An Interdisciplinary Graduate Course for Engineers, Plant Scientists, and Data Scientists in the Area of Predictive Plant Phenomics

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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

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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.

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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.

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Abstract

This paper describes the development and first offering of a new graduate course entitled "Fundamentals of Predictive Plant Phenomics," which is part of a recently awarded National Science Foundation Graduate Research Traineeship (NRT) award to Iowa State University. The focus of this particular NRT award is to train engineering, plant science, and data science graduate students in the area of predictive plant phenomics (P3), with the goal to develop researchers who can design and construct crops with desired traits to meet the needs of a growing population and that can thrive in a changing environment. To meet this goal, the P3 NRT program will train next generation crop scientists to have broad technical skillsets as well as strong "soft skills" in communication and collaboration. A companion paper (Dickerson et al., 2017) provides an overview of the P3 NRT program, whereas this paper focuses on a new course developed as part of the P3 NRT.

One of the challenges associated with providing the students in the P3 NRT program with the needed multidisciplinary skills to thrive is to ensure that all students have a common knowledge base in engineering, plant sciences, and data sciences, no matter their background. The goal is to get all students communicating in the same language. The course "Fundamentals of Predictive Plant Phenomics" was developed to meet this challenge. The course planning took nearly one year and incorporated input from faculty with various disciplinary backgrounds. The actual course is coordinated by an engineering faculty member and taught through a series of guest lecturers covering various plant science, data science, and engineering topics over a 15-week period. In addition to the three 50-minute lectures per week, a 3-hour laboratory each week provides an experiential learning opportunity where students can apply the knowledge they learn in the lectures. The first offering of this course occurred in fall 2016, with 16 enrolled students, 7 from engineering disciplines, and 9 from plant and data science programs. Lessons learned from the first offering of this course are summarized in this paper. The course is providing the needed background so students can develop a successful research topic in the area of predictive plant phenomics and communicate with others in this broad multidisciplinary field. Because the course is a leveling or survey of three disciplines, and each student has a good background in at least one of the three, it has been challenging to keep all students interested and engaged for all lectures (but not labs). To address this challenge, expanding the application of Inquiry-Based Learning approaches during the lecture period in future years is proposed.

Introduction

As highlighted by the National Academies (2000) and by the National Plant Genome Initiative's current five-year plan (National Science and Technology Council, 2014), increasing agronomic output is a key challenge of the 21st century. Compounding the challenge, increases in crop production must be accomplished using less agricultural land than is currently available due to urban development and desertification. At the same time, climate change is expected to lead to increasingly adverse and variable environmental conditions for crop production.

To address these challenges, next generation crop scientists must know plant science and agronomy, but they also must be familiar with data science and engineering. For example, linking complex traits with genetics and the environment requires skills in plant science, data analytics such as machine learning, and engineering to properly sense the environment. Similarly, engineers using nanotechnology to design and build new sensors need to know big data analysis and plant science to better develop new applications for their devices.

With this motivation, Iowa State University was awarded a National Science Foundation Graduate Research Traineeship (NRT) award in the area of predictive plant phenomics (P3). The goal of the P3 NRT is to train transdisciplinary scientists and engineers with the tools to address the key agronomic challenges of the 21st century. A companion paper at this conference provides a summary of the P3 NRT program (Dickerson et al., 2017).

One need of the P3 program was to develop and then offer a transdisciplinary "leveling" course to first-year graduate students. The leveling course needed to meet two key objectives: (1) bring all students' knowledge up to the same level for issues that pertain to plant phenomics, basic transport phenomena and sensor engineering, and data analysis, and (2) begin the process of teaching students the needed terminology to speak across disciplines. The result was a new course entitled "Fundamentals of Predictive Plant Phenomics" that was first offered fall 2016. The remainder of this paper discusses what is included in this course, the logistics of course implementation, course assessment, and lessons learned from the first offering.

Course Content

One particular challenge with this new course is the interdisciplinary nature of the area: students come from different undergraduate disciplines (e.g., Agronomy, Biology, Mechanical Engineering, etc.), and are enrolled in diverse graduate programs (e.g., Bioinformatics, Genetics, Mechanical Engineering, Statistics, etc.). Thus, the only prerequisite to the new course was any calculus-based undergraduate curriculum and approval of the lead instructor. A laboratory component to the course was also desired so students could extend and practice the knowledge they receive in lecture.

Iowa State University has a 15-week semester (another week for finals) and 44 class periods for a course that meets three times per week in 50 minute blocks. A course laboratory component can meet for additional hours per week. We planned a 3-hour laboratory once a week for our new course. Hence, "Fundamentals of Predictive Plant Phenomics" was designed as a 4-credit course with three 50-minute lecture periods per week and one 3-hour lab per week.

A planning team made up of faculty members from the breadth of the subject areas involved in the P3 program identified several content areas that encompassed specific knowledge within plant science, data science, and engineering that we wanted to highlight in the course. The content areas were then presented to different faculty groups for their input and refinement.

Faculty were also asked if they would be willing to present a lecture and/or lab on a particular topic.

The course was initially organized in approximately 5-week blocks, where engineering concepts were covered in the first 5 weeks, data science concepts were covered in the second 5 weeks, and plant science topics were covered in the final 5 weeks. However, we felt students should be presented with plant biology concepts first because all subsequent topics were intended to address research problems in plant systems. We also wanted to give the students an idea of why application of engineering and computational methods to plant biology would make a difference. Hence, the final schedule had the majority of the plant science content presented in the beginning of the semester and the data science and engineering content spread through the remaining semester.

The final course content and sequence is summarized in Table 1. Each of the 44 class periods identify what was covered during that period. Individual weekly laboratory topics are also identified. Table 1 also shows how each topic was classified, either plant science (P), data science (D), or engineering (E). Some topics fall under more than one category and are labeled accordingly. The “Score” columns in Table 1 will be discussed in the Assessment section.

With a wide range of topics in Table 1 that were presented during the semester, no single faculty member was able to cover all the content. We were fortunate at Iowa State University in that several faculty volunteered to cover one or more topics or create one or more laboratory experiences, many of which were done as an overload in their teaching assignment. In total, 19 different faculty presented on the lecture topics outlined in Table 1, while 6 faculty, 2 staff, and 6 senior PhD students developed and/or assisted with the laboratory experiences.

One particular challenge in organizing this course with so much faculty involvement was scheduling when faculty were available to present. Hence, some of the content in Table 1 may flow better if it was organized differently, but the final schedule was determined by faculty availability. The process of setting the final content was initiated 5-6 months before the course began by iterating with several faculty schedules until each class period was finalized, which happened about 2 weeks before the semester began.

Table 1: Course content and assessment scores for “Fundamentals of Predictive Plant Phenomics” in fall 2016.

Wk	Period	Lecture Topic	Area	Score	Laboratory Activity	Score
1	1	Introduction/Overview	—	17	Lab introduction; all students pot plants for semester-long project on plant phenomics	18
	2	Central dogma	P	10		
	3	Cell and molecular biology	P	15		
2	4	Plant anatomy	P	15	How to make plant measurements	17
	5	Plant Development	P	14		
	6	Plant Physiology	P	15		
3		Labor Day - No Class			Dissections of whole plants and look at slides of sections	14
	7	Biocyc	D	12		
	8	Genetics, cell cycle, and transmission	P	18		
4	9	Cytogenetics	P	15	Cytogenetics and DNA extraction	16
	10	Genomics	P	17		
	11	Comparative Genomics	PD	17		
5	12	Photosynthesis	P	14	Computer lab - annotating DNA with gene structures, GO terms	15
	13	Yield potential	P	17		
	14	Plant Breeding	P	17		
6	15	Genome-wide association studies - GWAS	PD	19	GWAS on computer	16
	16	Recombinant DNA technology, cloning	P	15		
	17	GMOs	P	15		
7	18	Cultivar development and the role of pheonotyping	P	20	MATLAB Introduction	13
	19	Mass, momentum, and energy balances	E	15		
	20	Fluid flow I	E	13		
8	21	Fluid flow II	E	13	Transparent soil systems for root phenomics I	11
	22	Basic optics and imaging principles	E	14		
	23	Advanced imaging technologies	E	16		
9	24	Introduction to image processing	D	16	Transparent soil systems for root phenomics II	11
	25	Image processing methods I	D	16		
	26	Image processing methods II	D	16		
10	27	Similarity/Distance	D	11	Image Processing	19
	28	Graph Models	D	17		
	29	Heterogeneous network data analysis I	D	15		
11	30	Heterogeneous network data analysis II	D	14	Visualization methods	16
	31	Heat transfer - conduction	E	12		
	32	Mass transfer - Diffusion	E	12		
12	33	Introduction to agricultural sensors	E	16	Network Construction	18
	34	Microscale sensor design	E	12		
	35	Microfabrication techniques	E	8		
13	36	Sensor measurement circuits and instruments	E	12	Measurements for soil water potential and leaf N status	14
	37	Random Forest	D	20		
	38	Random Forest	D	20		
		Thanksgiving Break - No class				
14	39	Heat transfer - convection	E	12	No scheduled lab	
	40	Heat transfer - phase change, transpiration, etc	E	12		
	41	Heat transfer - radiation	E	11		
15	42	Constraints to production	P	20	Plant phenomics project summary	15
	43	Enviratron – An example of a P3 Project	PDE	14		
	44	Course wrap up and assessment	—	16		

Course Implementation

This graduate course was first offered fall 2016. Before the semester began, all faculty involved it the course received the final schedule and suggested instructor guidelines to help them prepare for the course. The guidelines stressed:

1. The course was designed as a broad survey with the goal of bringing those students with an interest in predictive plant phenomics up to some base level of knowledge in the areas of plant sciences, data sciences, and engineering.
2. The content each instructor was presenting should be presented to students at a level that is introductory, but fast-paced. It was assumed that some of the students may have been exposed to some of the material as an undergraduate. However, all instructors were told to assume that at least half of the students may not have had an undergraduate course covering the specific lecture topic.
3. Instructors were strongly encouraged, but not required, to consider inquiry-based learning (Dostál, 2015) as they prepared their course materials.
4. Students could be asked to prepare for class by reading specific material that could be posted on BlackBoard at least 48 hours before the class met to cover the specific topic.
5. Course notes could be posted on BlackBoard prior to class to help facilitate class discussion.
6. Instructors were encouraged, but not required, to assess student learning through appropriate assignments and/or outcomes-based assessment (Tam, 2014).

The laboratory component of the course was the most challenging to implement but, according to student feedback, was one of the most beneficial aspects. The challenge was identifying appropriate space that could be used for all aspects of the proposed laboratory exercises. For example, one laboratory activity that we wanted to do was to have each student grow maize and soy beans throughout the semester. This required the allocation of dedicated greenhouse space for the course. A greenhouse fee was supported through the NRT grant; a laboratory fee will be required for this course when the NRT grant ends. Initially finding dedicated greenhouse space on campus for the fall semester was problematic, but was finalized about a week before the semester started.

A second laboratory challenge was finding laboratory space for the laboratory exercises during weeks 2-4 (see Table 1). We were fortunate to be provided access to wet-lab space used for biotechnology outreach during these weeks (see Figure 1 for examples). The remaining labs were computer-based and used a conference room and student laptops, or were completed in the research lab space of the faculty member directing the laboratory exercise. This worked, but some of the lab spaces were crowded and students had to be divided in small groups to complete the lab.

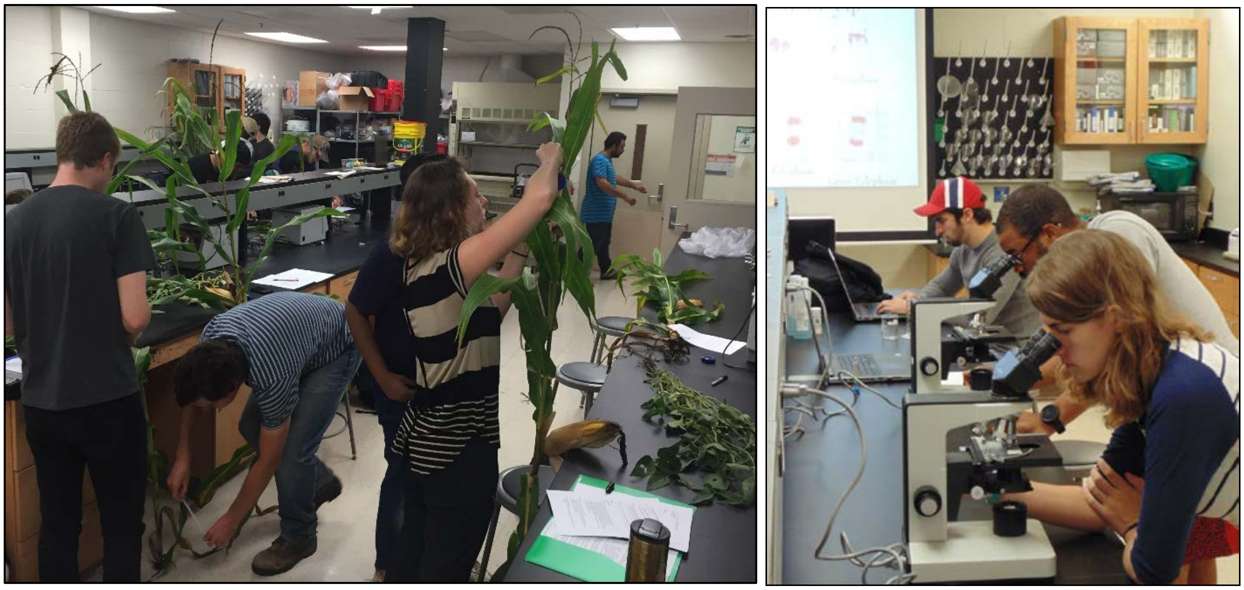

Figure 1: Students completing maize and soy bean phenotyping (left; week 2 in Table 1), and participating in plant dissections (right; week 3 in Table 1).

Ideally, the course should be composed of an equal number of students with plant science and engineering backgrounds, but this was difficult to achieve in practice. The initial cohort of students in this new course was composed of 5 students with an engineering background and 7 students with a plant science background. Another 4 students (2 engineering and 2 plant science) audited the lecture portion of the course because they had a conflict with the laboratory. Considering this was a first offering, the student background composition was deemed a success.

Course Assessment

The implementation of this course was assessed in two ways. First, all courses at Iowa State University automatically get administered an on-line end-of-semester course survey during the last 2 weeks of the semester with standard questions with numerical responses and space for written comments to specific questions. Of the 16 students registered for the course, 13 (81%) completed the on-line survey; many also provided on-line written comments. Overall, responses to standard questions were all very positive. However, because there were so many different instructors, it was hard to interpret the numerical results. More information was gleaned from the written comments. For example, responses to “What helped your learning in this class?” included:

- “Incorporation of students into interdisciplinary groups allowed the formation of a small, tight-knit learning group capable of teaching most of the topics to the group members from other disciplines.”
- “The instructors were chosen from a diverse background which helped in exchange of knowledge.”
- “The lab portion of the class was especially helpful.”

In response to “What hindered your learning in this class?”, selected comments include:

- “Because the breadth of this class was so large, it sometimes made it hard to really understand what the lecturer was talking about since they were trying to fit a semester’s worth of content into an hour.”
- “Poor organization and flow of topics from one topic to the next.”
- “Too many topics. It’s better to remove some topics.”

A second type of assessment included an anonymous content survey that was administered during the last class period of the semester and included a class schedule (similar to Table 1). Student were asked to score each lecture and lab topic with a 0, 1, 2, or 3, where the numbers correspond to “remove content”, “shorten the content”, “keep the content as-is”, or “add more content”, respectively. Eight students attended the last class period and completed the survey. The scores identified in Table 1 correspond to the sum of points for each topic. If all 8 students indicated the content should be kept as-is, the sum would be 16. A score less than 16 indicates at least one student indicated the content should be shortened (or removed). If all students wanted to add more content to a particular topic, the score would be 24.

It is interesting to note that the highest scores in Table 1 were 19 or 20 and were generally associated with big picture concepts (genome-wide association studies, cultivar development and the role of phenotyping, constraints to production), big data analysis (random forest), or common phenotyping methods (image processing/analysis). The lowest scores were associated with general background concepts (central dogma, microfabrication techniques).

A general trend evident in the scores in Table 1 is that the engineering concepts typically scored below 16 (one or more students wanted less content). Two reasons for this are hypothesized. First, many of the engineering students are familiar with the content and don’t need the review, and the non-engineering students are intimidated with engineering content and want less of it. Second, the examples presented during the engineering content were not explicit enough for the non-engineers, losing their interest. For example, when discussing convective heat transfer (period 39 in Table 1), boundary layers were discussed in reference to a flat plate and it was stressed that a leaf could be approximated as a flat plate; however, the non-engineers were not familiar (or comfortable) with making these types of approximations and they lost interest.

Lessons Learned

The overall feedback from the students and faculty involved in this course were very positive. Many of the students went out of their way to indicate the laboratory was extremely helpful. For example, after the second lab (how to make plant measurements), where we used mature maize and soy bean plants the measure various characteristics, an engineering student approached a course coordinator and mentioned how useful the lab was to him. He indicated his research focused on using images of maize tassels provided to him to develop an algorithm to automatically measure tassel features like number, length, angle, etc., but he is only given images of the tassel and, until the lab, had no concept of maize stalk size relative to tassel height.

Faculty involved with the lecture and laboratory presentations also provided unsolicited feedback that they thought the course was a great idea because they are now collaborating more with engineers (or plant scientists or statisticians, etc.) and their students need training in this area.

One of the main challenges and criticisms of the first offering of this course was the lack of coherency between course topics. Student assessment during the course was also problematic because some faculty provided assignments for assessment, but it was challenging to create assessment material that was at the right level for all students.

The course will be offered again in fall 2017. In the second iteration of the course, we plan to better arrange and coordinate the presented topics. We would also like to form class teams that have an equal representation of plant scientists, engineers, and data scientists, and then provide team projects utilizing inquiry-based learning (IBL) (Dostál, 2015). IBL has been shown to help focus student attention on problem solving instead of learning competencies. The application of IBL to problems in plant phenomics will help student teams to apply their knowledge to new situations that may involve several disciplines and could require knowledge from the other disciplines. With diverse teams, students could teach each other the content they do not know to solve the problem at hand. They will have to use a common vocabulary to communicate across disciplines, which is one to the goals of the P3 NRT program. However, the application of IBL will depend on if enrollment can be balanced from plant science, engineering, and data science.

Conclusions

A new graduate course entitled “Fundamentals of Predictive Plant Phenomics” was offered at Iowa State University 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. The first offering of the course was successful, but areas for improvement were identified, and include better coherence between course topics and improved student assessment throughout the course. A revised course is now being planned for fall 2017.

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