TRUE UNDERGRADUATE RESEARCH: FOUNDATION FOR GRADUATE STUDIES AND CRITICAL THINKING

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Abstract - The fast advance of computer technology and the economic pressure to increase profits force the industry research to focus on short-term goals that do not allow the in-depth study and theoretical investigation associated with long-term scientific research. Furthermore, today's attractive job market tends to absorb an enormous number of computer science graduates, reducing the quantity and quality of the student body seeking advanced degrees. This second factor may slow the technological progress achieved through academic research. In order to improve the chances of new discoveries in the Computer Science field, new graduates must be trained for critical thinking and motivated to pursue academic careers. This paper discusses the preparation of computer science undergraduate students for future participation in new discoveries through the pursuit of an academic career or more in-depth industry research. This preparation is conducted through a research methodology that improves the motivation of undergraduate students to seek new discoveries. First results of applying such a methodology in a study focused on developing new computer architecture features and supporting theory are presented. The method has also been used in the Software Engineering field with significant success. This paper reports a successful experience in this area, showing how the students were selected, motivated and coached to achieve the research goals.

1. INTRODUCTION

The computer industry is currently advancing at a very fast pace. Technological changes in microprocessor architectures are influencing new designs of hardware and software. While improving computational speed and human-machine interface, these changes are bringing back old problems of the mainframe era. Such problems include operating systems that require large amounts of memory, programming environments that produce inefficient code by adding unnecessary libraries to the executable code, poor performance applications, and hardware resources that may be constantly idle. The short-term goals established by the industry do not allow the extensive research and experimentation required to achieve optimized solutions [5,7]. This trend shows an apparent lack of interest in the search for more advanced and efficient techniques. This paper reports the introduction of research activities at the undergraduate level, motivating the students to improve their problem solving skills and to focus on efficient solutions. This methodology is now being applied to studies in new computer architectures and software engineering techniques.

The computer industry considers those with advanced degrees the main source of research efforts [4]. A brief survey of research grants awarded by the National Science Foundation to institutions proposing some sort of undergraduate research goal shows that most of these projects are focused on educational infrastructure or on practical training [12, 13]. By educational infrastructure one must understand the establishment of laboratories for class support or just the development of new courses. In either of these two cases, undergraduate student involvement is purely passive as a future beneficiary of the work being done by faculty or graduate students. As practical training, one must consider those research projects that include undergraduate students during a summer season or for a school semester. These short-term programs, usually, can not provide the necessary background to the student in order to have him or her participating in the findings of the project. In this group of funded projects, faculty and graduate students conduct the actual research, transferring to the undergraduate students the required experimental tasks. Such tasks usually involve programming, measurements, and simulations, which can be considered activities that do not require any extraordinary creativity but just a reasonable knowledge in their field or the study of existing results [3, 10, 11, 18].

While the current research funding efforts seem not to provide the appropriate environment for active undergraduate research, the job market in Computer Science is in constant expansion, immediately absorbing the more recent graduates [6]. National Science Foundation reports show a steady decline in the number of enrolled graduate students in science and engineering. This decline is noticed to have occurred after 1993, following a 20-year period of rising numbers [14,15,16]. Such a decline is expected to have a significant impact in the doctorate awards in the near future. In particular, the computer
science field has experienced a new trend of increase beginning in 1996. However, the number of doctorate recipients in computer science has been in decline since 1996 (Figure 1), which could imply that the increased number of enrolled graduate students is related to more Master's candidates, looking to improve their professional status, rather than a large number of students interested in research.

![Figure 1. Number of doctorate recipients in Computer Science (source NSF website)](image)

The lack of basic motivation for future research and the exciting idea of a rewarding job position tend to keep young students away from research oriented graduate programs, which creates a continuing cycle that reduces the possibilities of new discoveries. Since it is almost impossible to slow down the job market, our project focuses on the motivational aspect of undergraduate research. By focusing on the undergraduate motivation, this project also tries to increase the proportion of American citizens entering graduate programs. Such a number has been decreasing in recent years as verified by the National Science Foundation [13].

Recent studies point to the fact that students learn too many concepts and do not experience the practical aspects of their profession [1, 2]. The immediate consequence is a set of well-elaborated study programs that are supposed to address the urgent needs of the industry, generating a new batch of computer scientists that are focused on the engineering segment of the field and not in the science. A good example of a successful program following this concept is the research project in robotics reported by Koelzer [8]. Theoretical research efforts, however, are not seen as a productive investment and are losing their funding sources.

In this paper, a report on a research initiative that focuses on theoretical results, while preparing the students with the “on-the-job” training required by the industry is presented. The next section briefly describes the events preceding the project. Section 3 presents the actual implementation and a short description of the tasks assigned to the students. A summary of the current results and the trends is presented next, while Section 4 concludes the paper.

2. BACKGROUND

An interesting experiment conducted in a Software Engineering class in order to provide the students with some experience in teamwork while emphasizing the requirement analysis phase of a large software project was the origin of this study [17]. In that class, projects were assigned to the students requiring them to read scientific journal articles in order to obtain the basic information on the system to be developed. The goal was to introduce the students to the complex methodology of gathering data in an unknown field of knowledge. At that time, the faculty teaching that class was preparing a proposal to the NSF for funded research; no consideration was being given to undergraduate students as part of the project team. However, the creativity and motivation of the students reported in the class project was so significant that a decision was made to include undergraduate students in the NSF grant proposal, focusing on actual research and not just in developing the undergraduate students' skills.

The research topic involved study of loop transformations and parallel processing which comprised the main area of research of the faculty designated as principal investigators. Such a proposal was accepted and awarded US $ 240,000.00 for a 3-year period. The study was motivated by the fact that most of the optimized solutions applicable to multi-dimensional systems such as image processing, geophysical signal processing, and fluid dynamics, require the problem space to be traversed according to a wavefront movement. Existing hardware description languages, as well as general purpose programming languages, focus in row-wise and/or column-wise execution of the problem space through the use of nested loops in the code. This sort of subject, usually, is not part of the knowledge acquired by an undergraduate student at the junior level. The study was looking at the fact that if a wavefront direction was required by the optimized system and it was not parallel to the horizontal or vertical axis of the vector basis defining the problem space, then complex transformations on the source code were required in order to emulate the wavefront characteristic. The proposed study was in search of a compromise between hardware features and compiling techniques in order to reduce the programming effort required to obtain the optimized performance.

That project was planned on two distinct phases aimed at progressively achieving the balance between hardware and software necessary to support the desired optimization. Initially, the study of optimization techniques for uniform loops requiring execution similar to wavefront processing became the main target of the planned work. Such analysis
allowed the identification of which new features should be implemented at the programming language level to support the fine grain parallelism.

The loop transformation study is still being conducted with the secondary goal of preparing undergraduate students for advanced degrees. To achieve this goal, the students were required to focus on theoretical details of the project, elaborating their own conclusions and observations, participating in the implementation of tools and simulators and presenting their partial results at appropriate conferences. The NSF grant proposal was budgeted in such a way to provide stipends to one graduate and five undergraduate students. However, one might infer that the most significant factor in motivating the students’ participation was the possibility of improving their financial earnings; we will show that was not the case. Moreover, as stated in [9], the future of a doctorate student is not so brilliant (50% of recent graduates surveyed in that study reported working in temporary positions). In the next section, these factors are examined and described, showing that a successful result is expected when the students are really motivated to participate in the project.

3. PROJECT DESCRIPTION

Initially, there was a feeling that an externally funded research was the basic requirement to attract the participation of undergraduate students in this sort of work. After obtaining the NSF award, the first task of the principal investigators (PIs) was to assemble the future research team. It was important at this point to invite students for an informative meeting, which would allow those interested in the project to understand its objectives and the theoretical workload required. Some of the invited students were already recipients of some sort of assistantships and were informed that they would need to exchange their current award for the new one in order to avoid accumulative awards. This would make the decision in participating on the project almost independent of a financial decision. The number of work hours associated with the project was limited to ten hours per week, preventing conflicts or significant impact on the students’ academic performance, while keeping the stipend in a low range such that it could not be looked at as the motivational aspect of the project.

The receptivity of the students and their interest in participating in the project was extraordinary. The selection of the grant-supported students was based on their grades, interest in the research and a faculty analysis of the applicants’ academic history and potential. An important point here is that there was no evaluation of the applicants’ communication skills, and we will see that there were some interesting developments in this area. The selection focused on juniors who could work in the project for at least two years. Two seniors were also included to provide maturity for the group and a graduate student was selected among recently admitted students for the graduate program. However, the team was not limited to that group of six individuals. Other students volunteered to participate in the project without any financial support, increasing the team size to four graduate students and eight undergraduates – twice the budgeted numbers. Later, in a departmental decision, a financial award was made to the volunteers as a reward for their interest. The team was divided into 3 major investigation groups: compiler, architecture and simulation, according to the students’ interests and a balanced distribution among the three areas.

After one year, a first adjustment was made. The supervision of the large number of students done by a small number of PIs was not producing the expected results. The volunteer students were left with less significant tasks and did not evolve at the same level as the main group, with only two exceptions. Therefore, the students supported by the department had their activities redirected towards other goals. The two students considered exceptions, however, were called to substitute for one of the graduating seniors and one graduate student that had to leave the project.

Concurrently with the NSF funded project, other initiatives were taken in order to involve undergraduate students in faculty research. In these other cases, the absence of scholarships or stipends was considered the first obstacle to be overcome. Informative meetings were conducted in the classroom instead of conducting specific meetings. The most successful responses came from the Software Engineering classes. These students got involved in short-term research projects that resulted in published conference papers.

In a first approach to give the students a flavor of industry experience, they were also assigned to six service tasks: Unix system administration, Windows NT/95 administration, Latex programming, Web development, assembler language support, and Windows programming support. However, what was considered a significant parameter to keep the students motivated did not produce the expected results. Most of the students were already knowledgeable in some of the "industry oriented tasks" and did not get interested in working on them. On the other side, unknown tools, such as Latex, were not used during the first year of the project and the students responsible for those tools did not have a chance to show how much they had learned.

The three faculty members assigned to conduct the research shared the responsibility of producing the final results. Each one of them assumed the supervision of one of the three main areas. During the regular meetings of the group, the most significant and motivational aspect explained to the students was that in theoretical research nobody knows the answer to the possible questions that could arise from the investigation. This was equivalent to placing the students at the same level as the faculty.
approach introduced the student to the real research activity: search for the answer and disseminate the information among their peers. The project focus was to find a solution to a problem that was not described in books. Such a task would require the analysis of a large amount of information before achieving any conclusion. To make the task a little more difficult, the source of such information consists basically of scientific papers published in journals or conference proceedings, which the students usually consider hard to read and understand in a short time.

The students' feedback was surprising. During the first three weeks they were subjected to presentation sessions about the fundamentals of the research proposal and assigned to readings that supported those concepts. The number of questions, comments and suggestions made by the students during those three weeks were of exceptional quality. Some of them were able to provide intuitive solutions for the problems described, before knowing that those solutions were already recently published.

After this first period of adjustment, the students were asked to volunteer to study a specific topic, such as branch prediction techniques, instruction level parallelism and architectural implementation of such concepts. They later presented those concepts to the other elements of the team. Again, the number of volunteers exceeded the number of topics. Three students were selected for reading papers in those areas and making the presentations. Two other students were assigned to participate in a Conference in Computer Design and report the latest advances in the field of branch prediction.

The students had two to three weeks to get prepared and they could request any support from the faculty. By their own initiative, the students browsed through books and sometimes they read through five to seven other papers to improve their grasp on the topic. The result was a very participative sequence of meetings with undergraduate students answering faculty questions in a natural, informal manner, with very good knowledge of the topic. Unfortunately, this is the kind of situation that normally does not occur in presentation of homework or class projects where the students are more interested in their final grade than in the material they are presenting.

The completion of the first year of research came with a positive balance. Some of the students were able to demonstrate their research potential by submitting and publishing their results in traditional conferences. Half of the group, however, assumed supporting roles, limiting themselves to activities such as program analysis, development and simulations. These students' decisions did not impact the outcome of the experiment with undergraduate research, since those activities also produced significant results. However, knowing that all of them are looking for an advanced degree as their next step, it is almost certain that these students working in the supporting roles will experience a slight delay in their adaptation to graduate studies.

In the non-funded projects, there were some additional obstacles, since most of the students were also involved in some sort of part-time work and could not dedicate too much time to their projects. Even so, they were able to find enough free time to study the existing literature and participate in research meetings coordinated by the faculty. The research study was not as well organized as the funded research. However, it produced at least three published conference papers in the areas of software specification and genetic algorithms.

The common point of all projects was how to design an algorithm to implement a successful undergraduate research. Anyone should know that there is no exact recipe for this. However, we propose an algorithm described in the following steps:

1. Make the topic of the project a theoretical one.
2. Propose and, if possible, obtain initial funding for the project.
3. Conduct an informative meeting to attract interested students. Show them the possibility of getting their first technical publication.
4. Select a group of good students to participate. Allow other students to join the team.
5. Place the faculty members participating in the project in a double position: supervisors and at the same time researchers with as much knowledge as the students.
6. Present the problem and give everybody a chance for creative solutions and research initiative.
7. Assign literature survey tasks to keep the students reading and explaining the related work in the area.
8. In every meeting, remind the students about conference deadlines and the chances of participating in one.

The explanation for such an algorithm is simple. In step one we guarantee that the project will not become just one more programming assignment or homework since the theory is not yet developed. Step two gives soundness to the project: “someone out there has interest in its realization.” If the funding is not granted and the faculty still has interest in conducting the research, then a motivational speech can accomplish the same goal. One may say that without the funding, the stipend will not exist and there will be no interest. This can be partially true; however, at least three of the students working in this research were already working with the PI before there was any positive signal that the award was going to be granted. Also, the experiments in Software Engineering and Genetic Algorithms with students not involved in the grant project resulted in publications. Steps three and four are also easy to explain. Combining good students with motivated or interested ones, the research is guaranteed to survive any difficult obstacle such as a paper rejected in a conference.
or a group solution that is found in the literature. Steps five and six provide the extra motivation to the students, just like any faculty-vs.-student softball game. Students will perform beyond their class ability to show that they can get an answer before the faculty has a chance. Step seven is now in progress. The problem was conceptually developed and needs a solution. The students' work consisted of doing literature surveys, presenting current trends and previous results to their peers. They also developed new solutions and algorithms, including implementations when appropriate. Possible alternatives were discussed in the research meetings and new developments brought new challenges. The research team expected to unveil at least one significant contribution in each of the main areas by the end of the first year. The actual result was the publication of nine papers and the expectation of five new ones before the end of the second year.

Finally, step eight keeps the students thinking about achieving some deadline, which would allow them to participate in a conference. However, never allow them to assume that such a date is a hard deadline. They must have the freedom to work at their own pace and get the results that are really significant before being exposed to critical audiences. This paper cannot yet report the full success of the method; however, it shows the implementation of a true research environment, not just a programming task. In the last 18 months, 7 undergraduate students have participated directly in the NSF project, being rewarded with scholarships and monthly stipends. During the same period, 3 graduate students and 3 undergraduate volunteers also worked in the research. From the 7 supported undergraduate students, 3 of them have already graduated. Two are now enrolled in Ph.D. programs at Notre Dame and Central Florida and the third is working on his Master's Degree. Three others plan to graduate in the spring of 1999 and have already sent applications for admission to Ph.D. programs, one has been accepted at North Carolina and also at Georgia Tech. A junior will be working in the research for one more year; however, he is already scheduled to work during the summer on a research project at Notre Dame.

The results of the funded project are shown in figures 2 and 3, where the each bar represents the collaboration of one of the 13 students involved in the project. While figure 2 shows the number of months each student was involved with the project, figure 3 shows the number of publications they produced in order to disseminate their results. In figure 2, it is possible to distinguish the number of months worked with and without support of the NSF grant. The students supported by the grant averaged 10 months of work, while the volunteers averaged 11 months. These numbers support our conclusion that stipend is not the only motivation factor in undergraduate research. The student collaboration represented in these two figures, when overlapped, provide a relationship between amount of work of each student with his or her published results. If we proceed with an analysis of this relationship, it is easy to conclude that the time dedicated to the project is a significant factor in the results - students that have worked for longer periods produced more results. This observation may imply a low probability that one season research projects could give the students necessary experience in research. Some exceptions to this rule are students 3 and 5 who were able to co-author papers in a very short period. However, these students were exceptionally motivated and dedicated to the project. This is not the usual situation. In the non-funded research efforts, three other students worked in the Software Engineering projects and two of them have already graduated and are working towards their Master's degree. These students generated two published conference papers based on their study.

**Figure 2. Participation time per student**

![Figure 2](image)

**Figure 3. Published or submitted results.**

![Figure 3](image)

4. CONCLUSION

The research departments in industry are working with short-term goals and profitable targets. Research funding...
agencies are following the same trend by being pressured with small budgets and technology transfer requirements. New discoveries are being sidelined by lack of resources or interest. In order to build a new generation of scientists, it is important to submit undergraduate students to real, long range, theoretical research. This experience can provide the students the necessary skills to excel in industry or in advanced studies. The use of short term research and implementation projects do not satisfy the basic condition of exciting the students' imagination, abstraction and creativity required in a true research environment. The paper has shown that a good research team can be assembled by putting together students with good academic records and those interested in research. Also, the use of theoretical resources and the challenge of discovering the unknown are highly motivational factors for successful undergraduate research. This is an on-going research effort and not all the answers are available, however, they will be very soon.

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