Promoting Undergraduate Research in the Electrical Engineering Curriculum

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Abstract

Engaging undergraduate students in meaningful research experiences is considered a high impact educational practice. Benefits for the students include development of critical thinking skills, career preparation, improved retention within STEM disciplines, and increased interest in graduate school. This paper reports on our initial attempts to organize a course that promotes undergraduate research at the University of Texas at Tyler. The two main objectives are: (1) to develop the abilities of the students to do scientific research, and (2) to improve the technical communication skills of the students in the areas of reading, writing, and speaking. The projects include a field programmable gate array (FPGA) implementation of a video compression algorithm, acceleration of a sparse FFT algorithm involving general purpose graphical processing units (GPGPUs), computer modeling of a red fire ant colony, and low-power encryption circuits with differential power analysis (DPA) immunity. Four motivated students in their senior year were recruited to take part in this pilot course. The effectiveness of the research course is evaluated based upon the actual contributions of each assigned project, the dissemination of the results, and self-assessment of the students on a survey given at the conclusion of the course. This initial attempt at an undergraduate research elective is evaluated as a partial success based upon the goals and objectives laid out at the beginning of the course. All the students made substantial progress in their research but were not able to fully complete their projects. The primary reasons for this partial success were the optimistic goals set for the projects and the competing demands on the students' time during their final semester as seniors. It is significant however that one conference paper resulted from this research and all four students were able to present posters describing their research at our institution's annual Research Day. Based on the implementation of this research course, some guidelines for having a successful undergraduate research experience are given. Finally, some conclusions and future plans will be discussed.

Introduction

Increasingly, educators are realizing that authentic undergraduate research experiences are a high-impact educational practice as it promotes student-centered learning and inquiry-based activities.[1] In an ideal university, all undergraduate students would have the opportunity to do research under the guidance of a faculty mentor.[2] Several studies over the past decade have established many tangible benefits associated with students who engage in authentic research experiences during their undergraduate careers. This includes improved communication and critical thinking skills, the development of research abilities in reading the primary literature and collecting and analyzing data, enhanced learning abilities in subsequent course work as well professional development opportunities such as networking and co-authoring a publication.[3,4,5] In addition, undergraduate students who have a research experience are more likely to pursue an advanced degree.[6]

Managing an effective undergraduate research project requires significant effort and planning on the part of the faculty. Challenges include selecting appropriate research projects, developing the research skills of the students, and finding the time to adequately advise and mentor the undergraduate researchers. This paper reports on our initial attempts to organize a course during the Spring 2013 semester that promotes undergraduate research at the University of Texas at Tyler. While opportunities already exist for undergraduate students to do research with faculty through an independent study elective, past results have been mixed and their organization has been rather ad hoc. With this in mind, an undergraduate research elective was formed with specific course objectives to help students become competent researchers. The two main objectives are: (1) to develop the abilities of the students to do scientific research, and (2) to improve the technical communication skills of the students in the areas of reading, writing, and speaking. For this initial undergraduate research elective, four students in their senior year were invited to participate.

This paper is organized as follows. The next section describes the organization and structure of the undergraduate research course. The following section discusses the research projects that were assigned, giving some details on how they were selected and an overview of the objectives of each project. Then the results and assessment are described. The paper concludes with a summary and suggestions for improving this undergraduate research course.

Background and Organization of the Undergraduate Research Course

This section provides some background on how undergraduate research has been carried out at our institution followed by a discussion on the organization of the undergraduate research course.

The author has mentored several undergraduate researchers in the past during the summer months as well as during the regular semester. Setting up an authentic research experience during the regular semester is more challenging as the students are also doing regular course work and as such have limitations on their time. Our department has an independent research elective that students can enroll in to do research with a faculty member for course credit during the regular semester. The author's observations were that this regular semester research experience could be improved if there were more structure in terms of clear objectives and expectations for the assigned research projects, scheduled activities and tasks for developing student research skills, and a formal method of assessment.

The objective of developing student skills in all phases of research was designed to be accomplished through mentoring of the student research by the faculty advisor. Additional development of research skill was envisioned as the students interact with and observe their peers doing research. The goal of improving the technical communication skills of the students is accomplished through practice and constructive feedback in four activities: (a) reading of technical articles for form and content, (b) weekly group meetings where students give short presentations on their progress, (c) the formal presentation of a poster at the end of the semester, and (d) writing a technical paper for potential submission to a conference. The writing of the technical paper is what the author dubbed a "stretch goal" – something that is a desired goal but is dependent on the progress of the research.

The students also were required to keep a laboratory notebook to help them acquire skills in recording their results and to encourage them to reflect upon their experiences throughout the semester. The course met formally once per week. The main purpose of the meetings was to make the students accountable for keeping up with their research, to discuss the journal articles that they were assigned, to provide opportunities for presenting their results, and interacting with their peers and the faculty supervisor. The following excerpt from the course syllabus summarizes the expectations for this research course:

> *Laboratory notebook*. The student will keep a notebook recording all his/her findings. This will be reviewed periodically by the faculty mentor to ensure that the essential data is properly recorded and organized so that it can be used to write the final report and poster presentation.
>
> *Literature review*. The student will do a literature search and read the primary documents in his/her area of research.
>
> *Technical writing*. The student will submit two reports:
>
> a. An interim report will summarize the progress at the midpoint of the semester. It should include a short summary of key journal articles that were read and an annotated bibliography of all the readings. It will allow the faculty mentor to provide feedback on the technical writing and research findings to date.
> b. A final report will provide a detailed summary of the research completed during the semester.
>
> *Informal Oral Presentations*: The student will give several short presentations (about 10 minutes) to the research group throughout the semester.
>
> *Poster presentation*. The student will prepare a poster describing their research and will present it at the university-wide poster competition in the spring semester. There will also be an opportunity to write up a technical paper for a conference.

The ability to critically read and assess a technical journal article is an important research skill. As undergraduate students generally have limited experience in reading the scholarly literature they will need some guidance on developing this skill. Hence, it is a good idea to assign the students an initial set of articles to read which cover the relevant background material and ideally are tutorial in nature.[7] In this course, the author assigned each student two to three journal articles to read at the start of the course. The students were required to find three additional articles that were relevant to their research. For the interim report, the students were asked to write a one page summary on two of the journal articles that included some critical assessment and to create an annotated bibliography for all the articles that were read. The interim report itself satisfies three key objectives: (1) to ensure that the students are making steady progress on their research throughout the semester, (2) to give the students experience in formally writing up their research progress to date, and (3) to allow the faculty advisor to assess their progress at the midpoint and to provide helpful feedback, both in terms of the direction of their research and on their technical writing skills and ability to critically assess the journal articles.

When mentoring undergraduate researchers, it is vital to meet regularly with them to ensure they are on the right track and not wandering off in some tangential direction. While exploring

alternate strategies can be useful, it is in the author's experience that undergraduate students will often spend time working on things that are not critical when left on their own for too long. As such, the faculty advisor met twice a week with the students. The students met as a group with the professor to give their presentations and discuss their results. This allowed the professor to provide guidance and for their peers to ask questions and to offer insight. The second meeting was more informal and occurred in the laboratory, where the author spent some time with the students in reviewing results, debugging code, and providing more one-on-one interaction.

Successful research with undergraduate students usually requires the right type of students. For this research course, four highly motivated undergraduate students were recruited to take part in this course. Three of the students had previously been involved with the author in doing undergraduate research. Selecting the right project for the undergraduate researchers is another key to success. This is discussed in the next section.

Research Projects

This section briefly describes the research projects that each undergraduate student worked on and provides some rationale on how it was selected and why it was an appropriate project for the student. A key criteria for successful undergraduate research is one of authenticity: the assigned project should involve real research where the answers are unknown and that doing the research will lead to more questions than answers.[7] For the student, this is important because they will be motivated to work on something that matters and will make a real contribution to the scientific body of knowledge—that is, students should have "the sense of excitement that comes from working to answer important questions."[5] Working on a real project will allow the student to develop as a scientist and competent researcher under the guidance of his/her advisor. Only by doing authentic research will the student learn by observing and doing what real scientists and engineers do in the laboratory. Likewise, an authentic research project is important for the advisor as the undergraduate student can be an important resource for accomplishing the research goals of the faculty.

For the undergraduate research experience to be meaningful and successful, the faculty mentor needs to carefully define the goals and scope of the project. In this case, the projects were carried out over one semester during the regular school year. Since the time for doing research would be limited, the selection of the students themselves and their background received careful consideration. For this course, the author met with each student individually to arrive at a mutually agreeable project description. A half-page description was written up in collaboration with the student. The author laid out goals and objectives for each project to ensure that each student was working with a manageable framework. When developing a realistic set of goals and objectives for the student research projects, a balance needs to be maintained between giving authentic research experiences to the students and allowing for the projects to be completed in one semester. Table 1 summarizes the students involved and their assigned projects. The undergraduate researchers will be referenced by their initials in this paper.

Student IO had spent the previous summer (2012) as a research intern at MIT, where he had investigated the design of a key arithmetic circuit for the sparse fast Fourier Transform (sFFT) implemented on an integrated circuit and an FPGA. Recent research has demonstrated that for

signals with a sparse frequency spectrum, their Fourier Transform can be efficiently calculated with significant speedup over the traditional FFT in most cases.[8] The basic idea is to be able to capture the Fourier coefficients with the largest values while ignoring the ones with minimal values. As student IO had expressed interest in continuing this research and he was currently working on using GPGPUs to accelerate an image processing algorithm as a part of his senior (capstone) design project, it seemed a natural fit to consider implementing the sFFT on a GPGPU as well. While understanding the mathematical proofs that underlie the theory for the sFFT is somewhat complex and would be beyond the scope of an undergraduate research project, a manageable project is to reverse engineer the existing C code and find a portion that is amenable to parallelization on GPGPUs. The C code for the sFFT was available from the researchers at MIT who were working on the sFFT.[9] This code was used to validate their sFFT algorithm but the focus was not on optimization to take advantage of a multi-core system. Working through the code would also help with understanding the overall algorithm which is necessary before identifying the parts that can be sped up by parallelization. The goal of our research was to understand how the sFFT works and to evaluate how it can be sped up using the parallel computation capabilities of GPGPUs. Figure 1 illustrates how the Fourier coefficients are estimated. In the course of the research, it was determined that the optimization of the low-pass filter would be a good target for speed up using the GPGPUs.

Table 1. Student Research Projects for Spring 2013 Semester

Student	Project
1. IO	Sparse FFT implemented on GPGPUs
2. YG	Acceleration of MPEG-4 compression on FPGAs
3. JJ	Agent-based modeling of ant colonies
4. LR	Circuits immune to differential power analysis (DPA)

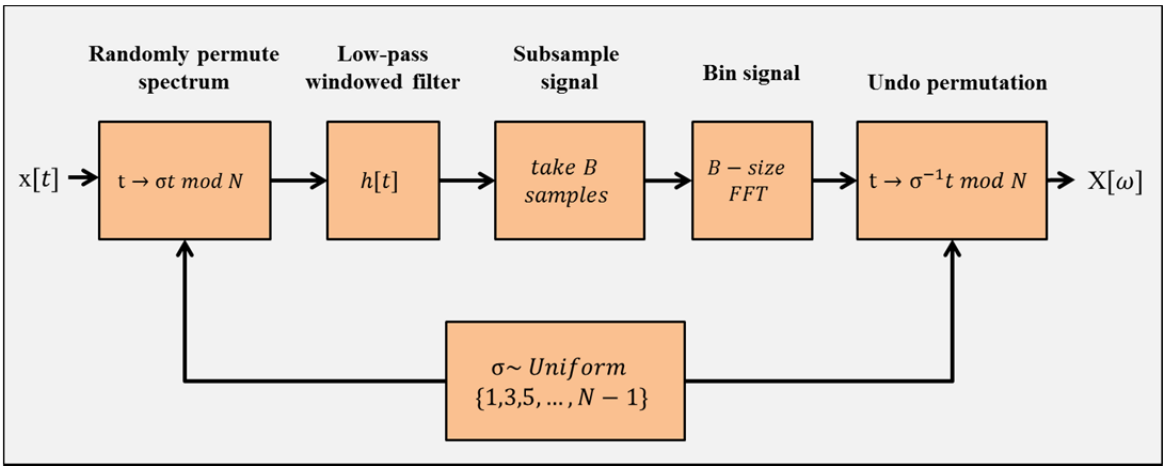

Figure 1. Block diagram of the coefficient estimation algorithm for the sFFT.[7]

Student YG had spent the summer of 2011 doing research with the author on wide-bit adder implementations on FPGAs. As she has an interest in multimedia, the MPEG compression project was assigned to her. While the MPEG compression algorithm is quite complex, a manageable project is to isolate a portion of the algorithm for acceleration on an FPGA. The motion estimation algorithm is the most computationally intensive part of MPEG encoding, typically requiring almost half of the computation time.[10] Most of the MPEG-4 encoding would be handled by a pair of soft processor cores implemented on the FPGA, similar to the proposal by Kumala *et al*.[11] as illustrated in Figure 2. Here both the "Master" and "Slave" blocks would be implemented by the soft processor cores. The critical computation in the motion estimation engine is the block matching routine that uses a Sum of Absolute Difference (SAD) calculation. A recent paper proposed a parallel adder tree for efficiently computing the values required by the SAD-based block matching algorithm.[12] This student research project involved devising custom hardware on the FPGA to implement the parallel adder tree and interfacing it with the "Slave" processor. This research leveraged YG's previous work on designing wide-bit adders on FPGAs and meshed nicely with her current interests in multimedia processing.

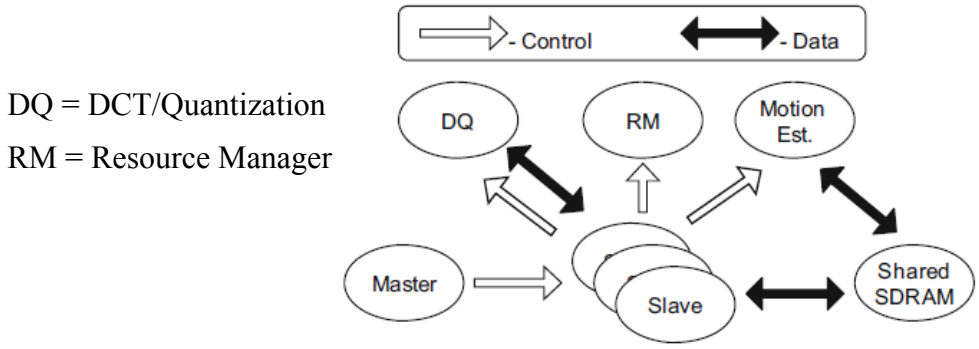

Figure 2. High-level view of the MPEG-4 Encoding Engine.[10]

The third project involves ongoing research with the biology department in modeling a red imported fire ant (RIFA) colony. There is an urgent need to find an efficient, yet environmentally-friendly method to eradicate the RIFA colonies. These ants, imported from South America in the 1930's, are a major pest in the southern parts of the United States, resulting in economic losses in the range of six billions dollars annually.[13] The main objective of this research is to develop an ABM of a fire ant colony to allow the accurate simulation of various interventions designed to destroy the colony, including the introduction of viral agents.[14] This ABM of the colony will allow researchers to change the metrics involving the interactions between different castes of ants, their environment, and the intervention methods. The goal is to determine the optimum levels and most effective entry methods for introducing toxins or viral agents designed to result in colony collapse. The scope of the student project involved understanding how agent-based models function, how they can be applied to modeling ant colonies, and then using the Netlogo program to provide an initial model for the colony. This Java-based tool is relatively easy to learn and program and provides a nice graphical interface for control and summary of results.[15] Figure 3 illustrates the Netlogo interface running an ant colony simulation as developed by the student researcher JJ. This initial work by an undergraduate student in modeling a RIFA colony was to show the feasibility of this approach. It should be noted that the rules used to program each "ant agent" can be relatively simple since it is known

that non-linear interactions based on simple ABM rules can lead to the emergence of complex behavior.[16] When modeling a complex system, simplifying assumptions are initially used in the ABM models. A cycle of experimental observation and comparison with simulations leads to model refinement, where eventually new insights are gained at the end of process. Collaborative work with the biology department was planned to develop the set of ant interaction parameters.

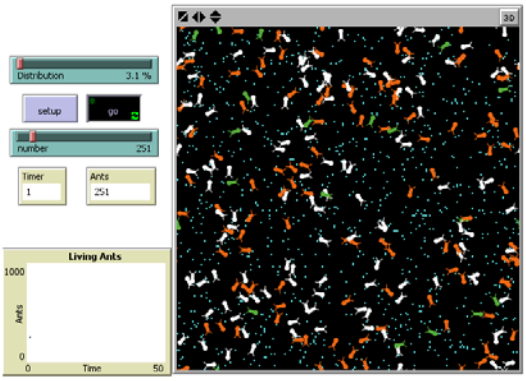

Figure 3. Netlogo software running the Ant ABM model.

The fourth project involves developing circuit designs for mitigating side-channel analysis methods used in the cryptanalysis of encryption devices. Student LR did research the previous summer and academic year on efficient stream ciphers on FPGAs. While the goals have shifted from FPGAs to transistor-level circuit design, the previous research provided the overall context. The proposed research built upon a course project from the VLSI design course the previous semester (Fall 2012) that was taught by the author. Hence, the student LR had a good background in understanding a basic encryption device as well as in integrated circuit design methods. The aim of the project was to evaluate some existing differential logic families via circuit simulation in terms of their effectiveness in mitigating differential power analysis (DPA). DPA is a method that monitors the amount of power consumed by an encryption device over time in order to gain insight on the internal states of the circuit. Hence, the power trace information can lead to "leakage" of the secret key used by the device. The hypothesis of the research is that a fully differential circuit that operates at low power will make DPA more difficult since there are complementary signals at each logic gate. This means that a high to low transition is always matched by a low to high transition. Hence, a perfectly balanced circuit will not leak any information in theory. The caveat is that a real circuit implementation will never be perfectly balanced. For this project, the student was tasked with examining a low power sense amplifier-based differential logic design.[17] A conceptual diagram is given in Figure 4 below.

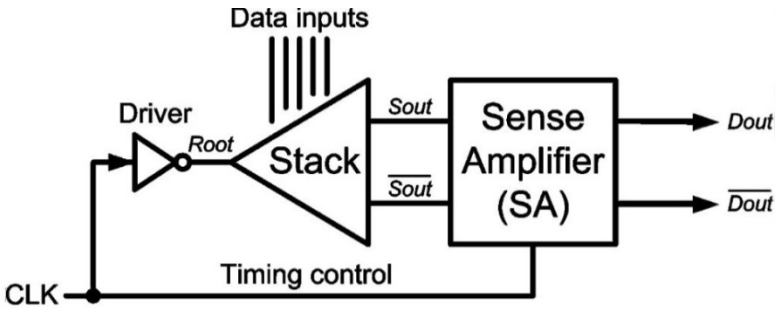

Figure 4. Architecture of SAPTL module with synchronous timing control.[17]

Results and Assessment

This section assesses the effectiveness of the proposed course on undergraduate research in terms of the contributions to research of each project, the disseminated results, and feedback from student surveys.

Overall contributions of the research projects: A brief summary of the key results of each project is given here and some assessment of how successful the project was.

The sFFT research by student IO identified the filtering component of the sFFT routine as a prime target for parallelization on GPGPUs. An important observation from this work is the impact that the filter tolerance has on overall estimation error of the sFFT routine. The filtering algorithm was coded for implementation on a GPGPU, although there were still some bugs in the code at the conclusion of the project. However, the project provided some good infrastructure which can be continued by another student. The analysis of the overall code and algorithm for the sFFT is relatively complex and required a substantial amount of time. As such, the partial success is not unexpected here.

The work by student YG isolated in the MPEG-4 C code the portions that needed to be sped up using an FPGA-based hardware acceleration. YG validated the SAD implementation at the Register Transfer Level (RTL) using C code but did not have sufficient time to get to the actual implementation on an FPGA completed. A framework is in place for the next student to continue this work.

Student JJ was able to set up the ABM models for simulating a RIFA colony using NetLogo. The biology department had some difficulties with cultivating a RIFA colony in their laboratory during the semester, and so we were unable to get some actual ant interaction parameters (e.g., probability of infection of the viral based upon degree of ant interactions). Nevertheless, the feasibility of the approach was demonstrated and future work will be able to refine the models and port the design to a GPGPU simulator as planned.

Student LR was able to simulate some key logic circuits using the SAPTL circuit and improve upon the design by extending it to a true pass-transistor logic implementation. The circuits were characterized based upon the metrics of functionality, power dissipation, and logic flexibility. The basic circuit building blocks are in place to design an actual stream cipher design. He has expressed interest in continuing this research as a master's thesis at our institution.

In sum, given the initial expectations for the completion of each project, the undergraduate research projects can be rated a partial success. However, the objectives were somewhat optimistic given the allotted time to work on the projects over one semester, which included surveying the literature as well as implementing the designs.

Disseminated results: The students applied to present their research at our institution's Research Day near the end of the Spring 2013 semester by submitting abstracts. Both undergraduate and graduate students from the entire university are invited to present their research to their peers and the faculty. All four of the abstracts submitted by the students were accepted for poster

presentations. In preparation for the presentation, the students presented their posters to their peers and the faculty advisor before the actual Research Day. The author used a formal rubric which evaluated the posters in seven categories: hypothesis, methods, results, conclusions and future work, overall presentation, and appearance of the poster board. The evaluation provided constructive criticism for improvement of the oral presentation and a grade was entered as part of their evaluation for the undergraduate research course. The author observed that the students were enthusiastic about giving each other comments on how their oral presentation could be improved. At the presentation for Research Day, student YG was awarded second place for her poster. This is a significant accomplishment as there were about 25 other students presenting posters at this event. The research by student JJ was also submitted to the SummerSim 2013 Work-in-Progress session. The paper was accepted and presented at the conference on July 8, 2013. The paper is entitled "Designing an Agent Based Model for the Efficient Removal of Red Imported Fire Ant Colonies."[18]

Survey results: The students were given a survey to complete at the end of the course. In the first part of the survey, the students were also asked to rate seven statements on a 1 to 5 scale regarding their attitudes towards their research experience. These are summarized in Table 2.

Table 2. Student Attitudes towards Their Research

(*Scale*: 1= Strongly Disagree, 2= Disagree, 3 = Neutral, 4= Agree, 5 = Strongly Agree)

Question	Rating
1. I feel that my research topic was appropriate for a senior undergraduate student.	4.75
2. I feel that my research this semester has the potential for making a meaningful contribution overall to its related field of study.	4.00
3. The goals and objectives of this research were clearly defined.	4.75
4. I feel like I will meet the goals and objectives for my research.	3.75
5. The amount of time spent meeting with the professor was appropriate.	4.75
6. Doing this UG Research has been good preparation for graduate school.	5.00
7. What I've learned from my other courses has prepared me for doing my research this semester.	4.00

From the survey results, the students were satisfied overall with their research experience, especially in terms of the research project that was assigned and the amount of faculty supervision received. There was some issue with meeting the objectives of the research. Part of this can be attributed to the amount of time to do the research during a busy semester. All four of the students were in their final year and busy with their senior (capstone) project which tends to take priority when various deadlines come up. As noted, upon reflection, the initial research objectives were a bit optimistic. While a stretch goal was being able to have enough results for a conference paper, only one student was ready to submit an actual paper as discussed above.

Another set of questions asked the students to give their opinions on how helpful various activities were for accomplishing their research objectives. These are summarized in Table 3. The two low scores in Table 3 deserve some further comment. The students did not perceive much benefit from interacting with their peers during the weekly meetings. This concurs with the faculty observation that the students generally did not ask many questions nor offer insightful observations during the presentations by their peers. The problem appears to be that the students were all working on different projects that did not have a common thread. This was due to the desire to give each student a meaningful project that fits his/her background and interests. With regard to the notebook, the instructor collected the notebooks at the midterm and end of the semester. In order to encourage the students to make useful observations and to include more meaningful reflection, a better framework was needed. This should include periodic collection of the notebooks with constructive feedback given and giving the students a clear outline of what is expected to be included in their lab books.

Table 3. Student Attitudes towards Research Activities

(*Scale*: 1 = Least Helpful 2 = Not very helpful 3 = Neutral 4 = Somewhat helpful 5 = Most helpful)

Question	Rating
1. Reading journal articles.	4.50
2. Interacting with the professor.	4.75
3. Interacting with my peers during the weekly meetings.	3.25
4. Preparing and doing the presentations in the weekly meetings.	4.50
5. Writing in my laboratory notebook.	3.50
6. Writing code/netlists for simulation.	4.75
7. Preparing and writing the reports.	4.75

The survey also asked the students two open-ended questions. The first was to list any other activities that they found to be helpful in doing their research. One student noted that being able to present a poster at the university's Research Day was helpful in clarifying the research. Another noted being able to interact with the professor in the biology department and his student was helpful. The second question asked the students how the undergraduate research course could be structured to improve on their research experience. One student suggested more presentations as it was helpful in "staying on track" and the desire for more interaction one-on-one with the professor as it was useful for "bouncing ideas back-and-forth and addressing issues." Two students observed the lack of constructive feedback from their peers during the weekly meetings and presentations in agreement with the faculty observation. One suggested that the projects should have "some over encompassing theme" or have the students tackle similar problems but from different perspectives. One also felt that his research problem was too open-ended and needed a clearer goal to focus on.

Graduate studies: As noted in the introduction, an undergraduate research experience increases the likelihood that a student will consider pursuing advanced studies. It should be noted in this case that all four students were already considering graduate studies before taking this research course and that three of the of four already had an undergraduate research experience. Thus, we can at best say that this particular research experience helped reinforce and encourage them in their pursuit of a graduate degree. Currently two of the four students are enrolled full-time in graduate school. Student IO is pursuing a Ph.D. degree in computer architecture at U. Michigan-Ann Arbor and student YG is pursuing an MSEE degree in multimedia at USC. Students LR and JJ took full-time jobs after graduation but are also seriously contemplating continuing their studies in graduate school in the near future.

Summary and Conclusions

Several important lessons learned for enabling successful undergraduate student research will first be summarized and then some suggestions on how this research course could be improved in the future are given.

The implementation of this course for promoting undergraduate research has led to several key insights. First, assigning the right project is an important aspect of a successful research experience for an undergraduate student. Tailoring a project to the individual interests and skills background of the student is critical. Also, having realistic expectations on the goals and outcomes of the research experience is important. The goals should be sufficient to challenge the student to do authentic research where the answers are not known but not so high that they become discouraged when the inevitable difficulties occur. A second observation is that establishing a schedule with specific deliverables (e.g., presentations, reports, lab books) is a key motivator. This is especially important when research is carried out over the regular semester as there are deadlines from other courses competing for the students' time. Third, is having a group of motivated students. While an undergraduate research experience is worthwhile for every student, if the end goal is to produce publishable research, having the right students is crucial. In this case, the author was working with a small group of undergraduate students, mostly who had done research with him previously. Fourth is the importance of disseminating the research. This provides an important motivator and end-point for the research. The student poster competition held during our institution's Research Day provided a good opportunity for all the students to present their research to their peers and our faculty and was a strong motivator for producing results and completing their work. Lastly, supervising undergraduate research requires time and commitment on the part of the faculty member. Having set meeting times where the advisor met twice a week with the students as a group was helpful for both the faculty and students in terms of establishing a set schedule and optimizing the impact of the meeting times.

In sum, it is found that with the right infrastructure, supervision, and motivation, undergraduate students can have an authentic research experience that makes meaningful contributions to their field of study. While most of the projects were only partially successful in this case based upon the original research objectives, they all contributed a good foundation that can be continued by other undergraduate students. In general, it is expected that an undergraduate research project carried out by a single student will be a part of a larger ongoing project. Future work will consider expanding the enrollment of the undergraduate research course. While supervision of

each student takes a considerable time commitment on the part of the faculty advisor, this can be accomplished by having students work on related topics and involve the help of graduate students. A useful observation from both the author and the students from this implementation is the need to have more synergy between the projects so that the group meetings could have more focus and there would be more peer interaction among the students.

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