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Redesigning US STEM Doctoral Education to Create a National Workforce of Technical Leaders

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Abstract

The knowledge and technologies that move our society forward and preserve our international competitive advantage rely upon a highly skilled workforce that is adept at conducting complex scientific and technical research—and in translating its outcome into useful products and services. “Use-inspired” research is driven by specific needs and interests and naturally focuses on socioeconomically advantageous application, whereas academic research tends to be driven by an intrinsic quest for new knowledge. Each has its role in overall technological development, however, the skills and knowledge crucial for success in these domains can differ significantly. To integrate these two approaches in doctoral training in STEM fields, a national workshop of ~100 leaders of industry, academia, funding agencies and non-profits was held with the goal of developing a robust understanding of the current status of the pipeline from graduate degree programs in STEM into professional research environments. At the conclusion, the Workshop participants identified gaps in the present training of STEM doctorates. Then they endorsed the Pasteur Partners PhD (P3) track recently established at Lehigh University as a new model for student-centered workforce training based on use-inspired research in partnership with industry. Here, we present the key outcomes of the workshop and describe the four distinctive features of the P3 program: 1. Pre-program summer internship; 2. Co-advising of students by a university faculty member and an industry researcher; 3. Instructions for developing essential professional skills; 4. Industry Residency (as in medical school). In this context, ‘Industry’ is defined broadly to include private corporations, national labs, defense organizations, healthcare institutes, etc., which hire PhDs. Collectively, we consider this as a model for the much needed *redesigning of the US STEM doctoral education to create a national workforce of technical leaders*. Finally, challenges to the implementation of the P3 track are identified.

1. Background - recognition of problems with the current structure of STEM PhD in the USA

Graduate education has been considered to be a prerequisite for maintaining the country’s technological, economical and defense competitiveness in the world as well as societal well-being at home. In particular, STEM doctoral education is needed for preparing the next generation of educators who will ensure a well trained workforce and researchers who will generate scientific and technological knowledge for addressing society’s grand challenges. The current model of STEM PhD was designed at the end of World War II (WWII), when a report by Vannevar Bush [1] set the direction of federally funded scientific research in the USA. It considered curiosity-driven basic research as the starting point from which technological applications emerged through basic research → applied research → development → production → marketplace. This model of research as well as doctoral training appeared to work well when there was steady growth of basic research at private companies until the early 1990’s, the golden era of (corporate) research [2,3]. Then the US industrial research enterprise underwent restructuring and decline, as most notably exemplified by the demise or transformation of prominent industrial research labs due to withdrawal of resources for short term goals, such as, AT&T's Bell Labs, IBM's T.J. Watson Research Center, Xerox's PARC, etc.

The large upheaval in STEM research raised questions about the relevance of Bush's model, and this linear model of scientific research was essentially abandoned in mid 1990s in favor of a two-dimensional description proposed by Donald Stokes [4], an advisor to the NSF at the time. Stokes distinguished basic research from applied research, as the two differ in the underlying motivation, being driven by curiosity vs. a specific application, respectively, with Bohr and Edison as prime examples, as seen in Fig. 1. More importantly, he emphasized the importance of use-inspired basic research, and this motivation is now canonized as Pasteur's Quadrant, in recognition of Louis Pasteur's groundbreaking investigations in microbiology that were fundamental to the treatment of diseases. Not surprisingly, there has been intense debate on the relative importance of Stokes' three quadrants[*], especially when the distribution of resources is at stake [5]. Therefore, policymakers have increasingly emphasized Pasteur's Quadrant, which can be seen most directly in the creation of the Technology, Innovation and Partnership (TIP) Directorate at NSF last year. The trend is exemplified by several funding programs initiated by the NSF itself such as Grant Opportunities for Academic Liaison with Industry (GOALI) established in 1995 [6], and Industry-University Cooperative Research Center (IUCRC) [7]. In spite of these programs running for decades, the interaction between universities and companies was not progressing fast enough. Therefore, a few years ago NSF's Directorates for Education and Human Resources; Engineering; and Computer and Information Science and Engineering introduced 'Non-Academic Research Internships for Graduate Students (INTERN)'. Even the critics of Stokes' model have recognized that 'working with industry can provide tremendous benefits and generate many new questions of fundamental importance' [5].

A key aspect that is absent in these various analyses of research has been the education and training of PhD students, who will ultimately conduct the research in whichever quadrant it belongs to. Professors have adjusted to the expectations of funding agencies, albeit hesitantly, such that the vast majority of students has continued to be trained following the age-old model of US PhD training. Essentially, the existing system of training has perpetuated with the professors training their students in the same way they were trained by their advisers. We believe that the entire spectrum of research must be pursued for the technological progress of society, but *the training of the workforce must be commensurate with the needs of 'market' that will employ them.* It has become clear from the 2021 survey that upon graduation more PhDs will seek positions in industry or business than in any other sector (see Fig. 2) [8]. The most

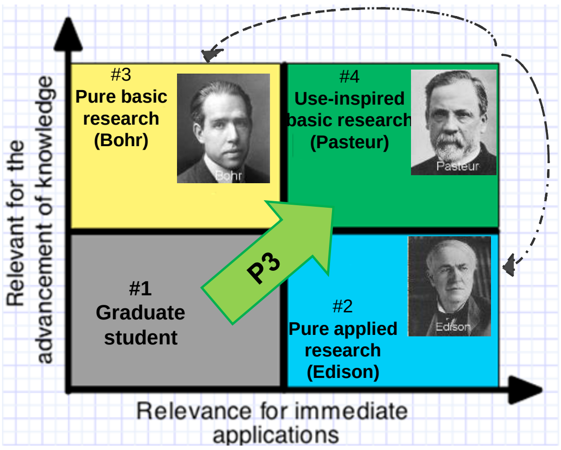

Fig. 1. Stokes' description of the nature of research. He argued that Pasteur's quadrant (#4) would make the strongest impact on technological progress.

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[*] Stokes left the first quadrant blank and focused on the remaining three quadrants. We place an entering STEM graduate student in the first quadrant.

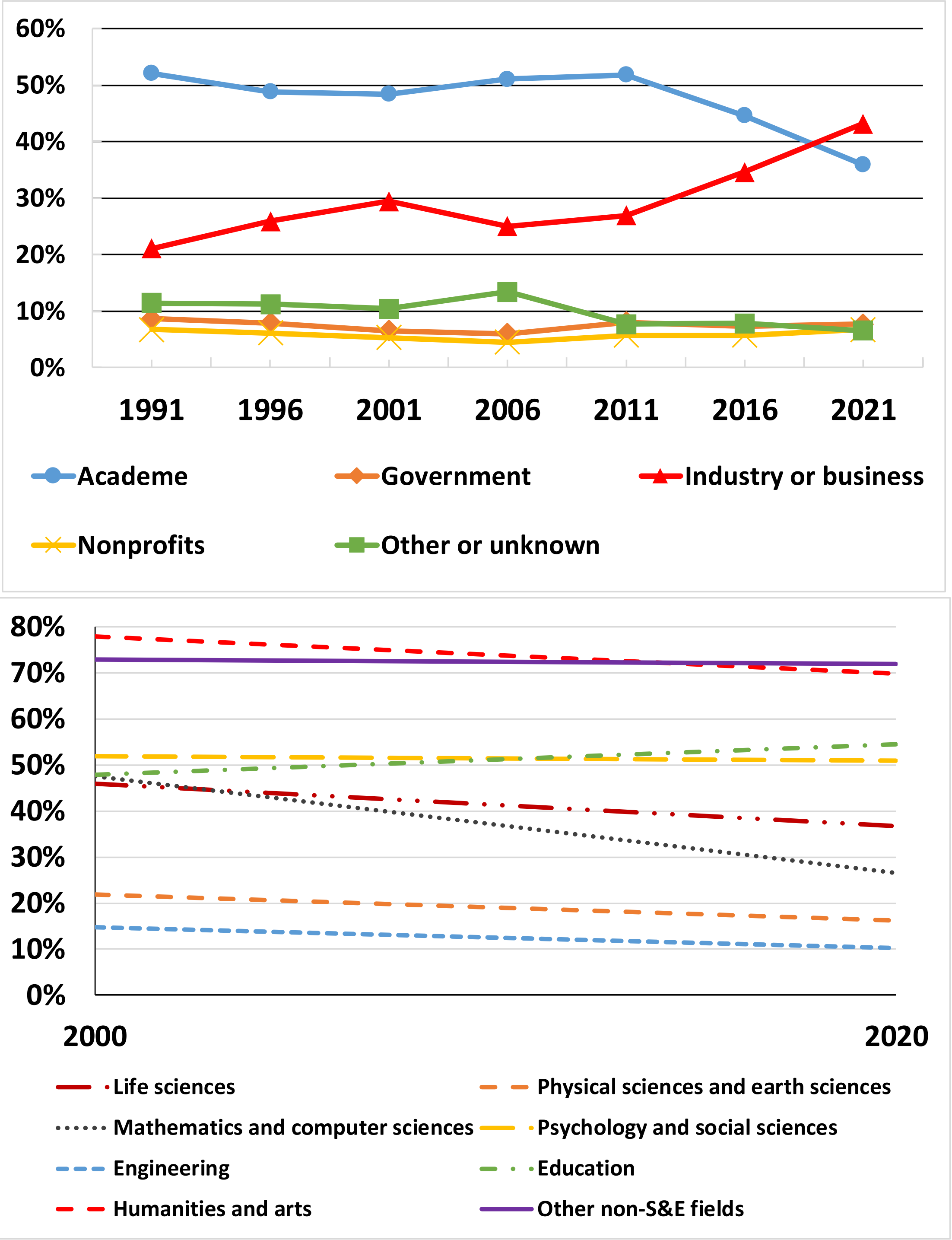

Fig. 2. Trends of definite first employment commitments of PhDs to various employment sectors (top), and to academe for different subjects (bottom).

recent data further show that 90% engineering and 84% physical+earth sciences PhDs are not likely to work in academia, and the trend is that these numbers will increase. Clearly, a major change is needed in the training of STEM doctorates who have been trained thus far mainly for a career in academia. The focus of training should shift to the needs of companies or non-academic employers that we call industry collectively to include private sector, national labs, defense organizations, healthcare institutions, etc.

A need for change of STEM graduate education, especially at the PhD level, was recommended in the first comprehensive assessment of the university system conducted jointly by National Academies of Science and Engineering, and Institute of Medicine. Their 1995 report, ‘Reshaping the Graduate Education of Scientists and Engineers, called for a change at the level of university departments [9]. The institution should inform graduate students of various career options and offer a variety of curricular options so that they make more fulfilling career choices while more effectively fulfilling national goals. In the ensuing decades, doctoral training continued to evolve in response to the demands of industry employers, but the changes were sporadic and inconsistent. The second comprehensive analysis of graduate education, also conducted by the National Academies more than two decades later, called for even greater changes [10]. It called for a substantial cultural change throughout the system, which “must become more student-centric and must increase the value it places on best practices of mentorship and advising… The mind-set that seems to most heavily value preparing students at the Ph.D. level for academic research careers must readjust to recognize that some of the best students will not pursue academic research but will enter careers in other sectors, such as industry or government”. Recently, the need for major changes in doctoral education worldwide has been advocated [11]. The optimal modifications are expected to vary depending on a country’s education system and employer needs.

Even before the second National Academies report was published, a group of faculty members at Lehigh recognized that the existing doctoral training was not aligned with the expectations of likely employers. Earlier, the senior author of this article was sensitized by a remark from the Executive Vice President of a major company that ‘you have very smart kids coming out of Lehigh but they don’t think like us’. Feedback like this motivated us to think of a solution to this systemic problem of STEM doctoral education. Our various experiences led us to redesign the STEM PhD model to one that would be student-centric and based on use-inspired research. The basic model was then proposed for support from NSF’s Innovation in Graduate Education Program for developing it further and testing in practice. The details of the model, now called Pasteur Partners PhD (P3) [12], the challenges faced in its implementation, and its very early assessment are presented in this report.

2. Collective analysis of the needs of STEM doctoral education in USA by stakeholders – National Workshop on the Role of Industry-University Partnership in Doctoral Education, Parts I and II [13]

The latest National Academies report [10], which attempted to define ideal STEM graduate education, is extensive and insightful. It provides an in-depth analysis and clear recommendations by a committee of experts who were predominantly from academic institutions and national laboratories. The perspective of companies appeared to be not as well represented. The report also had a disclaimer, “The committee was unable to explore graduate-level teaching practices in

STEM in great detail during the course of this study as a result of the limited available research". Therefore, we felt a necessity to bring together the leaders of industry, academia, and funding agencies to assess the needs of STEM doctoral training in a three-part National Workshop Series: Role of Industry-University Partnership in Doctoral Education. The overall goals of the Workshop were: (1) To develop a robust understanding of the current status of the pipeline from graduate degree programs in science, technology, engineering and mathematics (STEM) into professional research environments; and, (2) To promote innovation in U.S. academic-industry partnership around advanced research and graduate studies.

The workshop series included major stakeholders and leaders of doctoral training. Specifically, there were 111 participants from 33 universities, including the ones ranked in top 50 universities overall and top 50 in number of engineering PhDs granted; and 19 companies, including Fortune and Global 500 corporations. Additional participants represented NSF, the National Academies, national laboratories, national non-profit organizations with interest in STEM doctoral training and workforce development (American Chemical Society, American Society for Engineering Education, Council of Graduate Schools, Graduate Career Consortium, National GEM Consortium).

The participants agreed that the US system trained PhDs well in subject matter expertise but not so in essential professional skills. Stronger industry-university partnership in doctoral education was deemed critical for a comprehensive professional training via experiential learning during the formative years as the graduate students transition to becoming independent scientists. Thus, there was a consensus that the training will become qualitatively better through such partnerships. Through small and large group discussions and a panel discussion, the industry leaders identified 11 desirable professional skills, with the top five of them considered necessary. They are: (i) Effective communication; (ii) Teamwork, people skills; (iii) Critical, independent thinking; (iv) Learning agility, openness to collaboration, cross-disciplinary interest, broad perspective; and (v) Ethics, research integrity. These top 5 skills identified for industry career success were the same as top 5 skills identified for academic career success in the pre-event survey. This finding supports the hypothesis that, although focused on careers in industry, recommendations made here are likely to support careers in the academy and other sectors too.

Three major categories of challenges were identified in order to prepare doctoral students for successful careers in professions besides academia. (i) Identification and implementation of the mechanisms for providing skills, (ii) Faculty buy-in. Need for core competencies has been recognized for some years, but there has been lack of enthusiasm, even resistance from faculty, especially those who have excelled in the current system. (iii) Development of industry-university partnerships. Various mechanisms were proposed as opportunities to impart essential skills, but their relative effectiveness could not be considered within the allotted time. Industry-university partnership appeared as necessary for developing these mechanisms. However, the suggested role of the partners and their responsibility for implementation varied significantly. The suggestions included:

i. Long-term professor-industry relationships
ii. Broaden definitions of "career success"; make students aware of non-academic career paths
iii. Experiential learning beyond internships

iv. Adopt best practices from other countries' industrial PhDs. Develop a US industrial PhD track
v. Block grants to universities to educate STEM doctoral students beyond technical expertise
vi. Celebrate alumni outside academia who are making a difference in the world
vii. Centers of excellence for engaging students
viii. Support networks for underrepresented students
ix. Doctoral analog to undergraduate capstone collaboration to solve current problems
x. Co-advisors / mentors from industry
xi. Industry involvement in developing classes, programs
xii. Refer undergraduate interns in industry to relevant graduate programs depending on their interests and skills
xiii. Engage industry researchers to teach the skillsets needed, and to establish robust mentoring
xiv. Engage humanities and business faculty in the training of STEM PhDs

3. Pasteur Partners PhD (P3) – A comprehensive model of student-centered STEM doctoral training based on use-inspired research

A number of factors motivated and contributed to the development of the P3 model of STEM doctoral education. First, during the last couple of decades, the paradigm of scientific research has been shifting from the Vannevar Bush approach to use-inspired research depicted by Pasteur's quadrant in Fig. 1, but little was done to prepare the doctoral workforce matching this fundamental shift of expectations. It became clear quickly that it is the industry that tracks 'use' or market to serve the needs of the society – the 'customer' that ultimately pays the cost of conducting scientific research. Therefore, if the researchers were to be trained in use-inspired research, it would need to be done jointly through an industry-university partnership. It is important to recognize in this regard that not every PhD student must pursue use-inspired research. Universities remain the fountain for new knowledge, which often comes from curiosity-driven exploratory research. Therefore, it is natural and desirable that some small fraction of research remains primarily exploratory (vertical axis in Fig. 1). In other words, the P3 approach is meant for a great majority of PhDs but with some exceptions.

The recommendations that resulted from the National Academies analysis of the status of graduate education have greatly influenced the structure of P3 model [10]. A pervasive message of this extensive report is, ".. the ideal, modern graduate STEM education will require substantial cultural change throughout the system. As discussed throughout this report, the system must become more student-centric and must increase the value it places on best practices of mentorship and advising… The mind-set that seems to most heavily value preparing students at the Ph.D. level for academic research careers must readjust to recognize that some of the best students will not pursue academic research but will enter careers in other sectors, such as industry or government." Simply stated, the primary goal of PhD education must be the training of students and preparing them for the career they plan to pursue, not helping the research goals of a sponsor or the teaching needs of the university. Of course, these three sets of goals are not mutually exclusive. The P3 model attempts to coordinate what is best for the student while assuring that the support system also benefits sufficiently to provide resources for the student's training.

The third consideration for designing the P3 model reflects changes in the employment sectors, which would determine realization of students' career plans. The data in Fig. 2 show growth of careers in industry at the expense of academe. The absolute numbers as well as change in demand in favor of industry are particularly strong in STEM fields, most notably in engineering and physical+earth sciences; mathematics+computer sciences and biological sciences follow the same trend. From students' perspective the ideal doctoral training system should prepare them for each of the sectors, at least the ones distinctly classified by National Academies, viz. academe, industry+business, government and nonprofits.

Incorporating the above expectations for STEM PhDs to meet the society's workforce needs as well as students' career plans, four features were added to the formal P3 program as described below. It is important to recognize that these features do not attempt to change the scientific/technical depth and rigor of STEM doctoral training that are considered to be gold standard internationally. No change is proposed in the degree requirements such as preliminary exam, qualifying exam, proposal and dissertation defense, etc., which are set by the academic committee of the university and/or the faculty of the student's department or college. Instead, the P3 program's goal is to prepare the students with a broader perspective of the dissertation research by including the usefulness of the outcome of their work as part of research itself. It calls for changing the mindset when approaching a research problem at the outset and throughout the training. It follows that while the student's research generates new and academically exciting knowledge, their training should also include professional development skills, which will help the trainee implement the output of research into practice. It would prepare them well to take leadership roles in an organization, if they choose. In fact, this form of comprehensive training will also make them better professors for training the future generation of undergraduate and graduate workforce (the arrows in Fig. 1).

3.1. Pre-program internship at industry partner site (optional)

Usually, students planning to pursue PhD have only a vague sense of the research problem that they would like to pursue during the course of their degree program. Typically, an adviser assigned to or selected by them would describe the research topic with some directions to follow. The 'big picture' of the problem and its broader technological and societal impact remain remiss. We believe that it should be clear to the student at the outset why they would want to spend four or more years of their life pursuing a given problem. A pre-program internship during the summer before the Fall semester would provide the student clarity of the goals of research and also help them determine the coursework that they would need to address the problem. At present, this part of P3 is kept optional as some students may already have enough background or have made other plans for their summer.

3.2. Co-advising of the student by a faculty member and an industry researcher

Unlike in the present system where a doctoral student carries out their dissertation research primarily under the guidance of one faculty member,[†] sometimes with another faculty member as a co-adviser, the P3 program requires an industry researcher as a co-adviser. A rationale for this

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[†] A dissertation committee may also exist to review the progress and suggest directions for the student's research, but generally it does not participate in their day to day training.

requirement is to ensure that the student's training includes industry perspective throughout the degree program, including defining the research problem and carrying out its investigation. Obviously, this feature of doctoral training will require significant time commitment of an industry scientist on a regular basis, but it will also allow the industry to gain maximum benefit from the student's research. Note that co-advising stipulated here is a significantly larger involvement of the industry co-adviser than serving on a PhD committee that is typically charged with the evaluation of the candidate's progress annually and/or at the completion of dissertation.

3.3. Essential skills coursework

Lack of any formal training to gain professional skills, which are considered a necessity to be successful in industry but not presumably in academia, has been identified as a prevalent hole in the present doctoral training. However, there has been little consensus on how to address the problem [14]. Following the analysis described in Sec. 2, the P3 model requires acquiring at least three of the top five essential skills listed there, recommending all five especially if their goal is to have a successful career in industry. Students interested in a career in academia may replace two of the five listed skills by learning about classroom teaching skills. The recommended skills may be acquired through 1-credit courses anytime during the degree program. However, the students might find it more profitable to take these courses in the second half of the program when they would have already completed technical courses and have a better understanding of their career goals.

3.4. Residency

In keeping with the goal of helping the student develop a mindset of finding a practical solution to a given use-inspired scientific or engineering problem, the P3 program requires that the student completes a significant part of dissertation in residence at industry location. It could be for one to two semesters depending on the specifics of the research problem and facilities/expertise available at the residency location. The rationale for residency requirement is that learning for solving practical problems would occur not just in labs but also in informal settings and without deliberate planning.

4. Collective vetting of P3 model by stakeholders: National Workshop on the Role of Industry-University Partnership in Doctoral Education, Part III

After the needs of STEM doctoral training were identified and possible solutions were suggested by the participants of the first two parts of the Workshop (Sec. 2), the participants gathered for the third and final time to begin considering practical solutions. Two experts from Germany described their system, which has proven to be most successful in instituting industry-university partnership in the training of PhD students. They were then informed of the P3 model for the first time and asked for its appropriateness in addressing the challenge in the USA. The group recognized the P3 program as a promising model to address the lack of industrial perspective during doctoral training in the U.S. The participants considered it important to communicate the long-term benefits of a P3-like doctoral educational model to industry partners, which are expected to be: (i) universities conducting research on topics of direct interest to the company: (ii) the student trained under P3 program could be a future employee best-trained to address company's needs, (iii) access to faculty expertise and latest developments in related topics, and (iv) access to faculty connections to other organizations such as the National labs, international institutions, etc.

Considering the comprehensiveness and generality of the P3 model for all areas of STEM, the panel of stakeholders strongly recommended implementing it beyond Lehigh University. The panelists suggested forming a consortium to scale up and validate P3-like programs at partner institutions to achieve the needed transformation in STEM doctoral education in the country. The consortium could provide: (i) a core curriculum to deliver identified skills that students need; (ii) best practices to facilitate university/corporate partnerships through centralized IP agreements; and (iii) establishing a database of faculty expertise and internships/residencies in industry for setting up a student's P3 program. It would also help member institutions access broader funding sources like federal agencies, corporate consortia, individual corporations, and private foundations.

5. Implementation of P3 at Lehigh University

We were strongly encouraged by the enthusiastic support that the stakeholders at the Workshop provided for the P3 model and its four components. Individual components of the P3 model have been introduced at a few institutions, for example, the Accelerate to Industry (A2i) program pioneered at North Carolina State University [15]. Programs such as this have undoubtedly proven beneficial to the students [16], but they lacked the comprehensiveness of the P3 model that attempts to not only enrich a student's doctoral experience but also develop a mindset for finding and implementing solutions that are practical.

The implementation of the P3 model on a university campus required active engagement of the three training partners viz. the faculty, the administration and an industry organization, and, of course, the student trainee. It was recognized early on that the success of the program would depend on the recognition that each of the three partners appreciated the benefits of the program and was willing to make commitments accordingly – each had to have 'skin in the game'. Below we describe the process of P3's implantation at Lehigh University. Its individual components were offered starting in 2020 to select students who were already pursuing a PhD. The full P3 program was offered formally starting in Fall 2022.

5.1. Student engagement

As the P3 program was being developed and vetted by stakeholders, engagement of a few students was initiated by offering them co-advising by an industry researcher and courses on essential skills as test balloons of their interest. Although the guidance from industry co-adviser at this stage was unstructured, the response from the students was very positive. Only the students of a handful of faculty advisers, who were already promoters of the P3 model, received its above-mentioned components.

Development and offering of essential skills courses exactly as recommended by industry participants required expertise that did not fully exist. Therefore, to get started the students were offered courses for which expertise was available. The first essential skills course was a 1-credit course, '*Fundamentals of Intellectual Property*', taught by the director of Technology Transfer Office. The students found the information unlike in any other courses they had taken. They were fascinated and felt the course could be useful in the future, but some were not sure how to apply this knowledge in practice, especially during their PhD. It was already a cultural shift. Subsequently, three 1-credit courses (‘*Facilitation and Teamwork for Projects’*, ‘*Decision Making and Ethics on Projects*’ and ‘*Project Leadership*’) were offered. These courses, which were part of the Project Management Concentration within Lehigh’s MBA curriculum, were never before offered to STEM students. This change in students’ training reflected the first definitive step for STEM PhDs expanding their outlook of the needs of future careers.

The students greatly appreciated the various P3 inspired experiences (see Sec. 6), but the question remained: how will the P3 program be viewed by future STEM PhD students whose training it is trying to enhance? Will there be sufficient interest from prospective students in this program? To gauge such interest, hence the need for this type of doctoral training, a question was added to the graduate admission application for Fall 2022: Would you like to pursue the P3 track for your PhD, with a link provided to explain the program? We were pleasantly surprised that >95% of PhD applicants to STEM departments expressed interest in the P3 program. It was a clear demonstration of the overwhelming demand from the students for changing the nature of doctoral training through a program like P3. Unfortunately, less than 5% of applicants who were admitted and accepted to join Lehigh could be enrolled in the program - the rest of the system was not yet ready to meet the demand.

5.2. University administration engagement

There are new administrative, financial and legal implications of the P3 program, which required significant buy-in and support from university administration. This was recognized as a major challenge for implementing the program. The task was made particularly difficult by the fact that the management of doctoral programs had been highly decentralized at Lehigh, as at most institutions of higher learning. Thus, the admission process and curricular requirements are set by individual departments, the graduate tuition revenues are largely controlled by the deans, any programs cutting across colleges (College of Engineering, and College of Arts and Sciences for STEM) are to be approved by the Provost, and agreements with external institutions like industry partners are to be prepared and negotiated by the Office of General Counsel which reports to the Board of Trustees. This complexity of administrative structure requiring engagement and agreement of so many offices made the implementation of the P3 program very difficult. The strategy that made the process tractable was to have the Provost on board throughout the development of the P3 program. The Provost is the one who has a sufficiently broad perspective of the university’s education mission, and understanding of resources and return on investment that may be needed for implementing the P3 program. If convinced of the value of the program for the university, he or she can also obtain support of the president and the board of trustees/governors.

Fortunately, the Provost at the time recognized the benefit of P3 as a strategic initiative for enhancing the institution’s image nationally, even internationally, and therefore was willing to help implement the program. An important factor for establishing the value of the P3 program was the highly competitive award of an Innovation in Graduate Education grant from NSF for validating the model. This was a clear endorsement by the graduate education community well beyond Lehigh.

Whereas the structural support of the Provost was a prerequisite, it was just as important to make the program sufficiently attractive so that the faculty would want to pursue it and engage industry partners. Accordingly, a novel financial model was developed to support the students, called P3 fellows. It was based on incorporating the NSF Graduate Research Fellowship model, which the university had already accepted, in attracting industry partners. Thus, a P3 fellow will receive a competitive stipend, and the university would reduce tuition by 50% and waive all indirect costs. As a result, the cost of supporting such a fellow would be 35-40% lower than a partner company would need to provide under the standard research sponsorship model. To make the program even more attractive to students and industry, the university set aside a fraction of university fellowships for P3 applicants, which would provide full tuition and stipend for the first year of the program. In short, the Lehigh Administration has been fully engaged and provided unprecedented support for implementing the P3 program.

5.3. Faculty engagement

Lehigh is an R2 university with 13 academic STEM departments offering doctoral programs with each department having its own history, technical foci and views of PhD education. The students are predominantly supported through research grants, with a small fraction of support provided by teaching assistantships and fellowships. As a result, there is a broad spectrum of faculty perception of the need of a P3-like program for the students, and also its benefit to individual faculty members. When the initial announcement of the offer of P3 track was communicated to the research active STEM faculty, it received lukewarm reception. Overall, the faculty response to the P3 program can be divided into three categories: (a) Highly active senior faculty with large research groups. They were successful in the current system and did not see a need to make any changes; they simply ignored the program. (b) Mostly the junior faculty, who considered the program as a potentially attractive way of building and expanding their research program. However, they were unsure of how to establish industry partnerships. (c) The faculty at all ranks, who had a prior relationship with an industry partner. They fully recognized the necessity and value of the P3 model for graduate education, and therefore started participating in its implementation.

Unfortunately, the restrictions from COVID made broad faculty engagement difficult until the campus reopened for in person meetings. Attempts to describe the program via email and Zoom did not prove to be effective. Therefore, we reached out to the faculty by requesting time at departmental meetings via the deans and department chairs. This route to communicating the program proved most effective for reaching the College of Engineering, but not the College of Arts and Sciences faculty. It encouraged many faculty members to pursue the program, but finding an industry partner remained a persistent challenge for some. On the other hand, for the faculty members, who were able to find an industry partner for supporting the training of a P3 fellow, securing a collaboration and intellectual property (IP) agreement has been a non-trivial, time-consuming challenge. As these negotiations are highly dependent on the policies of the partner company, it has been difficult to frame a generic template.

5.4. Industry engagement

With the demise of major corporate R&D labs' commitment to long-term research towards the end of last century, few US industry organizations have been directly engaged in the training of STEM doctorates in recent decades. Therefore, for them to form partnerships in P3-like programs is as new as it is for academia. Some of them have been aware of benefits that they would get through participation in specific programs sponsored by NSF specifically for this purpose. The leadership of such organizations, such as Corning Inc., was receptive to expanding partnerships with Lehigh faculty, providing both the time and financial commitment for sponsoring P3 fellowships. They have helped identify the challenges for building the P3 model as well as serving as a model for other companies. The challenges faced by private corporations for supporting P3 fellowships are insightfully summarized by Gary S. Calabrese, who recently retired from Corning after leadership positions in other corporations:
" Companies that hire PhDs certainly want change, but incessant profitability cycles and short-term focus in publicly traded companies has a huge impact on ability to sustain financial and limited but essential internal staffing commitments. These barriers were far more surmountable decades ago when large corporations had big, centralized R&D organizations which could more easily afford programs such as P3. Today the industrial research ecosystem that hires PhDs is far more fragmented with far less critical mass in each organization to be able to make long term commitments to any external program."

In short, private corporations see the value in training STEM doctorates following the P3 model, but are reluctant to commit resources for multiple years at the outset due their financial model that calls for much faster returns on investment (ROI). At the present stage, there is also perception of risk in supporting a new program for which ROI will be known years later. These obstacles have been overcome when relationships between a faculty and company have been built and benefits demonstrated over the years.

6. Early assessment of P3

The implementation of the P3 program is too new to draw conclusions about its impact on students' careers. Notwithstanding this limitation, an independent assessment was conducted, as described below, to verify the needs of the program, and if a course correction was needed at this stage.

6.1. Method

In order to evaluate the impact of P3 on the professional development of doctoral students, semi-structured interviews were conducted in confidence. Convenience sampling methods were applied to recruit interview participants. Specifically, the evaluator sent out recruitment emails to doctoral students in the department of Materials Science and Engineering, and Chemical and Biomolecular Engineering. For a more in-depth examination of the academic and industrial experiences offered by the P3 program, he invited three industry advisors, three doctoral students who are part of the current P3 cohorts, and three doctoral students who are in the traditional program without any P3 components. The industry advisors were invited to share their experiences mentoring the student and their perspective on the program. The students in P3 program were requested to describe their pre-program internship, essential skill coursework, as well as the interactions with both academic and industry advisors. Students in the traditional program were asked to describe their PhD program generally and reflect on the aspects of the program that prepared them well or could be improved for future job searches or career advancement. The interviews were conducted via Zoom in the early Spring 2023 semester. Each interview session lasted from 30 to 45 minutes depending on participants' availability, all interviews were recorded and then transcribed.

6.2. Participants

The three industry advisors included two senior scientists from corporations and one scientist from a national laboratory, all of them mentored P3 students starting with the pre-program internship. The three P3 students are in different stages of the program, one is enrolled in the first year and the other two are enrolled in the second year. They have both participated in the first three features of the program (Pre-program internship, Co-advisory experience, and Essential skills coursework), However, they have not been able to participate in Industry Residency yet, as they are at an early stage of the program. The three participants from the traditional program were also in different but later stages of their program: 2nd, 4th and 6th year, respectively.

6.3. Data analysis

To ensure consistency, all interviews were conducted by the same researcher following the interview protocol. The framework proposed by Miles et al. [17] was applied to inform the analysis process. More specially, all collected transcripts were organized based on students' groups (P3, traditional group). To examine the organized data, a selective coding method was employed, which identified a central theme that linked all the sub-codes together, as well as an axial coding method that made connections between the codes. Typically, each code represents a single idea, and if a sentence contains more than one idea, then it is double-coded. The coding process was conducted iteratively following the constant comparative method of Creswell and Creswell [18]. The codes and themes were verified, organized, and refined during the entire coding and recoding process.

6.4. Findings from industry advisors

The feedback provided by industry advisors from both corporations and the national laboratory was positive. As a result of the interviews, three distinct themes emerged, including students' growth, benefits to the corporation or lab, and challenges associated with the facilitation and execution of the program.

Firstly, industry advisors emphasized their perceptions of students' growth in their professional knowledge as well as technical skills. For instance, an advisor from the national lab mentioned that the student gained "knowledge about control system"; he "saw how our melting processes work, and also the measurements, the characterization, which is really important." In addition, advisors also highlighted students gaining soft skills, "(student) got to interacting with people, to understand how you can utilize other resources and people to get things done, because you can't do everything yourself." To be noted, a finding that emerged only from the advisor in the national lab is their perceptions about students' growth in research skill: "we spent two weeks training them, making sure they understand the fundamentals but then, for the most part after that it's on them. You know, collecting data, interpreting it, asking the scientific questions that need to be pursued, and that's exactly a research process."

Moreover, advisors from corporations indicated that having P3 students benefited their company by accomplishing research projects, especially the long-term project. As one advisor mentioned: "We don't have the resources to do it (long-term project). The student can help us get things done that we otherwise couldn't find things out that will help our longer-term research." Whereas advisors from the national lab indicated that mentoring P3 students allowed the lab to extend their research opportunities, gained mentoring experiences, and maintained collaborative relationships with higher institutions. For example, an advisor pointed out the P3 students "brought a very interesting project. We got exposure to a different material system." In addition, mentoring is also "a big component of what we do here (national lab)," interacting and guiding P3 students in research projects allowed scientists in the national lab to gain more experiences in mentorship. Besides, P3 students also served as a bridge that connected the national lab and university to "work on projects together and driving science."

Industry advisors also shared their thoughts and suggestions about the potential challenges for future implementation. For instance, an advisor from a corporation expressed their concerns about cost-effectiveness: "you have to take time to mentor the student, and companies are afraid that they'll spend a lot of time with this person, and they'll get nothing out of it." While this issue was less of a concern from the national lab perspective, as "students will produce research paper that would benefit the lab." When asked about their suggestions for future implementation, advisors from both corporation and lab provided several ideas. For example, advisors mentioned that when joining the internship program, it is better for students to "have a project to work on already." In this case, students would receive more tailored feedback. Advisors also requested a more detailed timeline with clear milestones for students to achieve. Additionally, the advisors expressed an interest in participating in the interview and selection process. These suggestions are valuable in guiding the program to sustain collaborative relationships with industry advisors in the future.

In all, the outcomes from advisors' interviews presented positive feedback about the current implementation of the P3 program. Specifically, industry advisors acknowledged P3 students' growth in their professional knowledge, technical skills, and soft skills; confirmed the benefits P3 students brought to the corporation or lab including long-term research projects and connection with high institutions. More importantly, industry advisors also provided valuable feedback and suggestions such as the cost-effectiveness and a clearer timeline which is vital for informing the future implementation and improvement of the program.

6.5. Findings from P3 program participants

According to the three students who have participated in the P3 program, the program has been a positive experience overall. Two salient themes emerged from the interviews regarding their Pre-program internships: gained practical experience and became better prepared for the PhD program. As one of the students indicated, the internship enabled him to work on the project that aligns with his research interests, and he also had a chance to "coordinate with an entire team" by involving in lab management, equipment maintenance, and project progress monitoring. More importantly, this experience allowed him to have a “smooth transition to the research lab at Lehigh University” and helped him “gain a better research mindset.” In addition, since the participant was working collaboratively with a whole team, he was able to establish social connections with colleagues in the company. When asking about future career plans, one of the participants mentioned that now she would “have a foot in the door (industry)” and “figured out how research was done in the company.” More importantly, the participants stated that they felt more confident about finding a position in the industry after graduation.

Similarly, positive feedback was also expressed by another P3 student, who had a slightly different Pre-program internship experience as he was interning in a national laboratory. He stated that not only he gained “good technical skills, developed a clearer research direction,” he was able to build “really good personal connections” with his colleagues. As he mentioned in the interview, he has already written a research proposal “which normally I don't think that many other students would have the opportunity to do in their first semester unless you would have something like this (Pre-program internship).” In addition, this student also emphasized that he felt absolutely more confident in finding a position, especially in a national lab in the future since without this experience, he “would not know much about how national labs operated, or what their careers would look like, and even if I had read about it or done some emailing, you know, it wouldn't be the same as going there and meeting people.” In sum, as a result of the pre-program internship experiences, students gained valuable experience in the companies or national lab, which contributed significantly to their later PhD progress and enabled them to acquire significant industrial experiences, including technical and soft skills as well as social connections.

The P3 students also spoke highly of the co-advising experiences, especially the interaction with their industrial advisors. In general, P3 students expressed that the co-advising experience enhanced their technical skills, offered them up-to-date career information, and provided external resources such as data or equipment for experiments. One participant indicated that he communicates with his industry advisor monthly and that their discussions revolve around the collaborative research projects they are currently engaged in. Moreover, by interacting and communicating with industry advisors, the participant learned more “professional terms” in the field as well as “career tips to work for a national lab.” This finding is consistent with the feedback provided by another participant, who found that the advisor was always available to answer his questions about the research and provided him with good resources. Moreover, he learned how to “direct research towards an actual application, and I can easily talk to him to figure out how it gets there (actual application).” An interesting theme emerged is that the industrial advisor provided a good point of contact if students needed certain lab equipment that was not available at Lehigh. In addition, students also pointed out that they would like to have meetings with his industrial advisor more often, especially after narrowing down their research direction.

Since all the interviewed P3 participants were in the early stage of the program, one participant had not taken the Essential skills courses yet. Based on the feedback from the students who have taken at least one such course, viz. *Facilitation and Teamwork for Projects,* the experience has been particularly valuable: “We all enjoyed that course,” as mentioned by one of the participants. “(we) learned about how other people may think, how everyone has their own type of problem-solving approaches and learning how to work with them,” which was “very beneficial.”

6.6. Findings from traditional program participants

Regarding the interviews with traditional program participants without experience in any of the components of P3, the questions focused more on their perception and feedback about their traditional PhD program. In general, these students were satisfied with their current PhD journey. As an example, they felt that the program had prepared them well, particularly from the perspective of research: "I feel that I have been well-prepared for research jobs in terms of technical knowledge, experimental design skills, and so on." They also pointed out that their program provided them with sufficient resources to help achieve their goals: "The program already offers many valuable resources and sets its students up for success." Nevertheless, when asking what kind of assistance would be most beneficial to their success, a number of themes emerged that are worth noting. During the discussion, one participant underscored the importance of industrial connections since he is more inclined to work in industry rather than academia. He indicated that it would be beneficial to "have more industry speakers in seminars. That's one thing. Second, you can have more career development events, or you know, career fair events and make them more accessible to students", and he noticed that the program "has seminars every 2 weeks, and for whatever reason most of the speakers so far have been from academia versus from industries." These perceptions, in fact, revealed the needs of students looking to develop careers in the industry. It contrasts the feedback provided by P3 students who expressed confidence in finding a job in the industry as they already had a foot in the door.

Another theme relating to the industrial connection is the need for soft skills training, such as communication, collaboration, and problem-solving skills. "Communication is the key," as mentioned by one of the participants who is also an international student. He wished to have more support for international students like him for connecting to the "right company" that doctoral graduates with an international background would feel comfortable to work in. Furthermore, another traditional program student mentioned the importance of improving "trouble-shooting and problem-solving skills" to prepare for future practical research experiments in the workplace. In contrast, all P3 students reported that they had gained expertise in coordinating or collaborating during their Pre-program internships. This distinction between the two groups indicates that industrial internships could provide students with an opportunity to develop soft skills that would be beneficial to their future careers.

Finally, one of the most notable themes that emerged from the transcripts was the need for mentorship among traditional program participants, especially as they near the end of their PhD program. One participant mentioned that if he had more guidance about the end of the PhD program, he "probably would have more time to apply to jobs a little earlier, and maybe I would feel like I could manage my time a little better." The participants also pointed out that mentorship does not necessarily need to be provided by his academic advisor, but instead, it could "probably be better through a department or an engineering college to just kind of guide students through the transitionary part." This finding, again, contrasts the feedback from P3 students that a co-advising experience could be essential since it offers PhD students more contacts, resources, and opportunities to manage potential challenges they may encounter during their PhD journey and beyond.

6.7. Comparison of the two students groups

Outcomes obtained from P3 and traditional programs revealed insightful, detailed, and comprehensive information about their perceptions, experiences, and feedback regarding their PhD program. In general, both groups presented satisfaction about their growth especially regard to their academic research experiences. Among the two groups, outcomes from the P3 group presented more themes related to industrial experiences and mentorship connections. Specifically, for P3 students, the Pre-program internship provided more practical industrial experience and enhanced their preparation for their subsequent PhD program. In addition, participants were able to establish connections with professionals in their relevant fields and developed confidence in their future career prospects. However, the traditional program students wanted more assistance to gain a deeper understanding of the industry and establish more industrial contacts. The results present that the P3 program can provide the industrial experience and opportunities that PhD students are seeking, especially if they are planning to advance their careers in the industry.

Further, students in traditional programs stressed the importance of gaining soft skills such as communication and problem-solving in the interviews, which are the skill sets that have been mentioned by P3 students who have participated in internships at companies or research laboratories. It became evident that the P3 program provided students with the opportunity to develop the skills necessary for them to succeed in the job market. Additionally, based on the interview results from both groups, mentorship emerged as a key theme. More specifically, P3 students benefited from the co-advising experience by receiving technical training, information from the field, and external resources such as data sources or equipment from their industry advisor. In contrast, students from traditional programs were calling for more mentorship, especially for participants in the final stages of their PhD studies. With the support provided by industry advisors, these outcomes demonstrate that P3's Co-advising experiences were able to accommodate students' needs as they progress through the PhD program and that students had the opportunity to stay up to date with the field due to industry advisors. Furthermore, P3 students have also highlighted the benefits of the essential skill courses provided by the P3 program.

Overall, a comparative assessment shows that the program is providing students critical support and mentoring on both academic and professional levels. Since the interviewed P3 students were still in the early stages of the program, their experiences have been limited to Pre-program internships and Co-advising. It is expected that as the students progress through their degree program and participate in additional essential skills courses and industry residency programs, more valuable and applicable outcomes will be generated to test and guide the improvement of the P3 program. In short, the outcomes of this evaluation of the P3 program have been positive, informative, and inspirational, suggesting a promising future for the program.

7. Conclusions

There is wide consensus among stakeholders of STEM doctoral training that the present structure of PhD in the US, which was essentially established after WWII, has multiple deficiencies and does not prepare most students for their intended careers or meets the expectations of most employers and needs of the society. To rectify these deficiencies a new model of doctoral training, Pasteur Partners PhD (P3), has been developed. This student-centered model built on use-inspired research retains the traditional rigor and depth of US PhD, and then adds four components to prepare a student for successful careers in industry as well as academia.

Prospective PhD applicants at Lehigh University expressed overwhelming interest in pursuing their degree following the P3 model. However, only a very small fraction of such students could be enrolled in the program due to the lack of sufficient number of faculty-industry partnerships required by the P3 program. There are three main challenges to forming these partnerships [19]. (a) Only a fraction of faculty, mostly at the junior ranks, are interested in joining the program. (b) the doctoral education system has been driven by the research output (publications) rather than the relevance of student training practices. (c) The financial model of most private corporations prevents them from making commitments for the duration of PhD. There is also hesitation in a new program for which ROI will be known years later. To overcome these hurdles for the implementation of the P3 program, it is recommended to lower the perceived risk and barriers for forming partnership through targeted investments by the funding agencies, and restructuring of the academic system.

The impact of individual components of the P3 program was assessed by interviewing industry advisors and comparing the response of students from the current cohort with that of students in the traditional program. The results have clearly demonstrated that the P3 program has fostered a reciprocal relationship between industry and higher education that has benefited both the corporation and national laboratory by increasing research opportunities and strengthening industry-university collaboration. On the other hand, the P3 students were provided with valuable industrial support, opportunities for building industrial connections, and much needed mentoring to accommodate their academic and professional needs. Most importantly, the P3 experiences assisted PhD students in developing greater confidence in future career advancement in the industry.

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