

# Introduction to Scientific Research: Research Experiences for Undergraduates

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## Abstract

A course for research experiences for undergraduates in mathematics is described. The classroom environment is nontraditional in the sense that formal lectures, group discussions, *brainstorming* sessions, and structured computer demonstrations are used. The course is structured so that it is self-contained and requires students to have basic programming skills and calculus. The use of symbolic computational languages, such as Maple, allows students early in their academic career to explore many different types of models analytically as well as numerically. The course is centered around communications, task sets, and the development of knowledge sets. Oral and written communication is developed through completion of three PowerPoint presentations, a poster, and a research paper composed using L<sup>A</sup>T<sub>E</sub>X. To keep the students focused, task sets are used to ensure the students are always making progress. The knowledge sets are used to shape the content for the course. This course can be easily altered to develop a research course in any field by altering the knowledge sets. Suggestions are presented for changes in the knowledge sets for control research.

## 1 Introduction

Generally, meaningful scientific research experiences are not available to undergraduate students because the mathematical requirements to perform such research have not yet been learned by the students, with some exceptions. In the areas of engineering and control, relevant introductory courses begin later in the students' academic careers. Therefore, in many cases only ad-

vanced students on the junior and senior level are ready to begin a scientific research project. This is further complicated since those research opportunities that are available usually do not count towards graduation, thereby discouraging students from participating. Furthermore, students tend to become discouraged when periods of time pass without any tangible results. The research topic, while fascinating to the faculty member, may not be as thrilling to the student. Keeping the students motivated, positive, working, and interested is key to successful scientific research projects. Additionally, opportunities where the students can share their work give them a sense of accomplishment and encourage further work.

The course described in this paper counters these problems by directly addressing the concerns of the students and provides them with the opportunity to do research. This course is offered in the Program for Computing in the Mathematics Department at the University of California, Los Angeles. Due to the goals of this class, it was featured in the research experiences for undergraduates (REU) portion of a successful National Science Foundation (NSF) Vertical Integration of Research and Education in the Mathematical Sciences (VIGRE) grant, see [4]. The overall goal for this class is for the students to learn skills they can use throughout their academic careers and most likely in their professional endeavors. The focus of the course is to provide students with an *experience* in research without necessarily completing a project, so students are encouraged to pursue a topic they find interesting and to explore creative and unique approaches to the problem.

The target audience for this class is freshman and sophomore students. This is beneficial for the students

since skills are learned that will be of use in their advanced course work. Additionally, it may inspire students to pursue research in their academic and professional careers. It also provides a pool of students with certain skills that may serve as a potential future source for recruiting students for research and graduate school. Variations of this class using realistic or industrial problems may give students an additional edge when entering the job market. In order to maintain sufficient enrollment in the class, the future benefits for the student need to be emphasized.

In this paper, experiences from the development of this course are shared. Although this class is targeted towards the mathematical and computational sciences, it can serve as a paradigm for other disciplines, including the social sciences, business, engineering, and control by modifying the Knowledge sets used in the class. In Section 2, the course is described with student concerns and an outline of the topics covered is presented in Section 3. In Section 4, some ideas are presented so that the course can be adopted to control-oriented research classes.

## 2 Course Description

The course has a nonstandard format. Features of traditional classroom lectures and seminars are combined with group discussions, presentations, and structured computer experiences. This open environment liberates the students to be creative in the ways they approach their problems. Students are instructed to select a topic of their choice. As a result, the students are motivated since they are already interested in the topic. This leads to a high success and retention rate. Each student participates and shares with the class. *Brainstorming sessions* are used so students can share and help each other using their own experiences in the course. These sessions have proven to be extremely useful and beneficial to the students.

It is natural for most students to worry about their grades. Due to the nontraditional nature of this class, students often need to be assured they are doing well. The goal of the course is to provide a research experience, rather than complete an entire research project. Students are not expected to complete their projects, which reduces anxiety, but causes worry over grades. The most common concerns are topic selection and problem for-

mulation, relative progress made by the different students, failed approaches for the problem, finding sources that solve the research problem, and feeling that they have not made sufficient progress on the topic. Students need to understand that each research project is different, progress depends on their initial skill level, and that performing research is a stochastic process. Furthermore, students need to be guaranteed that their grades are based on their research experiences, presentations, posters, and papers, not necessarily on the research accomplishments. The structure of the class and the grading policy allows for the students to pursue creative solutions and helps to develop confidence in performing research.

The course is targeted for students with basic computer and calculus skills and is available to freshman students who meet these requirements. This can be done since the symbolic computational language, Maple [1], is used to perform analytical and computational tasks for the students. Population, predator-prey, and compartmental models are used to introduce the students to mathematical modelling, which are illustrated in the textbook, *An Introduction to the Mathematics of Biology: With Computer Algebra Models* [5]. The Maple codes for the entire textbook are available online from the publisher, and the author of the paper updates these codes and provides them to the students. The hope is that as the students mature in their fields of study and mathematics, they will want to continue to work on research projects.

The course is designed to teach communication and mathematical modelling skills while providing a research experience. These skills are developed by the students in an active process. The task sets or assignments help to keep the students focused on their projects so that progress is made. The students assist one another in their research projects in brainstorming sessions, which allows the students to benefit from the experience of others in the class. Additionally, the instructor, faculty mentors, guest speakers, and the teaching assistant for the class share their good and bad experiences in performing research.

Key components for the course are oral and written communication skills, which are beneficial to the student, regardless of career path. Students give three oral presentations using PowerPoint to hone their skills in

public speaking on technical and scientific topics. The first presentation is on an assigned topic so students learn how to convey all of the necessary information to the audience. The second is a short presentation, typically 5 to 8 minutes in length, that is used to introduce the project to the class. The students give a 15 to 20 minute final presentation, conducted as a *conference seminar*, on their research projects. A final paper for the course is prepared as a draft article for a journal using  $\LaTeX$ [2]. Since the students are not expected to complete their projects, they include a *Future Directions* section explaining how they would continue to pursue their projects. Microsoft Word is used to compose a poster for the students' projects.

Mathematical modelling and using Maple forms the core of the knowledge set for this class. Additionally, topics in data analysis, curve fitting, and ordinary differential equations are part of the skill set. First principles and the historical development of population dynamics are used as the basis for mathematical modelling. This allows the student to observe a constructive process for the development of a model by incorporating additional aspects of the physical reality. Basic predator-prey models are used to illustrate interacting populations, which exposes the student to mass interaction principles. Enhancements in interacting species models again show the students how to add physical reality to develop a better model. Normally, advanced compartmental models from epidemiology complete the skill set, but may be changed to accommodate the needs of the student. Maple is incorporated throughout the development of the various aspects of modelling. Through the use of Maple, the students are given the ability to explore models both analytically and numerically. The integration of technology in this class is essential to its success. By varying parameters of the model, students can almost instantly see the effects on the solution graphically. The ability to do this has greatly helped the students understand how models work.

To ensure the progress of the students, task sets are used that complement the development of communication and mathematical skills. All of the assignments, except for the group presentation, are based on the individual student projects. Therefore, the assignments help the student keep focused and working. Brainstorming sessions are used before the assignments are due to assist the students with creative input from fellow students.

This sharing and cooperation among the students provides a more relaxed environment that will help some students overcome their fears of public speaking. Additionally, insights and perspectives of the various students' approaches to their projects may be used by others.

### 3 Course Outline

At UCLA, a quarter system is employed. In a semester system, the outline presented here could easily be expanded to incorporate additional presentations, topics, and skill sets. This additional time would give the students an even more meaningful experience. A basic outline for the course is given below.

- **Communication Skills**

- Weeks 1, 2, 5, 6, 7, & 9: Scientific writing using  $\LaTeX$ .
- Weeks 1, 2, 3 & 4: Presentation design using PowerPoint and Equation Editor.
- Weeks 9 & 10: Poster design and development using Word.

- **Mathematical Knowledge Sets**

- Weeks 1 & 2: Topic selection, problem formulation, and finding references.
- Weeks 4, 5, 6, & 7: Basic mathematical modelling from first principles for population dynamics and interacting populations. Analytical and numerical analysis using Maple.
- Weeks 8 & 9: Advanced mathematical models are presented using Maple for physical systems depending on class desire. Typically includes compartmental modelling for epidemiology for SIR and SIRS models and advanced models for HIV/AIDS.

- **Task Sets**

- End of Week 2: Working title, abstract, and references written up in  $\LaTeX$ .
- Week 3: Group presentations in which all members present some aspect of an *assigned* topic.

- Week 5: Individual presentations of students research topic.
- Weeks 7 & 9: Draft of working paper is due.
- End of Week 10: Poster session.
- Finals Week: PowerPoint presentations of student projects in conference session format and papers are due. Students must include a *Future Directions* section in the paper and presentation to outline what they would do to complete their project.

- **Brainstorming Sessions**

- Weeks 1, 4, 6, & 8

The structure of the class continually undergoes fine-tuning to adjust for the needs of the students enrolled in the class. The majority of the fine-tuning is in the knowledge set so that the necessary skills in modelling and using Maple are available to students. Overall, the students like the format and enjoy the class. The experiences gained by the students should translate into tangible skills that can be used in their future endeavors. Below are some students' comments about the class.

*"I enjoyed this class very much. The opportunity to openly discuss & brainstorm our projects was very helpful. Before the class I knew very little about writing research papers & making formal presentations. I think the material learned in the class was very worthwhile."*

*"Good class, opened up my head and let the ideas flow. Very wide spanning real life math. One of the best courses I took."*

*"... Out of the two years that I was here, this is the class that I have enjoyed the most ... I've gained a lot of knowledge."*

*"As a student who did not look forward to research projects, I am extremely happy with my choice to take this class. I have learned a new way of analyzing a problem, and enjoyed the knowledge I got on my subject ..."*

*"This course was one of the best I have attended at UCLA in 4 years, wish I could take another just like it."*

#### 4 Undergraduate Control Research

It is important to involve undergraduates in research as soon as possible so as they mature in their areas of study, mathematics, and the use of analytical or computational tools they can perform more in-depth and meaningful research. Another result is their ability and desire to perform research grows as well. Selecting a minimal necessary set of course requirements allows the students to have more time in their undergraduate careers to pursue research. In some areas, such as mathematics, students may be able to start at the end of their freshman year or beginning of their sophomore year. Depending on the goals of the course, the necessary requirements may only allow for junior and senior students to participate.

For control research, the knowledge set should consist of elements for modelling the system dynamics, construction of the cost functional, and methods or software to determine the solution of the control problem. Additional topics to broaden the scope of the knowledge set can include filtering, stochastic processes, or other aspects that the students desire. The material for the knowledge set should be presented with theory and applications so that the students can understand how to formulate a unified solution to a problem. The use of laboratory equipment, technology, and software should be thoroughly integrated into the presentation for the material in the knowledge set.

It is important to note that software, such as MatLab [3], can be used to remove the students' need of advanced analytical and computational methods in control. By using such software, the student identifies a reasonable approach to the solution and has the ability to implement it. A benefit of such software programs is that they allow for students to explore the results visually and see the effects of changing parameter values and the formulation of the control problem. As a result, students gain real insight into the model for the physical problem as well as controlling the system.

The philosophy of the course is to provide students

with an *experience* and the tools to perform research in their areas of study. Since the goal of the class is an experience, students can participate earlier in their careers. This type of course could be offered as a freshman or sophomore seminar. This would expose the students to control theory and research and would be similar to the course described in Section 2. A particular emphasis in this course would be in problem formulation for the system dynamics and form of the cost functional. If the goal is to complete a project, then more requirements would be necessary, thus limiting the number of students who can participate. Research in control is not available to most students until they have taken the beginning course sequences in calculus, physics or chemistry, and have taken at least an introductory class in control. This type of class should be reserved for a junior or senior design experience. The scope of the research project should be limited so that students have a good expectation of completing their work in the time allotted. Students will be discouraged in participating in a class where they can not succeed. Other options could include using assigned problems that are to be solved in a research and development environment, the use of groups of students, or an integrated research team of students on all levels and faculty members. All of these options can be incorporated into the course described in Section 2.

## 5 Conclusions

The course described is an ideal way to introduce students to research. Key skills developed in this course are useful to students whether they go into industry or continue graduate studies. The ability to communicate mathematical or scientific concepts effectively in both oral and written forms is an asset to the student. Undergraduate students have enjoyed this course since a structured environment is provided with the freedom to explore their research topics. This course can be tailored to meet the needs of different areas of research by selecting appropriate skill sets. Additionally, the course can be easily tailored to meet the needs of a given department and can evolve to continually meet the needs of the students and include advances in technology.

## References

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