Training Students with T-shaped Interdisciplinary Studies in Predictive Plant Phenomics

Prof. Julie A. Dickerson, Iowa State University

Julie Dickerson is a Professor at Iowa State University in the Department of Electrical and Computer Engineering (ECpE). She served as a program officer at the National Science Foundation in the Advances in Biological Informatics Program and the Postdoctoral Research Fellowships in Biology Program in the Biology Directorate as the lone engineer. She has also served as the Chair of the Bioinformatics and Computational Biology program at Iowa State University.

She holds a B.S. degree in electrical engineering from the University of California, San Diego. She received her master's degree and Ph.D. in electrical engineering from the University of Southern California. She designed radar systems for Hughes Aircraft Company and Martin Marrietta while getting her Ph.D. Her current research activities are in systems biology, bioinformatics, bioinformatics education, and data visualization. She was a Carver Fellow in the Virtual Reality Applications Center and a member of the Baker Center for Bioinformatics in the Plant Sciences Institute and the Human-Computer Interaction Program. Dr. Dickerson has over 120 peer-reviewed publications in journals, book chapters, and conference proceedings and supervises research projects funded by the National Science Foundation, ARDA, and the United States Department of Agriculture.

Prof. Theodore (Ted) J. Heindel, Iowa State University

Theodore (Ted) Heindel is currently the Bergles Professor of Thermal Science in the Department of Mechanical Engineering at Iowa State University; he also holds a courtesy professor appointment in the Department of Chemical and Biological Engineering. He directs the Experimental Multiphase Flow Laboratory at ISU, which houses a unique instrument for performing X-ray visualization studies of large-scale complex fluid flows. This instrument can also be used to visualize root systems for phenotyping. Ted's teaching emphasis is in the area of thermal science (thermodynamics, fluid dynamics, and heat/mass transfer) and measurement and instrumentation. He has also developed two new graduate-level courses: "ME 531: Advanced Energy Systems and Analysis" and "ME 585: Fundamentals of Predictive Plant Phenomics." He has been recognized for his teaching efforts through the College of Engineering's Superior Engineering Teacher of the Year Award, and was twice selected by graduating seniors as mechanical engineering's Professor of the Year. He has co-authored one book and published over 75 peer-reviewed journal papers and over 220 conference papers, abstracts, and technical reports. Ted received his B.S. from the University of Wisconsin – Madison and his M.S. and Ph.D. from Purdue University, all in mechanical engineering with an emphasis in the thermal sciences

Dr. Carolyn J. Lawrence-Dill, Iowa State University

Carolyn Lawrence-Dill has devoted the last 20 years to developing computational systems/solutions that support the plant research community. Her work enables the use of existing and emerging knowledge to establish common standards and methods for data collection, integration, and sharing. Such efforts help to eliminate redundancy, improve the efficiency of current and future projects, and increase the availability of data and data analysis tools for plant biologists working in diverse crops across the world. Carolyn led the USDA's maize model organism database MaizeGDB (http://maizegdb.org/) for a decade, currently coordinates the development of the information platform for the US maize Genomes to Fields Initiative (http://www.genomes2fields.org/), and is an active member of the community working to put in place methods for phenotype data access, analyses, and re-use. To learn more about her contributions to plant biology and information access, visit https://scholar.google.com/citations?user=bHQPmtEAAAAJ&hl=en. In addition to research and development efforts, Lawrence-Dill is a coPI on the NSF-funded grant "NRT: Plant Predictive Phenomics," which supports the development of mechanisms to train the next generation of scientists and engineers to work together on shared problems that involve plant biology, data sciences, and engineering.

Patrick S. Schnable, Iowa State University
Dr. Jill Wittrock, University of Northern Iowa

Jill Wittrock is the Assistant Director at the Center for Social and Behavioral Research and an Assistant Professor in the Department of Political Science at the University of Northern Iowa.

Mary E. Losch, University of Northern Iowa

Mary Losch is Professor of Psychology and Director of the Center for Social and Behavioral Research at the University of Northern Iowa. Her classroom teaching has included courses in Psychology of Gender Differences and graduate courses in Research Design and Program Evaluation. In addition to her administrative and teaching duties, she has designed and directed over 90 survey, evaluation, and applied social science research projects. Her research publications span survey methods, social science and health disciplines. She is adjunct clinical associate professor at the University of Iowa College of Public Health and also serves on the Advisory Board for the University of Iowa College of Public Health. She is active in the American Association for Public Opinion Research (AAPOR) and has been elected twice to the Executive Council. Dr. Losch also has an extensive background in human research participant protections including previous service as chair of the University of Northern Iowa IRB.

Training Students with T-Shaped Interdisciplinary Studies in Predictive Plant Phenomics

Abstract:
Modern engineering and data analysis techniques make it feasible to develop methods to predict plant growth and productivity based on information about their genome and environment, however students trained with broader skillsets will be needed to unlock this potential. This paper describes the structure and activities of a National Science Foundation Graduate Research Traineeship (NRT) award focusing on Predictive Plant Phenomics (P3). Our program aims to increase agronomic output as highlighted by the National Plant Genome Initiative's current five-year plan [NST, 2014]. Ph.D. training production levels and types are not always a good fit for addressing complex technical and societal problems such as these. To train these scientists, the P3 NRT is using the T-training model proposed by the American Society of Plant Biology (ASPB) and described in "Unleashing a Decade of Innovation in Plant Science: A Vision for 2015-2025". This approach requires that students get broader exposure to multiple disciplines, work with industry and develop effective communication and collaboration skills without increasing the time to graduation. This paper describes how we are working towards meeting these challenges. Initial results show that the students have more contact with faculty across departments than single discipline graduate students and that the students are open to learning about new areas. However, we are still grappling with issues such as finding the best mechanism for balancing student skills as they start their program in leveling activities such as bootcamps and initial course training.

Program Overview:
The NSF Research Traineeship (NRT) Predictive Plant Phenomics (P3) Specialization implements the T-training model proposed by the American Society of Plant Biology (ASPB) [ASPB, 2013]. The goal of the Predictive Plant Phenomics (P3) program is to prepare graduate students with the understanding and tools to design and construct crops with desired traits that can thrive in a changing environment. Students with "T-shaped" experiences will differ from traditional STEM graduate programs that produce students with deep disciplinary knowledge in at least one area. This depth represents the vertical bar of the "T". The horizontal bar represents their ability to effectively collaborate across a variety of different disciplines [T-Summit, 2016], which is the focus of P3 as shown in Figure 1.

This paper reports on the progress of the project to date and presents results on the first year's project assessment on the effectiveness of the cross disciplinary training. The P3 program is preparing students for productive careers in plant phenomics research and development in academia and industry. The vertical stem of the T represents traditional research-based PhD training in an engineering, data science or plant biology based discipline. Adding horizontal skills, such as those shown across the top, prepares both masters and PhD students for a variety of career outcomes and reduces the frequency with which a tenure-track faculty position is seen as an all-or-nothing, overarching goal. Among the horizontal skills are those commensurate with data and Internet-driven science, in which programming, data mining, statistical analysis, visualization, and online collaboration are used to generate and execute research agendas [Miller, 2017]. Other horizontal components include entrepreneurial and private sector experiences.

This approach is in contrast with most graduate training programs, which focus on training new members of the professoriate without actively taking into account that many PhD students in STEM fields ultimately find employment in the private sector, the federal government, or other non-academic settings [CGS, 2012]. Unfortunately, many professors lack the experience to provide students with specific skills required for these types of positions [CGS, 2010; CGS 2012], e.g., the ability to participate in team-based research and professional skills that involve communication, data analysis, and synthesis of new ideas and areas of exploration given results. Students may also be discouraged from participating in internship opportunities for fear that such activities could disrupt their PhD research activities. Thus, P3 training activities will **not** be solely focused on the students; instead all P3 graduate mentors will participate in a required workshop on transdisciplinary mentoring that will highlight the best practices in advising transdisciplinary students [Smith, 2014].

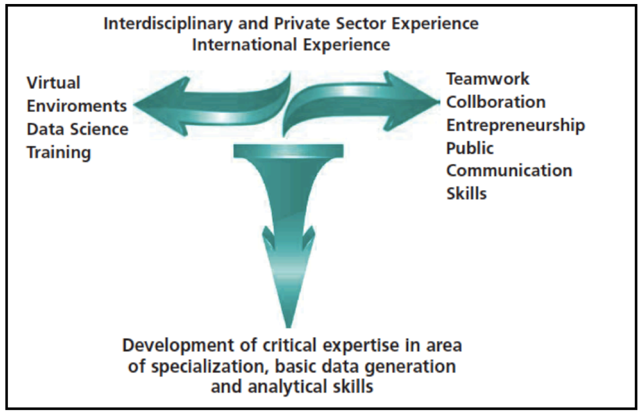

Figure 1. T-training for multiple career paths. Taken from the ASPB "Unleashing a Decade of Innovation in Plant Science: A Vision for 2015-2025".

The overarching objective of P3 is to teach students and faculty how to use transdisciplinary research to improve the understanding of crop plant and agricultural production. Specific objectives are to:

1. Advance the science of predictive phenomics by developing sensors, imaging systems, and robotic systems to measure specific phenotypes in a high-throughput manner.
2. Apply data science to large, heterogeneous time-course data sets that link genomic and phenomic data.
3. Apply engineering design principles to modeling plant performance under a range of conditions.

P3 Description:

The P3 program is also pioneering a new interdisciplinary model at our university, called an interdisciplinary specialization. The P3 interdisciplinary specialization integrates existing Ph.D. majors together with added training in communications, collaboration, and broader skill sets. A specialization allows a student to major in their primary area of study, say Plant Biology or Mechanical Engineering and participate in the P3 specialization that is noted on their diploma at graduation. This means that the student must meet the requirements of both the P3 program and those of the academic home department. This model is a flexible structure that uses existing courses and department structures to train students in specific areas without creating the infrastructure necessary for new interdisciplinary programs that require a lengthy train of approvals. The participating programs for this specialization span three colleges: Agriculture, Engineering, and Letters, Arts and Sciences. All three colleges contribute resources for student recruitment and training. Participating programs and departments include Bioinformatics and Computational Biology, Electrical and Computer Engineering, Genetics and Genomics, Mechanical Engineering, Plant Breeding and Plant Biology.

The strength of this interdisciplinary model is that it is flexible and does not create new bureaucracies. However, the lack of a single departmental core may have the effect of lessening buy-in by faculty and participating departments and it requires more effort to demonstrate the ongoing benefits to sustain the program after the initial extramural funding runs out. As described later in the evaluation section, ongoing buy-in by participating faculty and university administrators is being assessed.

P3 Education and Training Activities

The objective of the education and training activities is to develop scientists and engineers with broad skillsets to address the research needs described above, and who have an appreciation of the abilities and limitations of other disciplines and the confidence and communication skills to interact with them.

Retention and Success Activities:

Graduate Learning Communities: Each cohort of graduate students will comprise a P3 Graduate Student Learning Community. Our university has received several awards for its undergraduate learning community efforts. We plan to use our experience in this area to enhance the P3 graduate program. The learning community for the first P3 cohort was led by the project coordinator and other project collaborators. Future cohorts of P3 graduate students will be led by earlier P3 students, with assistance from the P3 project coordinator. Turning the learning community leadership activities over to P3 students has three benefits. First, it helps build a strong community among all P3 graduate students. Second, the second year P3 students have first-hand knowledge of what worked and what did not work during their first-year experience, and they will be motivated to make changes and provide continuous improvement to the learning community. And third, the learning community organization provides leadership opportunities to the P3 graduate students.

Two-week Boot Camp: The program starts with a two-week short course boot camp for all incoming students. The purpose of this boot camp is to introduce the students to the basic topics they will need to succeed and to their cohort of fellow students. The assumption is that the students will be knowledgeable about some topics, but not all. Each day consists of lectures in the morning and a lab session in the afternoon. There are field trips, to local industry and test fields near campus to demonstrate challenges in phenomics. Table I gives a sample schedule.

P3 Curriculum

(1) T-Base Common Core: All P3 students take a fast-paced transdisciplinary course with a hands-on laboratory component the first year of their program. The course has two key objectives: 1) bring all students' knowledge up to the same level for issues that pertain to plant phenomics, sensor engineering, and data analysis, and 2) begin the process of teaching students the needed terminology to speak across disciplines. This course has only a calculus-based undergraduate curriculum as pre-requisite and will therefore be accessible to P3 fellows from all disciplines in their first semester. This new graduate course entitled "Fundamentals of Predictive Plant Phenomics" was offered for the first time in fall 2016. The goal of the course was to provide graduate students who come with undergraduate degrees in engineering, plant sciences, or data sciences, with a common knowledge base in the area of predictive plant phenomics. Further details of this new course are provided in a companion paper [Heindel, 2017].

Table II. Sample two-week boot camp schedule.

Day	Topic	Lab
1	Team-building basics	Exercises in team building
2	Genomics	Working with genomic databases
3	Measuring genomic data	Visit to on-campus sequencing and flow cytometry facilities
4	Data Carpentry Workshop	Basics of using R, a statistical computing language
5	Plant development and basic plant anatomy	Macro- and micro-dissection of major plant research species
6	Research Ethics and Communications	Field trip to local company
7	Data Mining	Finding, downloading, and cleaning data sets
8	Machine Learning	Making inferences using data sets
9	Plant Physiology	Trip to fields to observe and measure phenotypes
10	Sensing technologies	Lab tour of sensor labs

(2) Experimental Methods: Statistical methods for designing experiments and analyzing data are essential for research in predicted phenomics and are part of the common vocabulary needed for research. The P3 students can choose between two different existing statistics courses depending on their mathematical preparation. Both courses teach students the basic skills in exploratory data analysis, hypothesis testing, linear regression, etc. These courses have a strong emphasis on applying methods to real-world data sets especially for genomics data, which will benefit the P3 students. Our original plan was to have a common statistics course for all students based on the statistics needed for engineering students, however, when students have drastically different preparation levels in mathematics and statistics it is not possible to create a course which is effective for all students.

(3) Depth Courses: Each PhD student must take a minimum of a 3-2-1 combination of courses in the three "major" thrust areas; that is, three courses in the student's discipline of focus (Engineering, Plant Sciences, or Data Sciences), two courses in a second discipline, and one course in the third, thus providing disciplinary depth and transdisciplinary breadth. Students can take additional courses within the other thrust areas as needed for their research and in keeping with existing program requirements. This requirement ensures students are research-capable in their self-identified thrust area, and have knowledge in the other thrust areas. Coursework-only masters students take the required core courses and the 3-2-1 course combination to provide some breadth and depth.

(4) Technology-Led Entrepreneurship: The P3 program partners with an existing biotechnology-focused entrepreneurship course. This one-credit course leads students through the process of developing a technology-led idea into an early-stage business or project proposition. The students learn skills that will help them identify a market for their work. This technology-led entrepreneurship course develops an understanding of: (i) discovery research and how technology relates to innovation and the potential for entrepreneurship, (ii) critical techno-commercial analysis, intellectual property and the evaluation of risk and reward, (iii) defining key assets in the context of generating a business model canvas, (iv) working through the elements of a business proposition, utilizing local resources, and (v) the process of founding a company and selling your ideas to secure early-stage funding.

P3 Student Skill Training

(1) P3 Collaborative (P3C) Seminar Series: This one-credit course (a seminar series) will be offered each semester and will be required of all P3 students (4 times) and faculty (50% of the year). The seminar series will serve to integrate teams and develop research skills. Each semester, research teams, consisting of students and faculty members working on joint research projects in predictive phenomics, will lead their assigned class period in discussion of topics and issues germane to their research. Peer review across the thrusts (fostered by peer mentoring) will improve inter-project and transdisciplinary connections and allow for an in-depth treatment of each project. The emphasis will be on presenting works-in-progress rather than polished final results. Electronic portfolios will be maintained throughout, serving to provide archived documents of how the learning and research evolve for assessment purposes.

(2) Communication: Expanding the use of engineering to design crops that perform better in different environments entails communicating with diverse stakeholders and the public. This can be a controversial topic with the public given current discussions of genetically modified organisms (GMOs). Principal stakeholder groups include farmers, their families and farming communities, agricultural companies, and policy-makers at the local and national levels, regulatory agencies, and the general public each of whom will have different information requirements and demands, as well as values. Communication entails understanding the public's perception of this relatively new enterprise. Students undergo "media training" during their boot camp and practice making short videos describing their research interests. The students have additional opportunities to use this training during P3C seminars and learning community activities. Such efforts will reinforce students' appreciation of their communication responsibility and their ability to actively engage in influencing policies at the local, state, and federal levels.

Ethics: All STEM students and prospective scientists/engineers need to have a strong background related to the responsible conduct of research (RCR). P3 students participate in GRST 565 – Responsible Conduct of Research in Science and Engineering, a course designed around case studies to help students understand and articulate broader ethical concerns. At the conclusion of this course, students will be able to: (1) understand and articulate major ethical issues raised by research and development; (2) distinguish between perceived and measured risk, and to discuss the moral and political significance of risk perception, measurement, and communication; and (3) understand and explain different competing views about human and environmental risks posed by engineering plants.

Industry experiences: The P3 program strongly encourages students to participate in industrial internships as part of their education. Ideally, the internship will occur during the summer of the student's second year of the program so the students can apply their learned T-training skills during their internship. Before and after, each internship, the student will be assessed on their attitudes and expectations of working in industry; they will also meet with their research mentor to facilitate a smooth transition to and from the intern experience.

Program status:

The first cohort of P3 fellows was selected in Spring 2016 and their demographics are summarized in the table below. The students come from a very wide range of backgrounds in their undergraduate majors. One issue that we have encountered is that recruiting students with engineering backgrounds in challenging as compared to students in plant sciences for many reasons. One is that few undergraduate engineering programs around the US expose their students to agricultural system applications of engineering. Another problem is that many Ph.D. programs in engineering have low rate of enrollment from US citizens. We are working to expand the ideas of what types of projects engineers work on by providing informational slides to collaborators in engineering departments. The P3 coordinator is also proactively searching the applications in participating departments to contact strong applicants to tell them about our program.

Demographics	**UG Major (s)**	**Admitted Degree Program**
White, Male	BS, Biochemistry	Bioinformatics and Computational Biology
White female	BS, Crop Sciences	Interdepartmental Plant Biology
White male	BA, Economics and History BS, Plant Genetics and Breeding MS, Horticulture Science	Genetics and Genomics
White female	BS, Biochemistry	Bioinformatics and Computational Biology
White male	BS, Agronomy – Plant Science and Biotechnology	Plant Breeding
White male	BS, Molecular, Cellular, and Developmental Biology	Genetics and Genomics
African American male	BS, Electronics Engineering Technology MS, Mechanical Engineering	Mechanical Engineering

The first cohort began their training in August 2016 with a two-week "boot camp" short course to introduce the students to the basic topics they will need to succeed. The initial boot camp received mixed reviews from the students and management team during the evaluation (evaluation methodologies are described in more depth in the next section). Overall, responses from both management team members and students indicated positive views of the boot camp implementation and experience:

- All four management team members that participated in the post Boot Camp questionnaire reported that Boot Camp *met* (n = 3) or *exceeded* (n = 1) expectations.
- All but one student reported that Boot Camp *met* (n = 5) or *exceeded* (n = 1) their expectations.
- All but one student reported that Boot Camp was *good* (n = 4) or *excellent* (n = 2).
- Daily student perceptions of Boot Camp were mostly positive as well: out of 44 SMS responses collected across Boot Camp, only one student indicated that they felt "*meh*" about a day and one student who indicated that they felt "*ugh"* about a day.

Later student discussion groups revealed that the students would like the days to be shorter with more time for the students to interact with one another and to get know the college community. The students found that the section on data carpentry during boot camp should be focused more on biological data and the subject of plant phenomics. Other topics such as the plant science presentation got responses ranging from the presentations moving too fast to not being at a high enough level. This range of responses makes sense when considering the diversity in student backgrounds. We plan to change the focus of the data carpentry workshop to better fit the skills that the P3 students will need in their first semester by focusing more on using R to work with real-world data.

The four-credit P3 core graduate course (Fundamentals of Predictive Plant Phenomics) was offered in Fall, 2016 with 16 enrolled students, 7 from engineering disciplines, and 9 from plant and data science programs. A companion paper submitted to the ASEE Graduate Studies Division discusses the first offering of this course in more detail [Heindel, 2017]. As with the bootcamp, the student response was quite positive. However, students were frustrated by the breadth of topics and the overall organization. The students also tended to struggle with the modules focusing on engineering topics such as heat transfer.

Evaluation

The P3 program features both internal and external evaluation. The P3 Program Coordinator oversees the internal evaluation, which focuses on metrics such as student recruitment and retention, program outcomes, and student performance. The Center for Social and Behavioral Research is conducting the external evaluation. A mixed-methods design that aligns with the evaluation framework proposed by the CDC (Figure 2) guides the external evaluation. The P3 evaluation framework is recursive by design so that the external evaluators are informing the P3 leadership team continuously on program performance and implementation.

The external evaluation includes formative (i.e., related to implementation and progress) and summative dimensions to assess the quality and success of the P3 program. Quantitative assessments to measure performance on program goals include online interviews with project leadership, P3 students, affiliated program faculty, and university administrators. A comparison group design has been incorporated to allow stronger evaluation of the P3 student outcomes. A cohort of graduate students who are unaffiliated with P3 were recruited and invited to participate in the evaluation activities. The outcomes from the P3 cohort will be compared to those of the non-P3 students who represent the training trajectory for students who are not in the P3 program. Pre-post designs are also being implemented to observe changes in P3 student outcomes to approximate the program effect.

Qualitative data collection activities for the external evaluation include in-depth interviews and focus groups of students, and they serve to enrich the findings of the quantitative assessments and also to gain insights from students and faculty on perceptions of and experiences with the P3 program. The feedback obtained during the qualitative data collection help the P3 leadership team learn more about how students, faculty, and administrators feel about the program, obtain insights on how it is working well, and determine where it could be improved or revised during the planning for future activities.

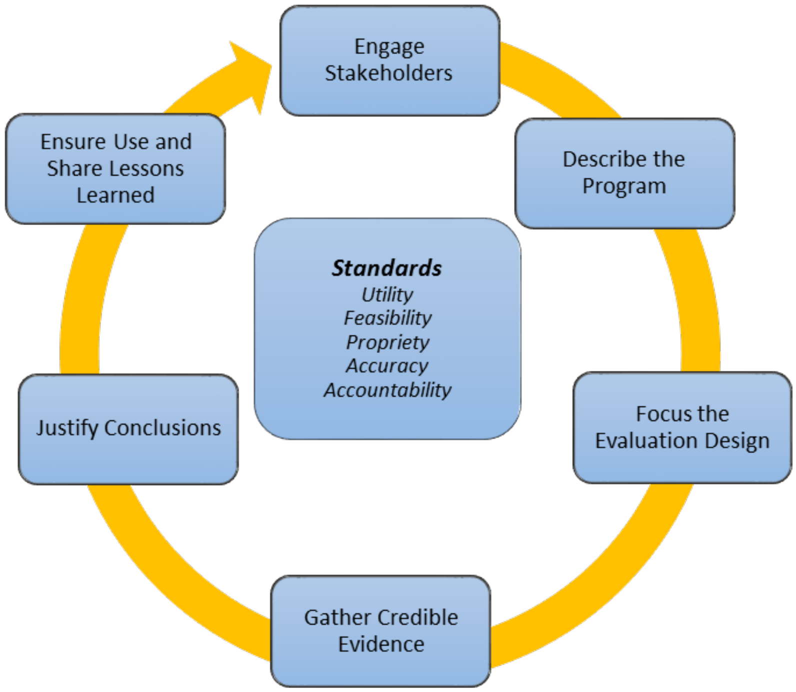

Figure 2: Framework for Evaluation [CDC, 1999]

Evaluation process so far:

To demonstrate the dynamic nature of the external evaluation, this section describes the data collection activities that took place during the first two years of the project. CSBR developed an initial evaluation plan in Year 1 with input from the project leadership team, and this plan is reviewed yearly by the external evaluation team. Early formative findings were the focus of the first year since program activities focused on planning, hiring a program coordinator, and recruiting a cohort for Fall 2017. In Years 2-5, the external evaluation is shifting toward output review to understand what actually occurred, whether the intended objectives and goals for P3 are being achieved, what the changes are (if any) between the P3 cohort(s) and the comparison group(s), and if any differences are observed between intended and actual P3 activities and outcomes. To evaluate the outputs and goals outlined by the leadership team, a full logic model was designed by CSBR and reviewed by P3 leadership. It is also reviewed annually to identify areas needing revision or additional focus.

During Year 1, a process interview was conducted in Fall 2015 to gather feedback from the leadership team. In particular, the external evaluator wanted to know about any challenges and responses to those challenges regarding program planning and implementation of P3. In general, the leadership team felt the programs was about where they expected it to be at the end of the semester of Year 1, and perceived challenges related to hiring the program coordinator, getting interdepartmental support for the P3 program, setting up the admissions process, and developing course materials for the leveling seminar required of all P3 students.

In August of Year 1, the external evaluator administered a series of online instruments prior to and immediately following the first training "boot camp" for the P3 students. Leadership team members and P3 students responded to questions before and after boot camp to better understand the experiences of both groups and to aid in the planning of future boot camps. In addition to the online instruments, students responded to daily SMS text-message questions asking about their thoughts on the day's activities. The findings from these assessments indicated that both the leadership team and students held positive views of the experience and overall implementation of the training. The external evaluator communicated areas of shared and divergent experiences and perceptions between the P3 students and the leadership team so this information could be taken into consideration for future boot camps. For example, students felt that the introductory sessions should be more hands-on and structured more for beginners in the field.

The P3 leadership team was queried in an online instrument prior to the start of Boot Camp to assess their perceptions of Year 1 program implementation and planning for Year 2. The team members felt the program was about where they expected it to be at the end of Year 1, and there were no perceptions that they were falling short on completing tasks or meeting deadlines.

Focus groups with the P3 students and comparison cohort were conducted in Fall 2016 to learn more about general perceptions of and experiences with their graduate programs, understanding of T-training and/or transdisciplinary research, communication with faculty members, and elements of their programs that they would keep or change. The observations from the focus groups were communicated to the leadership team in January 2017 to supplement student assessment and feedback received at the end of the first semester.

The external evaluators also sought feedback from faculty who were formally affiliated with the P3 program (but not part of the leadership team) at the end of the Fall 2016 semester. An online instrument was administered that gauged their familiarity with the primary goals of P3, communication with the leadership team, and general perceptions about the program. The findings were communicated to the leadership team during the Spring 2017 semester.

External evaluation activities in subsequent years of the project will continue to shift toward output review with quantitative assessments geared toward identifying the various contributions of program activities in terms of intensity and outcomes and qualitative methods focused on understanding process and implementation. The external evaluation will gather data to measure program activities from inception through various stages of outcomes with the goal of understanding what actually occurred in the project, whether P3 objectives and goals were achieved or fell short of expectations, what changes, if any, emerged between the P3 students and non-P3 students, and if there were differences between intended and actual outcomes.

Conclusions

The new P3 graduate program at our university is training its first cohort of students. Overall, the P3 specialization is succeeding at its core mission of exposing students to transdisciplinary research in comparison with students in traditional departments. Our team's first offering of the boot camp and leveling course was successful in the eyes of the P3 management team and students as the students were introduced to a broad range of topics. The program team will continue to address and improve our response to problems such as how to help level out student backgrounds across a wide range of disciplines and how to recruit a balanced cohort of students in terms of undergraduate majors. We plan to use the results from the evaluation team to improve courses by bettering integrating the training and laboratories, applying inquiry based learning methods such as flipped classrooms and more judicious selection of topics. The management team is also working at better defining the course requirements for the student cohorts to better accommodate different levels of expertise in biology, mathematics and data science.

Acknowledgements
This material is based upon work supported by the National Science Foundation under Grant Number DGE-1545463. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Bibliography

[ASPB, 2013] American Society of Plant Biologists, *Unleashing a Decade of Innovation in Plant Science - A Vision for 2015-2025*, in *Plant Science Decadal Vision*. 2013, American Society of Plant Biologists,. p. 36.

[Heindel, 2017] Heindel, TJ, Dickerson JA, Dill-Lawrence, CJ, Schnable, P, "An Interdisciplinary Graduate Course for Engineers, Plant Scientists, and Data Scientists in the Area of Predictive Plant Phenomics," To appear in the *2017 ASEE Annual Conference and Exposition*, June 25-28, 2017, Columbus, OH, Paper Number: 17970.

[CDC, 1999] Centers for Disease Control and Prevention. "Framework for program evaluation in public health." MMWR 1999; 48 (No. RR-11).

[CGS, 2010] Council of Graduate Schools and Educational Testing Service, *The Path Forward: The Future of Graduate Education in the United States. Report from the Commission on the Future of Graduate Education in the United States*. 2010, Educational Testing Service: Princeton, NJ.

[CGS, 2012] Council of Graduate Schools and Educational Testing Service, *Pathways Through Graduate School and Into Careers. Report from the Commission on Pathways Through Graduate School and Into Careers*. 2012, Educational Testing Service: Princeton, NJ.

[Miller, 2017] Miller, R. K., "Why the Hard Science of Engineering is no longer enough to meet the 21st Century Challenges," Olin College. Viewed January 2017. Available at http://undergrad.msu.edu/uploads/RebalancingEngineeringEducationTReadingrec.pdf

[NRC 2014] National Research Council of the National Academies, "Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond," National Academies Press:Washington D.C., 2014.

[NSF, 2013] National Center for Science and Engineering Statistics, *Doctorate Recipients from U.S. Universities: 2013*. 2013, National Science Foundation: Arlington, VA.

[NSTC, 2014] National Science and Technology Council, *NATIONAL PLANT GENOME INITIATIVE FIVE-YEAR PLAN: 2014–2018*. 2014, Office of Science and Technology Policy: Washington, DC.

[Smith, 2014] Smith, M.J.T. *Mentoring of Graduate Students in Interdisciplinary Programs at Purdue University*. in *Interdisciplinary Learning in Graduate Education and Research: Online Proceedings of 2014 Global Summit*. 2014. Newfoundland, Canada: Council of Graduate Schools.

[T-Summit, 2016] T-Summit 2016, "What is the T?" http://tsummit.org/t, viewed October 2016.