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SCIENCE AND SOCIETY

Is There Value in Training Scientific Generalists For Positions at the Edge of Academia?

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Contemporary scientific research faces major cultural and institutional hurdles. Some of the primary challenges include an exploding knowledge base and organizational complexity of many scientific projects, the overproduction of PhDs relative to the availability of faculty positions, and protracted educational trajectories for many aspiring researchers. Perhaps the most serious set of consequences caused by the fierce competition of modern science are low rates of reproducibility in research studies across many disciplines, a startling reality which undermines the scientific process and institutional authority itself. In an increasingly interconnected intellectual world, where fundamental and applied research are deeply interwoven, the implications of this state of affairs extend well beyond the research laboratory. In this article, I explore one possible strategy among the many necessary interventions for addressing these critical global issues, namely, new graduate programs to train scientific generalists. Rather than focus on developing niche technical skills, these programs would train outstanding communicators and decision makers who have been exposed to multiple subjects at the graduate level. The motivation for creating such programs is to introduce a large number of exceptionally trained individuals across all industries and organizations who have been encouraged to think critically about the practical realities and contemporary cultural trends of scientific research. I suggest possible avenues for structuring such programs and examine the roles that generalists might play in the modern research, policy, and industrial landscape.

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INTRODUCTION

The explosion of scientific knowledge after the Second World War has progressed hand in hand with an increasing trend towards specialization in the training of scientists (Bode et al. 1949; Bush 1945). This trend is hardly surprising and is perhaps an inevitability. As scientific advances build upon previous understanding, individuals who aim to work on the frontiers of research must progress through many levels of knowledge acquisition and training before they can become leaders in the field and supervise their own students.

On the other hand, it is worth considering if there are negative ramifications to the intense focus on specialization in modern graduate education. As the number of individuals pursuing a scientific education has increased, and the global capacity for research output has increased, the organizational and cultural complexity of the scientific enterprise has also increased. For instance, there is a greater demand for high-level scientific decision makers, whether in the guise of journal editors, program managers at government agencies, or chief technology and chief scientific officers at startup companies. The ideal skill set of these individuals is not necessarily aligned with the skills of the best scientific specialists.

The trend towards specialization can be taken as a lens with which to view 3 broad problems characterizing modern science. The first I have already stated, namely the need for a new scientific niche with individuals possessing advanced technical knowledge, but whose day to day responsibilities are not necessarily aimed at advancing fundamental research objectives. The second is the extremely protracted educational trajectories for many aspiring researchers, a large percentage of whom abandon research careers entirely (Alberts et al. 2014).

But the most alarming problem that the size, complexity, and competitiveness of modern science has given rise to is the "crisis of reproducibility," which has manifested itself most strongly in the bio-medical sciences. In the widely cited article "Why most published research findings are false" Stanford physician and health policy researcher John Ionnidis writes[i]:

> *There is increasing concern that most current published research findings are false. The probability that a research claim is true may depend on study power and bias, the number of other studies on the same question, and, importantly, the ratio of true to no relationships among the relationships probed in each scientific field. In this framework, a research finding is less likely to be true when the studies conducted in a field are smaller; when effect sizes are smaller; when there is a greater number and lesser preselection of tested relationships; where there is greater flexibility in designs, definitions, outcomes, and analytical modes; when there is greater financial and other interest and prejudice; and when more teams are involved in a scientific field in chase of statistical significance. Simulations show that for most study designs and settings, it is more likely for a research claim to be false than true. Moreover, for many current scientific fields, claimed research findings may often be simply accurate measures of the prevailing bias (Ioannidis 2005).*

Richard Horton, editor of the British medical journal *The Lancet*, echoed this sentiment in a recent article:

> *The case against science is straightforward: much of the scientific literature, perhaps half, may simply be untrue**[ii]**. Afflicted by studies with small sample sizes, tiny effects, invalid exploratory analyses, and flagrant conflicts of interest, together with an obsession for pursuing fashionable trends of dubious importance, science has taken a turn towards darkness. As one participant [of a recent workshop] put it, "poor methods get results" (Horton 2015).*

The connection between a questionable scientific knowledge base and broader social and global issues hardly needs to be stated. Science and technology are shaping the world at an ever accelerating pace, from the possibility of fully autonomous vehicular infrastructures, to ultra low-cost gene sequencing, to world-wide access to wireless and high-speed Internet, to space exploration. At earlier periods in the growth trajectory of institutional science, academic problems might have been more confined to the university system itself. However, as scientific and technological developments have come to have an increasingly widespread impact through applied and translational research, foundational problems in the scientific enterprise can have significantly broader consequences. For instance, one of the recent analyses that uncovered a large number of irreproducible research studies in cancer biology was led by a pharmaceutical company (Begley and Ellis 2012). In examining these recent trends and looking to the future growth of scientific research, it is worth considering if at many levels of organizational administration, whether in university science departments, state and federal governments, scientific journals, or international health organizations, there should be a critical mass of scientific decision makers who have been broadly educated and who are unfazed at the prospect of navigating both the intellectual and human complexity of the global scientific enterprise and its connections outside of academia[iii].

The issues raised above are significant contemporary topics for debate and are giving rise to active reforms in many aspects of the scientific process. From online-only, open-access publications, to reproducibility initiatives, to code-sharing and data hosting by scientific journals, the growing awareness of the problems facing modern science are increasingly on the forefront of the minds of many educated people and key decision makers at universities, journals, and funding agencies (See for example, the *Nature* special issue "Challenges in Irreproducible Research" (Campbell 2015)).

However, many of these changes are procedural in nature. They are analogous to the role that checklists have played in ensuring safety and reliability in many industries (Gawande 2010). In other words, many of these reforms- which are quite necessary- are aimed at ensuring that individuals are adhering to the known procedures and protocols of established scientific understanding. The perspective of this article is that in addition to these changes, there is a pressing need to enact long-term, organic changes to scientific culture of sufficient depth to address both present and future needs, and in particular, the needs of organizations at the edge of academia.

For instance, even without issues of reproducibility, an exploding knowledge base can create problems for policy makers or other high-level decision makers in other industries and organizations (venture capitalists, consultants, journal editors, or CTOs at technology companies, for example) if the the larger consequences of the most recent scientific advances are difficult to understand or to distill into plain language. In addition, the significant growth of university research has resulted in numerous practical and at times mundane academic realities, often localized to specific subjects, that outsiders may simply not be aware of. These are epistemic obstacles that are not directly addressed by reforms to the journal system or to the incentive structure of academic research. In other words, these reforms do not address the downstream consequences to industry and other organizations on the periphery of academic research.

The strategy that I focus on in this article is to examine the knowledge base, personalities, and intellectual outlook of individuals who have gone through advanced graduate training in the sciences and ultimately ended up in positions at the edge of academia. A major premise of this article is that there are already scientific generalists at the edge of academia. They simply take a very long time to get there, and along the way, acquire a significant amount of highly-specialized knowledge that they will never use. Therefore, I propose the creation of more time-efficient programs to train scientific generalists, that is, individuals who in addition to specialized training in a single field, are given broad exposure to multiple subjects at the graduate level.

RELATIONSHIP TO PREVIOUS PROPOSALS

The size and complexity of modern science and its accelerating impact outside of the research laboratory strongly suggests the need for scientists whose training has been designed to encourage strategic thinking about the big picture and competent decision making, rather than specific technical skills. No doubt such individuals need to have advanced technical knowledge, but it should be of a broad nature, rather than narrowly focused on the most recent developments in a specific subject. In addition, by encouraging students to think about big picture, organizational and policy issues from an early age, their technical skills will be organically integrated into a larger world-view, rather than focused on narrow research advances. In the long run, over the course of many years and decades, a critical mass of such individuals would play a significant role in shaping the ongoing evolution of scientific culture.

In a previous article (Sarma 2016), I examined the issue of training generalists by proposing the creation of a new set of graduate programs that would augment the structure of a normal PhD. Inspired by the structure of an MD/PhD, the proposal I made there was to add an additional component to a traditional PhD wherein a student prepares for and passes graduate level qualifying examinations in multiple subjects. Somewhat arbitrarily, but with an attempt to create a program roughly on par with an 8-9 year MD/PhD, I suggested 5 total qualifying examinations, 1 in the home department of the PhD, and 4 in additional subjects.

There is little doubt that such a program would be deeply demanding and few students would be capable of handling such an intense academic load. My personal opinion is that even a small number of such candidates would be in a position to have widespread impact. In informal discussions with classmates, I have been surprised to discover the level of enthusiasm many students expressed when presented with this idea, going as far as to say that they certainly would have applied for such a PhD program had one existed. Subsequently, I have found both students and senior researchers sympathetic to the idea of “scientific generalists,” and there have been a trickle of editorials in the popular press suggesting ideas along these lines and examining related issues in contemporary scientific culture (Bradben and others 2014; Arbesman 2013).

One of the fundamental aspects of this proposal when dissected into its constituent parts is the role of the qualifying examination. After several generations of scientific growth, we have arrived at a number of highly structured and modular examinations for testing- thereby effectively teaching- advanced scientific knowledge, from qualifying examinations in scientific subjects, to board examinations in pre-clinical and clinical medicine. If we look back on scientific history, there was a time when exactly 2 people knew differential and integral calculus, when one person could perform the intricate calculations of general relativity, and when only a handful could calculate the energy spectrum of a quantum harmonic oscillator. Yet these once advanced subjects are now considered basic knowledge in theoretical physics, and thousands upon thousands of students have passed qualifying examinations by preparing with many tens of thousands of practice questions honed from decades of thoughtful pedagogy and instructional materials created by researchers and instructors. The situation is only more saturated in today's world with the quantity of exceptionally high quality material from a wide variety of subjects freely available online and through novel educational initiatives being launched by universities and private companies. What might we create by integrating this more advanced knowledge into a single, efficiently designed graduate level program? In this context, the goal is not to train researchers with highly specialized interdisciplinary knowledge- that is already happening. Rather, the goal is to organically strengthen institutional culture over the long term by creating a critical mass of individuals with broad knowledge at a more advanced level than current programs are designed to instill.

Therefore, I mention at the outset that the present article should be viewed as a direct extension of the ideas proposed previously in (Sarma 2016). In reflecting on the conversations inspired by that proposal, I wanted to examine what would be possible by structuring a graduate program that was similar in spirit, but that would be more time-efficient and more achievable. The resulting program, which I describe below, achieves this balance by reducing or leaving open-ended the breadth of the set of qualifying examinations (potentially depending on the student), reducing the research component of the program, and in addition, ensuring that the students have an immediately employable skill set relevant to the contemporary job market outside of tenure-track research faculty positions. I describe the details of this modified proposal in more depth below. I hope it is clear to the reader that the proposals made in both of these articles are as much intended to be a means to stimulate discussion and draw attention to these critical issues as they are specific proposals to be readily implemented.

GRADUATE PROGRAMS TO TRAIN GENERALISTS FOR NON-RESEARCH POSITIONS

Below, I list a number of possible criteria for guiding the development of such a program:

1. The program should expose students to the basic vocabulary of multiple subjects at a graduate level.

2. Students should be able to read cutting edge scientific literature across a number of different subjects and ask strategic questions.

3. Students should develop a broad network of relationships across multiple academic subjects, industry, and policy. They should have the capacity to quickly organize teams to solve problems that are beyond their own capacity to solve, and to leverage the abilities and knowledge of individuals in their network.

4. Students should be part of a research laboratory during their PhD and have conducted research of sufficient depth to write a masters-level thesis.

5. Students should have conducted a significant in-depth analysis of a scientific issue of historical or policy significance and write a masters-level thesis on the topic.

6. Students should have a rich appreciation of the diversity of scientific culture spanning different subjects and the historical forces that shaped modern science.

7. Students should have immediately employable skills and should not need additional training

to be competitive in a job market.

8. Students should be well-positioned to gain additional training if they deem it necessary.

9. Students should have the means to forge their own path, find non-traditional niches, play key leadership roles and manage interdisciplinary teams.

10. The program should be highly structured, and should not extend longer than 4 - 6 years. Those who are interested in pursuing more in depth research oriented careers should be well-positioned to transfer at any point in the process to a traditional PhD program, or perhaps pursue extended post-doctoral research after the completion of their PhD.

As one possible means to structure a program which fulfills the above criteria, I propose the following. The program would give students broad exposure to multiple subjects at the graduate level via a series of oral qualifying examinations. In addition, the student would complete a masters-level research thesis in an area of specialization, a masters-level thesis on a topic of historical or policy relevance, and complete at least one internship in industry or government. In terms of immediately employable skills, a core part of the program, including pre-requisites for admittance, would be sufficiently developed computer science and statistics knowledge to be hired as software engineers or data-scientists.[iv] Many of these skills would be developed during their coursework and self-study leading to the qualifying examination, as well as during their research.

Let us now examine this program in more detail. I begin with the criteria for admissions. The ideal candidate will have an exceptional record in a double major, or at the very least, demonstrable competence at the upper undergraduate level in multiple scientific subjects. For example, someone who majored in physics and computer science, did summer research in physics, and also interned at a software company would be an ideal candidate. Likewise, a student who pursued a major in biology, a minor in statistics, did research in computational biology, and an internship at a bio-technology venture capital firm would also be an ideal candidate. Given that the aim of the program is to train students who are immediately employable as software engineers or data scientists, I would expect all students to enter with a minimum of 1 year of computer science coursework at the undergraduate level, a knowledge base which will continue to be developed during their PhD.

Next, I discuss the qualifying examination. Qualifying examinations, whether in oral or written form, are a standard part of any PhD program and are typically considered an important rite of passage in the development of scientific expertise. While most do not consider the knowledge tested in qualifying examinations to be at the level of cutting-edge research in a subject, this knowledge base consists of the basic vocabulary required to continue further along the path to developing research expertise. In addition to specific factual knowledge or problem solving strategies, the period of coursework and study leading up to the qualifying exam typically encompasses a critical initial phase in the development of scientific maturity.

The model I propose for the qualifying examination is inspired by the “100 questions” system employed at the California Institute of Technology in the Computation and Neural Systems PhD program, an interdisciplinary program aimed at training broadly educated researchers in the brain sciences. At the beginning of the program, students in the CNS department are given a list of 100 questions across a wide variety of topics in neurobiology, physics, computer science, cognitive science, etc. Over the course of the first year, through coursework and self-study, students explore these questions after which they complete an oral qualifying examination conducted by multiple faculty members.

I believe that the CNS qualifying examination system provides an excellent model for a program aimed at training generalists. To begin with, a student would define several broad areas of interest where they intend to pursue coursework and develop a basic graduate level understanding. For instance, a student whose research thesis would be in neuroscience might choose physics, statistics, and economics, with the ultimate aim of working in venture capital and biotechnology. A student whose research thesis is in materials science might choose mechanical engineering, computer science, and environmental engineering, with the aim of working at a government energy research laboratory. Students would then be given a list of several hundred questions to study over the course of 18 months - 2 years, after which they would have multiple oral qualifying examinations with relevant faculty.

What would be the value in having students pass multiple qualifying examinations? In addition to acquiring a broad knowledge base, one of the primary aims of this program would be to expose students to the different cultures and practices of different subjects. It is surprising how different closely related subjects can be, whether pure mathematics and theoretical physics, economics and statistics, or theoretical and experimental biology. Often times the subtle or not-so-subtle differences in these subjects can give rise to significant inter-subject tension and culture clashes. The aim of the multi-faceted qualifying examination system would be for students to be immersed in these cultures simultaneously and from the very beginning of their graduate education. Furthermore, by structuring the qualifying examination around an open ended, several hundred questions model, much of their learning should take place through seeking out research literature, teaching assistants, and faculty spread across multiple departments, as well as graduate students who are full-time members of a single department. These experiences will further expose them to the cultural differences between different subjects and allow them to develop a diverse professional network- the latter being a critical aspect of their subsequent career development. Ultimately, the development of their technical knowledge base should be in the context of an “anthropological” exposure to different scientific fields.

During the period of coursework and leading up to the qualifying examination, students would join a laboratory and begin to familiarize themselves with ongoing research in the group. For the purposes of this program, I believe that the completion of a single, substantial research project would be sufficient, perhaps comparable to a masters-level thesis. In addition, students would complete a masters-level thesis on a topic of historical or policy relevance. The purpose of this non-technical thesis would be to instill in students the notion that there is no “right” way of constructing a scientific infrastructure. They should have a deep appreciation for the cultural diversity of science and of the historical forces, deliberate or incidental, that shaped the modern research enterprise. Rather than focus on the most novel, cutting edge results, their mindset should be oriented towards the long-term future, to constantly think about the ramifications on the time-scale of decades and generations of current institutional decisions. Finally, internships outside of the university system should play an important role in such a program. Whether working at scientific journals, funding agencies, industrial research labs, or venture capital firms, students need to be exposed from an early stage in their career to situations and organizations where technical knowledge is necessary for high-level decision making. Non-academic internships will also play the role of helping these students develop their professional network, a critical facet of being a key decision maker in the global scientific landscape.

To review, the completion of the PhD program will require the following:

1. Successfully passing the qualifying examination, which encompasses multiple subjects.

2. A masters-level research thesis on a scientific topic conducted under the supervision of a research mentor. Although their responsibilities will be structured differently than other PhD students, they should be part of a laboratory for the duration of their PhD, attend group meetings, and develop their understanding of the specific research field.

3. A masters-level thesis on a topic of historical or policy relevance. This research will also be conducted under the supervision of a mentor, possibly different from their laboratory research mentor.

4. At least one internship at an organization of their choosing. Although the internship should not be at a university, the nature of the work might overlap with either of the two theses required for awarding the degree.

5. Through their undergraduate preparation and through the knowledge gained via preparation for the qualifying examination, and possibly other aspects of their research and internships, students should have the skills to be immediately employable as software engineers or data scientists. Program supervisors should ensure that students have the appropriate skills in these areas.

SOME RELEVANT ANECDOTES FROM MEDICINE

Depth versus breadth and high-volume curricula
I described the CNS “100 questions” model at the California Institute of Technology as a possible guide for structuring an oral qualifying examination system. Another relevant curricular model is the structure of the basic sciences portion of a traditional MD program. At American universities, a medical education roughly consists of two, 2-year programs, the first giving a broad overview of the basic sciences, and the second, a broad overview of the clinical sub-disciplines of medicine.

What is remarkable about the basic sciences curriculum is the volume of information that is taught and which is subsequently tested in a demanding 8-hour examination. It is very much a “generalists” education in the biological sciences, an education of sufficient breadth to give an appropriate foundation for subsequent clinical training. There is no doubt that cutting-edge research in any aspect of the basic sciences curriculum will be substantially more in depth than what medical students are presented with. However, this fact does not diminish from the substantive nature of the curriculum and the appropriate foundation that it provides for the type of decision making required of clinicians and clinician investigators.

I mention this example to raise the possibility of creating an intense and broad 2 year program analogous to the basic sciences curriculum of an MD which is tested in a similarly demanding fashion. The curriculum would need to have a significantly more technically oriented focus, but the outlook would be different than a curriculum designed to educate research specialists, and similar compromises would need to be made in terms of the depth of the material.

Another interesting possibility that this kind of curriculum raises would be for different universities to have different “brands” in terms of the training of scientific generalists. Whereas the structure of the basic sciences portion of the MD has a fairly well-defined motivation- the need to cover all of the organ systems of the human body, basic biochemistry, cell biology, etc.- the specific aim of the programs I describe here is much more open-ended. Consequently, it would be a rich opportunity for there to be a landscape of possible curricula for aspiring generalists, each reflecting the cultural and scientific outlook of different universities across the world.

The role of MD/PhD’s in a purely clinical context
The combined MD/PhD degree has existed since the 1950’s and was motivated by the belief that the standard 4-year medical curriculum is inadequate to train individuals whose work would lie at the intersection of clinical practice and fundamental research (Zemlo et al. 2000; Brass et al. 2010). As I mentioned at the outset of this article, the recognition of this need took place after the explosive growth of scientific research following the Second World War. Many medical schools now participate in the NIH-funded Medical Scientist Training Program (MSTP), allowing students pursuing combined degrees to be fully funded both for the MD and PhD portions of their education.

For the purpose of this article, I focus on the role that MD/PhDs play who ultimately choose *not* to pursue careers that bridge the gap between basic research and clinical work, which appears to be roughly in the range of 10-20% of MD/PhD graduates (Brass et al. 2010). The question one might ask is the following: what contributions can a person make who received such an intensive and extended education but who ultimately chose to pursue a purely clinical career?

What I have discovered in informal discussions with practicing physicians in a non-research context is that MD/PhD’s are often appreciated for their scientific maturity and greater depth of understanding and research experience, even if their PhD was not in a field directly relevant to their area of clinical practice. Even in a private practice setting, an MD/PhD may well play a critical leadership role in a field that is rapidly evolving and where up-to date knowledge of the research literature is a regular part of patient-care (such as oncology), and where the experience of having completed a PhD simply allows one to more easily assimilate novel developents of relevance to clinical practice.

I mention this analogy from medicine to suggest that there are many industries and organizations where individuals with a deeper level of advanced scientific knowledge would be appreciated and uniquely suited to play leadership roles. The structure of the program I have proposed here for training scientific generalists and its ultimate aim for other industries can be thought of as analogous to the role that MD/PhD's often play in a purely clinical, non-research context. By identifying these individuals at an earlier stage, the aim of the current proposal would be to shorten their educational trajectory and provide them with more targeted and relevant classroom and extra-curricular experiences.

OTHER CONTEMPORARY ANALOGUES

The idea for intensive curricula aimed at training generalists is not without precedent and there are a few programs today in this spirit. I list below several examples with which I am familiar- there may be others:

> **The core curriculum at the California Institute of Technology and Northwestern University's Integrated Science program**: Both of these programs require outstanding preparation at the secondary school level in order to provide an adequate foundation for an intensive undergraduate curriculum of substantial breadth conducted at an accelerated pace. Unlike the current proposal, these programs are at the undergraduate level and in that sense are in the spirit of the program described in (Bode et al. 1949). They do, however, provide good examples of the kind of preparation that would be required for the PhD program that I describe here.
>
> **The Cleveland Clinic's 5-year research track MD program**: The Cleveland Clinic's Lerner College of Medicine, a joint program between The Cleveland Clinic and Case-Western Reserve University is a program aimed at training physician-investigators in a more time-efficient manner than a traditional MD/PhD. The student body consists of a small, highly-selective class (only 32 students per year), all of whom participate in research for the duration of their degree, and who are ultimately awarded an MD with a Special Qualification in Biomedical Research. Some of the practical motivations of this program are unique to the challenges faced by the biomedical sciences, particularly, those faced by bench-to-bedside translational research in clinical medicine. For instance, all students at CCLM are awarded full-tuition scholarships. The aim is to ensure that those desiring to pursue academic, research-oriented careers will not opt out of this path out of need to repay student loans. I mention the Cleveland Clinic's unique program in the context of this article primarily because it aims to train clinician-investigators more efficiently than traditional MD/PhD programs. This is accomplished not only through the unique structure of the curriculum, but also by pre-selection of appropriately prepared and interested candidates, and the fact that every student in the program is involved in research, a critical facet of the program's intellectual culture.

Neither of the programs I cite here are motivated by the specific set of concerns that I set out to address in this article. I mention these programs here simply to ground the discussion in contemporary developments in the university system, as they do represent different aspects of the ways in which the complexity of modern science has woven its way into different fields, and the responses taken by different institutions.

ROLES FOR SCIENTIFIC GENERALISTS

The motivation for the current proposal is to envision a broad training that does not fit into a clear career path analogous to the tenure track at research universities. The ultimate aim is to organically strengthen scientific culture by training a critical mass of broad thinkers who have an impact in many different organizations, not simply by leading research groups.

As I have discussed, I expect that graduates of this program to be immediately employable as software engineers and data scientists. The choice of this knowledge base as defining the employable set of skills for generalists is that software and data science are emerging as nearly universal elements across all organizations and industries. Therefore, this core competency ensures that graduates of a generalist PhD program can traverse institutional boundaries and have a fundamental knowledge base that many organizations will find valuable, whether government research labs, consulting organizations, or NGOs working in the international health and development sector. Of course, there are many other possibilities for what might define an immediately employable set of skills- the program I describe here and the emphasis on data science is simply one possible way of fulfilling a more fundamental set of criteria motivated by broader scientific concerns. In addition, the other aspects of the program, including both the qualifying examination and research components certainly contribute to a set of employable skills- they are simply less defined. Programs could provide students with multiple options for how to fulfill this specific criterion- I hope this article serves as starting point for discussion as to what would constitute reasonable choices.

One would hope that many students would have as their primary career ambition to become journal editors, program managers, and scientific journalists. A large number of scientific generalists might also come to play a key role in novel journalistic practices such as a post-publication peer-review. One can easily imagine a new scientific niche emerging of scientific generalists whose reputation is developed on the basis of quality post-publication peer reviews. As journals evolve to the point where reviews themselves can be cited analogously to standalone publications, developing a reputation as a fair-minded and knowledgeable reviewer may come to play a role in an individual's career development.

As I wrote in the previous article, completing this PhD program is no more a sign that an individual is a mature scientific generalist than completion of a traditional PhD program is an indication that an individual is a mature specialist. This program would simply be the beginning of a life-long intellectual developmental trajectory, one that should follow a different path than that of research specialists. Indeed, the expectation would be that generalists continually strive to incorporate their ongoing work experience into an understanding of the big picture. They should be able to put together independent analyses of a wide variety of issues by creating compelling data-visualizations from open data sets. They should be able to analyze historical scientific information and collaborate with historians and sociologists to create narratives that explain why certain fields took the evolutionary turns that they did. They should be the ideal team members for investigating complicated scientific controversies, whether instances of scientific misconduct, helping to uncover subtle explanations in baffling new experimental results, or conducting forensic investigations in the case of major technological accidents.

Whether out of intrinsic curiosity and habit, or as a part of their professional responsibilities, graduates of these programs should be continually monitoring new organizational and social developments that are shaping science. They should be bloggers and occasional journalists, write well-informed and articulate review articles in publications intended for the educated public. They should have involvement with open science projects and help to lead fund raising efforts via crowd-sourcing platforms such as Kickstarter. In addition, I would hope that many would choose to become teachers at the elementary, middle, or secondary school level, play the role of intellectual leaders and communicators in their local communities, and mentor young, aspiring scientists.

CONCLUSION

The aim of this article is to draw attention to a critical set of issues relevant to scientifically informed policy, decision making, and culture in any industry and organization that depends directly or indirectly on academic research. These issues are 1) An exploding knowledge base resulting in an inherent complexity in understanding broader scientific trends and translating novel insights into actionable policy 2) The overproduction of PhD's relative to available faculty positions and extremely protracted graduate and post-doctoral education for many aspiring researchers 3) A severe "crisis of reproducibility" in which the veracity of large subsets of the research literature across multiple disciplines have been called into question.

Of the three issues raised above, it is the latter two that have received the most attention (Alberts et al. 2014; Ioannidis 2005; Steven and Sander 2007; Horton 2015; Campbell 2015). I suspect that this is largely due to the fact that these issues are more easily characterized. We can, for example, precisely state the number of PhD graduates in a specific field relative to the number of available faculty positions, or give crude estimates for rates of irreproducibility in a sub-discipline on the basis of sampling and attempting to reproduce key results.

On the other hand, the issues created by an exploding knowledge base and the trend towards specialization are more subtle and difficult to describe. Although these factors have almost certainly played a significant role in creating the circumstances surrounding the irreproducibility crisis, the precise contribution is not one that we can quantify, even crudely. Similarly, it is also difficult to precisely describe the reciprocal relationship and information flow between organizations firmly inside academia and those more on the periphery. Therefore, in addition to the many proposals for scientific reform being made today, I believe that a long-term strategy to organically strengthen scientific culture is to create graduate programs aimed at training scientific generalists targeted at positions at the edge of academia. Rather than focus on the development of niche technical skills, these programs would aim to train outstanding decision makers whose technical education has been guided by an effort to understand the big picture instead of advancing specific research outcomes.

The proposal in this article is an extension of a related set of ideas described in (Sarma 2016). The program I describe there consists of an augmented PhD program, where in addition to the normal requirements for a PhD, students would complete multiple qualifying examinations spanning several different fields. The motivation of the current proposal is related- namely, addressing the broad consequences of an exploding knowledge base and the trend towards extreme specialization- but with the intent of designing a program that would be more accessible to a wider array of students, which would not extend the length of a 4-6 year PhD, and which would give students an immediately employable skill set in a variety of industries outside of academia.

Therefore, while the program I describe here (in contrast to the previous proposal) would not train students to lead research groups at the frontiers of a discipline, it would give them advanced, graduate level knowledge of multiple scientific subjects, research experience, an opportunity to explore a topic of historical or policy relevance, and finally, immediately employable skills in data science or software engineering. Although the two programs I describe in these articles differ substantially in length and academic workload, as well as the intended career trajectories of graduates, I have used the term "scientific generalist" in both cases. If programs such as these were to be implemented, perhaps more precise terminology should be coined.

By creating a critical mass of scientific generalists spread across many industries, there would be an organic shift whereby sophisticated technical thinking and deep knowledge of the contemporary scientific process is simply more widespread. Some aspects of this knowledge might represent major, ongoing intellectual evolution in a field, such as novel theoretical developments relevant to practical statistics, other aspects might involve more mundane academic realities which are nonetheless of practical consequence. Such a shift would directly impact institutional decision making at any level and in any organization on the basis of novel scientific and technological advances. It is worth mentioning in this context that at liberal arts universities, many individuals choose their undergraduate and graduate degree programs not because of the specific employable skills of the degree, but because of the broad nature of the training and the opportunity to develop an informed world view and more refined thinking skills. The current proposal is in the spirit of this outlook, and I suspect that many students would find a 4-6 year graduate program that opened doors to any number of different industries without requiring additional training to be quite appealing.

With regards to the scarcity of faculty positions relative to the production of PhDs, in the contemporary research landscape, many individuals pursue extended graduate training and multiple post-docs, each lasting several years, and often end up abandoning their research ambitions in their late 30's. The irony is that the current academic situation has resulted in many outstanding, broadly educated thinkers who actively play the role of generalists in a number of different organizations. In other words, scientific generalists outside of academia already exist. In addition, the democratization of knowledge via the Internet has reduced the barrier of access to sophisticated technical literature, thereby allowing educated scientists to continue to develop their knowledge base, even after having left the university environment.

However, the unfortunate consequence of the status quo is an unnecessarily prolonged educational trajectory for many thousands of individuals who ultimately do not take advantage of the highly specialized nature of much of their training. By designing a shorter and more focused PhD program that from the outset is meant to train scientific leaders, organizers, and policy makers, we can both strengthen the global scientific infrastructure and reduce the burden of unnecessarily long educational trajectories for many talented individuals who ultimately do not pursue research careers.

Finally, the organic introduction of a critical mass of scientific generalists across many organizations and industries will have a positive and stabilizing role on the continuing evolution of scientific culture. There is little doubt that we will survive and move beyond the current "crisis of reproducibility." However, the fact that this situation has even arisen should be a cautionary tale reminding us that even the scientific process can be compromised. Programs to train scientific generalists should be one of several of long-term solutions to ensure a more resilient scientific establishment capable of handling future institutional obstacles.

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ENDNOTES

[i]Ionnidis’ analysis is not without controversy. See, for example, the response in (Steven and Sander 2007). The proposal in this article is largely independent of the specific details of this analysis.

[ii]One might argue that our reaction to the rate of irreproducibility of scientific research partly depends on how we view the research literature. If we view publications as stepping stones to more certain knowledge, then it might be reasonable to tolerate a high-rate of ultimately false conclusions. In other words, if we are simply abandoning previously held beliefs on the basis of newer, more refined, and more sophisticated knowledge, then we might choose to not be so alarmed that previous studies have subsequently been shown to be false. However, it does not appear that this is the situation we are confronted with. It is one thing for a theory to be displaced on the basis of more sophisticated understanding (for example, in areas of theoretical physics where experiments are difficult or costly to conduct), and it is another for a set of precise, laboratory procedures giving rise to concrete, immediately verifiable results not to be reproducible. One way to distinguish the two scenarios might be the time-scale on which the research in question is ultimately rejected. If we look back on research conducted several decades ago and conclude that 50% is false, we might attribute that to ordinary scientific progress. If, on the other hand, it turns out that 50% of the published literature in the previous calendar year is irreproducible, then it is quite certainly due to systemic institutional failures.

[iii]Narayanamurti, Odumosu, and Vinsel argue that we have traditionally underestimated the extent to which pure and applied research have been interwoven (Narayanamurti, Odumosu, and Vinsel 2013). The basic argument that they put forth is that there have been many occasions throughout scientific history where a technological advance preceded or went hand in hand with more fundamental theoretical understanding (as opposed to the other way around, as is traditionally thought), a critical example being Watt's steam engine, which was developed without an understanding of thermodynamics. Another example is the simultaneous discovery of the transistor effect alongside the development of the bipolar-contact transistor, which led to the 1956 Nobel Prize in physics being jointly awarded to Bardeen, Brattain, and Shockley. From these instances, they argue that the distinction between basic and applied research has always been a fundamentally flawed one, a mistake which has practical policy implications. Their perspective only reinforces the conclusions that I draw here-namely, the value of widespread, sophisticated technical understanding outside of the context of pure research in order to anticipate and guide future scientific and technological developments, from wherever they might appear.

[iv]Although I have chosen to emphasize data science and software engineering as the relevant employable skill set, there are certainly other alternatives, and I hope this article will stimulate discussion into the many possible ways one could structure programs that address the more fundamental concerns. I discuss the motivation for this choice in a subsequent section.