Can Great Research Be Taught? Independent Research with Cross-Disciplinary Thinking and Broader Impact

Authors Removed

ABSTRACT

This paper describes a course we have developed for preparing new Ph.D. students in computer science for a career in research. The course is intended to teach the skills needed for research and independent work, prepare students psychologically and socially for years lying before them, and help them find a good Ph.D. topic by providing principles and examples. In this course, we emphasize and encourage impact through cross-disciplinary research and broader societal outreach. To our knowledge, the course represents a first-of-its-kind systematic introduction to a graduate research career. This paper describes our high-level goals for this curricular initiative, the structure of the course (including lecture components and assignments), and the challenges we faced in developing this course. As we continue to develop this course, which is now in its second year, we hope it will serve as a model "introduction of Ph.D. research" course for other computer science departments.

Categories and Subject Descriptors: K.3.2 [Computers and Education]: Computer science education, Curriculum

General Terms: Human Factors, Design

Keywords: Ph.D., graduate education, research

1. Introduction

This paper describes a course we developed and taught for the first time in Fall 2006, CS 7001, as a revamping of the required introductory course for new students in our Computer Science Ph.D. program. We are teaching in Fall 2007 (in progress) an improved version of the course.

Previously, the course was mainly a semester-long seminar series intended to present the research of the faculty for the purposes of advisor selection, with a requirement for short exploratory "mini-projects" for testing the waters with a few faculty members. We expanded its scope far beyond advisor selection, to address a number of observations about current graduate education in Computer Science:

- **The general skills of independent research are not taught programmatically.** Though diverse topics and research styles exist within Computer Science, there are universal skills of research and independent work which could in principle be taught, but are currently learned in *ad hoc*, ill-defined and haphazard fashion, if at all. In other words, to our knowledge, there is *no existing pedagogical practice for teaching independent research* which is widely used. We believe that some of the consequences of the current culture leaving Ph.D. students to figure out these "meta" aspects of independent research on their own include unnecessary and avoidable contributions to:
  - High attrition, or drop-out rates, in Ph.D. programs.
  - Long graduation times in Ph.D. programs.
  - Slow ramp-up time toward productivity in research.
  - Poor job preparation and marketability.
  - A tendency to follow advisors blindly rather than blaze new directions.
- **Computer Science research has an opportunity to change all other disciplines, yet this is not taught.** Much current CS research is of an incremental "stovepipe" or inward-looking nature, even though Computer Science has a unique ability to fundamentally transform virtually every other discipline. Though acknowledged often, we do not teach Ph.D. students in CS to actively seek out and forge the necessary connections to other disciplines. Unfortunately, to our knowledge, there is *no existing pedagogical practice for teaching cross-disciplinary research* which is widely used. We believe that this results in unnecessary contributions to:
  - Researchers in other disciplines effectively develop their own computational solutions, with less expertise.
  - Untapped potential, in terms of impact and quality of research.
- **Computer Science has an opportunity for broader appeal, inclusion, and societal impact.** Enrollment in Computer Science programs at all levels is affected by perceived societal impact, as evidenced by the effect of highly-visible but limited glimpses into the impact of CS such as the dot-com economic boom and bust, the effect of Google on daily life, and demographic perceptions regarding computer scientists. The reality, that these perceptions are limited, needs to be transmitted by the leaders of the field—CS Ph.D. students are not taught about the need to change these perceptions, inspire, and communicate their impact. We believe this deficiency has resulted in consequences regarding:
  - Dwindling enrollments in CS Ph.D. programs.
  - The perception that CS is "dead" even though demand is high.
  - Low enrollments by women and minorities.

To correct many of these problems, we have developed a first-of-its-kind "introduction to graduate research" course; this course is now in its second year. The primary goal of the course is to immerse students in an environment where they can *immediately* become engaged in high-impact research; a related secondary goal is to teach students the necessary skills that enable them to quickly "ramp up" their research careers and to set them on a trajectory for fruitful research careers, as well as marketability. We have designed a compendium comprising 8 assignments, a research project, a mini-project, and a series of 33 lectures that is organized into modules that give students the ambition—and the capability—to excel in a graduate research program. This paper summarizes the high-level goals of the course, how we achieve these goals with 5 course modules, and our experiences and lessons teaching the course over the past two years. Although it might seem that the course itself contains nothing that is not "obvious in hindsight",

Assignment	Description
Assignments	
Recognizing good ideas	Read proceedings from top conference in field, select two "best" papers, and provide a research summary and defense for each.
Generating good ideas	Read other students' summaries from first assignments. Combine two ideas from first assignment to propose a new research direction, idea, or solution.
Critiquing ideas	Read proposals of research ideas from second assignment, write reviews, and meet in a mock program committee to select "best" proposals.
Communicating ideas	Deliver a presentation to the class on a term-long research project.
Mini-Assignments	
Why Ph.D.?	Write down your goals and expectations for the Ph.D. program. Also, summarize the characteristics of the researchers and research results that you most admire.
Time audit	Log how time is spent in 10-minute increments over the course of a week.
Web page	Create a personal research Web page.
Elevator pitch	Compose "elevator pitches" of various lengths (30-second, 1-minute, 5-minute) and deliver the 30-second pitch to the class.

Table 1: Summary of assignments.

feedback and data collected from the first offering of the course suggest that the course provides significant benefits.

The rest of the paper is organized as follows. Section 2 describes the components of the course, including a high-level overview of the course syllabus. Section 3 describes the progress we have made in teaching the course to incoming graduate students and discusses various challenges we encountered, as well as how we addressed them. Section 4 describes related work, and Section 5 concludes.

2. Course Components

In this section, we describe the components of our introductory course to the Ph.D. program. We have organized the course into five components, which we describe in detail in the rest of the section:

- *Research skills* comprise topics that help students recognize, generate, critique and communicate research ideas.
- *Research mechanics* include topics that help students develop essential techniques for performing various common tasks in computer science research.
- *Skills for independent work* comprise lectures that help students develop skills for working independently, including how to stay motivated, set goals, and manage time.
- *Career development* is an area students should be be working on as early as possible in the Ph.D. program so they can select and plan for an appropriate career path.
- *Exemplars and bootstrapping.* The course includes a set of lectures to help students become better oriented with computer science both within the department and at-large.

2.1 Research Skills

The first module, research skills, teaches students how to develop creativity and critical thinking skills needed to perform research. We divide research skills into four main tasks, each of which correspond to an assignment, as shown in Table 1.

Recognizing good ideas. Helping students recognize good research ideas is critical for helping them develop taste in research problems, as well as to help them develop essential skills such as reading papers. To help students develop the ability to recognize good research ideas, the course includes a lecture on reading research papers. We then ask the students to put this knowledge into practice in the first assignment, where they must read the papers from the top conference proceedings in their field, select two papers from that set of proceedings, summarize the main ideas from these papers, and defend their choices of these papers as representing good research problems (e.g., the paper solves a longstanding open research problem, defines a new field or direction). This assignment not only helps students develop research taste, but it also helps them get into the habit of reading research papers early in their research career.

Topic	Lectures
Research Skills	
Background: How research works/Impact	1
Recognizing good ideas	0.5
Generating good ideas	2
- Problem selection and cross-disciplinary work	
- Creativity and idea generation	
Critiquing ideas	0.5
- Reading and reviewing papers	
Communicating ideas	2
- How to write a paper	
- How to give a talk	
Research Mechanics	
Background: Research patterns	1
Math skills	1
Data and empirical skills	1
Programming skills	1
Human-centered research skills	1
Skills for Independent Work	
Background: Executing Great Research	1
Goal setting	1
- Why Ph.D.?	
Motivation	1
Time management	1
Information management	1
Personal development	2
- Student life and social activities	
- Graduate school survival skills	
Career Development	
Overviews of job opportunities	3
- Professor life	
- Industry vs. academia	
- Commercialization	
Teaching and TAing	1
Personal and research promotion (networking, etc.)	1
Exemplars and Bootstrapping	
Internal speakers (department and area overviews)	6
External speakers	2
Broader impact	2
- Computing for social good	
- Diversity and women in computing	

Table 2: Syllabus Overview.

Generating good ideas. Once students are equipped with the the skills to read conference proceedings and have begun to develop their own research taste, we help them develop the skills to generate research ideas. Of course, there is no formula for creativity, but certain approaches to research can put students in a position where they are more likely to have creative thought. In keeping with our goal to counter "stovepipe" research and foster interdisciplinary thinking, we encourage students to solve problems that exist at the gap between two research areas. To this point, we incorporate several lectures on "research at the gap" to help develop cross-disciplinary thinking.

The second assignment encourages students to think about cross-disciplinary research problems by having them generate a research

idea by combining two ideas selected by students in the first assignment from different research areas. The assignment is motivated by the observation that great progress on problems is often made by applying ideas or concept from one discipline to a second, seemingly unrelated problem area. To save time and survey a broader range of ideas, students can use the research summaries generated by other students, but, if they so choose, they can also select their own set of problems. The output from this assignment is the equivalent of a short research proposal, comprising the following three aspects: (1) a concise description of the problem; (2) an explanation of why the problem is important and what practical or broader impacts solving the problem would have; and (3) an explanation of why the problem is challenging or interesting. This assignment not only helps students gain experience in creative thinking, but it also gives them valuable experience in communicating their research ideas and explaining their importance, skills that are useful for writing papers and, eventually, research proposals.

Critiquing ideas. After learning how to generate research ideas, the course gives students the opportunity to develop critical thinking skills by writing reviews of other students' research proposals. The course includes lectures on how to critically read and review research papers and proposals (a skill that is also intimately tied to recognizing good research ideas and developing taste in research problems). The course includes a corresponding assignment to help students write reviews: each student is given a selection of other students' research proposals from the second assignment to critically review. Based on these reviews, students then form mock program committees to select the "best" research proposals, each of which receives a cash prize. This assignment helps students understand several important aspects of research: First, they develop further experience critiquing other research ideas. Second, they gain some insight into how research ideas are selected by program committees. This insight into the (sometimes imperfect) review process may provide some comfort to a student when his or her first paper is rejected.

Communicating ideas. Equally important to developing the research ideas themselves is communicating them clearly to others. We impress upon students the importance of communicating research ideas as a critical step towards having their ideas adopted, applied, or built upon. Accordingly, the course has many assignments, such as those above, that involve developing writing skills. Additionally, students have a major writing assignment that is tied to their term-long research project. In this assignment, students are asked to write a paper—in conference-paper format, composition, and style—that summarizes the term-long research project that they perform throughout the duration of the term. In addition to developing writing skills, students also have a mini-assignment that helps them develop multi-resolution "elevator pitch" talks of various lengths on their research that can be used in different settings. This collection of assignments helps students develop a multi-faceted approach to communicating and promoting their research ideas.

2.2 Research Mechanics

Students not only need skills for performing research, they also need to develop mechanics for performing research tasks that are common across all disciplines of computer science, particularly for cross-disciplinary tasks. We focus on developing mechanics in three areas, devoting a lecture to each: (1) math and analytical skills; (2) programming skills; and (3) skills for human-centered research and experimentation. We briefly survey the material covered for each of these three topics.

Math skills. For work involving a mathematical/theoretical component, many students may only have mathematical knowledge but lack a number of intuitions which emerge only from research practice. We will cover issues such as what constitutes a mathematical "theory", varying levels of rigor in proofs, various proof approaches and strategies, the importance of good notation, and idea generation in mathematics.

Data and empirical skills. Although some areas of computer science are more empirical than others, many aspects of research involve experimental design and data analysis. Thus, the course includes one lecture on how to design experiments and draw meaningful conclusions from experimental data. We pay close attention to avoiding common pitfalls with experimental design and data analysis, as well as clearly presenting experimental results.

Programming skills. We devote one lecture to essential programming skills that are common across computer science research. This lecture discusses specific research programming skills, such as version control, rapid prototyping, common design patterns, documentation for public release of prototypes, and programming skills for executing reproducible experiments.

Skills for human-centered research. Various areas of computer science ranging from computer networking to human-computer interaction, require either data that is generated from humans or direct interaction with human subjects. To help students prepare for this type of research, the course includes a lecture on various human-centered research techniques (e.g., ethnography, discourse analysis), as well as other logistical issues with human-centered research, such as institutional review board approval processes.

2.3 Skills for Independent Work

Although much research is collaborative in nature, Ph.D. students ultimately assume a large amount of responsibility in pushing their own research forward. Unlike earlier stages of education, Ph.D. research is largely unstructured and involves setting goals on very long time horizons. Accordingly, the course includes lectures and assignments that help students develop skills to work independently towards seemingly distant goals.

Goal setting. The course includes lectures on setting goals and systematically and methodically working towards those goals. On the first day of the course, we ask students to answer questions that help them think about why they have enrolled in a Ph.D. program and what they hope to achieve by the end of the Ph.D.; we have an accompanying lecture that discusses the various reasons for obtaining a Ph.D. (e.g., we discuss the various job options that having a Ph.D. enables). By encouraging students to explicitly write down their goals early in the program, we fend off the potentially dangerous situation where students enter a Ph.D. program as a default option without a codified set of goals. We impress upon students that setting goals early in the program is important both so that they have something concrete to work towards and also because long-term goals can help inform priorities and tactical decisions throughout the program (e.g., how to allocate time to various research projects, when and how to promote one's research, etc.).

Motivation. The Ph.D. is a long process with many ups and downs; sustaining a high level of motivation can be challenging. As such, the course includes a lecture on how to stay motivated in the face of common trials and tribulations of a graduate research career (e.g.,

paper rejections, self-doubt about the direction of one's research, day-to-day motivation).

Time management. Incoming Ph.D. students are typically accustomed to working on well-defined assignments with fixed, near-term deadlines. In contrast, graduate research typically involves working on loosely defined problems (at least initially) over significantly longer time periods. Without appropriate time management skills, a graduate student can fall into traps at either of the two extremes: either working all the time (but not necessarily efficiently) or not working at all until a deadline is imminent. Either approach can lead to inefficiency, lack of productivity, and ultimately lack of sufficient progress, resulting in attrition or longer graduation times. To combat these problems, the course includes a lecture and a mini-assignment on time management. We teach students common tips and tricks for managing time and also have them perform a "time audit" assignment, whereby the student records how he or she spends an entire work week, broken down into ten-minute increments. Students are surprised to learn in this assignment that what might seem like a 12-hour workday is filled with significant "gaps" of unproductive activity and interruptions.

Information management. Another difficulty faced by Ph.D. students is managing the thoughts and ideas that arise when students read papers, attend talks, meet with their advisors, and so forth. We thus include course material managing information, such as maintaining a research notebook, a research project wiki, and how to manage email correspondence and notes. We also introduce tips on how to have productive advisor meetings, which includes important information management skills such as coming to the meeting with an agenda, taking notes on the meeting and sending a post-meeting summary, etc.

Personal development and adjustment. Researchers cannot be productive if they are not happy personally. Accordingly, we also include several "personal development" aspects in the course. We scheduled the class period in the late afternoon to facilitate transition to community-building social events (e.g., picnics, happy hours), and incorporated a student panel on living in Atlanta. We also incorporated a panel where more senior Ph.D. students shared their experiences about life in the graduate program.

2.4 Career Development

A systematic introduction to employment possibilities early in the Ph.D. program can help students prepare for their career after graduate school before it is too late for many options to be viable. Keeping certain career options open (e.g., academia) often require building a solid research reputation over many years. To help students appreciate the full range of post-Ph.D. employment possibilities and make appropriate career choices to help them be marketable when they graduate, we include course material that explains both job opportunities and promotion of one's research.

Overviews of job opportunities. As previously mentioned, the second lecture of the course, "Why a Ph.D.?" includes a high-level overview of the job opportunities that either become viable as a result of having a Ph.D. or are natural consequences of graduate research: academia, industrial or government research, and entrepreneurship. We include specific lectures on life as a professor, the differences between working in industry vs. academia (including guest speakers from researchers who have had experience in both areas), and how to commercialize one's research.

Personal and research promotion. An important factor in a student's marketability at the time of graduation is how well known the student and his or her research is in the broader research community. This oft-overlooked aspect of a student's development as a researcher can sometimes cost a student opportunities in academic and industry research positions, where employment opportunities often correlate with other researchers' familiarity with the student's research work. To help students form their research reputations early, the course includes a lecture on publicizing one's research in the broader community (e.g., popular press), as well as lecture material on networking within the professional community; it also includes mini-assignment where students must construct a personal research Web page.

2.5 Exemplars and Bootstrapping

One of the most difficult aspects of the graduate career is getting started and, more importantly, appreciating that one's research can, in fact, have broader impacts. Thus, a primary goal of the course is to get students involved in research as soon as possible (i.e., immediately) and to appreciate that their work can, in fact, have broader impacts. To achieve this goal, we involve students in projects that incorporate both breadth and depth, and we provide students with specific examples of computer science research projects that have had real-world impact. We also provide basic logistical information to help students bootstrap at the beginning of their research careers.

Main project and mini-project. We require the students to perform one "main" term-long research project (typically with their *de facto* advisor) and one exploratory mini-project. The main project has several benefits: First, it gives students a sense of immediate accomplishment and defends against students' tendency to feel "lost" when they first arrive in the program. Second, it quickly provides students with a sense of what it is like to do research; this experience allows them to quickly discover both the joy and challenge of research, to appreciate the difference between graduate school and undergraduate education, to adapt their working skills as needed to be successful, and to decide whether they like research at all. The mini-project can be done with any faculty member in the department and is intended to give the students an excuse to explore research topics that may be further afield from their main interest (and, incidentally, might prove useful in helping them apply cross-disciplinary thinking to their own research).

Internal and external speakers. The course includes an internal lecture series to help students familiarize themselves with various aspects of the department. Rather than simply providing an overview or advertisement, however, we asked faculty within the department to provide a research overview in the form of "big picture" research questions (e.g., What are the five biggest open questions in Computer Science research? What are current research trends?). We also include a lecture from the dean that includes a discussion of broader research directions, and we have both students and faculty give advice on other logistical topics, such as how to apply for fellowships.

Broader impact topics. Anecdotal evidence suggested that many Ph.D. students fail to complete their studies because they don't get a sense that their work has important broad impacts. To account for this, we include several lectures in the course on broader impact topics (e.g., how computing can help people in developing regions, integration of research with diversity and education).

3. Evaluation and Progress

We collected data on the Fall 2006 offering of the course from: (1) a student focus group in February 2007 (which was attended by students who took the class in Fall 2006 as well as students in pre-

vious offerings); (2) a town hall meeting with students and faculty in June 2007; (3) course evaluations; and (4) many conversations with students and faculty (in person and over email).

3.1 Observations

We observed the following phenomena based on the above feedback and data:

- Student attendance was often poor.
- Student contribution to group assignments was very uneven.
- Senior students were quick to criticize the course when logistical and organizational wrinkles occurred.
- Senior students told new ones to selectively attend lectures.
- Both students and faculty expressed tension between mini-projects (which encourage exploration) and term-long projects (which encourage depth).
- We had trouble recruiting high-profile speakers to speak in an introductory course to first-year Ph.D. students.

3.2 Inferences

Integrating and distilling the above observations led us to the following conclusions:

- Many students lack the context and experience to fully appreciate the importance of the course material, which largely comprises "soft" skills and advice contained in lectures, rather than traditional testable material.
- Giving a choice between the mini-projects and a single main project created confusion and also resulted in a failure to meet our original goals for redesigning the course (i.e., involving students in in-depth research projects early in their graduate careers *as well as* encouraging exploration).
- Due to inertia, our radical changes to the course were met with skepticism from older students who had taken the previous version.

3.3 Corrective Measures

As we are only now teaching the second offering of the course, is not yet clear what the impact of the changes will be, but we are confident that the current offering incorporates many of the suggestions offered by students and faculty. Specfically, we are taking the following corrective measures:

1. We now offer a cash prize for the best research ideas, now take attendance, changed the required course from pass/fail to letter-graded, and changed the time of the course to late afternoon to encourage attendance.
2. We now require students to perform both a main project and a mini-project, as they both serve critical functions: the former providing an opportunity to explore a problem in-depth, and the latter allows students to explore other research areas and meet other faculty in the department.
3. In the current instantiation, all assignments are done individually, with the exception of the mock program committee. Unfortunately, this leaves only one activity involving teamwork, which is unfortunate given the ever-increasing importance of teams in research. We regard this as an open issue, which we intend to address in future instances of the course.
4. A number of obvious logistical wrinkles regarding organization, clarity of the assignments, and scheduling of the course time were ironed out in the current instance of the course.
5. We are coupling external speaker invitations with department-wide distinguished lectures.

4. Related Work

There are a number of works treating or touching upon various elements of the course, both general and specific [6, 8, 7, 10, 2, 11, 4]. For the elements of the course which are not specific to the Ph.D., such as aspects of time management, there are many popular works. A number of works have touched upon the educational side of cross-disciplinary research [9, 3, 5, 1]. Many interdisciplinary PhD training initiatives exist for specific topics, such as mathematical biology, rather than for Computer Science with any external discipline, or for any discipline in general. To our knowledge there exists no other computer science Ph.D. preparation course similar to ours, which integrates all of the above elements into a single coherent framework.

5. Conclusion

While much of the information we present in this course is available in books and on various websites created by students and various Ph.D.-holding individuals who have taken interest in certain subsets of this topic, no single unified and coherent source seems to exist, no less a structured course. Our course appears to be the first programmatic attempt to give students all the unwritten rules for performing great research and having successful careers in research. Also, our emphasis on cross-disciplinary work and broader impact brings these topics stemming from important current trends in science and society into students' purview at as early a stage as possible. We believe these are transformative viewpoints to which students might not otherwise be exposed at all. We ultimately hope this course can serve as a cornerstone for a cross-disciplinary Ph.D. program.

REFERENCES

[1] L. J. Anthony, M. F. Palius, C. A. Maher, and P. V. Moghe. Using Discourse Analysis to Study a Cross-Disciplinary Learning Community: Insights from an IGERT Training Program. *Journal of Engineering Education*, April 2007.

[2] W. I. Beveridge. *Art of Scientific Investigation*. Heinemann, 2004.

[3] Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. *Facilitating Interdisciplinary Research*. National Academies Press, 2004.

[4] P. Cryer. *The Research Student's Guide to Success*. Open University Press, 2006.

[5] L. J. Davis. A Grand Unified Theory of Interdisciplinarity. *Chronicle of Higher Education*, June 8 2007.

[6] P. J. Feibelman. *A Ph.D. is Not Enough! A Guide to Survival in Science*. Addison-Wesley, 1993.

[7] L. Mitchell. *Ultimate Grad School Survival Guide*. Peterson's, 1996.

[8] National Academy of Sciences, National Academy of Engineering, Institute of Medicine. *Reshaping the Graduate Education of Scientists and Engineers*. National Academies Press, 1995.

[9] C. L. Palmer. *Work at the Boundaries of Science: Information and the Interdisciplinary Research Process*. Kluwer Academic Publishers, 2001.

[10] G. Rugg and M. Petre. *The Unwritten Rules of PhD Research*. Open University Press, 2004.

[11] D. K. Simonton. *Creativity in Science: Chance, Logic, Genius, and Zeitgeist*. Cambridge University Press, 2004.