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THE PHD INNOVATION PROGRAM AT THE THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Eric R. Fossum, Carolyn E. Fraser, and Joseph J. Helble

Thayer School of Engineering at Dartmouth, Hanover, NH, USA

Dartmouth's PhD Innovation Program at the Thayer School of Engineering is described. The rationale, structure, and results to date for the program are discussed. Despite the program's youth and small size, significant success in better preparing engineering Ph.D. recipients to engage in technology commercialization and enterprise building has been demonstrated and a contribution to the nation's technological and economic leadership established.

Key words: Engineering; Innovation; Enterprise; Entrepreneur; Ph.D.; Dartmouth

INTRODUCTION

In 2005, *Innovate America,* a report from the National Innovation Summit, was released by the Council on Competitiveness (1). This report, authored by individuals drawn from the corporate world, academia, and government, argued that for the U.S. to maintain technological and economic leadership, a substantial investment in the development of a technically competent workforce was required. As the report articulates, nations that can provide conditions favorable to innovation and entrepreneurship, including a strong technically-trained workforce, stable government, culture that accepts and rewards risk taking, and the availability of early-stage capital, are those most likely to claim positions of leadership in the 21st century. While this report and others appearing at that time (2,3) described the need for developing more engineering talent within the U.S. and demonstrated an overall need for changes in engineering education to incorporate more open-ended problem-based learning and foster skills needed for innovation and entrepreneurship, their emphasis was generally on undergraduate science and engineering education. Discussion of graduate programs focused primarily on the need for increased research and fellowship funding to encourage greater numbers of domestic students to pursue advanced degrees in engineering and science, yet a similar national need exists for Ph.D.-level students to develop skills in technology innovation and enterprise creation.

Engineering Ph.D. programs focus, appropriately, on helping students develop the skills needed to conduct original research. Their structure, emphasizing advanced coursework and publishable research, differs little from Ph.D. programs in the sciences. Similarly, some might argue that for many programs, "success" can be defined as placing top doctoral students in academic positions at peer institutions. While

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Address correspondence to Eric R. Fossum, Ph.D., Thayer School of Engineering at Dartmouth, 14 Engineering Drive, Hanover, NH 03894, USA.
Tel: +1 (603) 646-3486

this is one important outcome for Ph.D. engineering students, we estimate, based on the number of engineering assistant professors in the United States and the number of Ph.D. degrees granted in engineering each year, that only approximately 10% of graduates obtain tenure-track faculty positions even after post-doctoral appointments (4). Most engineering Ph.D. recipients pursue careers in industry, often in industrial research and development, where their deep technical knowledge is of immediate application. In both paths, however, the educational program focuses entirely on the students' technical education. Little attention is paid to the potential benefits associated with helping engineering Ph.D. students develop, as part of their Ph.D. program, the business and organizational skills needed for technology entrepreneurship. Programs designed to help students explore commercialization of their research, often in collaboration with business schools, do exist at many universities, but there are not many programs that focus on helping Ph.D. students develop the knowledge and understanding necessary for technology entrepreneurship as a core part of their Ph.D. education.

To address this, in 2007-2008, the faculty of the Thayer School of Engineering at Dartmouth College developed a specific Innovation Program with the objective of providing a much more structured approach to developing the skills needed to be a Ph.D.-level technology entrepreneur. In our program, in the context of new technology generation, innovation is defined as the process of translating and transforming a discovery or invention into a form suitable for commercialization. Innovation is thus the bridge of directed research between pure research and advanced development. The program was structured with the goals of providing introductory exposure to the relevant business curricula, providing practical experience through a mandatory internship in a start-up company late in a student's Ph.D. program, providing mentorship from successful entrepreneurs and venture capitalists, and building an understanding of the process of turning complex research into commercializable technology. The program is designed to teach students to recognize the skills needed to bring about successful innovation and associated new enterprise and to provide the opportunity to take risks, possibly fail, and ultimately learn from the experience in a structured environment. In addition to these educational outcomes, the program aimed to prove that acquisition and practice of these skills in the context of an engineering Ph.D. program can lead to increased national technological and economic leadership through an increase in intellectual property generation and enterprise formation by its students over their professional lifetimes.

PROGRAM OVERVIEW

Curriculum

The PhD Innovation Program shares a large common core with Thayer's Ph.D. program, which comprises applied math and engineering coursework, a multi-year research project, professional skill-building, an oral qualifying examination, and a Ph.D. thesis defense. The PhD Innovation Program includes coursework from the Tuck School of Business (adjoining the engineering school on the Dartmouth campus), Thayer innovation coursework, and an internship, preferably in a start-up, which, under some circumstances, could be the student's own venture. Internships in larger established corporations can also be instructive if the student has no prior work experience. Entrepreneurial courses are taught by full-time tenure-track faculty, but guests are often invited in the advanced coursework to provide supplemental information and experiences. Several faculty are experienced entrepreneurs. The required course load at Dartmouth for completing the PhD Innovation Program is only a few courses larger in total than the regular Ph.D. program since some of the required innovation courses supplant required courses in technical breadth. Upon successful completion and conferral of the Ph.D., an innovation certificate is granted. Innovation Program coursework includes corporate finance, a course in law for technology and entrepreneurship, an elective such as accounting, and Thayer School's unique Introduction to Innovation course. The Introduction to Innovation capstone course, taught by a faculty member and entrepreneur, is specially designed for the program and provides instruction and practice in commercialization of new technologies over a several-term period. Thayer is able to deliver a rich experience in this regard due to a long history of integrating the practical aspects of market analysis and business

planning into interdisciplinary engineering design project coursework at the undergraduate level. Guest lectures are presented by visiting entrepreneurs, venture capitalists, and inventors. An enterprise plan based on the development and commercialization of novel technology research is developed and presented to a panel of experts for a grade. Students report on their projects both orally and in written form and are graded on a pass-fail basis.

Financial Constructs and Administration

The program director oversees the program with guidance from the dean of the engineering school and assistance from the assistant dean for academic and student affairs. In most cases, five full years of funding support the student through the completion of the Ph.D. in engineering, advance the adviser's research agenda, and support the student's innovation training and personal research agenda. PhD Innovation Program students are supported by graduate research assistantships for the first two years of the program, which are funded via adviser-secured grants or fellowships. In this period of the program, coursework and professional skill-building is emphasized as adviser-directed research ramps up, and the student is part of a thriving research lab while nurturing their own novel research ideas. In the third year, research focus shifts from being adviser-directed to being candidate-directed, and fellowship funding is provided through Thayer School in support of the candidate's research agenda. In addition, in years three through five, the school makes up to $10,000 in supplies and equipment funding available per year per student for research activity that is divergent from their adviser's own research and which furthers their innovation and enterprise-building endeavors.

Funding to start the program was raised through philanthropy. Grants and fellowships that align with the program's objectives have been employed as funding sources. For example, a Luce Foundation grant has been employed to support development of women through the program, and a National Science Foundation Partnerships for Innovation grant funded student collaboration with existing small business enterprises. Thayer's Energy Challenge Initiative has supported students in the field of energy, and Holekamp and Crump Funds have supported additional PhD Innovation Program students.

Recruiting

A core requirement for students selected for our program is the same as the regular Ph.D. program—strong promise for academic success in coursework and research. The overlay emphasis on business and entrepreneurship coursework and activities must not come at the expense of rigor in advanced engineering sciences coursework and performance in the adviser's lab, whether on the adviser's or the student's own research. While the core requirements are the same, the challenge in recruiting is finding students who have characteristics and interests that go beyond the core. The way we look at this has changed in a subtle manner over the first few years of the program as students come into and successfully complete the program. Initially, the assumption was that a percentage of the Ph.D. candidate population either has a strong interest in entrepreneurship or a research idea they want to develop, and this type of student was the main target for the program. Our program is the only one that combines research and entrepreneurship in such an integrated fashion, and finding ideal candidates has been challenging. In addition, because the program is unique and very selective, prospective students can be intimidated by the program description and requirements.

We have noted that many of our own faculty entrepreneurs are what one might call "adventitious entrepreneurs" who did not necessarily pre-meditate an entrepreneurial role, and that, perhaps, is the more common story for engineers with advanced degrees. Recognizing this, we expanded the target and messaging beyond speaking to students ready for entrepreneurship or bent on commercialization to include those that are interested in preparing for this opportunity down the road and broadening their future options. This change supports what we always knew: All engineers will benefit from additional training in business and entrepreneurship. To cast the net more widely, we have employed highly targeted tactics such as recruiting through alumni and faculty networks and from within our own pool of existing students, but also broader tactics such as posters and Facebook ads to reach Ph.D. prospects at both domestic and international universities. We've also experimented with positioning the opportunity as a program versus a fellowship opportunity

but have not yet made any conclusions about which presentation is more attractive to students. We continue to refine these approaches in the program.

Admissions

Candidates submit the same core application materials as for the regular engineering Ph.D. program, including GRE/TOEFL scores, intent essays, letters of recommendation, and transcripts. Additional materials required are a two-page essay elaborating on their interest in innovation and providing an example of creativity in arriving at a solution, a sample funding proposal for a technology development project, and a C.V. Applications are due at the same time as our regular Ph.D. program applications, and the screening process begins in a similar way but is performed by a dedicated faculty panel focused on innovation requirements and fit. Students who are chosen for consideration are invited to a panel interview. The panel further confirms the interest and aptitudes of the candidate and provides the candidate an opportunity to demonstrate fundamental knowledge, critical thinking, and presentation skills around their technology interest area. Each student offered admission into the program must have an established faculty sponsor who will be their adviser and who may provide financial support during the student's first two years.

Brief History To Date

The program began in July 2008 with a goal of enrolling up to five students a year based on interest and match. As of Fall 2017, thirty-six students (twenty-six men and ten women) will have entered the program. Of the fourteen who have received Ph.D. degrees, six founded start-ups, two became postdocs in the medical field, and the rest are involved with start-ups. None of them have gone on to academic teaching positions. Two have withdrawn, and twenty are currently in the program. The curriculum has remained consistent during this period, with modest changes to innovation coursework content and approach. Internships have taken a variety of forms, but most involve early-stage enterprises: the student's own venture, early- and later-stage start-ups, technology incubators, and venture capital firms. Feedback from students is strongly positive, and we continue to evolve the program and its features based on our assessment activities.

ASSESSMENT

The program has joint goals of teaching skills for innovation and preparing students for generating intellectual property and forming or joining enterprises that bring intellectual property to fruition. In addition to assessing outcomes in terms of intellectual property generated, technology enterprises formed or joined, and student feedback on courses targeting innovation skills, we have employed high-touch mechanisms such as student meetings and check-ins with the dean and the program faculty coordinator and an annual meeting with at least one member of the school's Board of Overseers. In addition, a comprehensive assessment interview was conducted with all current and finishing participants in 2012, with another scheduled for 2017.

Assessment interviews indicated the need to enhance networking and informal events for the program participants. In response to this feedback, several events were planned on an annual or semi-annual basis to bring participants together to meet with inventors and entrepreneurs, network with each other and faculty, and connect with cross-campus student and alumni entrepreneur networks and programs. Students also gave feedback about courses, including the Introduction to Innovation course. Students have noted positive learning outcomes in the innovation skill and knowledge areas of intellectual property and law, marketing, finance and accounting, enterprise planning and formation, and the development and oral presentation of enterprise proposals. In the area of the internship, students asked for additional mentoring and support in order to be able to optimize the integration of their internships with other Ph.D. activities.

Since the program is entering its ninth year and has had thirteen participants who have completed a Ph.D., it is possible to begin looking at outcomes in terms of intellectual property generated and start-up enterprises formed or joined by participants. While looking at the number of patent filings can be misleading and ignores issues of quality vs. quantity, it is a convenient metric. The average number of patents filed per student by students over the life of the program is about twice that of the regular Ph.D. program students, and, similarly, the percentage of program students who have filed at least one patent is also about twice that of the regular program students.

The involvement of program students in start-ups during or after graduation is substantially greater than regular program students. This is likely due in part to heightened awareness and training as well as self-selection of students entering the program. We acknowledge that, due to the small size of the PhD Innovation Program, one cannot draw strong conclusions, but we feel it is still useful to report the data.

In Figure 1, a graph by year shows participation rates of students in formal intellectual property generation. It can be seen that generally the participation of innovation program students is higher than that of the regular Ph.D. program students. But, it also shows an upward trend of participation by regular Ph.D. program students. This can be ascribed, in part perhaps, to a collateral effect of the PhD Innovation Program on the peer group of regular Ph.D. students.

In Figure 2, pie charts illustrate where our regular Ph.D. program and PhD Innovation Program students go after graduation. To minimize the number of categories, we grouped students into one of five categories: 1) Postdoctoral and medical programs, 2) Entrepreneurial activity, which includes co-founded start-ups, other start-ups, and venture fund advisers, 3) Industry and/or Government non-entrepreneurial positions, 4) Academic teaching positions, and 5) Other. As can be readily observed, there is substantial difference in outcomes between the regular Ph.D. program students and the PhD Innovation Program students. Likely most of this may be ascribed to self-selection of the students in the PhD Innovation Program, but outcomes show the program is meeting its objectives of training new technical Ph.D.'s in entrepreneurial thinking and thereby helping to invigorate the U.S. economy.

As with all long-term investments, program success will need to be measured over a longer timescale, and assessment results and feedback addressed through program adjustments going forward.

OTHER PROGRAMS

In 2014, Dartmouth's Thayer School of Engineering was awarded the National Academy of Engineering's Bernard M. Gordon Prize for Innovation in Engineering and Technology Education "[f]or creating an integrated program in engineering innovation from undergraduate through doctorate to prepare students for engineering leadership." Fundamentals in innovation and entrepreneurship concepts are

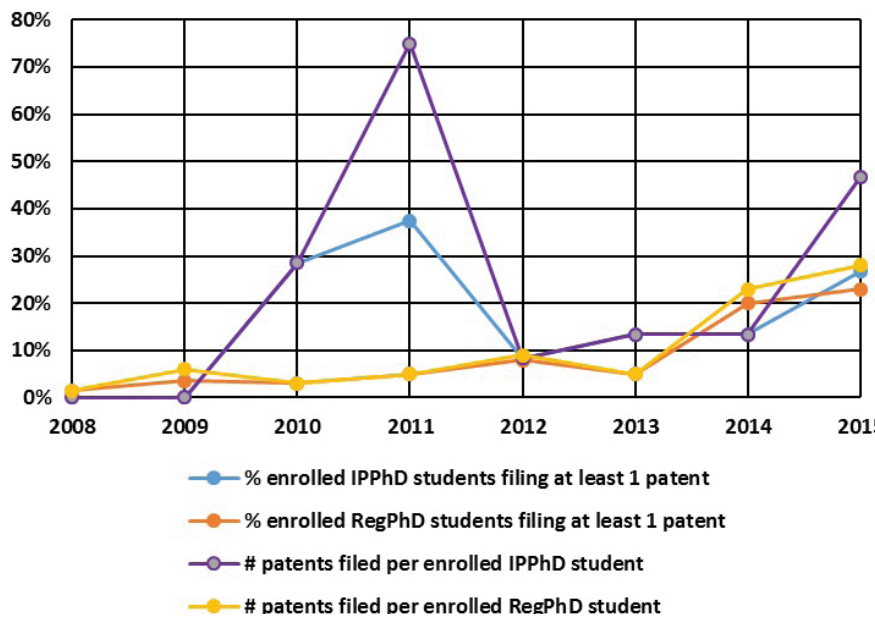

Figure 1. Patent filing rates for regular Ph.D. program (RegPhD) and PhD Innovation Program (IPPhD) students at the Thayer School of Engineering at Dartmouth. Due to the small size of the program in the earlier years, the variance in the data is larger for the PhD Innovation Program. In 2015, 15 out of 94 Ph.D. students were in the PhD Innovation Program.

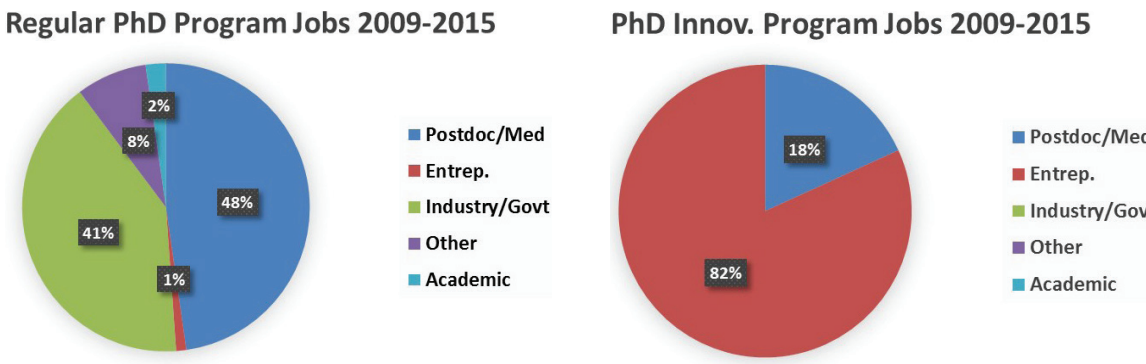

Figure 2. Initial employment (jobs) outcomes for Ph.D. students in the regular and Innovation programs. See text for category descriptions.

perhaps something all engineering students should be exposed to at the undergraduate level (e.g., 5), and, indeed, a multitude of programs at the undergraduate and master's degree level exist in the U.S. and elsewhere. However, we find few engineering programs that carry the same philosophy to the Ph.D. program, although their number has grown in recent years. Universities that have specific innovation and entrepreneurship training for Ph.D. engineering students include Stanford, Yale, Brown, Massachusetts Institute of Technology, and Duke, but not dozens more. We find that our program is unique in its emphasis on the integration of research and enterprise planning in learning, skill-building, and practice in a doctoral program. While having a unique curriculum in this area is good for attracting excellent engineering graduate students to Dartmouth, we would like to see more programs in the U.S. and feel it is vital for national competitiveness.

LESSONS LEARNED AND IMPROVEMENTS

Perhaps one of the most important lessons learned in this program is that a modicum of education in the area of innovation and enterprise goes far in overcoming the natural barriers engineering personalities have with creating enterprises. In fact, it seems many engineers often find a lack of education in the area of business a formidable psychological barrier to taking the leap to initiating a new enterprise. However, most Innovation Program PhD students, already well-equipped with mathematical and analytical skills, find that core entrepreneurial business concepts (e.g., legal, intellectual property, accounting, business plans, etc.) are relatively easy to learn. In a phrase, learning entrepreneurial business mechanics is not rocket science. Of course, taking risks does not come easily to most engineers, and we can only diminish the perceived risk through preparation.

Another lesson learned is that training students in this area, as in research, requires one-on-one mentorship and coaching. In a program that is a small subset of just over 100 engineering Ph.D. candidates school-wide, each student's background, needs, and trajectories are rather different from one another. A one-program-fits-all approach does not work well and has been difficult to fashion. Instead, great flexibility is required to achieve the program objectives. The ability to offer such flexibility is a strength of a smaller institution.

One area of concern among some of the participating faculty is that the Innovation Fellows are extraordinarily independent, especially once enabled by fellowship and research funding. These intellectually strong students may adjust or possibly abandon the research path foreseen by the faculty member or may be reluctant to accept their adviser's advice. While ultimately the student's dissertation must be examined and approved by the adviser and dissertation committee, the independence of some of the Innovation Fellows can be disruptive to normal lab culture and thus unnerving to the faculty adviser.

Like all faculty, Dartmouth's engineering faculty are diverse in their opinions about most subjects except perhaps for the need for quality education for undergraduate and graduates alike in engineering. The PhD Innovation program, while still in its youth, has

garnered a range of opinions from its faculty. While generally supportive, faculty who are highly focused on the academic track without much exposure to industry are less convinced of the need for such a program compared to those who have had some exposure to the commercial world. Some believe that all our engineering students should have some minimum training in innovation and enterprise, a view held by many junior faculty members interviewed at Dartmouth in the past few years and indicative of a possible change in thinking in the next generation of faculty. Engineering has always been associated with the invention and application of new technology for society in both public and private sectors and often calls for the creation of new enterprises. It is therefore important to communicate continuously the need and importance of such innovation and enterprise training for some of today's Ph.D. students. This is an ongoing process, and our successful outcomes help cement the relevancy and importance of the program.

An area of improvement for Dartmouth is in creating a larger pool of well-qualified applicants for the program. Relative to most of its Ivy League and other peer institutions, Dartmouth is a modest-sized school, especially for graduate study, and the climate in northern New England is for those who relish strong seasonal variety. Thus, the pool of students that are cognizant of our program and apply to Dartmouth for graduate engineering study is growing but has not reached our targeted size. Our selectivity is currently about 15%. We need to better communicate our PhD Innovation Program to our feeder schools and develop new feed paths for our program. We are also working on strategies to further engage women to grow our applicant pool and increase the percentage of women in the program nearer to the fifty percent level we have recently seen among our undergraduate engineering degree program students.

CONCLUSIONS

Having celebrated its eighth birthday, the PhD Innovation Program at Dartmouth's Thayer School of Engineering has already been able to measure significant successful outcomes in terms of innovation and entrepreneurship skill development and intellectual property and new technology enterprise generation from a relatively small group of PhD Innovation Program students. We believe that such training in innovation and enterprise is an important step in sustaining and increasing technological and economic vibrancy in the U.S. and worldwide, and there is evidence that other institutions agree. While our program is young and continuously improving, we feel we are on the right path for leadership at the forefront of future engineering education.

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