria in areas reflecting the impact of cyberlearning, including the use of resources such as C^4, on workforce development:

1. Encompass all ages and multiple learning levels in CLWD programs.
   This may involve new audience categorizations along knowledge/skill level continua. Projects should address skill acquisition by broad constituencies rather than by age/grade levels. CLWD programs should encompass learning in both formal and informal spaces, with the recognition that students have more time and opportunities for informal learning than formal learning.

2. Use cyberlearning networks to build from outcomes rather than reinventing.
   The NSF should require grantees to use cyberlearning networks to make their findings, materials, and results broadly accessible, and challenge new grantees to describe measures they will adopt to build upon the successes of others.

3. Promote access to and utilization of CI (essential for exploiting cyberlearning opportunities) as a fundamental expectation for all funded projects.
   The NSF should play a clear and apparent leadership role in this area through its explicit goals and its review criteria, particularly through:

Defining and supporting universal access and effective processes toward that end.

Promoting processes for understanding best practices in terms of bandwidth and access technology for effective cyberlearning.

Characterizing minimum bandwidth required for effective delivery of cyberlearning (to help define networking investments and making maximum use of current connections), facilitating effective use of current capabilities, and providing guidance for next development steps.

Exploring alternative delivery systems for providing access through alternative CI (e.g., utilize Web delivery of interactive content rather than books).

Expanding the "Broader Impact" review criteria to include a requirement that proposals show evidence of awareness of the technology levels necessary to participate in programs, and strategies for ensuring access.

4. Leverage human resources to build learning communities.
   Online resources alone are insufficient for most people to gain competency with new skills and knowledge. Practice, application, and critical thinking through personal interactions reinforce and strengthen technology-enabled education and training. Teachers, coaches, and mentors can come from many places and interact in many ways. We recommend that the NSF strongly encourage projects that:

Identify available human resources that can support and expand capacity for training diverse populations.

Support and/or expand apprenticeship programs for on-the-job training and skill development. REUs and Graduate Fellowships are examples of ways that the NSF already does this well.

Expand service-learning models to address cyberlearning skills and knowledge development for diverse populations.

Engage the large and growing retiree population to support cross-generational learning, which will result in mutually beneficial CI skill development across generations.

Develop coaching and mentoring tools, skills, and methods for diverse audiences

Establish systems for recruiting and matching skilled people with needs for teaching and mentoring.

Themes and Recommendations for NSF Program Expansion and Development

The Committee recommends expanding the scope of programs within the NSF portfolio that relate to STEM workforce development goals in specific ways related to cyberlearning. Four themes describe the directions for program scope expansion and development. The themes and the recommendations related to each follow.

Theme 1: Lifelong Learning and Professional Development

Emerging technologies and the data deluge serve to both drive and facilitate nearly all professions in the emerging economies. In this rapidly evolving, global knowledge economy, students and workers need skills and competencies that reflect the latest scientific and technological advances. Unprecedented rates of change in both areas mean that workers must adapt and update skills throughout their careers for themselves—and the U.S.—to compete successfully in the global economy.

Particular challenges are faced by education professionals at all levels, who must adapt both content knowledge (what is taught) and pedagogy (how it is taught) to changing technologies at a pace that is challenged by institutional processes and professional development programs. Solutions must include education professionals throughout educational systems—including school boards, administrators, CIOs, faculty, and pre-service undergraduates.

Even as it drives the need, cyberlearning holds a key to addressing these professional development challenges. Innovative solutions will include diverse approaches that integrate cyberlearning—taking advantage of Internet-based resources, including C^4—with other learning approaches and techniques. For example, pre-service teacher instruction can be coupled with in-service instruction to encourage cross-generational learning. The role of teachers can expand into coach and mentor; complementing, integrating, exploiting, and supporting cyberlearning.

Cyberlearning is based on a “pull vs. push” approach to learning. Those who wish to learn find their own levels and define themselves without regard to traditional classifications of age or grade level. Through networked computing and communication technologies, learning experiences are redistributed across time and space, capturing the approach of natural learning. Our scope incorporates the entire range of learning experiences over the course of a lifetime—not only formal education, not only in classes, but also throughout the waking hours[44].

<u>We recommend</u> that the NSF create and support bridges among various governmental agencies, educational institutions, and industry. Multiple entities will need to communicate and coordinate to create effective training and professional development for diverse workers throughout their lives (from K to Gray). Organizations and institutions need to do more than just coordinate services and programs. Cyberlearning and essential workforce training and development components will require seamless CI among those entities, and personalized platforms for learning that persist through individuals’ working lives.

Theme 2: Attracting and Retaining a STEM Workforce

The NSF must show leadership among federal agencies and investigate approaches and methods for using cyberlearning tools and media to stimulate interest in STEM studies and career pathways for diverse learners at all stages of career development and pursuit. Specific recommendations follow:

<u>We recommend</u> that the NSF investigate approaches and methods for using cyberlearning tools and media to stimulate interest in STEM studies and career pathways for learners at all stages of career development and pursuit. Several avenues of inquiry may prove fruitful to understanding the most effective approaches and methods for attracting and retaining diverse audiences.

We recommend the exploration of the diversity of incentives and motivators that drive users of various forms of online tools. For example, cognitive theorists have been exploring individuals' motives for communications, both personal and mediated, which might help us better understand the incentives and motives for using social networking sites.

We recommend that the NSF explore the diversity of metrics related to the actual use of technology, including data on retention and completion in courses, course progression, attainment of industry-recognized certificates and degrees, placement in jobs, and career progression. The NSF should partner with relevant agencies (e.g., U.S. Department of Labor and U.S. Department of Education) to determine how best to integrate education and career progression data. Interaction between the NSF and the Department of Education in the area of assessment standards is particularly promising (see for example http://www2.ed.gov/legislation/FedRegister/other/2010-4/12201e.html).

We recommend the exploration of the diversity of pathways and preparation to STEM careers. Working with industry and agencies such as the U.S. Department of Labor, investigate and map possible career pathways for the wide variety of existing and projected STEM careers. This work should highlight both core competencies as well as the specific education, credentialing, and work experience required to enter and advance in STEM careers.

We recommend that the NSF explore social and cultural barriers (and assets) to peer support and network development. Examine resistance to technology and the idea of technology and what it represents to different groups. Consider age as well as social and cultural factors. Consider levels of social support needed, staff training, and education needed to introduce STEM to various groups and sustain their involvement.

We recommend the identification of the tools that are most effective at each level of sophistication, and barriers that exist due to technology changes. More than just levels of sophistication, this refers as well to different populations being served. For example, a working adult in need of skills upgrade might require different tools than a traditional undergraduate student.

Theme 3: Managing Cyberlearning Resources—Investigate data and resource platforms and metadata for efficient access by diverse audiences and purposes.

There are an overwhelming number of STEM resources available on the Internet. Some resources, such as online courses, have obvious educational uses while others, such as scientific journal articles, may not be as obvious. The number of resources continues to grow. With the recent President's Council of Advisors on Science and Technology (PCAST) [45] report and U.S. Department of Education National Education Technology Plan (NETP) [42] recommending development of resources specific to K-14 education, including whole-course materials that will take advantage of available technology, this trend is likely to continue.

Resources obviously specific to education are likely to become more diverse in nature—ranging from PowerPoint and worksheets to interactive simulations and models, from lesson supplements to entire courses delivered online. Therefore, for any individual or group of individuals to navigate through them can be daunting and determining which resources are appropriate can be difficult. Resources tend to be unorganized and fragmentary. Teachers tend to need coherent whole course materials with suggestions on how the materials can be used in classes. They lack the time to search through content to find and integrate materials into lessons, particularly since it is usually very difficult to determine the quality of any given resource and there is usually little information on how it can be used effectively. If teachers can't immediately find what they need, they tend to develop something on their own.

Clearly, there is a need to find ways to organize the vast amounts of content in ways that will enhance the use of high-quality proven resources. Many questions arise when thinking about a potential organization: Who determines quality? What factors impact quality? How can any given resource be utilized in a classroom and if the resource is used, what is the impact on student learning? C^4, as described throughout this report, should be considered a vital part of this organization system as it is developed.

These questions become even more difficult to answer if we broaden the audience to include anyone interested in STEM resources for supplementing their education outside of the brick and mortar environment of traditional schools—students seeking independent study, adults reinventing themselves for the workforce, children seeking advanced study.

The NSDL has made good progress on collating various materials in a Web-based portal, but it does not adequately address the issues identified above. It is online, but resources are often not technology based. There is a classification system that allows users to search, but the classification system is not necessarily intuitive to every audience. Quality of resources, how they are best used in various settings, and user reviews are all aspects that are being addressed as part of the NSDL's Ensemble Pathways project, but more needs to be done in this area. And any system that is used for managing content needs to be easily used by a diverse set of learners.

<u>We recommend</u> that the NSF provide support for:

Research on systems and processes for information retrieval that address the unique needs of diverse audiences.

Research and evaluate systems and processes for verification, validation and accreditation of information/resources that meet the needs of diverse audiences.

The establishment and application of metrics that not only measure number of uses of various materials in various audience types, but also how resources are used, how they are revised, and what impact there is on the learning of the "student."

Research on methods and approaches for validation and verification of alternative delivery methods for diverse audiences.

Theme 4: Modeling and Simulation: Introduce quantitative reasoning, modeling and simulation, and parallel methods throughout the lifelong learning process and across the domains of scholarship.

The NSF has identified CDS&E as fundamental for NSF funded projects. To support the CI framework for 21st century science and engineering, it is essential to prepare current and future generations of practitioners to be able to apply and/or develop computational and data-enabled tools, resources, and methods in all STEM domains. This preparation will require the introduction of quantitative reasoning, modeling and simulation, and parallel methods throughout the lifelong learning process.

<u>We recommend</u> that the NSF support the immersion of learners in doing science and engineering through the applications of computing and data-enabled methods (e.g., using agent models to study the spread of diseases), as well as introducing learners to computational science methods (e.g., how to design algorithms for modeling nature). This support should include internships and fellowships within existing NSF programs and centers, with a focus on modeling and simulation.

<u>We recommend</u> that the NSF effect national scale systemic change through the support of institutional incorporation of CDS&E within both formal and informal learning. For example, institutional change at the K-14

level will directly benefit from the preparation of future teachers and administrators who understand, value, and support the needed curricular changes and the CI needed to support this learning. For informal learning programs (e.g., Boys and Girls Club, 4-H, Association of Science-Technology Centers) development of CDS&E resources (materials, training, and support services) at the national level will have considerable impact, effecting adoption at the local level.

Chapter Four 4

Campus Bridging and Education

The CLWD Campus Bridging and Education Committee focused on developing a vision for campus bridging and education that informs current NSF programmatic efforts and shapes future NSF funding programs to:

Foster broad deployment and utilization of CI-enabled learning and research environments.

Stimulate new developments and continual improvements of CI-enabled learning and research environments.

Campus Bridging and Education Status and Challenges

The development of a robust, integrated, and easy to use CI is absolutely essential for its widespread adoption and use in support of workforce development and learning. A government, higher education, and industry partnership should be established, focused on developing and providing a robust, standards-based, dynamic and integrated CI that is easy to access, easy to use, and enables widespread learning and research. This environment must be dynamic and one that encourages innovation at all levels. A competent workforce is needed to provide the design, development, user support, and ongoing enhancement of this CI "system." New high-quality knowledge-intensive jobs and innovative enterprises will emerge that will lead to discovery and to new technology. As described in the National Academy of Sciences Report[46], without this workforce, "our economy will suffer and our people will face a lower standard of living."

Campus bridging and education will be critical to achieving this vision. The development and proliferation of campus and national CI has been rapid, but has occurred in a disorganized manner. Although there are pockets of organized national CI components, such as TeraGrid and Open Science Grid, faculty, students, staff, and researchers have difficulty in accessing and integrating information technology (IT) resources that cross administrative or research domains at the campus level, between campuses, and with national and international resources. There are three fundamental aspects to these problems:

CI developed and utilized for specific disciplines may only function at a level suitable for discipline domain research and graduate level education.

> Local access through the campus or national infrastructure has been met with serious barriers in usability, availability, reliability, and interoperability making it difficult for educators to take full advantage of the resources to be applied to teaching and learning.
>
> CI development through the NSF has been primarily in support of big science and the top two layers of Branscomb's Pyramid, show in Figure 2. Development at the local, campus, and national layers has only made the problem worse by expanding resources and capabilities within their respective layers too often without regard for the other layers, to the detriment of building an integrative national CI.

Government and university efforts to develop CI have largely focused on the top of Branscomb's Pyramid. By contrast, business and industry has focused their development of cyber tools and infrastructure on the lower levels of Branscomb's Pyramid through the proliferation of robust consumer devices, such as smart phones, consumer broadband, the iPad, and infrastructure such as broadband and Cloud computing and storage. Much of this consumer-based CI and other technologies are easily accessible and are in the mainstream of our nation's culture especially for our younger generations.

For cyberlearning and workforce development to truly move forward, a coherent and coordinated national vision must be created to integrate and develop private consumer and public-based cyber tools, infrastructure, and capabilities in unison across the local, campus, and national levels. C^4 provides the opportunity to address this national vision in a cohesive means. The ultimate goal should be a ubiquitous and robust CI readily available and easy to use to provide classrooms, campuses, homes, schools, libraries, museums, and mobile devices with the tools and technology to support the overall vision for cyberlearning and workforce development.

One important aspect of our work is to broaden the community of practitioners and researchers who can effectively use CI by focusing efforts on the lower rather than the higher layers of the Branscomb's Pyramid, where most far-reaching and significant effects of promoting the development of computational thinking[47] within the community can be realized. Many researchers are intimidated by the additional skills and knowledge currently necessary to incorporate CI into their work.

A government-industry-academic partnership is needed to create an effective CI, similar to the way in which the NSFnet model and the promotion of TCP/IP as a standard Internet protocol facilitated the creation of the Internet. Based on this historic success, the NSF should facilitate initial work and creation of incentives that will lead to the broad diffusion of CI technologies that build on prior work and commercial solutions.

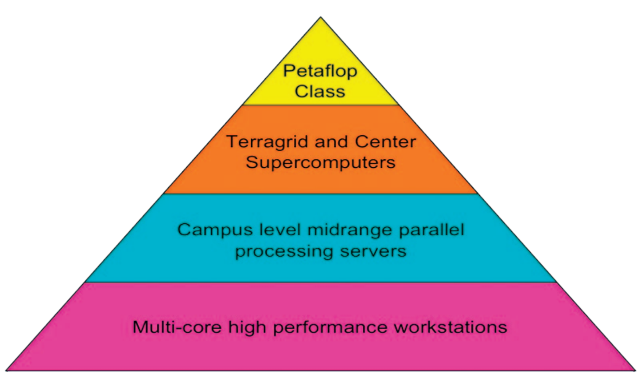

Figure 2: Petascale Era Branscomb Pyramid

Campus Bridging Defined

The Committee took a very broad view of CI that includes all four layers of Branscomb's Pyramid, as well as the cyber tools, technologies, and infrastructure developed commercially. This broad view is depicted in Figure 3 and shows the functions and resources that comprise the underlying technology infrastructure in support of cyberlearning.

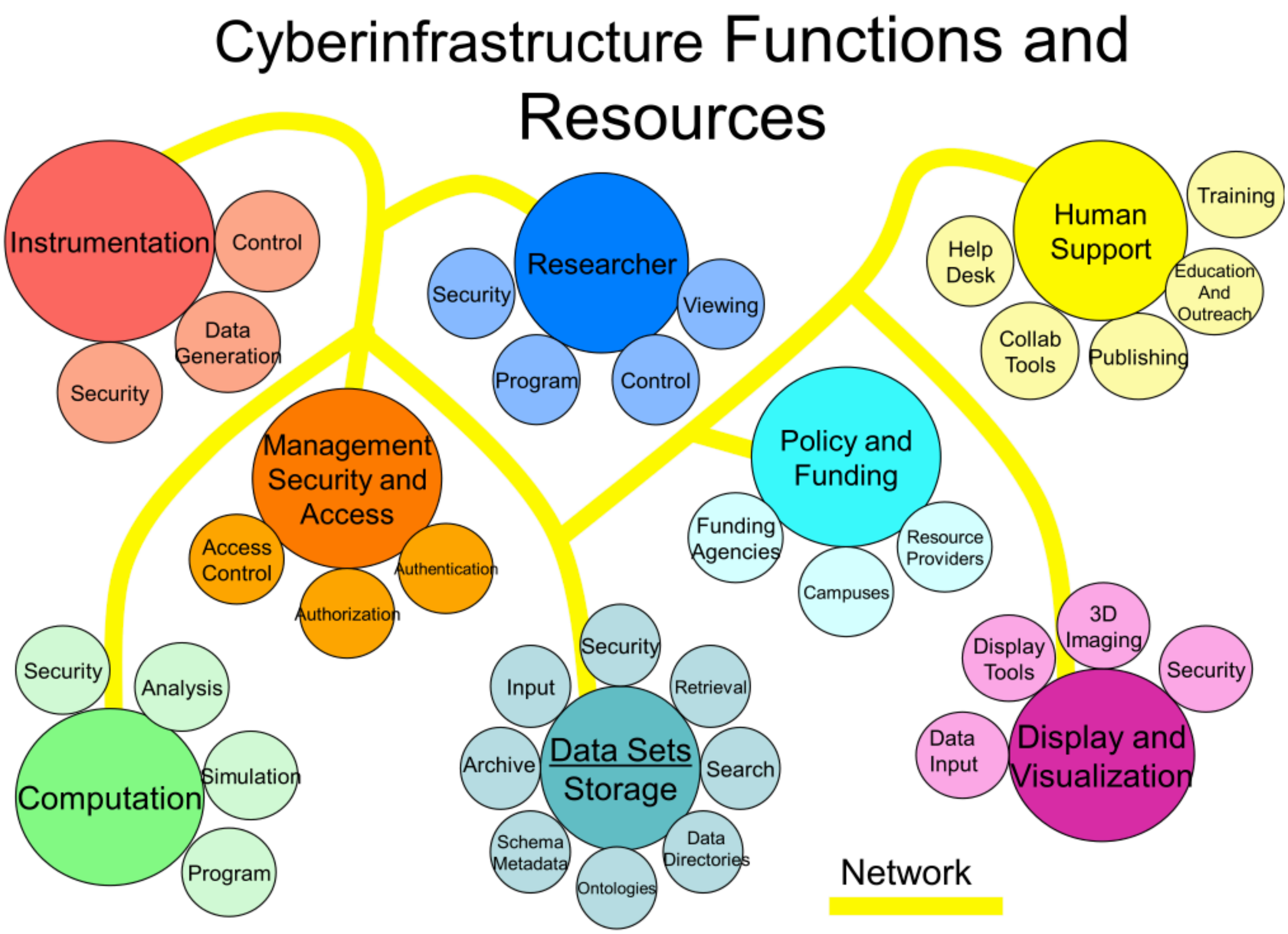

Figure 3: Functions and Resources in Support of Cyberlearning. Image source: Russ Hobby

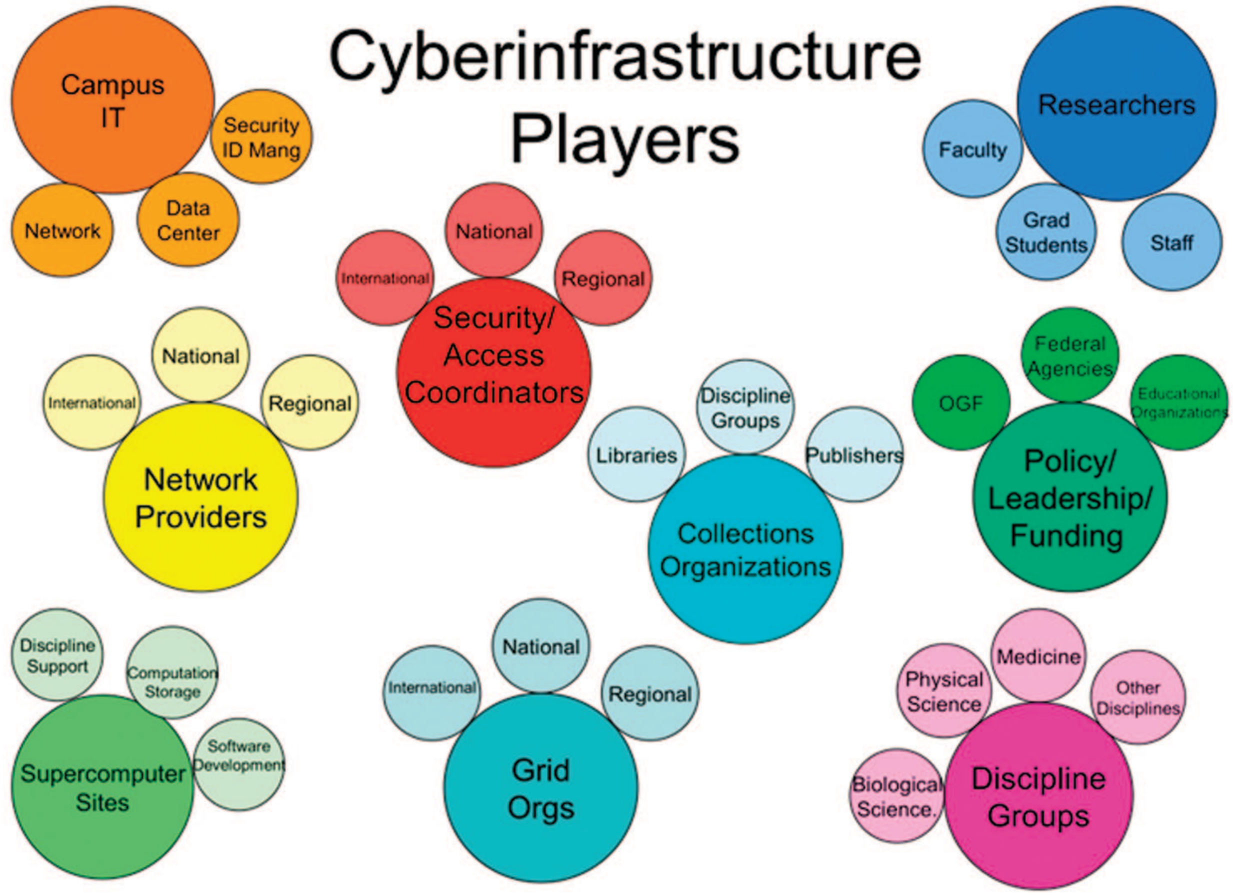

Figure 4: Cyberinfrastructure Players. Image source: Russ Hobby

The Committee views CI as encompassing not just computational resources, but as shown in Figures 3 and 4, comprised of functions, resources, and people.

In terms of people, CI involves not only the direct users of CI systems, but also includes resource providers (campus IT, network providers, security/access coordinators), funding agencies, discipline oriented research groups (e.g., American Physical Society), supercomputing centers, national and international Grid and commercial Cloud computing organizations, and the community of practitioners and industry (such as Amazon and Microsoft).

Summary of the NSF's Efforts at Campus Bridging and Education

The NSF has successfully built-out the CI primarily in the support of research through NSF programs and funding. TeraGrid, the TeraGrid's Campus Champions (on-campus advocates for CI), the CI-TEAM program, soliciting public comment, and high-end computing resources distributed through centers located across the nation are some examples of the NSF's funding efforts. This funding has primarily satisfied "deep users," which are represented at the top two layers of Branscomb's Pyramid. Other examples of the NSF's work include the middleware initiative, nanoHub, fostering distributed group research—going from the individual researcher in the lab to groups at multiple institutions. Funding of virtual workshops (e.g., "Big Data for Science Workshop," held in July 2010 at NCSA) has been very helpful in educating students (through summer workshops). Creation of the Office of Cyberinfrastructure, and having CI as part of the mission of the NSF Directorates has led to a broadening of the vision for CI. Joint funding among Directorates for CI projects is a result of this broader vision.

Distributed and distance-learning based workforce development programs, as best exemplified by the nanoHUB, provide excellent models for campus bridging where users can readily access learning material through a Web browser and Webinars. One advantage of the nanoHUB is that it can act as a veneer layer to screen users from a constantly evolving infrastructure that may have transient performance and design problems. Providing user training through the nanoHUB framework, along with capabilities that allow users to compare computational simulations with experimental results, are particularly useful and consistent with the broader goal of promoting computational thinking. The NEEShub is another example of a cyber tool that can serve as a model for the development of learning environments for workforce development. TeraGrid's successful Campus Champions program is a model for extending involvement through campus bridging.

Summary of Campus Bridging and Education Needs

A coherent approach to managing CI is needed. A cohesive, cogent, and uniform CI is required to encourage interoperability among CI components and use across disciplines. Software standards must be established to facilitate reuse and a common software stack to facilitate campus bridging throughout the higher education community.

We need to better understand how people interact with and use CI across disciplinary applications, focusing on both social and cognitive processes that can be manipulated to optimize learning, problem-solving, and collaborative work aspects of CI.

Trained campus IT and other technical support staff who are available to help deploy and use CI are essential for the effective diffusion and adoption of CI technologies and resources such as C^4. This need is especially pressing on small campuses, where there are no colleagues or IT staff willing or specifically assigned to work with faculty interested in research computing and CI. A common example of this problem involves difficulties in utilizing and providing services that require configuration of a campus network firewall. To address these problems, the CI community needs to encourage and support the development of a cadre of skilled practitioners that will serve as a key resource for campus CI adoption.

In general, there is a need to facilitate best practices in CI and data curation. The academic CI community needs to partner with industry to solve the pressing CI problems and to learn from industry's experiences. Moreover, "lessons learned" must be effectively tracked and disseminated to avoid repetition of mistakes. Best practices based on lessons learned must be shared with all campuses and national organizations. Implementation of the TeraGrid concept provides an important case in which significant issues could be addressed through effective sharing of best practices and lessons learned. These issues include the failure to engage a larger and broader set of users, the existence of barriers to moving between TeraGrid centers, and the relative inaccessibility of TeraGrid resources by smaller campuses. These issues encourage the perception that the NSF is focusing resources on the "top" users and institutions to the exclusion of the broader community of users. An example of an effective CI best practice is the Purdue Community Cluster program, which, through strategic and collegial partnerships between the central IT organization and faculty research groups, has created a new model for developing cost-effective and efficient campus research computing clusters. As these best practices are facilitated, replicated, and scaled, the ongoing development and use of C^4 resources should be considered.

Despite a decade of effort in CI development, core CI technologies suffer from poor usability that provides significant barriers to adoption. New users seeking to explore and adopt these technologies require one-on-one support that is not widely available.

Accountability and assessment are essential for determining whether specific approaches are achieving desired outcomes. The community needs to develop effective mechanisms to objectively assess impacts of specific CI initiatives. Proposals to produce cyber tools and infrastructure must include a well-designed assessment component to measure their impact.

Building a cyberlearning environment designed to address the needs of smaller campuses, particularly those serving rural populations (e.g., tribal colleges and universities) must be a priority.

K-14 education is an enormous area of need and opportunity in which the NSF must support the exploration of CI applications.

Recommendations

<u>We recommend</u> that the NSF convene a broad-based NSF advisory group in 2011 to develop the vision and requirements for a CI architecture that is comprehensive, cogent, and accessible in support of cyberlearning and workforce development. This group will initiate, nurture, and facilitate the recommended actions described in this document.

The membership of this group should include NSF Assistant Director level, industry representatives, and academic leaders. Members of the advisory group should be thought leaders for the development of effective CI in support of teaching and learning.

The advisory group should be similar to the Blue Ribbon Advisory Panel on Cyberinfrastructure that led to the Atkins report a decade ago[48]. A new Blue Ribbon panel is needed to address the problem of "Cyberinfrastructure for the Rest of U.S.," especially for the application of CI for learning. The Atkins panel produced a vision—now we need an effort focused on implementation and application, particularly emphasizing teaching and learning.

<u>We recommend</u> that the NSF support the creation of a standard framework that will serve as an aggregator to provide the place in which learning objects and content can be gathered and integrated in an orderly and productive way in support of cyberlearning and workforce development. The framework should be robust, standards based, dynamic, integrated, easy to use, and enable widespread learning and research. In addition, development and dissemination of this framework should:

Be robust, standards based, dynamic, integrated, and easy to use.

Be easy to use and enable widespread learning and research.

Contain a detailed architecture that includes components, protocols, and relationships between the components, standards for components and data, and curation standards. This architecture should be sufficiently detailed and focused to allow people who work on each component to focus on the specifics of the components rather than expending energy on concerns about the big picture of the framework.

Include a group that creates that framework. A government, academic, and industry partnership should be considered.

Demonstrate and deploy the framework at the centers and large projects currently funded by the NSF.

Include NSF leadership as well as a forum to coordinate the efforts of major CI organizations and industries to create best architectural practices for major national CI assets concerning discovery, access, use, and support of cyberlearning and workforce development.

Leverage existing best practices on campuses in a bottom-up approach. Good developments that happen throughout the Branscomb Pyramid need to be promoted throughout the Pyramid.

Allow the lower layers of Branscomb's Pyramid to be more accessible to national CI users. Moreover, based on the availability of technologies and standards, lower layers of Branscomb's Pyramid can leverage and take advantage of CI at the higher layers of the Pyramid. This will create the paths that can be followed by K-12, community colleges, Historically Black Colleges and Universities (HBCUs), smaller colleges and universities, and industry to aid in regional economic development. This will allow easier access to data and tools for teaching and learning. An example of this is the NSF National Middleware Initiative. An effective strategy for this approach would eventually allow, for example, regional university cooperative extension services to work with local businesses and industries to effectively exploit CI technologies to promote regional economic development and innovation.

Support the creation (through NSF funding) of metrics to measure the effectiveness of the CI framework so that there is an accountability loop in the system to ensure that efforts are productive and meet the user requirements and needs.

Support efforts (through NSF funding) related to the accessibility and usability of cyber tools and technology to lower the barrier for the use in support of cyberlearning and workforce development.

Address the unsolved Grand Challenge represented by a persistent problem that remains in gaining access to national scale HPC and large-scale data resources. This impediment was identified by the Committee as one of the major barriers to diffusion, adoption, and impact of these vital resources on science and engineering nationally. A good example that could provide a path forward to address this problem is the HUBzero framework.

Include funding for an effort to create tools to ease the process of installing and using the HUBzero environment for a larger community.

Expand the access and usability of tools for visualization and data analysis that are applied to teaching and learning.

We recommend that the NSF develop and fund a formal approach to create Cyberinfrastructure Institutes (CII) that partner with other universities to focus on developing a sustainable program and infrastructure in support of research and education, which includes training staff and sharing knowledge to help expand and sustain the cohort of skilled programmers, systems staff, and user support staff that can sustain the national supercomputing/CI enterprise and provide a pipeline of skilled practitioners for U.S business, industry, and government. C^4 should serve as part of the basis for the development of shared CII initiatives, allowing the participating institutes to collaborate and share resources and experiences. The CIIs would have several distinguishing characteristics and efforts, including:

CIIs could leverage the work of EDUCAUSE, ELI, Internet2, and other organizations, and may include creation of regional CI support centers.

With adequate funding, CIIs could sponsor and promote "joint techs meetings" for CI, similar to the Internet2/ DoE model.

Support for an initiative for "CI librarians" who take responsibility for creating, nurturing, and maintaining collections of software tools, data, and computational resources in support of cyberlearning and workforce development. NSDL can serve as the aggregator and conduit for cyberlearning curriculum material and learning objects, and provides assistance for creators of information put it into formats that can be curated.

Provision of funding for CI librarians at the local campus level who would take the responsibility to work with content creators. This will aid campus efforts to meet the NSF requirements for the data management plans for funded grants.

Support for the development of comprehensive campus level training programs and prototype models for data curation, provenance, representation, and long-term preservation to aid researchers in meeting the new NSF data requirements.

Cultivation of the creation and sustainability of virtual organizations through funding to provide the basic tools and services they require. The HUBzero approach at Purdue is an exemplar of this recommendation.

Expansion of the Campus Champions program to be more campus bridging-based in support of teaching and learning rather than NSF TeraGrid/research support-based.

Creation of a Staff Fellows program that allows staff (not faculty) to compete for an NSF Cyberinfrastructure Cyberlearning and Workforce Development Fellowship that provides a significant fraction (over two thirds) of a staff member's salary to the person directly for five years.

If we are to make a real, lasting and significant impact on STEM education by more effectively using our nation's cyberinfrastructure, we need to have a bold and far-reaching initiative that will be transformative and long lasting. Currently this nation is not effectively using our rich technological resources to improve teaching and learning in STEM and not inspiring our nation's youth to pursue careers in the STEM disciplines. There is ample evidence that the use of technology can improve teaching and learning and increase the motivation of students. The NSF has invested heavily in CI primarily to support research and big science. Business and industry in the nation has also invested heavily in CI and the technical artifacts that can be applied to teaching and learning if there is the will and focus to do so.

The NSF can take the lead role and facilitate the organizing and development necessary to create a robust, accessible, and easy to use cyberinfrastructure that can transform the way we teach and learn through the effective use of technology especially for STEM education from PK-12 to higher education, and workforce development. This Grand Challenge cannot be solved over a short period of time and not without significant investment by the NSF, other government agencies, business, and industry, and should particularly take into account the role of the U.S. Department of Education in supporting the long-term implementation of policies and practices. There must be a long-term strategy that has a tactical component that will form the basis for a long-term sustained effort.

It is proposed that the NSF create an Engineering Research Center-like program to fund multiple Cyberlearning and Workforce Development Institutes (CWDIs) located regionally across the nation. Each Institute would specialize in an important aspect of cyberlearning with one lead Institute to coordinate the activities and keep the Institutes focused on the vision and Grand Challenge problem(s) being addressed.

Several Institutes are needed to support a broad array of needs, such as:

- Cyberlearning and Workforce Development (Coordinating Institute)
- Data-Intensive Computational Science and Engineering
- Cyberlearning Theory and Practice
- Cyberlearning Broadening Participation
- Cyberinfrastructure Workforce Development
- Campus Bridging
- Computational Thinking
- Industry Bridging
- Cyberlearning Science
- Cyberlearning Engineering
- Cyberlearning Math
- Cyberlearning Technology

Each Institute would have an area of research and dissemination focus, and all efforts would be coordinated through the lead Institute and the NSF. The overall goals of this far-reaching program would be to create and support a cross-disciplinary community to conduct research and implement the recommendations of the CLWD Task Force. The Institutes would work closely together to accumulate the outcomes of the work and make it broadly available to the community.

Chapter Five 5

Broadening Participation and Cyberinfrastructure

Broadening participation, that is eliminating the underrepresentation of women, persons with disabilities, and underrepresented minorities:

> In the meaningful use and creation of CI resources, and
>
> Using CI to help increase participation and provide a quality education to under represented minorities, persons with disabilities, and women, thereby advancing the promise of diversity in STEM,

is both essential and critical to this nation's workforce development. It is essential because infusing diversity in perspectives and approaches to complex problems spurs innovation, furthering the rapid advancement of science and engineering. It is critical for meeting the STEM workforce requirements necessary for ensuring our nation's continued leadership and competitiveness in the emerging global, knowledge-based economy. Our current scientific and economic leadership is at risk and unsustainable until full participation is achieved.

The urgency to broaden participation in STEM is driven by the rise in global competition, the need for accelerated innovation and advancement, and the rapid growth of underrepresented minorities (the nation's fastest growing populations) that can bring new perspectives and experiences to fill industry demands[49]. Innovation is fed by diverse experiences and viewpoints, and addressing the need for broader participation can also have additional positive consequences. For example, in designing systems of accessibility for persons with disabilities, entirely new technologies or applications of existing technologies can be developed that are of benefit to the entire population.

To be a true competitor the nation must produce diverse talent at the highest level from among its people and provide the research and education environments that are attractive, welcoming, and productive to top talent from home and around the world.

To simply achieve the sheer numbers of well-qualified individuals from a sustainable source to fill the expected human resource needs of academia, industry, and government in the foreseeable future, we need the participation of all groups. This is based upon our current understanding of the needs of the emerging economy; the workforce needs of which are continually evolving with new advancements in STEM and STEM-driven economic activity. Given the dramatic shifts in the demographics of our nation, schools, and college campuses and the continued growth in underrepresented minority populations, our country can no longer expect to rely on a relatively homogeneous population to build out the STEM workforce and leadership. We simply will not have a workforce that can keep up with the national demand. Equally important, the nation's continued leadership in innovation and advancement in STEM research and education depends upon the diversity in perspectives, approaches, and ideas that persons with disabilities, women, and minorities can provide[50].

The STEM-based industries and their tax revenue-producing jobs (that support our world-leading institutions and system of higher education) will follow the talent and help build the educational infrastructure where the optimal workforce is found. Business and industry no longer recognize borders—their allegiance is to the bottom line, their stockholders from around the world, and the global market. Top talent is also not constrained by borders and will relocate to wherever the most attractive environment and offer may be. This fluidity in business and talent is inherent to a global economy. However, most people prefer to remain close to home, as long as there are markets, supportive environments, and opportunities to develop, achieve one's professional aspirations, and enjoy the associated rewards and benefits. If we are truly interested in the economic, social, and political betterment of all the people of our nation (and humanity in general), the optimal conditions for growth of STEM economic and intellectual capacity must be secured in every sector of the nation and in every nation on our planet.

Global friendly competition should occur on an equal playing field in which the obstacles to "play" are minimal, and imbalances in the availability of local talent to meet workforce needs are transitory. Under peaceful conditions adjustments are made that tend toward a dynamic equilibrium in the global system. Other nations will respond to opportunities, prosper, and rise, eliminating such imbalances. Then it will be in our best interest to be a welcoming center of intellectual and economic excitement that can attract top talent from around the world (where we already excel), while also optimizing our own home-grown talents (where we have not fully succeeded) [49]. This is the challenge of broadening participation, and it requires the elimination of underrepresentation in STEM education and research within our borders—facilitated by CI-enhanced learning systems.

The Role of the NSF

The NSF has played and must continue to play a significant role in broadening the participation of women, underrepresented minorities, and persons with disabilities in the sciences and engineering. There have been important programmatic successes, and the NSF recognizes there is still more that could be done as it continues to review, evaluate, and revise programs and policies on an ongoing basis. But there is an ongoing difficulty in striking an appropriate balance in the NSF's budget between research and education, and within education among general programs and those much-needed programs that are specifically designed for broadening participation. The dramatic advancements of women in some of the sciences show that the problem is solvable, although very difficult. One need only consider the persistent and growing underrepresentation of women in such fields as computer science (although there has been progress for women in biology, chemistry, and psychology [51]) and the pernicious underrepresentation of Hispanics and African Americans, especially women of color, in all the sciences and engineering. However, the solutions are not always obvious. The problem lies more in implicit individual and institutional biases than explicit choices. We are confronted with a deep-rooted system that functioned well in the context of a homogeneous population, but does not necessarily serve diverse populations. It is a system that can be changed, but changing it poses a problem that will require all of the tools of science to address it. The NSF can and must continue to play a leading role in driving this change.

Furthermore, the NSF must take responsibility for STEM education and the development of the STEM workforce, including the elimination of the underrepresentation of women, minorities, and persons with disabilities. Admittedly, this is a daunting task and a monumental responsibility, very well beyond the resources and capabilities of the NSF alone. It will take a collaborative team effort with other agencies, such as the Department of Education, the National Institutes of Health, the Department of Energy, and NASA, and with state and local entities where the NSF can exert considerable influence and leadership. Taking full responsibility as a the leader of a multi-agency team involves bringing considerable programmatic and research resources to bear on the problem, providing and receiving support from the other agencies and setting common goals, objectives, and general metrics by which progress will be measured. Metrics should include the absolute increase or decrease in numbers at various stages on the STEM workforce development pathway by targeted groups, as well as the percentage of underrepresentation relative to proportion in the overall population.

Such metrics as those described above help quantify the extent of the problem, but not the complex social mechanisms and processes by which they occur. Knowledge not only of the extent of the problem, but also the causal or catalytic mechanisms involved, are required to monitor success and derive lasting solutions[50]. The recent report from the National Academy of Sciences (NAS), "Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads"[52], presents many of the issues involved and much of the research in and theoretical understanding of these issues. Of particular note for underrepresented minorities are the issues of retention and transitioning from community colleges (where many minorities begin college) to four-year institutions. Most Tribal Colleges are community colleges, and about half of the Hispanic-Serving Institutions are community colleges. Taking Hispanics as an example, it is interesting to note that the percentage of Hispanics enrolled in two-year institutions is and has been almost the same as their percentage in the overall population: 11.2% enrollment in 1998 compared to 11.4% of the nation's population[53] and 14.6% enrollment in 2006 compared to 14.7% of the nation's population with similar comparisons for the intervening years[54 [enrollment percentages derived from 55]]. If only their AA degree attainment and enrollment and completion at four-year institutions could follow suit[56].

The NAS report highlights the Tinto Model of Student Retention [57] with its focus on academic and social integration of students into an institution. It has been the basis for additional developments such as that of Nora and colleagues'[58-60] Model of Student Engagement with six major components: pre-college factors and "pull-factors," initial commitments/sense of purpose and institutional allegiance, academic and social experiences, cognitive and non-cognitive outcomes, and goal determination/final commitments leading to persistence/retention. The evaluation of the NSF Louis Stokes Alliances for Minority Participation (LSAMP)[61] also provides a good review of some of the student retention literature. It incorporates the Tinto model in deriving successful elements of the LSAMP program model listing student, faculty, and institutional/departmental strategies or activities under general factors of STEM academic integration, STEM social integration, and/or STEM professionalization depending upon the focus of the strategy.

Over time such evidence-based approaches to the elimination of underrepresentation will further lead to the identification of strategic interventions and approaches for measuring their effectiveness that involve metrics and data models derived under developing theoretical frameworks [52, 62, 63]. As has been noted elsewhere [50, 52, 62, 63], there is a need for applying scientific rigor to researching and developing, designing, implementing, and evaluating current and proposed interventions. There is a need for furthering a science of broadening participation much as discussed in a recent "Dear Colleague" letter to stimulate research in this area by the NSF's Social, Behavioral, and Economic Sciences Directorate [64].

Given the complexity of the issues involved in broadening participation and their interactions, research in this area would be greatly strengthened by a multidisciplinary approach among the social, behavioral, economic, and cognitive sciences, as well as with scientists within the various domains of science. Given that broadening participation is an issue across all fields of STEM, it is "transdisciplinary," and that the saliency of factors, variables, barriers, and supports may differ by discipline, research should be focused appropriately upon particular disciplines and supported across the agency. Its findings should be broadly disseminated to the scientists and educators in the impacted fields, institutions, and to the general public, perhaps through professional associations and other organizations formed from within the communities. They should also be disseminated within the NSF and to other agencies to help in the development of requests for proposals for workforce, education, broadening participation, or research award supplements, such as for research experiences for undergraduates.

The NSF should also provide broadening participation support supplements to research awards to enable researchers to do such things as recruit and/or support undergraduate or graduate students from underrepresented groups to be involved in their research, to inform students in elementary and secondary schools about research and careers in their fields, to work with educators at any level to develop cyberlearning tools or resources particularly targeted toward underrepresented groups, or otherwise work toward broadening participation in their field.

A difficulty with respect to addressing the needs of underrepresented groups in STEM is the use of euphemistic terminology that tends to obscure the essence of the issue. Terms like "broadening participation" and "diversity" have been used to reference general efforts to increase participation or encourage alternative perspectives on the part of a variety of groups or individuals in various STEM activities with no obvious connection with the problem at hand—underrepresentation in STEM of women, minorities, and persons with disabilities. Such impreciseness in usage does not encourage proposals to provide strategies for mitigating the underrepresentation of individuals from these groups, or efforts to include their perspectives in STEM advancement for the benefit of our nation and the world. Use of these terms should be made clear or replaced with terms that more accurately convey the problem.

The problem is further compounded by "broadening participation" being one of several possible types of "Broader Impacts" used as a criterion in NSF's proposal reviews. STEM has the potential for many positive impacts on society. The America COMPETES Reauthorization Act 2010[65] puts forth eight such broader impact areas including, "increased participation of women and underrepresented minorities in STEM." From among the eight, only this one has a specific, achievable, desired outcome that could result in it no longer being an issue confronting our nation. We will always be concerned about and need activity in all the others. Elimination of underrepresentation in STEM of minorities, persons with disabilities, and women is a problem the science and engineering communities our nation must resolve and put behind us. An important change for the NSF that would significantly advance the effort would be the establishment of a separate proposal review criterion specifically focused on elimination of underrepresentation of women, minorities, and persons with disabilities.

Minority-Serving Institutions (MSIs) and Broadening Participation

Minority-Serving Institutions (MSIs)—including Historically Black Colleges and Universities (HBCUs), Hispanic-Serving Institutions (HSIs), and Tribal Colleges and Universities (TCUs)—are effective and efficient resources for advancing the participation in and contributions of underrepresented minorities in STEM generally and CI specifically. The engagement of MSIs has proven to be a highly effective national strategy for increasing the participation of underrepresented minorities because they prepare a disproportionate number of individuals from their respective minority groups [56]. HSIs, for example, while being less than 10% of all intuitions of higher education confer almost a third of the total number of Hispanic baccalaureates in STEM [56]. HBCUs are consistently among the top 10 institutions where African Americans with Ph.D.s begin their academic careers [56, 66]. Similarly, TCUs have been successful in generating one of the largest pools of American Indian students that then go on to complete a Ph.D. in STEM[52, 67].

While it is generally true that MSIs are key to any strategy for broadening participation, each community of institutions, including HBCUs, HSIs, and TCUs have their own set of unique salient factors, histories, strengths, and weaknesses. No single program could provide the focus and attention needed for advancing these communities of institutions any more than a single general purpose science program could adequately promote the advancement of all the sciences. This is in concurrence with the America COMPETES Reauthorization Act of 2010 [65] and the recent National Academy of Sciences report[52] that states "Thus, it would be a mistake to consolidate programs that are tailored to the specific missions, histories, cultures, student populations, and geographic locations of HBCUs, TCUs, and HSIs that have demonstrated to be successful in the preparation and advancement of groups underrepresented in STEM" [52]. Furthermore, MSIs should be active participants in the development and use of C^4 and other national resources. Their engagement in the CI community must be on par with their proven ability to educate minorities.

Cyberinfrastructure and Broadening Participation

The nation cannot continue to be competitive scientifically, intellectually, and economically unless we take effective action on broadening participation. Full participation can be greatly advanced by using the power of the new tools and resources of cyberinfrastructure, including C^4. Used effectively, CI can motivate and properly prepare the members of any group to be part of the next generation—the Net Generation—of undergraduate and graduate students, post-docs, and professorate, a generation better prepared and more capable than the prior generation. It can help renew the hope and promise of education as the means of inclusion for those that continue to be left out of the world of STEM work. It can help foster the intellectual, economic and social benefits to the nation and the individual that technological fluency, computational thinking, CDS&E, and careers in science and engineering provide.

Two overarching themes emerged in the discussion around broadening participation and cyberinfrastructure. First of all, CI resources and tools can significantly advance research and education opportunities for all underrepresented groups, particularly through institutions and organized efforts to serve them, prominent among which are MSIs. Secondly, optimizing the transformative possibilities of CI requires that there be maximum diversity within the workforce engaged in the design and development of CI, particularly the computational and data-intensive science and engineering (CDS&E) research and applications that are driving CI innovations.

Cyberlearning is an area of CI application that can have a particularly strong impact on broadening participation, if support is provided for efforts to design, develop, refine, and implement tools and resources that are responsive to the requirements, conditions, concerns, strengths, and shared interests of specific groups. Well-designed and deployed CI resources can provide the means for establishing learning environments accessible to everyone. Within the emerging global knowledge-based economy of large multi-national corporations, both jobs and workers are mobile on a global scale. Tools are needed that optimize the available workforce, helping education and training providers target their services precisely where and when they are needed, and in a manner that ensures their effectiveness.

The development and use of CI—particularly through the development of C^4 and its resources— to aid in the inclusion of underrepresented groups and the institutions that serve them can greatly help in the elimination of underrepresentation, such as virtual organizations that meaningfully include MSIs, or that bring research tools or resources to MSIs, particularly if repurposed for education and learning purposes in line with cyberlearning as described earlier.

Work in CI focusing on broadening participation offers the opportunity for a transformative impact on our understanding and practice of STEM learning, education, and research. Through comprehensive application of universal design principles (understood as broadly as possible), no child (or group) will be left behind because no barrier to participation will be left unbreached. Far from being tangential to the research and development of CI, efforts toward broadening participation will be essential for defining the central role of CI in the advancement of science and the public good.

Recommendations

For evidence-based broadening participation efforts to be both broadly effective and sustainable they need to be informed by the needs and strategic goals of the communities and institutions involved and take into account the proximal and root causes of the current levels of participation across the nation's diverse populations. Some of these causes are to some extent identified and understood. However, much work remains to be done.

Optimizing the potential of CI to overcome barriers to full participation in STEM will require a significant investment by the NSF in research that will advance our understanding of the dynamics of differential participation and build a knowledge base of effective broadening participation practices[52, 62, 63]. This requires first and foremost the development of a community of researchers and practitioners, particularly within the underrepresented groups. Considering the current economic climate in the U.S., and the associated awareness of the potential loss of our capability to lead the world in advancements in all fields of endeavor, such investments should be urged and supported at the highest level.

The NSF was established to support activities that will advance scientific and engineering knowledge, understanding, and practical application, and build the STEM workforce. The value the NSF places on a given scientific activity is evidenced by the amount of resources that it invests in it. Broad participation in STEM that fully engages all sectors of the population is of extremely high strategic importance. The investment on the part of the NSF in this critical element as an area of scientific knowledge, practical application and workforce development should reflect that strategic importance. Broadening participation is indeed a "Grand Challenge" and should be approached with that level of commitment on the part of the NSF and other federal agencies with a STEM mission appropriate to addressing it.

<u>We recommend</u> that the NSF strengthen and bolster its national leadership in broadening participation toward the elimination of underrepresentation of women, persons with disabilities, and minorities. Leadership starts within the agency from the Director and Assistant Directors emphasizing the importance of solving this problem, monitoring and reporting on progress, and reinforcing or creating agency-wide requirements and programs, such as targeted broadening participation programs and a separate proposal review criteria for broadening participation. It will further require a team effort of authentic interagency, state and local government, and industry collaborations with shared responsibilities and goals, as well as the promotion of effective practices and strategies. This is an area where C^4 can be put to great use, facilitating the intergovernmental, policy, and programmatic collaborations as it facilitates meaningful collaborations for scientific research and education. C^4 can also be a strong enabler of broadening participation by making generally available remote resources, tools, and expertise to and from underrepresented researchers, educators, students, and institutions. Such efforts can re-invigorate the hope and expectation that education and learning will help heal the great divides of our nation. The aim—to broaden participation to encompass the full diversity of our nation's talent—is critical to meeting the demand for a globally competitive STEM workforce. The NSF can accomplish this goal in the following ways:

Convene a multi-stakeholder team tasked with coordinating efforts to eliminate underrepresentation in STEM and growing the STEM workforce. The team should include representatives from the general STEM academic, governmental and industrial communities, the Congressionally mandated Committee for Equal Opportunities in Science and Engineering (CEOSE), and professional associations and concerned non-profit organizations, especially those representing the communities of underrepresented minorities, persons with disabilities, and women.

Integrate broadening participation efforts of the Department of Education, the National Institutes of Health, the Department of Energy, NASA, the Department of Agriculture, the Department of Commerce, and the Department of Labor, identifying areas of synergy and resource leveraging.

In consultation with the stakeholder team mentioned above, implement and expand upon where practicable the recommendations made in the NSF Broadening Participation Framework [68], the Math and Physical Sciences Advisory Committee, Broadening Participation Working Group [58] and the recent National Academy of Sciences report on Expanding Underrepresented Minority Participation [52].

Establish broadening participation as a separate review criterion in addition to broader impacts and intellectual merit. A description of the role of a proposed activity within existing institutional and departmental efforts to advance diversity and broaden participation of underrepresented groups is an example of an appropriate response to this review criterion. The proposers should be encouraged to implement or participate in on-going evidence-based activities for broadening participation such as described in the LS-AMP evaluation[61], the recent NAS report [52], and elsewhere [e.g., 58-60, 62, 63 & 69], or contribute to the science of broadening participation [64].

New online resources could be established to support a community of broadening participation practice, providing researchers with the latest results from broadening participation research and evaluation, and facilitating collaborations.

With community support and input, develop and incorporate metrics for assessment and planning for broadening participation at the agency, NSF Directorate and programmatic levels, and track progress at the these levels and the national level.

Appropriately fund interdisciplinary research on the science of broadening participation [64]. Research should include computational and data-intensive approaches that utilize large datasets on learning and education that can be used to model broadening participation processes and diffusion of effective practices. The NSF's and other agency broadening participation efforts should be an essential component of this research program, so that they are both informing and informed by the research.

Fund specific computationally intensive broadening participation Grand Challenges, such as: "What is the human ecology of differential resource access?" that combine biological, political-economic, cognitive developmental, socio-cultural, and other factors within the problem-space ontology that is needed to describe the emergence and persistence of poverty in human communities. What kinds of models have the best chance of suggesting interventions that can effectively manipulate these elements and factors to achieve more equitable access to resources across diverse populations?

Encourage and support community and relationship building using virtual and in-person strategies, particularly among underrepresented communities, and with the NSF and other agencies.

Provide sufficient funds to not only evaluate the effectiveness of partnerships and collaborations, but to support focused research on the dynamics of sustainable collaborations.

Initiate the phasing in of a requirement that all hardware, software, datasets, etc. developed with NSF funds be designed with universal design principles that maximize the potential for inclusiveness, particularly for persons with disabilities.

<u>We recommend</u> meaningfully involving MSIs by enhancing their capacity as efficient and effective mechanisms for significantly engaging underrepresented minorities in STEM. MSIs need support to build their research, education, and student retention and advancement capacity. MSIs could particularly benefit from virtual collaborations and the repurposing for teaching and learning of CI-enabled science and engineering research tools and resources; provided such efforts reflect the specific educational and cultural needs of the students served. MSIs will require additional support and capacity building, including human and technological infrastructure, to fully exploit their potential and the potential of CI and cyberlearning for eliminating the underrepresentation of African, Hispanic, and Native Americans. Toward that end, it would be fruitful to consider them not only as individual institutions, but also as communities of institutions. The NSF could accomplish this goal in the following ways:

Consider MSIs not only as individual institutions, but also as communities of institutions through which broad community-wide collaborations can provide an effective means for impacting a significant percentage of underrepresented target populations.

Help build the research, education, and student retention and advancement capacity of MSIs. MSIs will require additional support and capacity building, including human and technological infrastructure, to fully exploit their potential and that of cyberinfrastructure and cyberlearning.

Support the research, development, and implementation of tools and resources for use by MSIs. As under-resourced institutions, MSIs could particularly benefit from the incorporation and repurposing of science and engineering research tools and resources as available through C^4, especially when these efforts address the specific educational and cultural needs of the students served. This includes support for teacher, faculty, and student development in the effective application of CI resources in the classroom.

Emphasize mentoring relationships between and among faculty, students, institutions, government, and industry.

Provide research opportunities for MSI students to work with faculty and students at R1 institutions, government institutions, and industry that include both on site and cyber-enabled collaboration, emphasizing capacity-building distributed group projects.

Encourage and support projects that have the potential to provide job opportunities for students within their community, emphasizing economic development, workforce development, and entrepreneurial research projects that are sustainable beyond initial funding.

Integrate innovative and entrepreneurial programs and projects into CI and broadening participation educational and research programs, including novel approaches to economic development within communities largely comprised of underrepresented groups.

Support underrepresented students through CI and computational and data-intensive science and engineering project graduate fellowships, internships, and/or undergraduate scholarships, to encourage them through completion of terminal degree programs in CDS&E or CI related fields.

Provide special graduate student fellowships, post-doctoral awards, or early- or mid- career awards for doctorial students, post-docs or faculty in computational and data-intensive science and engineering programs or fields, or computer science, to spend a year teaching or doing research at an MSI; particularly those from underrepresented groups who may act as role models for students at MSIs.

Encourage and support representatives from industry and government labs to teach for a year or teach part-time, in-person or remotely, at MSIs, particularly those from underrepresented groups.

Encourage and support community and relationship building, particularly within and among underrepresented communities, and provide sufficient funds for evaluating the strategies used to establish partnerships and collaborations.

Strongly encourage and support supplemental grants to highly successful CI projects that focus on broadening participation, particularly in meaningful collaboration with MSIs or groups from or supporting women, persons with disabilities, or underrepresented minority communities.

Encourage and support student design competitions around specific CI projects or goals, particularly those advancing accessibility.

Support model collaborations between MSIs and mainstream institutions that demonstrate best practices in distributed research partnerships and collaborations.

Include a specific focus on women of color in all programs directed toward women or underrepresented minorities, as well as others with potential for broadening participation.

Encourage and support the dissemination and expansion of tools, resources, or practices developed for underrepresented groups to the broader STEM community to promote full engagement across the entire population.

We recommend establishing a Hispanic-Serving Institutions Program (HSIP) and augmenting two important NSF programs that have been extremely important to their respective target institutions—the Historically Black Colleges and Universities Undergraduate Program (HBCU-UP) and the Tribal Colleges and Universities Program (TCUP). The establishment of a Hispanic-Serving Institutions Program (HSIP) was mandated in the original and is supported in the America COMPETES Reauthorization Act of 2010. These programs should be implemented as cross-cutting programs throughout the NSF, similar to the ADVANCE program. In addition to more general cross-disciplinary efforts, this would enable the NSF Directorates to focus more specific efforts toward elimination of underrepresentation within a discipline or set of related disciplines. The recent evaluation of the HBCU-UP program supports the effectiveness of this program and approach [69]. Accordingly, the NSF should:

Establish a Hispanic-Serving Institutions Program (HSIP) modeled after HBCU-UP and TCUP to provide the necessary focus and directed efforts to help eliminate the underrepresentation of Hispanics in STEM.

Maintain the Historically Black Colleges and Universities Undergraduate Program (HBCU-UP) and the Tribal Colleges and Universities Program (TCUP) as independent programs to provide the focus and directed efforts necessary to help eliminate underrepresentation of African Americans and Native Americans, respectively.

Establish cross-cutting components for HBCU-UP, TCUP, and HSIP, to both help all NSF Directorates direct focused attention and funding toward the targeted communities of institutions and provide support and funding for the Directorates to bring in the targeted communities into their research and education efforts.

Direct a component of the above programs toward assisting with the establishment of computational and data-intensive science and engineering programs at MSIs, or CDS&E faculty positions within the strengthening of such sciences and engineering—both of which should aid in the development of and also take advantage of C^4 resources.

Promote meaningful partnerships with authentic roles for underrepresented groups and institutions at the local, regional, national, and international levels with sustained funding of such relationships, especially through faculty release time and faculty and student exchanges or other strategies that will allow them to fully participate in research, development, and education activities involving CI.

<u>We recommend</u> that CI tools and resources be investigated, developed, and implemented for the express purpose of advancing the elimination of underrepresentation in STEM and growing and broadening the STEM workforce and participation in STEM. To lead this effort, the NSF could:

Leverage the work of existing groups to develop tools and resources for courses, labs, collaborations, etc., particularly for the repurposing of CI research resources for learning, and supporting the establishment of virtual organizations for building collaborations..

Support the design of CI resources for persons with disabilities and require that software and resources developed with NSF funding be labeled for its suitability for persons with disabilities, including multi-sensory representations of data; accessibility design features that promote computational thinking and enhancements to commercial C^4 to maximize accessibility.

Build campus CI and related information and communication infrastructure for research and education capability at MSIs and institutions serving persons with disabilities and women.

Support broadening participation of the STEM workforce within MSIs—that is, support activities intended to increase the number of minority, women, or persons with disabilities within the faculty and administration at MSIs.

Support projects that restructure education to advance personalized and locally relevant learning environments, propagating a wide range of learning strategies such as student-centered active learning, student-generated content, project or problem-based learning, and learning communities.

Build CI tools and resources that encourage cross-disciplinary efforts on campuses to broaden participation.

Encourage and support the use of current and emerging developments of the Internet for broadening participation, examples could include for example social networking tools like Facebook and Twitter, and knowledge retrieval tools like Google, Wolfram Alpha, and Bing that can facilitate CI-enabled research and education projects.

Encourage and support projects to build Learning Gateways—equivalent to Science Gateways—that provide access to science and engineering resources for education.

Encourage and support partnerships between MSIs and R1 institutions to develop CI-relevant courses and curricula in STEM, particularly computational and data-intensive science and engineering and CI related fields for a general audience and for specific underrepresented groups at both MSI and R1 institutions.

Encourage and support CI tools and resources that enable large-scale research projects that engage young people, and that address research priorities of MSIs, the communities served by MSIs, and the NSF.

Encourage and support development of CI tools and resources for identifying and exploiting opportunities for collaboration between MSIs, private industry, and government institutions.

Support projects that encourage the use and novel application of existing CI tools and resources that could promote broadening participation. For example, Nanohub has a business incubator at a small community college focusing on oxidation growth on semiconductors that could be replicated at MSIs.

Develop common metrics for improving CI learning resources relevant to underrepresented groups and broadening participation.

Encourage and support participatory design projects in which a community develops CI resources that address their specific needs.

Encourage and support the research, development and utilization of CI tools and resources for community and relationship building, particularly among underrepresented communities.

Fund the Grand Challenge of using CI and computational and data-intensive science to investigate the causes, processes, and factors associated with poverty and its mitigation.

Chapter Six 6

Closing Remarks

The nation and indeed the entire world have entered a period of rapid change fueled in large part by new developments in science and engineering, especially computational and data intensive science and engineering, and information and communication technologies. While these advancements are full of hope and excitement for a promising future, they require widespread commitment to continual learning and adaptive response. Some of these changes are incremental while others are disruptive and even revolutionary. We see this period as one of great opportunity, and call upon the NSF, the science and engineering communities, and all who have a stake in intellectual, social, and economic progress not only to embrace this period of change but also to join in promoting, managing, and directing it.

Accelerating advancements in science and engineering are feeding the rise of a global knowledge-based economy that in turn is placing new demands upon the workforce. Increasing pressures are being put to educational systems worldwide to meet the needs of a global workforce that must continually acquire new knowledge and skills, apply new ways of framing issues and thinking about problems. We identify CI as key to the national response to these challenges.

In this report, we refer to the evolving system of new resources, tools, and services accessible through the Internet as the Continuous Collaborative Computational Cloud (C^4). C^4 can be harnessed through cyberlearning to provide a ubiquitous yet finely tunable learning environment that will meet the knowledge and skill acquisition needs of not only the Net Generation but also anyone with a need to learn. This especially includes those economically displaced by tectonic shifts in local, regional, and global production and distribution systems in large part actuated by the same advancements in science and engineering C^4 is helping to bring about.

C^4-enabled cyberlearning makes possible an engagement in science, technology, engineering and mathematics (STEM) that is both deeper and broader, enabling greater participation by women, underrepresented minorities, and persons with disabilities into the STEM educational system and workforce if appropriately developed and applied. Great hopes are endued onto this vision of the present and future just as great challenges confront its full conception, creation, and development.

These interesting times replete with both great opportunities and enormous challenges call for leadership and vision. They call for not only the work of great individuals, but —particularly given the collaborative focus of C^4 and related technologies—strong communities and collaborations with a shared vision and distributed responsibilities. The NSF continues to be a leader and convener of the science and engineering communities of researchers, educators, and learners because it is very much at the core of that community of communities. The members of this community of communities are united by a shared belief in and passion for science and engineering discovery and development. Advancements in science and engineering are critical for continually improving our understanding of the world and for identifying applications that can move us toward a better world with peace and economic prosperity for all. In this report, we have shared our visions and concerns for STEM workforce development. Our hope is that this community, with the NSF as a lead player, will strongly embrace the moment, and move the nation toward a stronger, sustainable, innovative, highly diverse, and globally competitive workforce.

Acronyms and Definitions

Acronyms

C^4 - Continuous Collaborative Computational Cloud
CDS&E - Computational and Data-intensive Science and Engineering
CEOSE - Committee for Equal Opportunities in Science and Engineering
CI - Cyberinfrastructure
CII - Cyberinfrastructure Institutes
CLWD - Cyberlearning and Workforce Development
CS - Computer Science
CSE - Computational Science and Engineering
CWDI - Cyberlearning and Workforce Development Institutes
FERPA - Family Educational Rights and Privacy Act
FLNW - Fostering Learning in a Networked World
GOALI - Grant Opportunities for Academic Liaison with Industry (NSF program)
HBCUs - Historically Black Colleges and Universities
HBCU-UP - Historically Black Colleges and Universities Undergraduate Program (NSF program)
HPC - High Performance Computing (HPC)
HSIP - Hispanic-Serving Institutions Program (proposed NSF program)
HSIs - Hispanic-Serving Institutions
ICT - Information and Computing Technology
IGERT - Integrative Graduate Education and Research Traineeship (NSF program)
IT - Information Technology
MSIs - Minority-Serving Institutions
NAS - National Academy of Science
NCSA – National Center for Supercomputing Applications
NETP - U.S. Department of Education National Education Technology Plan
NSDL - National Science Digital Library
NSF - National Science Foundation
PCAST - President's Council of Advisors on Science and Technology
STEM - Science, Technology, Engineering, and Mathematics
TCUP - Tribal Colleges and Universities Program (NSF program)
TCUs - Tribal Colleges and Universities
VRML - Virtual Reality Markup Language

Definitions

C^4: Continuous Collaborative Computational Cloud (C^4) - a ubiquitous "Internet of things" supplying data to and driven by information from services in the cloud. C^4 is a massive pervasive always-on information source linking networks, sensors, personal systems (smart phones, laptops, pads, pods, and players), repositories, servers, and supercomputers. This provides personalized knowledge on demand and is a medium where human creativity, collaboration and communication is unleashed to new heights.

Computational and Data-intensive Science and Engineering (CDS&E) - interdisciplinary computational approaches, including mathematics, computer science, informatics, and domain sciences and engineering, enabled by cyberinfrastructure.

Computational thinking – the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent. (From Cuny, Sndyer, Wing – Center for Computational Thinking, Carnegie Mellon University, http://www.cs.cmu.edu/~CompThink/)

Cumulativity - to incorporate into promising innovations knowledge and technology gained from prior projects and evaluating them in the context of existing alternative innovations

Cyberinfrastructure –the broad collection of computing systems, software, data acquisition and storage systems, and visualization environments, all generally linked by high-speed networks, often supported by expert professionals (From Cyber Science and Engineering: A Report of the NSF Advisory Committee for Cyberinfrastructure Task Force on Grand Challenges).

Cyberlearning – learning (personal, social, and distributed) that is mediated by a variety of rapidly evolving computational devices, (e.g., computers, smart phones), and CI (e.g., Web, Cloud)..

Cyberlearning platform - a platform (shared, interoperable designs of hardware, software, and services) that is both cognitive, one that best supports student learning and teacher effectiveness, and metacognitive, one that is built to improve through reflection on past performance.

Cyberscience – computational science… enabled by the cyberinfrastructure. (From Cyber Science and Engineering: A Report of the NSF Advisory Committee for Cyberinfrastructure Task Force on Grand Challenges)

e-learning - all forms of electronically supported learning and teaching, including the use and development of communication systems, devices, and curriculum.

e-science - a computationally intensive science that is carried out in highly distributed network environments, or science that uses immense data sets that require grid computing; the term sometimes includes technologies that enable distributed collaboration, such as the Access Grid (from Wikipedia, also sometimes another term for cyberscience or cyberinfrastructure).

Grand Challenge – "a fundamental problem in science or engineering, with broad applications, whose solution would be enabled by high performance computing resources…"(cf. http://www.nae.edu), or more broadly problems that "…also require extraordinary breakthroughs in computational models, algorithms, data and visualization technologies, software, and collaborative organizations uniting diverse disciplines" (From Cyber Science and Engineering: A Report of the NSF Advisory Committee for Cyberinfrastructure Task Force on Grand Challenges), and even more broadly to formidable problems of major significance to society, such as those listed by the National Academy of Engineering (http://www.engineeringchallenges.org), including Advanced Personalized Learning.

K to Gray - kindergarteners to retirees.

Metacognitive platform - one that is built to improve through reflection on past performance.

Net Generation – the next generation entering the workforce (with birth dates approximately from the 1970s to the present), having a lifelong experience and relationship with Internet resources.

Sustainability - to ensure that learning materials targeted for the platforms are widely usable and remain so over time, or internal sources for its workforce that will remain available to the nation over time.

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