3

Convergence Is Informed by Research Areas with Broad Scope

Many of the obstacles to effective convergence discussed in Chapter 4 have as much to do with interpersonal interactions as they do with science at the boundaries between disciplines. As a result, social and behavioral scientists who study human interactions, learning, collaboration, and communication as well interdisciplinary scholars who study new forms of knowledge creation and institutional structures and strategies have furnished valuable insights into the process of convergence and strategies to foster it.

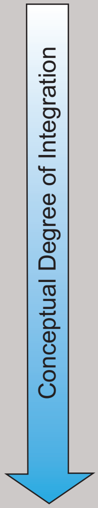
3.1 TERMINOLOGY AND CONCEPTS

Convergence has characteristics in common with other terms used to capture the concept of research that spans disciplines. A foundation of research from social sciences, humanities, organizational theory, higher education studies, and studies of science and technology in society has deepened understanding of different kinds of integration defined in concepts of transdisciplinarity, interdisciplinarity, and multidisciplinarity. Although they have been understood in multiple ways by different groups, a core vocabulary is now accepted and consensus based within these research communities. It forms a basis of understanding of the challenges and implications that combining inputs presents, including theories, data, models, and methods from diverse disciplines. These definitions, which are not meant to be absolute, to be one size fits all, or to indicate the superiority of one mode over another, appear in Box 3-1. As

BOX 3-1
Definitions

The academic community that studies the process of research has developed terminology to describe different forms of knowledge creation within and across disciplines. For the purpose of this report and to provide a structure for discussions, the committee adopted the following definitions (based on a composite of Klein 2010a and Wagner, et al. 2011, extended to include Sharp and Langer 2011). An important shared characteristic is that various forms of research involving social and/or cognitive integration of knowledge cannot be distinguished readily at their boundaries. They are not absolute states, temporally or spatially, and multiple types of approaches to working within and across disciplines are needed in the research enterprise.

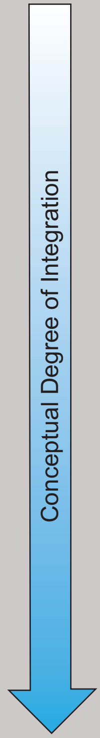
- ***Disciplinarity*** refers to a particular branch of learning or body of knowledge whose defining elements—such as objects and subjects of study, phenomena, assumptions, epistemology, concepts, theories, and methods—distinguish it from other knowledge formations. Biology and chemistry, for example, are separate domains typically segmented into departments in academic institutions.
- ***Unidisciplinarity*** is a process in which researchers from a single discipline, field, or area of established research and education practice work singly or collaboratively to study an object or to address a common question, problem, topic, or theme.
- ***Multidisciplinarity*** juxtaposes two or more disciplines focused on a question, problem, topic, or theme. Juxtaposition fosters wider information, knowledge, and methods, but disciplines remain separate and the existing structure of knowledge is not questioned. Individuals and even members of a team working on a common problem such as environmental sustainability or



evident from the descriptions, many defining characteristics of convergence are similar or even identical to defining traits of transdisciplinarity, key among them merging of distinct and diverse approaches into a unified whole. The merging of expertise from fields of engineering with fields of physical and life sciences in order to create a new systems framework for integrative cancer biology is one example—bringing together areas such as experimental biology, computational modeling, and imaging technology.

Tremendous advances in knowledge and understanding have come from discipline-based scholars, and research within disciplines will continue to contribute to the advancement of knowledge. While there is evidence that incorporation of inputs from diverse fields of inquiry may a public health initiative would work separately, and their results typically would be issued separately or compiled in encyclopedic alignment rather than synthesized.

- ***Interdisciplinarity*** integrates information, data, methods, tools, concepts, and/or theories from two or more disciplines focused on a complex question, problem, topic, or theme. The scope and goals of research programs range from incorporating borrowed tools and methods and integrating them into the practice of another discipline to generating a new conceptual framework or theoretical explanation and large-scale initiatives. The key defining concept of interdisciplinarity is integration, a blending of diverse inputs that differs from and is more than the simple sum of the parts. Individuals may work alone, but increasingly research is team-based. Collaboration introduces social integration into the process, requiring attention to project management and dynamics of communication.
- ***Transdisciplinarity*** transcends disciplinary approaches through more comprehensive frameworks, including the synthetic paradigms of general systems theory and sustainability, as well as the shift from a disease model to a new paradigm of health and wellness. In the late 20th century, it also became aligned with problem-oriented research that crosses the boundaries of both academic and public and private spheres. In this second connotation, mutual learning, joint work, and knowledge integration are key to solving "real-world" problems. The construct goes beyond interdisciplinary combinations of existing approaches to foster new worldviews or domains.



increase the likelihood of creative results, this does not mean research combining diverse inputs is on an evolutionary or deterministic path. Scientific advance has always been, and will continue to be, a combination of results from a multitude of incremental advances in knowledge and their verification with occasional notable breakthroughs of many different origins and arising from many different modes of knowledge creation: examples include serendipitous discoveries, eureka flashes of insight by individuals, and powerful integrations of knowledge from diverse fields by individuals and by teams. One challenge is to identify and understand the factors that influence the outcomes of research which successfully integrate diverse inputs, whether labeled interdisciplinary, transdisciplinary, or convergent. Another is to recognize that multiple types of approaches—including unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary—may occur simultaneously in a field or in an initiative because of the complex array of activities its participants undertake and diverse institutional contexts. As a result, disciplinary and interdisciplinary units, such as research centers, play complementary roles within many academic organizations.

3.2 MANY FACTORS AFFECT THE SUCCESS OF INTEGRATIVE AND COLLABORATIVE RESEARCH

Individual disciplines are associated with patterns of training and socialization, the ways that research questions are formulated, the methods and conceptual models used to address those questions, and the manner in which knowledge is communicated. They help to promote instruction, research, scholarship, and assessment for their fields. Prior investigators have explored the nature of disciplines and characterized some of their similarities and differences. For example, Becher (1994) identified fields as falling into intellectual clusters consisting of the natural sciences, science-based professions, humanities and social sciences, and social professions. But even within what might be categorized as basic sciences, characteristics typical of research conducted by a mathematician (often working singly or with one or two others, and using theoretical and computational resources) and a chemist (often working as part of team of senior investigators, postdoctoral researchers, graduate students, and technicians and requiring a range of chemicals, instruments, and other equipment) can vary in significant ways.

In a university setting, discipline-based departments typically form the bedrock organizational structure. These units have a tradition of autonomy. However, over the course of the 20th century, a substantial intellectual history of inter- and transdisciplinary research and education arose. This history extends from problem-oriented research at the Social Science Research Council in the 1920s to large-scale interdisciplinary initiatives such as the Manhattan Project in the 1940s to the rise of new interdisciplinary fields in such diverse areas as molecular biology, women's studies, urban studies, environmental studies, and clinical and translational science. The scope of activities is wide: from the daily borrowing of tools, methods, and concepts across disciplinary boundaries to projects and programs focused on complex societal and intellectual questions, to the formation of new fields, interdisciplines, and transcending "transdisciplinary" paradigms. In the latter half of the 20th century, boundary-crossing also became a recognized characteristic of knowledge production that was permeating disciplines, not simply a peripheral interest at the edges of "normal" work. The literature on institutional change expanded in kind, with heightened attention to new organizational structures and management strategies along with new models of curriculum and training. The literature on epistemological foundations of knowledge expanded in turn, fostering new understandings of cognitive integration while calling for expanded criteria of evaluation beyond discipline-based metrics. Interdisciplinarity and collaboration also became increasingly entwined, especially in scientific disciplines.

The amount of collaborative research that is undertaken (as captured by simple but imperfect metrics such as coauthored journal papers) varies by field but has shown a pronounced increase over time. Science and Engineering Indicators 2012 (NSF 2012) indicated that 67 percent of science and engineering (S&E) articles were coauthored in 2010 and papers across all S&E fields had an average of 5.6 authors. Field-specific differences in degree of interaction persist, though. The report noted that "the average number of authors per paper more than quadrupled [over the period from 1990 to 2010] in astronomy (3.1 to 13.8) and doubled in physics (4.5 to 10.1). Growth in the average number of coauthors was slowest in the social sciences (from 1.6 authors per paper in 1990 to 2.1 in 2010) and in mathematics (from 1.7 to 2.2)" (NSF 2012, pp. 5-35). These results echo the findings of a study of universities in Australia, New Zealand, and the United Kingdom in which the authors observed that 96 percent of articles published by faculty in the "science" cluster were coauthored, compared to 14 percent of articles in the "arts" cluster, and that the average number of paper coauthors was larger for the sciences (Lewis et al. 2012). There is also some evidence that the trend toward interdisciplinary research may reflect expansion of collaboration into fairly closely related scientific disciplines (Porter and Rafols 2009). However, it is clear that the number of authors per paper and coauthorship *per se* does not necessarily indicate interdisciplinary collaboation, nor does it substitute for more complex descriptions of the substance of the work itself. Moreover, particular disciplines may dominate, and standard databases do not necessarily account for the emergence of new interests and fields (Wagner et al. 2011).

While heterogeneity of fields can increase combinatorial opportunities and contribute to the success of a research project by bringing together diverse insights, such differences may also increase tensions among members (Boardman and Bozeman 2006; Nooteboom et al. 2007; Disis and Slattery 2010). Since scientists from different disciplines are likely to have different networks of peers, to participate in different conferences, and to publish in different journals, their weaker social bonds may increase the difficulty of developing goal interdependence and a sense of trust (Cummings and Kiesler 2005). At least one study has found that a graph of "cognitive distance" and collaboration success takes the form of an inverted U, whereby optimal distance balances the benefits of knowledge diversity with the barrier to finding common collaborative ground (Nooteboom et al. 2007). This research focused on collaborative alliances among technology firms using measures such as patent data; thus, the extent to which the findings can be extended to academic researchers remains unclear. A survey of collaborative research experiences of academic investigators concluded that multidisciplinarity did not have a significant effect on collaboration success, but that outcome measures were negatively impacted when collaborations spanned multiple universities because of reduced opportunities for close coordination (Cummings and Kiesler 2005). However, the survey found no negative impact on projects that involved development of tools such as software, reflecting the complexity of factors involved in studying collaborative research.

The nature of the research question, norms among the fields involved, and individual characteristics and experiences of participants all influence outcomes in addition to institutional factors. Figure 3-1 summarizes the multiple factors that are involved. In *Creating Interdisciplinary Campus Cultures* (Klein 2010b), Klein also presents an overview of Barriers and Disincentives to Interdisciplinarity, as well as Facilitating Strategies and Mechanisms that are relevant to those that confront convergence initiatives (Klein 2010b, Tables 3.1 and 3.2).

The integration of disciplines that start from a point of fewer shared cultural characteristics would be expected to provide additional tensions that would need to be resolved, be it within a single laboratory or across a multi-investigator or multi-organizational team. For example, certain fields in the humanities and social sciences are dominated by individual scholars rather than structured into group laboratories, make greater use of single-author publications, draw largely on qualitative analysis, or have other disciplinary characteristics that may be less familiar to researchers practicing in the life, physical, medical and engineering sciences. The committee emphasizes that these differences do not mean that insights from these fields should not be integrated in convergent research, but that greater levels of cognitive dissonance among participants and greater starting differences in areas such as faculty expectations and organizational structures may factor in strategies used to support convergent initiatives. This caveat is affirmed in the formal distinction between Broad and Narrow Interdisciplinarity (Klein 2010a).

Despite the challenges recognized here, convergence efforts that merge insights from across life, physical, medical, and engineering fields integrate science disciplines that have several characteristics in common. This shared foundation helps provide a starting platform for development of the multilingual capacity and integrated research culture needed for convergence.

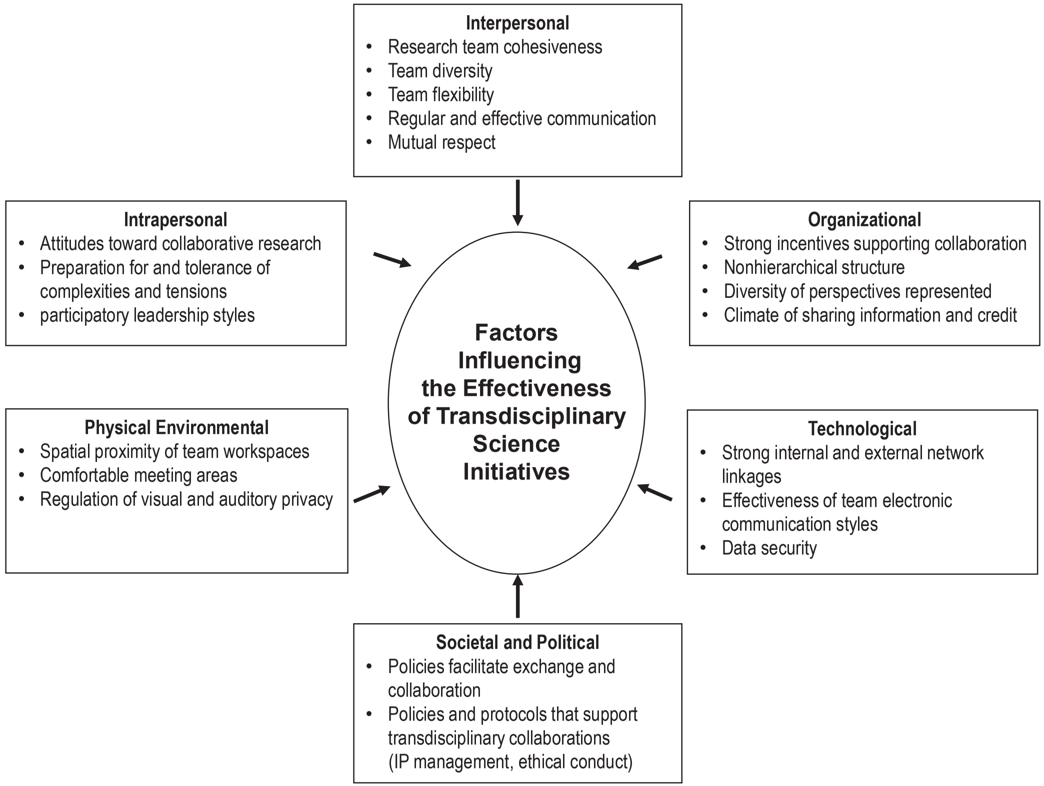


FIGURE 3-1 Factors influencing the effectiveness of transdisciplinary science initiatives. SOURCE: Adpated and reprinted from Stokols et al. 2008, with permission from Elsevier.

- **Research design and data collection**: Disciplines of life, physical, medical, and engineering sciences commonly draw on quantitative experimental data analysis and make use of individual case-study analysis or development of new theory less often than humanities and social sciences. Although there is a tradition of publishing clinical case studies in medical literature, a significant amount of basic biomedical research is undertaken by academic medical centers and a third of faculty at these centers report that they conduct basic science studies (Zinner and Campbell 2009).
- **Forms of knowledge dissemination**: Publication of peer-reviewed journal articles is a primary method of sharing research advances in these disciplines and is an important consideration in career advancement. Emphasis is also placed on participation in conferences as a forum in which developments may be shared prior to formal publication. Science and engineering disciplines vary in the relative weights given to different forms of knowledge sharing and in the details of article and conference practices, but together they share a base of norms on what it means to conduct and publish research.
- **Engagement in knowledge-transfer activities**: Although the extent varies, science and engineering disciplines also engage in knowledge dissemination through the generation of patents. For example, a study of the curricula vitae of 1,200 scientists affiliated with Department of Defense, Department of Energy, and NSF research centers found that mean patent rates were higher in computer science, engineering, and physical science fields than in biological science, although these fields were all higher than social science and humanities (Dietz and Bozeman 2005). In 2012, 96 percent of the U.S. journal article citations in issued patents were in five areas: biological sciences, medical sciences, chemistry, physics, and engineering. Biotechnology patents also made up the largest percentage of patents granted to U.S. universities in 2012 (NSF 2014).
- **Patterns of coauthorship and collaboration**: As discussed above, a majority of publications in science and engineering disciplines are now coauthored, although there remain disciplinary differences in the typical numbers of coauthors or number of disciplines cited in a given article. As noted earlier, coauthorship alone is not an adequate indication of the kinds of knowledge integration necessary for transdisciplinary collaboration, but may serve as a simplistic indicator of norms within these fields.
- **Traditions of open sharing as well as competition**: Some disciplines have a tradition of depositing prepublication papers in

open-access repositories (such as arXiv for physics and mathematics) or making use of open-source development strategies (for example, in the Linux operating system in the computational sciences).[1] In life sciences, norms as well as funding agency requirements call for the deposition of biological data such as nucleic-acid sequences and protein structures in databases such as GenBank or the Protein Data Bank, respectively, where the information is accessible to all researchers. However, legal questions surrounding patient consent and privacy complicate clinical information sharing in the medical field. Moreover, although there are both traditions and requirements for data sharing, competition to understand and make use of data is an important characteristic in many science fields.

Multiple case studies of interdisciplinary and collaborative research exist, particularly in the context of National Science Foundation (NSF)- and National Institutes of Health (NIH)-funded center programs. These case studies can provide further insight to inform the process of convergence in organizations. Examples include the following:

- *Knowledge and Distributed Intelligence Program (NSF)*: An analysis of 62 collaborations that received 3-year support through an NSF program in 1998-1999 suggested that collaborations involving investigators at multiple universities were associated with lower positive outcomes compared to single-university collaborations. Investigators reported a number of practical barriers to multi-university projects, including different university calendars and teaching schedules and negotiations over budgets and intellectual property. Institution-spanning collaborations were associated with reduced opportunities for information-sharing and coordination mechanisms such as face-to-face interactions, regular project meetings, co-taught courses, and direct faculty supervision of participating students, and the use of technology such as email did not fully overcome these barriers. The study suggested a role for longer-term funding for complex collaborations that recognizes the effort involved in undertaking such projects and the need for coordinating infrastructure (Cummings and Kiesler 2005).

[1] The Defense Advanced Research Projects Agency (DARPA) has recently announced that the source code for its supported projects will be available in the DARPA Open Catalog (DARPA 2014), reflecting this ethos within the software development community.

- *Transdisciplinary Research on Energetics and Cancer Centers (TREC) and Transdisciplinary Tobacco Research Use Centers (TTURCs) (NIH)*: To conduct an early-stage evaluation of centers in the NIH-funded TREC program, researchers developed a survey that analyzed participating investigators' orientations toward uni-, multi-, inter-, and transdisciplinarity and evaluated characteristics of proposals submitted for program development funds. The study reported that "perceptions of greater institutional resources at their TREC centers were related to a more positive outlook for a variety of collaborative processes and outcomes" (Hall et al. 2008, p. S170), suggesting that institutional investment can help facilitate the success of such endeavors. The TREC program includes a supporting coordination center, and it may be interesting to examine how this feature influences program outcomes as part of future assessments. A comparison of TTURC center awards with individual-investigator awards revealed that transdisciplinary teams demonstrated lower productivity during initial years of a project, but appear to become more productive and creative after a 3-year period (Hall et al. 2012), further supporting the longer-term nature of complex, collaborative efforts.
- *Comparison of the Texas Air Quality Study (TexAQS) and cross-center collaboration through the National Cooperative Program for Infertility Research (NCPIR)*: Environmental scientists from multiple partners (universities, federal laboratories, industry, and state bodies) and multiple sponsors were involved in TexAQS, which operated through a largely informal structure. Those engaged in the project undertook extensive planning, were in frequent communication, agreed on core aspects such as research questions, methodological approaches, and resource sharing, and generally already knew each other and had formed a sense of trust and competence. The NCPIR collaboration, on the other hand, was imposed by the funding agency, involved two geographically distant universities with researchers from basic and clinical fields who did not previously know each other and had different approaches to the research questions, and was in a scientific area (particularly polycystic ovary syndrome) that was still developing. Reportedly, "the result was that individual researchers conducted their own research (some of which was quite successful on an individual level), but the collaborative efforts of the group failed" (Corley et al. 2006, p. 991). The study highlighted how partners with similar cultures and relative scientific unity may share information more effectively to facilitate a positive group dynamic, while partners who approach research from different epistemic perspectives can

encounter barriers even when more formal structures are in place and the research question falls broadly within the health sciences field.

In addition to case analyses such as those above, the Engineering Research Centers (ERC) program at NSF has created an online guide for scientists and academic leaders to provide information on factors to consider when establishing these centers (ERC 2014). Knowledge obtained from such program materials and from case studies that investigate the association of center attributes with metrics of success provides insights for existing convergence programs and useful guidance for developing new programs. The online Science of Team Science toolkit is another potential resource on the conduct and evaluation of team-based science. It is hosted by NIH (NCI 2014), which has also served as a sponsor and partner for annual Science of Team Science conferences (http://www.scienceofteamscience.org/). The committee especially looks forward to the results of a forthcoming National Research Council (NRC) study that is examining how factors such as team dynamics, team management, and institutional structures and policies affect large and small science teams. This study aims to capture the existing literature and wisdom of practice while illuminating gaps in the evidence base needed to improve team science processes and outcomes and to enhance collaborative research effectiveness. While the study focuses broadly on team-based science, it should provide valuable insights for convergence programs since these entail transdisciplinary integration of expertise, frequently undertaken in teams (NRC 2014). Finally, a large literature exists on how to foster interdisciplinarity in academic settings (Klein 2010b); the resources they provide for addressing barriers in organizational culture, faculty development, and program review can be adapted and extended to convergence.

3.3 REVISING STEM EDUCATION WILL FACILITATE CONVERGENCE

Science, technology, engineering, and mathematics (STEM) education has emerged as a key factor for facilitating the goals of convergence. The report *A New Biology for the 21st Century* suggested that "using biology to solve important problems could provide a platform to engage all students in the process of science, and illustrate the excitement and benefits of using science and engineering" (NRC 2009, p. 79). Complementing *A New Biology*'s recommendations on the role of life sciences in addressing broad societal challenges in areas such as food, health, and the environment, *Rising Above the Gathering Storm* (NRC 2007) and the *National Bioeconomy Blueprint* (White House 2012) highlighted the role of STEM education and entrepreneurship for enabling the knowledge economy, contributing to U.S. economic competitiveness, and training the bioeconomy workforce. Convergence approaches, which bring expertise from multiple fields to bear on innovative basic discovery as well as applied research and development, align closely with both of these goals. These reports furnish institutions considering how to foster an environment conducive to convergence with models and strategies for embedding this process into education and training programs.

Significant efforts have been made over the past decade to revise STEM education at the undergraduate and graduate levels, with particular emphasis on promoting training that makes interdisciplinary connections, incorporates problem-based learning and access to research opportunities, and draws on validated, evidence-based teaching methods (NRC 2003, 2012c; PCAST 2012; *Science* 2013). A recent report from the Association of American Medical Colleges and the Howard Hughes Medical Institute, *Scientific Foundations for Future Physicians* (AAMC and HHMI 2009), and new revisions to the medical school admission test, MCAT^{2015}, echo this trend. The revisions focus on demonstrating core competency in key biological concepts and draw on the integration of several fields, rather than on testing specific courses or disciplines in isolation. As the committee heard during its workshop, the environment provided by undergraduate liberal arts colleges and small, STEM-focused schools already models teaching and learning strategies that support the goals of convergence, through institutional policies that encourage faculty to develop new methods of teaching that span disciplines and because smaller physical size fosters random interactions that can lead to unexpected collaborations. These colleges send more students on to graduate training programs than would be expected based on their size (D. Singer 2013).

Revisions to STEM education also need to address the needs of the future workforce. At graduate and professional levels, the life sciences and biomedical workforce is diverse and continues to grow. Based on 2006 data, the biomedical research workforce included approximately 126,000 U.S. doctoral degree holders (approximately 64 percent male and 36 percent female) and over 63,000 foreign trained scientists. Twenty-six thousand were serving as postdoctoral fellows and an additional 25,000 were graduate students (NRC 2011b). Between 2000 and 2009, the largest increase in awarded science and engineering doctorates occurred in biological/agricultural sciences, medical/other life sciences, and engineering. In addition, the biological/biomedical, health sciences, and engineering areas received the largest allocations of academic research space and the largest new research space construction (NSF 2014). Meanwhile, career paths for science and engineering graduates are continuing to change, with reports on "best practices" and accreditation standards increasingly highlighting the importance of interdisciplinary and collaborative capacity. More than half of those who receive new doctorates across all academic fields now work outside of academia in industry, government, and nonprofit sectors and the number of professional science masters programs is increasing (NRC 2012a).

Recent reports have explored additional aspects of STEM education such as who participates in graduate science training, how long degree programs take, what percentage of students complete their degree, what types of training grants and funding sources support students, and what needs and opportunities exist for career paths to the workforce at both master's and doctoral levels. Several insights for fostering convergence emerge from these studies, including the increasing role of interdisciplinary and collaborative work in all stages and types of careers, the need to provide students with information on diverse career paths, the value of understanding of how to put research contributions into a broader context, and the role of skills such as communication and teamwork (Wendler et al. 2010; Wendler et al. 2012; NRC 2011c, 2012a, 2012d; NSF 2014).

The growing role of interdisciplinarity in the biological sciences, in particular, was highlighted in the most recent edition of the NRC assessment of doctoral programs. The rapid pace of development in biological and health sciences and the increasing interdisciplinary character of programs since the NRC's last assessment (in 1993) posed challenges to its classification methodology, which was largely based on an older taxonomy of discrete academic programs that did not recognize the emergence of new boundary-crossing interests and fields.

The report noted that, "although most doctoral work is still organized in disciplines, scholarly work in doctoral programs increasingly crosses disciplinary boundaries in both content and methods. The committee tried to identify measures of multi- and interdisciplinarity, but it believes it did not address the issue in the depth deserved, nor did the committee discover the kind of relation, if any, between multidisciplinarity and the perceived quality of doctoral programs" (NRC 2011c, pp. 105-106), concluding that this issue should be dealt with more fully in subsequent editions.

Viewed together, these and other reports affirm that possession of skill sets beyond disciplinary knowledge and research training are increasingly important for the success of students at all levels. A 2013 report on the role of "21st century skills" identified the related skills as clusters of competencies in cognitive, intrapersonal, and interpersonal domains that included aspects like creativity, flexibility, collaboration, and conflict resolution. Although this report was not able to definitively link such skills development during K-12 years with adult outcomes, it recommended expanding the evidence base for how to effectively teach and learn them and how to make them transferable (NRC 2013). The importance of skills that enhance research impact, including "communication, teamwork, relating work to a broader context, and application of research to larger corporate or social purposes" was similarly identified in recent reports on graduate school training from the Educational Testing Service and Council on Graduate Schools (Wendler et al. 2010, p. 44) and highlighted by participants at a workshop on graduate study in the chemical sciences (NRC 2012d). The types of 21st century skills identified by these reports all align with the skills that will be needed to work in a convergence environment, in which challenges are tackled across disciplinary boundaries through the integration of multiple areas of knowledge, and in which problem-solving may draw on the contributions of multiple team members and multiple partners within and outside of academia.

As academic institutions prepare their students for the research challenges and work environments they will likely encounter in the future and as they design education and training programs that incorporate new evidence-based teaching practices, all of these factors will be relevant. Beyond the reports already mentioned, institutions can also draw on guides such as the roadmap for interdisciplinary learning released by Project Kaleidoscope and the Association of American Colleges and Universities (Elrod and Roth 2012), which provide ideas for strategies to mobilize support, undertake pilot activates, define outcomes and assessment plans, undertake pilot activities, and sustain commitment. Other examples of strategies used by institutions to foster convergence at undergraduate and graduate levels are discussed in Chapter 4, along with some of the perceived challenges and needs for the future.

3.4 CONVERGENCE MAY CONTRIBUTE TO UNDERSTANDING QUANTIFICATION AND REPRODUCIBILITY IN LIFE SCIENCES

As the chapter highlights, a significant body of research has examined the relationship of individual and organizational factors to integrative and collaborative research and teaching, with insights that might transfer to the goal of fostering convergence. Discussion during the data-gathering workshop illuminated several additional differences in the ways that life scientists and physical scientists or engineers are perceived to approach problem solving, with potential impacts on fundamental research challenges at the frontier of the life, medical, physical, and engineering sciences.

Engineering fields generally approach challenges through quantification, since quantitative understanding of a system enables control. Quantification is becoming increasingly important in the biological sciences as well, and thus biologists increasingly need training in mathematics and computation. However, the living systems of interest in life sciences are complex, adaptive, and often not at equilibrium, making the mathematics required to model, analyze, and understand them extremely sophisticated. For example, modeling the signaling pathway of the epidermal growth factor receptor requires equations that cover 322 components and the 211 reactions in which they are involved (NRC 2011d). Effectively integrating an engineering approach to mathematical complexity into life sciences is a major goal for convergence that would help tackle the challenge of understanding and controlling biological systems, with results that would be applicable across questions in health, sustainability, and innovation.

Data reproducibility is another well-recognized challenge in the biomedical sciences. It has received wide attention due to pharmaceutical industry reports that results of published studies on cancer biology and drug targets could not be fully replicated (Prinz et al. 2011; Begley and Ellis 2012; related discussions appear in a special collection of *Nature* articles at nature.com/nature/focus/reproducibility). Numerous factors contribute to poor result reproducibility. Possible factors that have been suggested include limited ability to fully describe methods in written journal articles, uncharacterized variance in experimental conditions, limitations in preclinical cell culture and animal models, pressure on scientists to publish positive results, low value placed on replicating the results of others, and insufficient statistical expertise or experimental design. This is an area which needs further study in order to address a key stumbling block to research progress. Many believe that life and medical sciences have not focused as extensively as physics and engineering on developing common measurement standards and common guidelines for collecting data from biological samples. In order to move beyond information encoded in individual genomes to translational application, further attention to this challenge of standardization and reproducibility is required. Strategies adapted from the physics and engineering communities can contribute, although the complexity and individual variability of living organisms make measurement challenges in life and medical sciences unique. As one participant in the committee's workshop stated, "Let's figure out how to take the important biological processes and annotate them so that we're not simply accumulating data that's reproducible, but leading to knowledge that's actionable" (Dennis Ausiello, Workshop on Key Challenges in the Implementation of Convergence, September 16-17, 2013, Washington, DC). Convergence holds potential to contribute to the goal of incorporating rigorous measurement and analysis toolkits into life sciences while continuing to draw on the empiricism and observation that have formed the foundation for many life sciences advances of the past.

3.5 CONVERGENCE EXTENDS BEYOND THE INTEGRATION OF LIFE SCIENCES, PHYSICAL SCIENCES, MEDICINE, AND ENGINEERING

Most of the examples of convergence programs and institutes discussed in Chapter 4 were established around a core subset of life, physical, medical, and engineering sciences. However, many of the challenges these programs report encountering and strategies they have employed to foster convergence reinforce existing recommendations on how to nurture research that spans disciplinary boundaries more broadly. Where applicable, this report highlights similarities where information from convergence programs echoes such prior findings, notes aspects that may be specific to the combination of life, physical, medical, and engineering fields, and suggests how they affect challenges encountered in fostering convergence.

There is widespread recognition among scientists that addressing critical challenges in health, energy, and sustainability at both the research and application stages draws on contributions from disciplines beyond the life, physical, engineering, and medical sciences. Well-established areas such as cognitive neuroscience merge research in cellular biology and neural circuitry with behavioral studies to better understand complex human processes such as emotion. The economic and social sciences also make crucial contributions to the translation of innovations from fundamental research to widespread adoption. For example, "you can get engineers and use bio-fuels to build a great car, but people still have to buy it, it has to be priced. Behavior has got to play a big role. So I think that a true, complete solution to many of the problems we care about should include economics, psychology, behavior, sociology" (Carl Simon, Workshop on Key Challenges in the Implementation of Convergence, September 16-17, 2013, Washington, DC). The extent to which disciplines such as the social and economic sciences and humanities are being increasingly incorporated into an expanded concept of convergence and what additional cultural and institutional barriers this will present remains a matter of discussion, although the committee's view is that these fields have important insights to contribute in many areas of discovery and application.