DISCUSSION PAPER

Training the Workforce for 21st Century Science

A Vital Direction for Health and Health Care

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Introduction

Continuing to improve human health at reasonable costs is one of the biggest challenges facing society in the 21st century. Prior scientific advances have led to longer life expectancies, which in turn have led to the emergence of chronic diseases often related to aging (IOM, 2001). Our health-care system was designed primarily for acute care, whereas today chronic disease is responsible for 80% of health-care costs (McKenna and Collins, 2010). The current system is characterized by episodic care, fragmentation of services, and a less-than-holistic view of the patient, all of which lead to a growth in inefficiencies and costs (IOM, 2001).

The need for more coordinated and seamlessly integrated multidisciplinary care is obvious. In parallel, advances in our knowledge of biologic systems and their complexity will require an unprecedented convergence of biologic, physical, and information sciences to solve the issues that we face. The life sciences are moving from an era of monodisciplinary and reductionist explorations of the fundamental elements of biologic systems to a multidisciplinary understanding of human biology and the course of disease. Given that evolution, the hope of precision medicine is unlikely to be realized without a transformation in how we educate and train a new generation of physicians, scientists, engineers, and population-health professionals. These experts need to be able to create and implement new ways of tackling complexity with the goal of reducing disease burden at a cost that society can afford.

Today, our biomedical educational and scientific training pathways are fragmented (Kruse, 2013). Young talents are often discouraged because of the longer and uncertain pathways to a successful career, especially when they will be saddled with a much greater debt burden at the end of their studies than was the prior generation.

Over the last 100 years, the United States assumed a global position of unparalleled scientific achievement and has reaped the many health, economic, diplomatic, social, and military benefits of its preeminence. United States citizens have been awarded more Nobel prizes in physiology or medicine than those of any other country—by a factor of 3 (Kirk, 2015). Those accomplishments have contributed to remarkable improvements in human health, innovation, and economic success and to a great sense of national pride. Our preeminence, however, is now being challenged by external and internal factors.

Other countries are competing more successfully in science and technology. The United States used to be preeminent in attracting the best and brightest in the world to its shores, but that dominance is not as pronounced today. China, for instance, has markedly increased its R&D funding and the quality of its top universities (IRI, 2016). As a result, China can increasingly attract its expatriate scientists back to enrich local institutions with world-class talent trained in the United States and Europe while a well-trained generation of young scientists is emerging from top Chinese universities.

"It is a miracle that curiosity survives formal education."

—Albert Einstein

A visit to any US laboratory today reveals the dependence on foreign-trained scientists at postdoctoral levels (Matthews, 2010). At the same time, young and American-trained talented people, who face a financial burden greater than do their colleagues in other countries because of high tuition costs in the United States and consequent high debt, increasingly shy away from scientific endeavors. They see the greatly increased length of training imposed on them by our academic institutions, delay of opportunities to work independently until their late 30s (NAS et al., 2007), and grant funding that is uncertain (Harris and Benincasa, 2014) and highly competitive. It is not surprising that many of the best and brightest view this path as forbidding relative to more lucrative nonscientific careers, less fraught with uncertainty.

With the retirement of the extraordinarily productive current generation of US scientists, our nation will have to plan carefully and act swiftly to continue to attract young people to science and to train and retain a world-class scientific workforce from within its citizenry if it hopes to retain its longstanding advantage. Furthermore, novel training paradigms and multidisciplinary skills that combine life sciences and physical sciences will be essential. For instance, solutions to the most intractable disease problems, such as those related to Alzheimer disease and diabetes, will require both new scientific discoveries and fundamental and integrative health-system changes if we hope to control the soaring health-care costs associated with those problems. The United States will need to create and sustain a competitive and highly skilled new generation of talented people who are unafraid of challenging the status quo and who can create the knowledge and the new industries that can emerge from innovation. In short, if the United States is to maintain leadership in biomedical research and the development and delivery of medical innovation, the training of a new generation of scientists and engineers will need to become as innovative as the science that they are expected to deliver. That must have high priority for the nation.

In brief, our analysis identifies four interrelated key issues that we must address if our scientific workforce is to remain preeminent:

- The lack of high-school exposure to cutting-edge science by the best teachers.
- The increasing financial burden of a scientific education with unsustainable student debt that forces many, especially members of underrepresented minorities, to forgo scientific research careers.
- The unjustified lengthening of our postgraduate training system with poorly defined career pathways even for promising scientists, who today do not reach independence until their late 30s.
- The persistence of rigid disciplinary silos that make multidisciplinary training and research unnecessarily difficult.

What needs to change? We must find ways to attract the most talented science, technology, engineering, and mathematics (STEM) students and support them throughout their education and training. To do that, we must create new pathways to help to ensure that they are trained in the skills and knowledge necessary to succeed in 21st century biomedical and health-care sciences.

To understand the problems and plan for the educational revolution that will be required, we need to look at the current systems through the eyes of the young people who are contemplating or navigating a life in science—high-school students, undergraduate students, graduate students, and postdoctoral fellows.

The High School Experience

Brittany is an entering high-school freshman in a small town. She has already been identified as a star student, excelling in her classes and performing well above her peers on standardized tests. She has always loved science and likes to imagine herself working on a cure for cancer. In the coming years, however, she will be faced with biology classes drawn almost entirely from textbooks, lectures about the taxonomic classification of plants and animals, and a brief exposure to basic Mendelian genetics. She will receive little exposure to laboratory work that is not simply "cookbook science", and she will not get any experience in hypothesis-driven research or an opportunity to be creative. In short, her high-school biology class will be distressingly similar to that experienced by her parents 2 decades earlier. In class, she yearns for the excitement, the cutting-edge advances, the new science applied to treating disease and saving lives that she sees on television and the Internet. Unfortunately for Brittany, that exciting science is many years away if she continues to tread the traditional academic path. After her freshman year in biology, she will be channeled into chemistry in the 10th grade. Physics will come the year after that. There is a shortage of skilled teachers for more advanced classes. Because of this experience, Brittany, like many of her peers, will most likely have lost enthusiasm for biology by the time she applies to college. She is aware that her cousin in the United Kingdom is simultaneously studying biology, chemistry, and physics in each of the 2 years of her A-level program, giving her an extensive basis in all three subjects before college entry. Like most other high school students, Brittany has not signed up for classes in computer science or engineering and therefore is not acquiring skills essential for a future in research. Most important, she does not understand the consequences of not taking the advanced mathematics required for a career in 21st century biology. She and her parents do not know that the United States was ranked 27th among Organisation for Economic Co-operation and Development (OECD) countries in the performance of 15-year-olds in mathematics (OECD, 2014).[1] With most developed countries producing students who have stronger mathematics skills, Brittany's potential to compete at a high level in science may already be compromised unless she can catch up in college. If society is lucky, Brittany will enter a fine undergraduate institution one of whose professors will reignite her interest in biology, and she will be able to catch up to the rest of the world in mathematics. But it is equally likely that Brittany will veer off the path of science altogether.

The Undergraduate Experience

Michael is entering a prestigious university as an engineering student. He has already shown an aptitude for mathematics, having won a national competition in high school. He has had little exposure to laboratory science, inasmuch as his time in high school was devoted largely to mathematics courses and the required curriculum. He has taken biology but found its emphasis on rote memorization of facts discovered decades earlier stultifying. Michael has had no exposure to and therefore no interest in research and does not see how his mathematics skills and interest in engineering could be applied to biological research anyway. His college adviser steers him down the path of civil engineering and more advanced mathematics but fails to recommend that he expose himself to chemistry or large-scale data analysis. In his junior year, Michael learns a bit about molecular biology from his roommate and sees that this field of research is fascinating. He gets a chance to work in a university genetics laboratory over the summer and finds it exciting—some of the required data analyses even allow him to use his advanced mathematics skills. But when he returns to college for his senior year, he is advised that it is too late to change direction in his undergraduate program and he would be unlikely to be accepted by a premier graduate program in biology given his lack of college courses in the subject. In contrast, he could choose from among a number of well-paying entry-level jobs as an engineer immediately. His professors tell him that if he does try to pursue a PhD in a biological science, it would be a 4- or 5-year commitment followed by a postdoctoral fellowship (or two), which would require 2–6 more years and give him no guarantee of a job at the end of it. Michael envisions himself getting to the age of 36 years and not having a stable, well-paying job—and carrying the substantial debt incurred by his college tuition. A career as a civil engineer working for a construction company is increasingly attractive.

"Study hard what interests you the most in the most undisciplined, irreverent and original manner possible."

—Richard Feynman

The Graduate Experience

Jamar grew up in the inner city. He is a master's-degree student in a school of social work. He chose this profession because he saw the system failing his family and the families around him. He is particularly interested in the health services for nonworking single mothers. He has done a number of internships as part of his training and sees that community services around the city do not use a standard approach to care. No one seems to know what works. They know what seems to feel good but not what will actually improve the health outcome of mothers and their children. He has a terrific idea for a citywide demonstration–research project to test various models of care delivery empirically. What is more, he intends on using real-world data to test his hypotheses. He does not, however, have the skills to undertake such complicated analytics and no resources to hire expert help. His faculty adviser is supportive, but grant funding for health-services delivery research is limited. He reaches out to the city, the state, and the federal government for funds for research to no avail. When he receives his master's in social work, he finds himself, much to his dismay, in a new job implementing one of the untested service-delivery programs that he had wanted to study. He is destined to spend his career in helping people while having little opportunity himself to develop the evidence so needed to improve the health-care system. He sees no path to a PhD.

The Postgraduate Experience

Jose is in medical school and is heading off to a residency in neurology. His parents emigrated from South America when he was a baby, and he is the first person in his family to graduate from college. He is enjoying medical school and working with patients and is doing well. Along the way, he has developed a deep interest in clinical research. He sees the problems that patients are facing and sees that innovation is the only way forward. He has many good ideas for new research projects and is even tinkering with an idea for a new device to help late-stage Parkinson disease patients ambulate. However, he had to borrow heavily, using student loans to pay for his medical-school tuition, because his parents were not in a position to help him financially, and he has been barely getting by. On graduation and starting his residency, he looks forward to paying down some of his debts—and raising his standard of living a bit and possibly helping his parents financially. As he surveys his career options, however, he is discouraged about the prospects of combining a career in medicine with one in research. Watching the medical-school faculty members around him, he sees them struggling to deliver high-quality care while finding the time to get research grants and conduct the research itself. He begins to think that maybe he should abandon the idea of more research, take his device idea, and just start a company. But his training and his medical-school mentors have not told him much about the steps needed to move from an idea to a marketable product. He will probably be a successful medical practitioner, but his ideas for innovation will never come to fruition.

The Postdoctoral Experience

Preeti has a PhD and is a postdoctoral trainee in a large medical school. She comes from a family of scientists. Both her parents were trained in India and now have faculty positions in the United States, her father in biochemistry and her mother in nursing. She is in her 4th year of training and has published several important papers. Recently, her intellectual interests have veered away from those of her mentor, who is focused on the role of kinases in heart muscle. Preeti has some innovative ideas about how kinases play a role in muscular dystrophy, but she does not have the computer-science skills that she needs to do the modeling necessary to explore the ideas. She would like to work with a colleague in the computer-science department, but her mentor does not have a grant in this disease field, and Preeti does not have the time or independent resources required to pursue her ideas unless she obtains a faculty position of her own. Her father, who has been a productive scientist for years, just lost his major grant and is having a hard time keeping his laboratory running. Preeti sees the lack of job stability in the academic sector, and it worries her. Meanwhile, her mentor depends on her leadership in the laboratory and wants her to continue to work with him on his projects. She feels stuck. She sees several more years of postdoctoral effort ahead of her and the long odds against gaining a tenure-track position, followed by grant-seeking activities that may or may not bear fruit. She does not know how to look for a job in industry and has never met an industry scientist, so she has no idea whether this is an interesting, let alone viable, career option. She also wants to start a family and is trying to figure out how to fit this into her life plans. She may decide to follow a clearer path to a well-paying and stable career as a financial analyst for a firm that deals in biotech stocks.

Key Issue: The Challenge of Attracting and Retaining the Best and the Brightest in the 21st Century

The stories above highlight the problems faced by aspiring scientists at critical stages of their career development. Those young people all have a fire in the belly that may be extinguished not because of a lack of passion or willingness to work hard but because of environmental circumstances. That is the case even though we have decades of experience in learning how students find their way into science careers. There have been a number of cogent and well-received reports on the nation's scientific workforce (NAS et al., 2007; NAS et al., 2010; NRC, 2012b). As a result of the recommendations in those reports, a number of agencies and even private-sector entities have sought to address some of the challenges we have laid out above. But the problems persist, and much bolder action is needed.

For high-school students, we know about the importance of early school-based research experiences, informal out-of-school science experiences, and motivating information about a career in science (NRC, 2011). Even so, there is little opportunity for students to be exposed to the process of science—exploration, discovery, and validation—as opposed to memorizing previous discoveries. That circumstance limits their understanding of science and dampens their enthusiasm for science as an exciting and creative activity. The current cookie-cutter approach to science education makes it hard to keep the brightest students intellectually engaged and interested in science in general and in biology in particular. Some students may want the opportunity for more rigorous and in-depth learning in their high-school years; for example, classes in molecular genetics or neurobiology in high school would undoubtedly ignite young minds. But state education budgets are shrinking at the very time when more money is needed. More important, state curriculum requirements effectively limit how far students can go in high school (NRC, 2002; Schmidt et al., 2013). The adaptability of the system to the potential of the promising student is the key. Today, it is the student who adapts to a rigid system of programs, rather than the opposite.

Implementing substantial change will require changes in K–12 teacher training. Only a minority of STEM teachers have robust research experience (NAS et al., 2007; PCAST, 2010). Furthermore, the knowledge and skills of STEM teachers, as opposed to teachers in such disciplines as history or English, will rapidly go stale if they are not kept up to date. Few school districts have the resources to send their STEM teachers to annual meetings or continuing education in the form of advanced coursework or bench science (NRC, 2002; NRC, 2007; NRC, 2005a). As science becomes more complex, the training of the nation's science teachers must keep pace—teachers themselves need more exposure to hypothesis-based thinking, problem-solving, mathematics, and computer science in addition to continuous exposure to the evolving knowledge in their fields.

Higher-level mathematics, computer science, and data analytics have become critical for success in most arenas of health research, especially with the rise of genomics and real-world evidence. But most US students do not even go as far as calculus in high school, let alone to linear algebra or statistics (NAS et al., 2007). The same can be true in college. Statistics is almost absent from curricula, and many students, not recognizing the importance of exposure to such subjects, take as few mathematics and statistics courses as permissible. Moreover, almost no high-school or college training in computer science is focused on biology, in which the need for computer science and large-dataset analytic skills is increasing. In middle school, 74% of girls express interest in STEM, but when choosing a college major, just 0.4% of high-school girls select computer science (Girls Who Code, 2016). The number of men and women who have college degrees in mathematics or computer science is a small fraction of the number who are pursuing careers in business administration, and the number of women is much lower than the number of men (NCES, 2014). In addition, the larger problem of attracting members of underrepresented groups, especially minority groups, to careers in science and retaining them must be addressed if we are to take advantage of all America's brainpower. As a country, we are losing many smart young people who could not only become important scientists but bring a richness and diversity of experience and thought to bear on the health challenges of the future.

In college, even when high-level courses in mathematics and computer science are available, they are often rigid and siloed. Curricula are narrowly focused and offer few examples in computer-science classes of how analytic techniques can be applied to modern-day biology, leaving computer scientists largely ignorant about career opportunities in the biomedical workforce. For freshmen still undecided about a career, opportunities for laboratory-based, hypothesis-driven research are sparse. For students with traditional goals, a high mark in organic chemistry has become the Holy Grail of success and serves as a requirement for admission to medical school. Rather than just high marks, the goal of the students should include the development of the problem-solving skills needed in research.

Of all the groups in the biomedical workforce, PhD students are under particular stress in the current environment. Some argue that we are training too many PhDs, others argue that we have too few PhDs in critical fields (Benderly, 2010; Cyranoski et al., 2011; Trivedi, 2006; Domer et al., 1996), and still others suggest that the training is too long and too narrow. The needs of both PhD students and society will be served better by aligning training programs with varied career research options, including "big pharma", biotech, device companies, foundations, government, data-analytics companies, and patient groups.

Despite the growing number of possible careers, we are operating with an outmoded model of training PhDs. It leads to students and postdoctoral scholars who are coming out of their training hoping simply to replicate the careers of their mentors rather than to contribute to the exploration of novel ideas through more diverse careers. Such students finish their training with inadequate exposure to the wider array of career options and the skills that would allow them make informed decisions about their career paths. It has been suggested that universities and their faculties continue to promulgate that approach because trainees are critical for the productivity of their laboratories. It can be argued that the current postdoctoral system is an apprenticeship program for the benefit of the faculty and results in longer and longer periods of postdoctoral training. Instead, the endgame should be focused on independence as soon as possible rather than having postdoctoral scholars continue to serve as a low-paid labor pool. The current situation is no doubt discouraging to the most creative. It is no surprise that dropping out of college is an increasingly popular recommendation that some entrepreneurs, such as Peter Thiel (Brown, 2014), have made to brilliant students if they are to succeed creatively; Steve Jobs, Bill Gates, and Mark Zuckerberg did not complete their college training, but each has changed the world. Although that recommendation has worked in technology fields, such as computer science, it would not work for such fields as modern biomedical research (Powell, 2015; NRC, 2005b).

Breakthroughs in medicine often move from the bedside to the bench, and this is why the physician–scientist is critical for medical advancement (NIH, 2014). But there are few formal research-training programs for physicians, especially after residency. The National Institutes of Health (NIH) Medical Scientist Training Program (MD–PhD) (NIH, 2015) program has been successful, but many argue that it requires too great an investment of time. Even when physicians try to eke out time for research, health systems end up discouraging such activity in the face of needs to ensure adequate clinical-care services and more predictable revenues than those gained from competitive research-grant funding. For example, physician–scientists who have an idea for a product with immediate and direct effects on treatment must often take a leave of absence from the workplace to devote time to such efforts at the risk of damaging their careers.

In the distant past, biomedical scientists could master all the relevant research fields needed to be productive scientists, for example, physiology, pharmacology, anatomy, and genetics. Such scientists toiled away in their academic laboratories, talking to each other in the hallways or at scientific meetings with like-minded academic researchers. And with that experience, they could be successful in conducting cutting-edge research. Now, to be successful, scientists need to collaborate simultaneously with colleagues in academe, industry, nonprofit organizations, patient groups, and government in the United States and around the world.

The need for collaboration is a result of changes in the health-science research enterprise, which depends increasingly on nontypical biomedical disciplines. Engineering, mathematics, and computational science are now essential. The scientific disciplines, which used to be learned as separate subjects, are increasingly overlapping and complementary. For example, it is now hard to work in genomics without competence in computer-based data analytics. To formulate and test hypotheses, scientists increasingly need to be knowledgeable about and able to apply the skills from not only their own fields but many other fields. That is particularly true of the emerging discipline of translational research, which sits in the space between basic discovery and "first-in-humans" clinical studies.

Translational research itself has its own methodology (Emmert-Buck, 2014; Trochim et al., 2011; Fang and Casadevall, 2010) and is essential for moving a discovery into an innovation in health care. Today, the most often cited obstacle to the development of novel and more successful therapies is the general lack of a deep understanding of human pathogenesis. For example, after a century, we still do not understand the fundamental causes of diabetes. We can control the disease in some patients, but it progresses inexorably in the large majority of them. The tools and methods arising from the extraordinary progress of the basic sciences—such as genomics, proteomics, and many other advances of the last few decades—need to be applied directly to large patient cohorts who are followed for years. The tools are available, but where are the trained physicians and scientists who will dedicate their lives to such long and difficult explorations and be free of the need to generate large revenues from an increasingly cost-conscious academic health system?

The traditional disciplines of population and behavioral research are also increasingly important. Data from those disciplines have become crucial for even basic science in helping to devise testable hypotheses and identify precisely the patients who would benefit most from existing or new therapies.

The necessity for collaboration is driving new ways of working together. Research has moved from solely a single-investigator model to include team-based science and multidisciplinary and interdisciplinary research. The collaborative approach itself is not based on a single model. For example, team-based research in academe, where the outcome is new knowledge, can be different from team-based research in industry, where the output is a product. Current training programs fail to help young researchers to understand and appreciate the difference between working in academe and working in industry; academe-based training and industry-based training do not comingle enough to allow young researchers to appreciate the differences first-hand. The situation is exacerbated by the perception that industry tends to act primarily in its own interest and often underinvests in R&D. Some argue that industry does not work for the greater good of the scientific enterprise or society. In fact, at a time when public funding for scientists is unstable, it is important to be aware that industry invests much more in R&D than does NIH—by at least $10 billion a year (Powaleny, 2016). The absence of industry experience aggravates the false perception and can keep the best and brightest out of this crucial component of the innovation pipeline. Ironically, it is happening at a time when industry is moving to an external-innovation model, in which much innovation is derived from work with small companies or academics rather than from internal research in industry-owned laboratories.

For all the reasons described above, we need to move from reliance on the old view of scientific training to a new view that takes into account the complexity of biology and the changed environment. No single training pathway is the answer; flexibility and adaptability to the needs of trainees will be essential for success. Most important is the need for incentives for academic institutions to change the scientific culture and be open to new models of training.

That said, large-scale changes in our training systems and infrastructure are probably not all possible at once, certainly not within current national budget constraints. Nevertheless, there are many opportunities for true training innovation. The question is, Which innovations would have the greatest near-term or long-term impact?

At one time, we had only anecdotes to help us to understand how students found their way to careers in scientific research. Today, we have several decades of research to illuminate the importance of early school-based science training, informal out-of-school science experiences, information about careers in science, parental support, and other factors (NRC, 2011). The short scenarios in the section above are intended to be simple illustrations, but available data support the common intuition that students who have access to a robust set of early science experiences are more likely to have scientific careers than are students who do not receive such access (NIH, 2014). As we seek a robust set of pathways into the health-sciences research workforce, how can we ensure that we are supporting students (K–12, undergraduate, and graduate) by making them aware of specific opportunities in the health-sciences research enterprise? How can we be sure that we are reducing barriers to success and linking students to the jobs and careers where there is unmet demand?

In recent years, steps have been taken to correct the cacophony of K–12 educational standards and curricula that characterized the American education system for many decades. The Common Core Standards and the Next Generation Science Standards (NGSS, 2016b) are available for states to use voluntarily. By using them, states can elect to collaborate in curricular materials and student assessments. Such collaboration offers substantial opportunities for cost savings. The standards, although far from perfect, constitute a substantial improvement on what most states had in place before their adoption. The mathematics and science standards (NGA and CCSSO, 2010; NGSS, 2013) will require periodic revision, and the scientific community should remain ready to assist in this process as the National Academy of Sciences did when it played an important role in the draft document that led to the NGSS (NGSS, 2016a; NRC, 2012a).

Exposing students at all levels of education to the wide variety of health-science careers available in industry and policy, as well as academe, will make it easier for them to envision themselves working in these settings. Students able to see themselves in a particular career early are far more likely to prepare themselves for it. Recruitment efforts would benefit from coordinated public–private initiatives. In today's economy, many students (and their parents) are concerned about the availability of well-paying jobs at the end of a particular educational pipeline.

In all sectors and at all levels of biomedical science, there is an urgent need to improve the diversity of the workforce. A diverse scientific workforce will improve our efforts to explore the whole array of health issues that affect our diverse demographics. And yet, while the number of women in science has been rising in the last 2 decades, the number of minority-group members remains unacceptably low (NSF, 2015). Clearly, we must do much more to attract and retain underrepresented minorities to STEM education (NAS et al., 2011). Some suggest that despite the desire of many institutions to increase faculty diversity, many minority-group students are unsure how to navigate the job-hiring process or choose to move to higher-paying positions outside academic research. To that end, it may be necessary to develop plans for mentoring for these students to help them to transition from doctoral studies into research positions in the academic workforce.

In sum, changes in high-school STEM will require complementary federal, state, and local efforts, perhaps with the new US president working with governors to stimulate new initiatives. That will be especially important in light of budget crunches that force states to cut education budgets. Federal matching grants could be an incentive for states to invest.

What opportunities exist at the undergraduate and graduate levels to address the problems that we have articulated here? For example, should there be a reinvigoration of master's programs, especially in such fields as statistics and computer science, in which a PhD may not be necessary? Should we consider programs similar to those in Europe (Martinho, 2012), where especially talented students go straight from high school to MD or PhD programs or where parts of undergraduate and doctoral training are condensed? It would certainly be feasible to consider national programs, perhaps supported by federal or state grants, which give more undergraduate students summer research experiences. Why not create accelerated pathways for the most gifted students, especially members of underrepresented minority groups, rather than impose the same programs on all, primarily for the purposes of credentialing?

It is undeniable that the debt burden amassed by a student pursuing a high-level credential in science in this country is substantial and is a disincentive to pursuing such a path (Zelser et al., 2013). Is it time to consider debt forgiveness for students completing PhDs in some high-need fields, such as bioinformatics? Another big problem is the lack of faculty (Sainani, 2015; Dinsdale et al., 2015), especially in the United States, to train bioinformaticians and biostatisticians. In the nation's graduate schools, including medical schools, the opportunity to take courses in biostatistics and bioinformatics is limited by the lack of adequate qualified staff to teach them. There is such a high demand for those skills that schools cannot keep up. Would government support for master's-program students, especially in disciplines with shortages, such as biostatistics, help to meet the need for more faculty?

With all the evidence of problems in the system, it should not be surprising that there has been no lack of initiatives aimed at solving at least some of them. But there has been no comprehensive examination of outcomes. Federal STEM programs have involved projects at different stages of development. For some, innovation and initial prototype development are the goal; for others, scalability and effects need to be evaluated. It is important to understand not only what works but why it works and what appears not to be working and why. Governmentwide evaluation funds should be used to create an educational knowledge base for the benefit of future programs and interventions. For example, what can be learned from existing undergraduate research programs, including the National Science Foundation (NSF) Research Experiences for Undergraduates program (NSF, 2016b)? How can we build on successful diversity initiatives, such as the NIH Building Infrastructure Leading to Diversity initiative (NIH, 2016a; NIH 2016b), The University of Maryland, Baltimore County Meyerhoff and Howard Hughes Medical Institute–funded adaptation (UMBC, 2016; HHMI, 2014), and relevant NSF programs (NSF, 2016a)? Are there programs that are working well but could be improved, such as NIH's Broadening Experiences in Scientific Training (BEST, 2016), Pathways to Independence (K99-R00) (NIH, 2016e), Early Independence Awards (NIH, 2016d), F32 (NIH, 2016c), and T32 awards (NIH, 2016f)? We need to know which programs should be expanded and which could or should be ended. In creating new programs, one always needs to look for ways to prevent the tendency for programs, once put into place, to stay forever—long past their utility.

The discussion above articulates many of the initiatives that could be considered in an effort to optimize the 21st century scientific workforce. They have been presented to illustrate the breadth of issues and to draw attention to some solutions that could address them. However, it could be argued that if we try to change everything at once, we will end up changing nothing. Rather, a realistic approach to change is needed—change that will not require wholesale reinvention of the current system. We must focus on the biggest problems and try to make immediate and pragmatic changes, which are likely to promise lasting effects.

Policy Suggestions

A visible response to ensure the future competitiveness of the country by creating a new generation of innovators in the life sciences is of strategic importance. The life sciences will undoubtedly embody the largest economic opportunity for growth of novel solutions for addressing disease and disability and for control of runaway health-care costs and burdens. We do not have the full array of programs that will ensure that the best and brightest pursue, and do not deviate from, careers in biomedical research. We need to ensure that these young people have the opportunity to realize their most creative ideas with all the support and encouragement required. We must work at all levels simultaneously to instigate change. Below are two policy suggestions that taken together could make a critical difference in the nation's ability to tackle the challenges of creating and supporting a truly 21st century health-science workforce.

BOX 1
Sample High School Initiatives

- Create biology-related curricula in computer-science classes.
- Create opportunities to take on-line college courses for credit in such subjects as computer science where appropriate courses or appropriately qualified teachers are not available locally.
- Ensure that all federal science-mission agencies play a formal role in improving the nation's high-school education system via appropriate authorizing language.
- Create "science-teaching fellows" who work in high schools with the most talented students.
- Provide more early school-based science training, informal out-of-school science experiences, and information about careers in science.
- Provide federal matching grants as an incentive for state investment in innovative science curricula for the best and brightest.

BOX 2
College and Graduate Initiatives

- Create more master's programs, especially in such fields as statistics and computer science.
- Explore programs in which especially talented students go straight from high school to MD and PhD programs.
- Create programs in which parts of college and doctoral training are condensed.
- Provide debt-forgiveness programs for students who are working toward master's degrees or doctorates in some high-need fields, such as bioinformatics and biostatistics.
- Provide federal training and research support for the best and brightest master's and doctoral students who are interested in health-services research and public-health research.
- Create more master's programs, such as programs like the Sloan Professional Science Master's program, focused on multidisciplinary approaches to problem-solving.
- Expand on existing industrial postdoctoral and other internship experiences, such as the NIH T32 and F32 training programs.
- Provide incentives to identify the best and brightest members of underrepresented minority groups and women in high school and college.
- Set time limits on institutions for the maximum duration of PhD training.
- Change the Office of Management and Budget indirect-cost calculation for NIH-funded universities on the basis of time to first independent job for postdoctoral fellows.
- Create new mechanisms to promote careers as staff scientists (non-tenured with no teaching responsibility) in academic settings.
- Create a new Entrepreneurship Division in NSF or the Department of Commerce to provide postdoctoral fellows with startup funds.
- Provide incentives for 4-year colleges to work with community colleges for early identification of science interest and talent.
- Create new programs for medical students and residents to have the time and resources to conduct research.
- Expand community-college and college programs that create opportunities for exceptional students who have suffered from weak K–12 experiences.
- Create programs to help students, particularly minority-group students, who need guidance on completion of a doctorate or postdoctoral fellowship as to how to navigate the job hiring process.

A NextGen Opportunity Fund

The president could create a NextGen Opportunity Fund, whose resources come from a 2% set-aside from the appropriations of each relevant federal health, science, or education agency, which could rise to as much as 5% over the next decade as it is evaluated for impact. Strategic use of the funds would be guided by a presidential panel that comprises heads of federal agencies and divisions, state governors, and representatives of academe, payers, providers, industry, and patient groups. It would function under the aegis of the Office of Science and Technology Policy's National Science and Technology Council Committee on Science. Resources would be used to expand current programs and create newer, more focused opportunities in relevant federal agencies. The goal is to attract the most talented into biomedical research, train them for the 21st century, foster their creativity, and ensure that they become independent researchers earlier. The programs would ensure that the next generation of health scientists is multidisciplinary, collaborative, and working in an environment that fosters their most creative ideas.

The opportunity fund could be used to support existing and new programs at the federal and state levels to train the brightest aspiring scientists with the goal of engaging them in urgent improvement of the nation's health.

The fund should be an incentive for the nation's governors and K–12 educators to ensure that the most talented students are given the opportunity and encouragement to excel (see Box 1 for sample programs). Working with academe and through federal agencies, it should also be used for creating new incentives to shorten the time from undergraduate and graduate training to independence (see Box 2 for sample programs).

All new programs funded in this manner should have a 10-year limit with an opportunity to renew after favorable evaluation.

The Health-Science Corps for the 21st Century

The profile of health scientists will need to be different in the future from today. To that end, an additional policy approach to training the next generation of health scientists could be to create a National Health-Science Corps for the 21st Century. The corps could be funded either from the NextGen Opportunity Fund described above or through appropriations directly to relevant federal agencies and departments. The mission of the corps would be to address the lack of high-school exposure to the best science by the best teachers; the unjustified lengthening of our postgraduate training system with poorly defined career pathways even for promising scientists who today do not reach independence until their late 30s; the increasing financial burden of a scientific education with unsustainable student debt levels that forces many, especially members of underrepresented minorities, to forgo scientific careers; and the persistence of rigid disciplinary silos that make the multidisciplinary training and research experience more difficult and longer than necessary.

Admission to the corps would be highly competitive. Such an "army of innovators" would be nurtured at all stages of career development, from high school to early independence. This cohesive program would provide customized opportunities for members of the corps with the singular goal of turning out highly trained independent scientists ready to contribute to improvements in health. The program would address all educational levels, with corps members being admitted to the program as early as high school and as late as postdoctoral fellowship and medical residency. Corps members would be assessed regularly to evaluate progress and success. People entering the corps would be able to participate in advanced curricula designed to speed their trajectory toward becoming independent scientists. For example, new programs might include opportunities for high-school students to take college classes in computer science for credit and to do it while replacing, for example, a history requirement. Undergraduate colleges could be required to provide corps members the opportunity to conduct 4 years of hypothesis-driven research with a mentor in an assigned laboratory.

Unlike programs that address different phases of the career pipeline independently, this program would address the big picture by pushing forward at all stages of the scientific workforce simultaneously, ensuring continuity for the best and the brightest as they progress from high school through postdoctoral work and residency. Thus, the program would serve as an umbrella for all phases of science education, training, and early career development. It could draw on and include existing programs as necessary and appropriate.

Relevant agencies, state governors, and the private sector should be responsible for operationalizing the corps, that is, designing the programs that would deliver the expected outcomes (see Boxes 1 and 2 for possible initiatives). Plans for evaluation would be designed so that the most effective aspects of the corps could be continued and others discontinued, as needed.

Conclusion

The scientific workforce of the 21st century will be different from that of the 20th: it must be more diverse and multidisciplinary. Many workforce initiatives to date have involved directing existing federal and some private-sector investment into agency or foundation initiatives. We have trod that path before. The BIO2010 report (NRC, 2003) and Rising Above the Gathering Storm (NAS et al., 2007), both raised many of the issues addressed here.

Efforts to instigate change, however, have been uneven and have lacked cohesiveness. We cannot allow history to repeat itself, so we respectfully put forth these proposals that would immediately and persistently change the training landscape in the United States. The absence of such bold moves would put the nation at risk. Historically, presidents have changed the fortunes of the nation by launching specific initiatives, such as the GI Bill and the space program. We are at a comparable historical juncture with regard to the life sciences in this century.

Motivated and talented human capital is the core determinant of national competitiveness. Nothing is more critical than ensuring that our next generation of health scientists accomplishes even more than the current one. It will require courage, perseverance, and leadership at the highest levels of the nation.

Summary Recommendations for Vital Directions

1. Establish a NextGen Opportunity Fund.
2. Create a Health-Science Corps for the 21st Century.

Endnote

1. The results of the 2012 Program for International Student Assessment (PISA) study conducted by OECD ranked US high-school students 27th in mathematics among the 34 OECD member nations. In the same study, US students placed 17th in reading skills and 20th in science. Overall, that means that our high-school students score at or below the international mean in the key measures of academic readiness. Shanghai, China (not an OECD member nation), was the top international performer in mathematics. Shanghai's average score placed it more than 2 full school years ahead of the average in Massachusetts (one of the top-performing US states). Setting aside average performance and focusing instead on top-performing students does not provide much solace. About 2% of US high-school students score at the highest level of mathematical achievement—compared with an OECD average of 3% and Shanghai's standout performance of 31%. America has to aspire to be more than "average" to have any chance of retaining its position as a world leader in STEM (OECD, 2014).

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