On The Benefits of Applied vs. Basic Research Projects for Undergraduate Engineering Students.

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ABSTRACT

Undergraduate students are typically provided with research opportunities that let them incrementally develop their research skills, that is, from little or none to the ability of performing simple tasks without being supervised. Whereas rationale behind the traditional approach seems to be clear, the author argues that this may not be the best approach for engineering students interested in real-life applications and may even lead to a student quickly losing interest in research or a chosen professional field. In the paper, an alternative approach that resulted from author's observations and experimentation as an advisor and mentor is discussed. The main difference of the suggested approach from a more traditional practice is that a student is assigned an active role in the project choice and in making decisions about the project development. As a result, the initial project is always a real-life application of student's liking. With the project starting, a student gradually comes to recognize and appreciate the amount of knowledge and skills required for such an application. Self-evaluation of own skills/knowledge motivates the student to gain missing skills/knowledge even if they are outside the standard Department syllabus. The project also usually changes from complex to simple during its lifetime, with the student making decisions on where and how to downsize the project to be able to progress in the given timeframe. Advisor's role in the suggested approach is helping students to make realistic choices, provide recommendations on the literature and courses relevant to their projects, and stay focused on the project goals and milestones. Another outcome of the suggested approach is increased interest of students in graduate education. Almost 100% of students from author's research group have been enrolled in graduate programs after their research experience as undergraduates.

Introduction

Research opportunities are invaluable for undergraduate students because they provide students with the experience of working in the professional environment in the field of their choice. In such an environment, a student observes and learns how projects are formulated and assigned, how workload and responsibilities are distributed between researchers, and how and when the results are to be reported. A student also gains more clarity on the knowledge and skills required from a researcher and how the academic education is relevant to those requirements. This leads to better understanding by students of their educational goals, and as a result, better professional preparation.

A stimulating effect of research experience on the student academic progress is what the students and their research advisors hope for. Reality may be different though, up to the degree of a student losing any interest in research or even in the chosen professional field.

From many factors affecting student research experience, the current paper analyzes how the choice of a project assigned to a student may influence the outcomes from his/her research experience. The analysis is based on author's observations and experimentation as a research advisor and mentor for undergraduate students from 2004 to 2015. A total of 31 undergraduate students participated in her research program during this period, with 12 students at the Florida State University (2004-2010) and 19 students at the University of New Mexico (Fall 2010 - Spring 2016). Students' majors included Mechanical Engineering, Electrical and Computer Engineering, Physics, and Mathematics. The research project duration was 1, 2, 3, and 5 semesters, with the number of participating students being 13, 9, 5, and 4, respectively. From the total number of assigned projects, 18 projects had partial or full financial support.

Project Assignment: Basic vs. Applied

Research experience of an undergraduate student starts from a student approaching a potential advisor and both of them agreeing on the student receiving such an experience with the advisor. The author suggests that this agreement does not necessarily imply that they share the same ideas about the goals of research experience.

Indeed, the advisor's perspective on the goals of undergraduate student research is that of an experienced researcher, who understands that a student has little or no skills/knowledge to successfully accomplish a project of significance for a research field. Before making such a contribution, a student has to develop basic understanding and skills relevant to the research area of the advisor's expertise. As a result, a typical student project is formulated by an advisor with the focus on student's incremental skill development, from none to the ability of performing basic tasks without supervision. Hereafter, such projects are called basic. On the level of complexity, the basic project progresses from simple to more challenging depending on student's progress during the project lifetime. A link between a student project and real-life applications may or may not exist. If it does, the importance of such a connection may not be emphasized, as this is not the project goal.

The advisor's perspective is rooted in his/her experience as a researcher, professional knowledge, and rational reasoning. The student's perspective comes from a different background. As the author observed in most cases, a student sees a research opportunity as a possibility to contribute in advancing an important real-life application that advisor's research is relevant to. This is what he/she expects from the start: to make an impact on the field. A student has understanding that training will be required, but has no idea how much effort and how much time will it take. As a result, training is not viewed as the project goal, but as a means to reach the goal.

For an advisor, the student's goal is unrealistic. Nevertheless, it is as valuable as that of an advisor, because this is what motivates a student to seek research experience in the first place. This is what fuels a student's curiosity and creativity, and keeps him/her going through mundane tasks, which are plenty and unavoidable in any research field, and during training in particular. Excitement comes from the student's feeling of importance of his/her work, and no rational reasoning can substitute for that. This is why the advisor has to find a way of introducing a student to the reality of research without cooling off his/her enthusiasm.

Multiple creative ways may exist to reconcile the research goals of the student and his/her advisor. One of the factors that has to be taken into consideration when looking for a solution is the project lifetime. In the paper, the projects are categorized into two groups: short-term (~ one semester or less) and long-term (two semesters and longer).

Short-term projects.

Short-term projects are more challenging for demonstrating to a student the connection between his/her project, its results in particular, and real-life applications. It is also difficult to assess the long-term impact of advisor's short-term efforts on student's academic success and to compare with that of basic projects.

Nevertheless, the author believes that such efforts do have a positive effect on the project outcomes. Examples of how short-term projects were linked to real-life applications in author's advising practice are as following.

- A student was working on developing an algorithm and an interactive Matlab code for two communicating agents searching for a given number of stationary targets in virtual two-dimensional space within specified boundaries, with no information about the area landscape being provided. The project topic could be intimidating even for a graduate student, but it was linked to a search by mobile robots of wounded firefighters during wildfires, which are common in New Mexico. The student was fascinated with robots and by the project idea and successfully accomplished the project in two months. In this case, a small-scaled project was presented as a downsized large-scaled real application.
- In another summer project, a student learned to extract useful information from a large database collected from direct numerical simulations (DNS), typical for the computational fluid dynamics research. He used the extracted data to generate new ones, and to present the results in power-point format. Microsoft software initially unfamiliar to the student was used at each stage of his research. Working with a large database can be daunting for many people. Yet, such work

requires particular attention to detail. In addition, DNS databases typically contain a lot of terminology unfamiliar to an undergraduate student. The student was presented with other options for his summer project, but when it was explained how this project could contribute to the author's research with NASA and how important the project results could be for meeting the grant deadlines, this particular project was his choice, and he successfully accomplished his tasks on time.

- A student project on a more abstract subject can be linked to a possible publication. One NSF REU project mentored by the author is such an example. Students' results were included in the conference paper [1]. In cases like that, it has to be clearly explained to the student in advance whether he/she will co-author a paper. It is important that the given promise is fulfilled. What motivates a student in such a case is a possibility to enhance his/her resume with a publication. When it is explained how a resume is linked to successful job launching or application to a graduate school, a student assigns high priority to the project.
- Experiment-based projects may be easier to link to real life by presenting them as an active part of a large-scaled high-impact project. Two such projects that the author co-advised with her colleague, Prof. A. Mammoli, from the Department of Mechanical Engineering (ME) at the University of New Mexico (UNM) were relevant to the development of UNM solar-assisted HVAC system with thermal storage. The system is incorporated in the ME building and serves as the education and research subject for students, in addition to being used for its direct purpose of heating/cooling the building. The undergraduate students worked in teams with graduate students and could understand the immediate impact of their contribution on the real engineering system.

Long-term projects.

Long-term projects provide an advisor with more opportunities to demonstrate to a student how the project results are relevant to real-life applications. Two approaches to formulating an application-oriented long-term project for an undergraduate student are discussed in the paper.

The first approach is essentially an extension of the basic project idea. Similar to basic projects, the advisor takes the lead in making choices and decisions. He/she formulates the project goals, monitors student's progress, and decides how the project develops with time. The project trajectory is from simple to complex with incremental skill development. The only requirement of the approach is to emphasize the project connection to real-life applications, preferably at the early project stage to ensure student's interest. Hardly innovative, this approach with the traditional role assignment is certainly beneficial for some students, as the author has found. This is a case when, for example, a student is more interested in abstract matters than of an applied nature. A student may also still explore his/her choices of major or even need more time to build his/her confidence.

On the other hand, many students majoring in engineering disciplines have clear ideas of what their future professional field will be. Of course, these ideas may not be realistic and are likely to evolve with time to something quite different. One of the goals of research experience is to help a student to clarify his/her view on this subject. However, at the beginning of research experience, these initial ideas are what a student has in his/her mind and this is what an advisor has to respect, so that the outcomes from the student's experience will be the most beneficial. Flexibility should also be allowed for a student to change the project trajectory if in the process, he/she realizes a deeper interest in an overlapping, but overall different topic than covered by the initial project.

Allowing a student to take an active role in making choices and decisions about his/her research project is the main idea behind the second approach presented in the paper, to formulating long-term research projects for undergraduate students. This innovative approach developed by the author is rooted in her experience as an advisor and mentor and is actively practiced in her research group.

When a student approaches the author looking for research opportunities, the author describes, in general terms, her area of expertise – Fluids and Energy – and the existing student projects in her group as research examples. The discussion then shifts to the project goals that the student would like to accomplish during his/her project. That is, the student formulates a project based on his/her liking within author's area of expertise or close to.

Different students formulate different projects, but what remains in common between the projects is that all of them were real-life applications, such as, for example, design of wind turbines and helicopter rotors, alternative wind harvesting technologies, bio-inspired systems and designs, power system analysis, and target search by autonomous robots. In other words, a typical project proposed by an undergraduate student can be a challenge for a Ph.D. student and definitely not something that an undergraduate student can accomplish. One can also see how some proposed projects may challenge the limits of the author's expertise. In such cases, collaboration with other colleagues is sought to provide the student with resources and expertise matching the project.

Once a student starts digging into the subject matter (with the guidance from the advisor on literature to read), he/she gradually realizes two things: how much knowledge/skills are required to meet the project goals and how little of that he/she usually has. At this point, to avoid student's frustration, it is the advisor's task to show the student how his/her current level of knowledge can be brought to the level required to accomplish his/her initial goals. Such a path (plan) typically consists of several steps (depending on the project complexity) that include courses to take at each step and research subtopics that can be accomplished with the skills acquired at each step (see Appendix for a path example). The student is also assigned a mentor to help him/her through each step of the project. A mentor is usually a more experienced student from author's research group and/or from the group(s) of her collaborators and can be changed during the project lifetime depending on the expertise required.

The student now has all the information necessary to re-evaluate the initial project goals and substitute them with realistic ones that can be accomplished in the given time. Typically, this initial project stage does not last long, but this is when significant advisor's input is required.

For the student, once research and educational plans leading to accomplishing the project goals are in place, a joyful time of exploration begins. This research stage is not free from mundane tasks, but they are not viewed as burdensome, because the student can now clearly see how they are relevant to his/her ultimate goal. Another danger though at this point, as the author noticed, is that students get so excited from the newly discovered ocean of unknown that they tend to forget about the project goals and enthusiastically dive into every new topic. Then, it is again the advisor's task to explain to the student that research has several important components. Wandering in the unknown is one of them, but meeting the project goals in a timely manner is what ensures the research success.

Since students formulate their projects as applied, and because the project connection to real-life application is never lost during the project lifetime, such projects are called *applied* in the paper.

Let's summarize the differences between applied and basic long-term research projects.

- The trajectory of an applied project is from complex to simple, from desired goals to realistic tasks corresponding to student's level of skills/knowledge and the project duration.
- A student makes all important choices and decisions relevant to the applied project topic, goals, and development. An advisor helps the student to make realistic choices and decisions and provides resources and guidance. Not only does this experience lead to the development of a student's skills in making decisions and taking responsibility for them, it also helps the student to build confidence in his/her own decisions and choices in other areas. Thus, the experience is invaluable for future professionals and leaders at all society levels.
- Perhaps even more importantly in an applied project, a student receives an opportunity to come in touch with his/her own professional dream (real-life engineering problem of his/her liking) and to self-evaluate his/her level of preparation for performing such tasks. Stimulating effect of such an experience is difficult to overestimate. Not only has it led to impressive research results and academic excellence, but often to the student making the decision to continue his/her education in a graduate school to ensure proper professional preparation.

A few words have to be written on allowing a student to change the research project topic. From author's experience, this happens rarely with the undergraduate research projects. One of the examples from author's practice is when a student initially started to work on power systems of satellites. In the process, he was introduced to the concept of renewable energy (through solar panels that are a part of the power system in study). Eventually, he came to the decision that this is what he wanted to explore in more detail. Since the author does not work with solar panels, she suggested, as an alternative, to look into wind energy harvesting, because the student seemed to be more attracted to the renewable energy concept rather than its particular application. The student agreed and this is how he was introduced to computational fluid dynamics, which apparently fascinated him in such degree that he chose this field for his following Master and Ph.D. Theses.

The example above shows benefits for a student of changing the project topic. However, there is also a risk associated with this. Specifically, a student may not learn the important professional lesson such as that any assignment has to be completed and its results reported in a proper manner. To prevent this from happening, advisor's task is to ensure that the project change only occurs after the initial project has been completed, with the final report being written and the results being presented. In the case described above, the student successfully accomplished the first project, before moving to the next one with the results being published.

Student Success Associated with Long-Term Applied Research Projects

In this section, success of applied long-term student projects conducted in author's research group by undergraduate students is evaluated using the following metrics: the number of publications with undergraduate students as co-authors, students' research recognition, and the number of students pursuing graduate education vs. the total number of participating students.

The total number of students who conducted long-term applied projects under author's advising is 18. Student research results were included in 11 peer-reviewed papers (since 2006) of the author with undergraduate students as co-authors. Three papers of 11 are journal publications. Two papers received recognition at conferences: the 1st place award at the AIAA Region IV Student Conference [4] and a nomination for the best student paper at the 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference [6].

Since 2010, four students have completed their undergraduate education with Honor Theses (3 *summa cum laude* and 1 *cum laude*), 6 students will receive their B.S.-ME degree with Honor in Spring 2016. Information about 1 student who will also graduate in Spring 2016 is currently missing. Before 2010, such data were not collected.

Two students received NSF fellowships for graduate studies at MIT and the University of Texas, Austin. One student received the New Mexico Space Grant Consortium fellowship for his undergraduate project. Two students received the AIAA Albuquerque scholarships.

Nine students continued their education at the graduate level and 6 students graduating in Spring 2016 have submitted their applications to graduate schools. Information about 2 students is missing.

Conclusions

In the paper, a new approach to assigning a research project to an undergraduate student is presented. In this approach, a student is assigned an active role in formulating his/her project and making decisions about the project development. It is shown that students tend to choose as their first project a real-life, large-scale application, so that their research would have immediate impact on the professional field of their choice. The importance of respecting a student's motivation is emphasized, as it leads to the most beneficial outcomes from the student's research experience. Also discussed is how initial, unrealistic project goals are re-evaluated by a student once the project starts and gradually substituted with realistic tasks, without the student losing his/her enthusiasm. Advisor's role in the proposed approach is described. Examples from author's experience as an advisor and mentor are provided. Numerous benefits for a student from such an approach are demonstrated and compared with those from the traditional one. The effect of such an approach on a student's decision to continue his/her education in a graduate school is shown.

Although both short-and long-term projects can be formulated in such a manner that demonstrates their connection to real-life applications, students working on long-term projects benefit the most from the suggested approach.

Due to its applied nature, the approach can be particularly beneficial for engineering students oriented on the application of engineering concepts to real-life systems and designs.

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Notations: * undergraduate student.

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Appendix

This section provides an example of a 3-semester path for a student whose initial goal is a helicopter rotor design. The only pre-requisite for such a research is ME317L Fluids Mechanics course at the UNM Department of Mechanical Engineering.

Semester 1. In the first semester, a student is introduced to commercial computational fluid dynamics software used for flow simulations, such as Star CCM+[12], for example. The student starts learning using simple examples on how to conduct simulations and immediately realizes new terminology and concepts specific for fluid dynamics and computations. Simulation of a laminar flow in a simple geometry, such as, a planar flow over a flat plate is attempted. The accuracy of computational solutions is demonstrated. Basic data post-processing techniques are learned. At the end of the semester, the student understands that i) the flow physics has to be learned in more detail, ii) simulations have to be conducted on high-performance computers rather than laptops and desktops to get results in timely manner, and iii) time also has to be spent on learning how to make proper numerical grids for complex geometries and to conduct the sensitivity study to ensure the converged solutions with reduced errors. The initial project is downsized from a helicopter rotor design, to the rotor blade design.

Semester 2. At this stage, the student takes ME534 Boundary Layer course, where he/she is introduced to turbulent flow modeling and simulation. Simulations of planar turbulent flow without separation over a flat plate are conducted. The student also learns the basic of UNIX, operational system used on high-performance computers, and how to send jobs to supercomputers and conduct simulations there. Initial CAD models of a standard rectangular blade design and computational grids for this design are generated for two- and three-dimensional stationary blades. The basic ideas of aerodynamics are learned. First results from simulations of a flow around a stationary blade are discussed along with the new blade design ideas.

Semester 3. The student is now ready to take ME562 Rotorcraft Aerodynamics, introductory course. Grids are generated and simulations are conducted for stationary and rotating blades. Results are post-processed and presented in a form of report and/or a conference paper. How to move from here to the helicopter rotor design is discussed. The student at this point has realistic expectations about the time, resources, and knowledge requirements for such a project and at the same time he/she has learned all necessary basics for conducting CFD simulations with commercial software along with limitations of commercial software and flow models.