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Successful Undergraduate Research Experiences in Engineering: Student, Faculty, and Industrial Perspectives

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Abstract

When ideas for improving the education and graduation rates of engineering students are presented, one practice often promoted is increasing the number of students performing undergraduate research. Often, the benefits achieved by high-achieving undergraduate students engaged in research activities are cited as evidence of the potential that undergraduate research offers all students. However, relatively little study has been devoted to the impact and benefits of research experiences on ordinary engineering students. Yet, in order to achieve broader participation in undergraduate research experiences, it is these students to whom undergraduate research opportunities need to be provided. Therefore, it is necessary to understand how these experiences can mesh with the career goals of these students, and how they can best meet the students' expectations and needs.

The primary purpose of this NSF-sponsored work is to develop definitions of what constitutes a successful undergraduate research experience for a wide range of engineering students. Particular attention is devoted to students whose academic background and performance is solid, but not outstanding. For such students, some of the benefits seen in high-achieving students – such as increased likelihood of graduate school attendance – may not be appropriate measures of a successful experience. To develop the definitions, we have surveyed and interviewed students who have been engaged in undergraduate research experiences in engineering, faculty members who have supervised undergraduate students working on research projects, and industrial representatives who have employed recent engineering graduates. In this paper, we present the perspectives of these groups. With the perspectives of the three groups as input, the definitions of a successful undergraduate research experience for non-elite engineering students have been developed and are presented.

In addition to these definitions of a successful undergraduate research experience, the paper also presents insights from the faculty and students on how to make the experiences more beneficial for the students. Such information can help other faculty as they design research experiences for their own students.

Introduction

Interest in increasing the number of graduates with degrees from STEM disciplines has been strong for some time in the United States, as this is seen as an important part of keeping the nation robust economically.[1,2] As a result, many interventions have been developed to achieve this goal and to improve the skill-sets of STEM graduates. One of these activities is to increase the number of STEM students engaged in undergraduate research experiences. Two reasons often given for increasing participation in undergraduate research experiences (UREs) are to improve student retention in a discipline and to increase the number of students who pursue graduate studies.[3-7] Increasing retention in a discipline is a key component necessary for increasing the number of graduates. However, if the primary impetus for using UREs is to increase the number of students attracted to graduate school, it is likely that the focus of efforts to recruit students to participate in UREs will be on higher-achieving students who are already succeeding academically. These stronger students are already more likely to finish their degrees than weaker students. Therefore, if the UREs are targeted primarily to top students, the use of UREs may not be effectively increasing the number of engineering graduates. The potential benefits with respect to retention and graduation from engaging students in UREs would best be achieved by providing more “average” and even “weak” engineering students with such experiences. Therefore, in order to gain a better understanding of the effectiveness of engaging in UREs for a broader range of students, there is a need to study students who are not among the elite students in the nation, but rather who are more representative of the majority of engineering students.

The University of Wisconsin-Milwaukee (UWM) is an urban, doctoral, research institution. Students in the College of Engineering and Applied Science (CEAS) at UWM range from being relatively strong to being rather weak in comparison to engineering students nationwide. For example, the mean ACT score of freshmen entering CEAS in the Fall 2015 semester was 26.1, which is the highest it had been in at least 10 years. This value has been steadily increasing over the years. Such an average indicates that there are some students in CEAS who could attend most engineering schools in the nation, but there are also a significant number who might not be accepted into many other schools. Even though there are many relatively weak students in CEAS, because UWM is a research institution, most faculty have active research programs and many employ undergraduates as part of these research programs. Typically, about 70 undergraduate students each year in CEAS participate in research projects.

Based on past post-graduate activities of graduating students from CEAS, the large majority of students in CEAS does not intend to directly enter graduate school upon graduation, and instead are more interested in obtaining a job in industry upon completion of their program. Most of the students work part-time while in school, and relatively few graduate in 4 years (most require 5 or 6 years to graduate). Students of this profile have been the focus of few studies on the impact of UREs. As a result, it is not clear what the expectations of these students are from the participation in UREs, or how to determine if the experience is a success. The profile of students in CEAS, coupled with the number of students and faculty engaged in UREs provides a starting point for gaining a better understanding the potential impact of undergraduate research on a wide-range of students, including those students who are more vulnerable to leaving STEM disciplines.

Previously, the results of a study of the students in CEAS engaged in UREs on what they perceived as the benefits they received from UREs have been presented.[8] These engineering and computer science students generally fall into the “average” category desired to be explored. In this paper, those results will be briefly reviewed, and then additional input from CEAS faculty who have interacted and supervised students in UREs will be discussed. A survey of primarily local industrial representatives who employ graduates of CEAS on what they have experienced with graduates (both who engaged in UREs as students and who did not engage in UREs) was conducted, and the results of this survey are also presented. The input from these three groups is combined to create a definition of what describes a successful URE for common engineering students.

Background

Increasing student retention in a discipline and motivating more students to pursue graduate studies are two reasons commonly given for encouraging and increasing participation in undergraduate research by STEM students.[3-7] The reasoning behind these assertions is that students engaged in meaningful research in their discipline become better connected to it and develop a deeper understanding of their field. In some cases, this has been shown to increase the retention of students if they begin research early in their undergraduate careers. Other suggested benefits are that the students gain confidence in their abilities and become more interested in pursuing graduate studies. Other studies have suggested that some undergraduate students actually choose to change disciplines after being in a URE due to learning more about their field and experiencing typical research set-backs.[9]

Other benefits that have been associated with engineering students in engaging in UREs include the students gaining a better understanding of the research process, improving communication and collaboration skills, the development of problem-solving skills, and the students developing enhanced critical thinking skills.[10-11] While the increased understanding of the research process may not be as important for students interested in pursuing careers in industry, the other attributes are often seen as necessary outcomes of an engineering program, so much so that some are specifically included in the ABET accreditation criteria.[12] Therefore, it appears that there is the potential for professional development by students engaged in a URE without the expectation that they will attend graduate school.

A considerable amount of research has been devoted to students who participate in special summer Research Experiences for Undergraduates (REU) programs, including that of Willis, *et al*.[9], Hung, *et al*.[13], Mahmud and Xu[14], and Willits and Barnett[15]. Hathaway, *et al*.[16], and Nagda et al.[17], studied students from a wide array of disciplines engaged in UREs at the University of Michigan. Seymour et al., and Hunter et al., studied the impacts of UREs on science students in a school that was focused on liberal arts.[18,19] Kang[20] focused a study on UREs for underrepresented minority students in science programs. These studies generally found positive results for the majority of students engaged in UREs, with more details on the individual studies described elsewhere.[8]

Russell *et al*.[21] performed a survey of thousands of undergraduates who had participated in undergraduate research in STEM disciplines. They also surveyed faculty and graduate students who mentored these students. Many of the students had high grade point averages and had participated in very competitive NSF-sponsored programs; therefore they tended to fall into the description of high-achieving students. Russel, *et al*., found that engaging in a URE increased students' confidence and raised students' awareness of graduate school. Moreover, the number of these students who expected to obtain a Ph.D. noticeably increased after participating in an URE, suggesting an increased motivation to attend graduate school.

While valuable, these studies illustrate the limitations of work that has been done on students engaged in STEM UREs. First, many of the studies focus on high-achieving students who participated in competitive summer REU programs. Second, focusing on summer programs neglects students that participate in URE during the normal academic year, when it may be difficult to balance the URE with coursework; many students need to work during the summer to earn money to pay for college. Third, many of the studies only considered a very small number of students, which limits the significance of the results. Fourth, many of the studies in STEM disciplines have concentrated on students in the physical sciences. These students may have more limited career options with a B.S. degree than do engineering and computer science students. Students in the physical sciences may therefore tend to focus on developing skills necessary for graduate school, whereas average engineering students may be more interested in finding a job in industry upon graduation, and developing the skills necessary for securing such a job. The work from the study described in this paper was performed to start to fill these gaps in our understanding of the benefits and impacts of UREs on average students in engineering and computer science.

Results of Student Surveys and Interviews

As part of this project, 110 students in CEAS who had been engaged in UREs in the previous two years were sent an on-line survey. Forty-one students completed the survey, which is a response rate of 37.3%. Details on the survey content are provided elsewhere[8], and summarized here. Students were asked demographic information, as well as questions about their specific URE, such as time spent weekly on the URE and the nature of their interactions with other individuals on the project. This type of information allowed us to determine if we were receiving input from a representative cross-section of the student in CEAS engaged in UREs, and to provide us with details that could impact the quality of the URE for the student. The students were given a list of potential benefits and asked to identify the benefits that they perceived to have gained from the URE; the perceived benefits list is provided in Table 1.

Figure 1 depicts students' perceptions of the benefits received from their undergraduate research experience. The number listed for each benefit refers to the benefit as listed in Table 1. Note, 3 students did list an "other" benefit, but these were considered either similar to one of the 11 other benefits, or had only one person with that other benefit identified. Reisel, *et al*.[8], contains a detailed analysis of the survey results. While all benefits were cited by at least half the respondents, the most frequently cited benefits were the ability to work independently (#4) and learning how to conduct a research project (#6). It should be noted that there was a noticeable difference between the numbers who indicated that working independently (#4) was developed in comparison to developing teamwork skills (#5). Additional insights and details were obtained through the student interviews, and these results are also detailed by Reisel, *et al*.[8]

Students were also asked if they were willing to be interviewed about their experiences in greater depth. Of these, twelve students were selected for interviews based on their demographic information as representative of the respondents as a whole. Details on the interview format and questions can be found elsewhere.[8]

Based on the survey results and in-person interview responses, a <u>preliminary</u> definition of a successful undergraduate research experience for the average students considered in this project was developed.[8] The goals for a successful URE for these students are

Table 1: List of potential benefits presented to students in the on-line survey.

Number	Perceived Benefit
1	Developed student's critical thinking skills
2	Developed student's communication skills
3	Developed student's problem solving skills
4	Learned how to work independently
5	Learned how to work as part of a team
6	Learned how to conduct a research project
7	Improved student's relationship with faculty and/or other students
8	Increased confidence in student's research skills
9	Increased confidence in becoming a successful engineer/professional
10	Academic coursework became more relevant
11	Developed/increased interest in pursuing graduate studies
12	Other

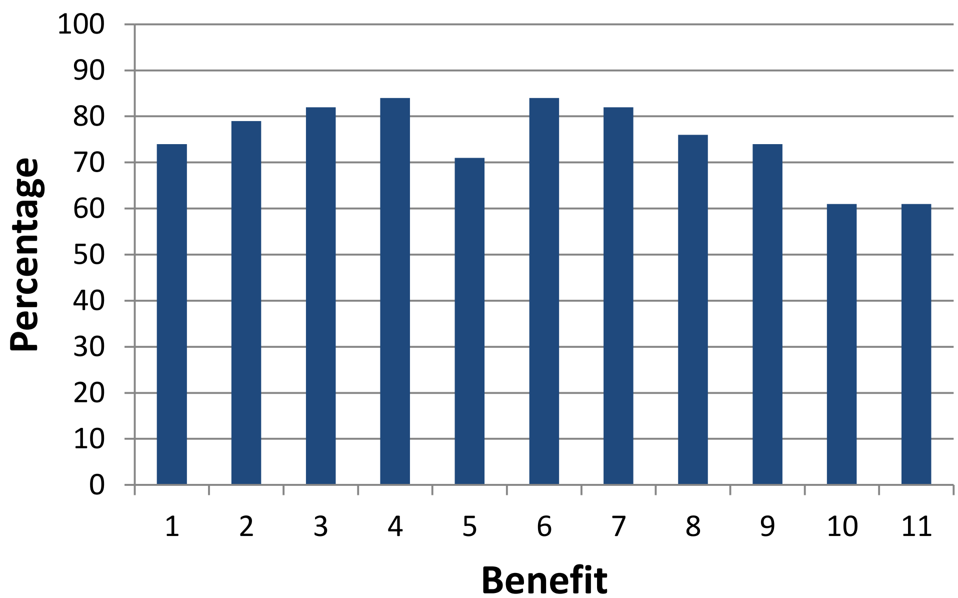

Figure 1: Percentage of students (n=41) who responded in the survey that they received the particular benefit (as numbered in Table 1) from their URE.

1) The URE should develop applied engineering, critical thinking, and problem solving skills of the students to help prepare them for a career as an engineer, likely in industry.

2) The URE should improve the communication skills of the student.

3) The URE should increase the confidence of the student in their abilities, and help clarify their career goals.

4) The URE should both help the student learn to work independently and as part of a team.

5) The URE should provide the students with an understanding of how to conduct a research project.

With these results based upon the student perspective in mind, input was also sought from faculty in CEAS and industrial representatives. These results are described in the following two sections.

Results of Faculty Survey and Interviews

CEAS faculty were invited to respond to a survey regarding their experiences with students in UREs and their expectations for students participating in UREs. The questions asked in the survey were very similar to that of the student survey, with the primary differences related to determining the extent of the faculty member's experience working with students in UREs as opposed to compiling information on the demographic and academic background of the students. Sixteen survey responses were received, out of approximately 70 faculty, representing a response rate of 23%.

The faculty members were asked to choose which of the benefits listed in Table 1 that they felt were expected outcomes for students participating in UREs. Faculty were also asked to identify those benefits that they had personally identified as being received by the students that they have overseen. The percentages of the 16 respondents to the survey who selected each benefit as expected of a URE and identified as achieved by a student in a URE are shown in Figure 2. One thing to note in Figure 2 is that for almost all the benefits, the percentage of faculty who identified a benefit as being achieved was smaller than the percentage who expected that the benefit would be an outcome of a URE. This suggests that faculty may have either too high of an expectation for what a URE can accomplish for students or there may be a belief that a benefit must be demonstrated to a large extent to be acknowledged by a faculty member as it having been achieved. This latter interpretation may be supported by a comparison between Figures 1 and 2, which shows that a larger percentage of students felt that they received a particular benefit at a generally higher rate than faculty perceived the students as having received that benefit.

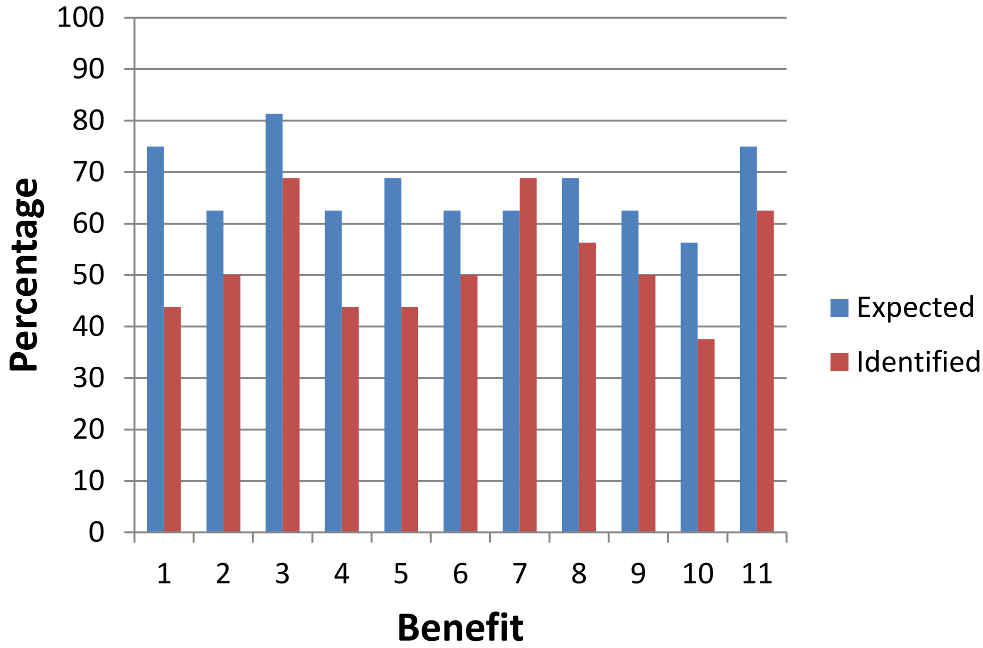

Figure 2: Percentage of faculty (n=16) who responded in the survey that they expected that a particular benefit (as numbered in Table 1) should be received from students participating in a URE, and the percentage of faculty who perceived that that benefit was achieved by students in UREs that they have overseen.

Two analyses of the data in Figure 2 will be made. The first analysis will consider what faculty expect what benefits a URE should impart on the students, and the second will consider a comparison between what students stated were received benefits and what faculty perceive the students to have received. For the analysis of what faculty expect a student to receive from a URE, it should be noted that each of the perceived benefits were expected by at least half of the respondents.

The benefit of URE participation that was identified as an expectation by the largest percentage of faculty was #3, that a URE should develop a student's problem solving skills. Tied for second in terms of agreement were #1 (develops critical thinking skills) and #11 (develops or increases interest in pursuing graduate studies. Interestingly, while #3 was nearly the most frequently cited benefit received in the survey from the students, #1 was in the bottom half of the benefits in terms of the percentage of students stating that they received each benefit. In addition, a relatively low percentage of students saw the URE as increasing or developing their interest in graduate studies.

It should also be noted that more than 80% of the students identified that the UREs provided the benefits #4 (working independently), #6 (learned how to conduct a research project) and #7 (improved relationship with faculty and/or other students), but a relatively small percentage (in comparison to some of the other benefits) of faculty (62.5%) saw these as benefits of working on a URE. This suggests that some faculty may not be recognizing the potential importance of these benefits to students from participating in a URE. Similarly, while a relatively low number of students listed receiving increased teamwork skills (#5) from a URE, this was identified as an expected benefit by a relatively large percentage (tied for 4th) of the faculty. This suggests that some faculty may be placing too high of an expectation for teamwork among their research team members, and that the URE is not naturally leading to great team activities.

The second analysis can be done by comparing what faculty identified as benefits actually received by the students and what the students perceived themselves as benefits they received. This can give insight into potentially developing more beneficial UREs for students. As noted, the percentage of faculty who saw a particular benefit in the students was generally less than the students themselves saw. For some benefits, that is logical as an individual may often understand what they themselves are experiencing more than someone else. For example, a student is likely to be a much better judge than a mentor of whether or not they had experienced increased confidence in being a successful engineer. But for other benefits, this discrepancy may be a result of different expectations held by students and faculty as to what is needed to be shown before being given "credit" for receiving a benefit. For example, a student and a mentor may have different ideas of what constituted developing communication skills, and what a student might deem as noticeable improvement may not be adequate for a mentor to make the same determination of receiving the benefit. With these thoughts in mind, some observations on the comparisons can be made.

(1) Both relatively high percentages of students and faculty identified improved problem solving skills (#3) and improved relationships with faculty/students (#7) as received benefits, with these scoring at or nearest the highest percentages in both groups.

(2) Faculty tended to expect, but not see, improved critical thinking skills (#1) while students generally perceived gaining this benefit at a much higher rate; this may suggest that students and faculty have different ideas of what constitutes a critical thinking skill.

(3) Faculty perceived students learning how to work independently as a much lower rate than the students themselves identified, likely reflecting what each group would consider to be "independent" work. Faculty also saw significantly less success by the students in learning how to conduct a research project (#6), which may indicate that the students are not fully sharing their mentor's vision of what is involved in conducting research at a high level. This is mirrored by benefit #8, regarding a student's research skills, which a much larger percentage of students thought was a benefit received in comparison to the percentage of faculty who saw this benefit received.

(4) A much larger percentage of students also saw the URE as improving their communication skills in comparison to the faculty member's impressions. Again, this likely relates to what a student perceives as good communication skills versus what a faculty member considers to be good communication skills.

(5) There is a significant discrepancy on benefit #9 (increased confidence in being a successful engineer), with a much larger percentage of students identifying that as a received benefit than faculty identifying as a benefit that they saw achieved by the students. As mentioned above, in this case, the student's impression is probably more accurate than the faculty's impression, as it is difficult for someone else to gauge one's confidence.

The results of the surveys indicate that both students and faculty find benefits for students working in UREs. However, some faculty may not be recognizing or appreciating some of the benefits that the students are truly experiencing in their UREs. In turn, a better understanding of how the UREs positively impact the students may alter the design of the URE by the faculty, both to enhance these benefits and to modify the URE to increase attainment of the benefit. For example, if faculty members are engaging average engineering students in UREs to entice them to attend graduate school, they may be disappointed by the results. Results of this nature have been noted elsewhere.[22]   Another interesting contrast is in the teamwork skills versus independent work skills development. Students, at least as a larger percentage, see the UREs developing independent work skills at a higher rate than teamwork skills, but faculty see the opposite. This suggests that the faculty may be thinking that the students are working as part of a team much more so than is actually occurring in practice.

Faculty members were also provided the opportunity to participate in interviews on student participation in UREs. Five faculty members completed interviews, and these interviews had a similar format with similar questions to those performed with students.[8] These interviews provided some additional insights into the faculty members' perspectives on UREs. Some of these insights are listed below.

1) Multiple faculty members mentioned the need for students to adhere to safety protocols while working in the labs, and that UREs were an opportunity to educate students on such protocols.

2) Faculty expected that students would become more self-sufficient over the duration of their URE.

3) The faculty who were interviewed did not view UREs as just an opportunity for students to earn money, but rather as a means to gain valuable work-related experience.

4) Four of the five faculty interviewed viewed the URE as a way for students to improve their ability to find a job that they wanted upon graduation. In fact, these faculty were less concerned with students pursuing graduate education than with the students achieving their particular goal, which the faculty recognized was often getting a job in industry upon graduation. As such, most of the faculty interviewed wanted to tailor the URE to best help the students in getting a job in industry.

5) Faculty wanted the students to obtain applied engineering skills in their URE.

6) The faculty interviewed saw both soft skill development (confidence, responsibility, leadership) and applied engineering skill development by the students that they have overseen in UREs.

From the survey results and the interviews of the faculty, it can be seen that the preliminary definition of a successful URE developed from the student survey is generally in agreement with what faculty also perceive. One item that may be missing from the preliminary definition is development of self-sufficiency by the students, although this can be viewed as part of developing confidence for component (3) of the definition. What was also revealed in the faculty survey and interviews is that there may be some disconnect between what students believe they are gaining from their UREs and what faculty think that the students are gaining.

Results of Industrial Representative Survey

As representatives from industry were less likely to have directly interacted with students in a URE, a somewhat different approach was taken with regards to surveying industrial representatives on what were expected outcomes for students participating in a URE. This survey concentrated its questions on which general and which technical skills were expected of new engineering and computer science graduates, and which skills they have been seen lacking of graduates in the last 5 years. Then, if the representative was familiar with graduates who had participated in a URE while a student, they were asked what benefits of URE participation they had observed for those graduates.

The survey was taken by 34 industry representatives; these were engineers or supervisors who had directly worked with CEAS students or graduates in an industrial setting. Of these, only 5 were certain that they had hired graduates who had had an URE while a student; therefore the sample size for the noticed benefits of URE participation is very small.

Figure 3 presents the percentages of the 34 respondents who agreed that the general skill or attribute listed was expected of newly-hired recent engineering or computer science graduates. These results indicate that problem solving skills, critical thinking skills, and teamwork skills are the most expected attributes, with communication skills and the ability to work independently as also frequently expected skills. These agree well with benefits seen by students from participation in a URE. There is less success in UREs developing teamwork skills than perhaps desired by industry, which suggests that faculty need to concentrate on this development for these students when participating in a URE.

The industrial representatives were also asked if they expected recent graduates to have the ability to conduct research. Only 39% of the respondents indicated that this was an expected skill for new hires, which indicates that it is not necessary that a goal of participation in a URE for students seeking a job in industry be to develop the ability to conduct research. While it might be beneficial for some students interested in careers in industry as engineers, choosing this as a specific reason for encouraging participation of average students in a URE is not warranted.

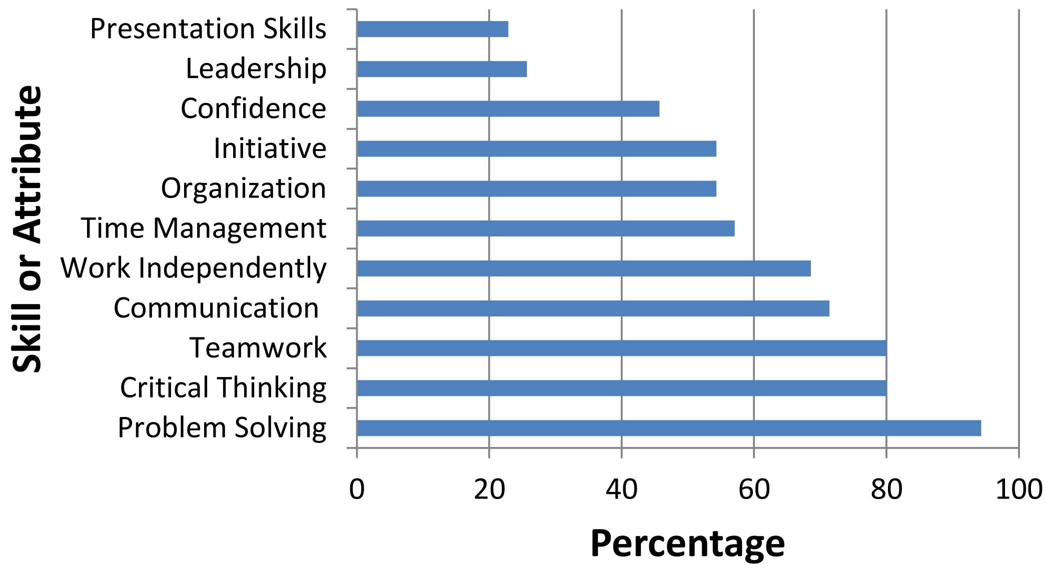

Figure 3: Percentages of industrial representatives who agreed that the listed general skill or attribute was expected of recent engineering and computer science graduates.

Figure 4 contains the percentages of industrial representatives who identified the skill or attribute listed in Figure 3 as lacking in recent engineering and computer science graduates. Of the skills identified by most as being expected, the skill that appears to be most lacking is written and oral communication skills. This is a benefit that a relatively low percentage of faculty saw as an expected benefit of URE participation by students, although half of the faculty did identify seeing it as a benefit received by students. Meanwhile, it was a benefit identified by more than 75% of the students surveyed. This suggests that there is an opportunity to make the UREs more beneficial to students if faculty mentors expect the students to make written and oral presentations, and work with the students to improve these communication skills. It can also be noted that the interviewed students who participated in either conferences or written publications viewed this as one of the most positive aspects of the experience.

As mentioned, only 5 of the respondents were certain that they had hired graduates who had participated in a URE, and as a result these results are not statistically significant. With this in mind, the noteworthy point from this survey is that 4 of the 5 respondents indicated that graduates who had participated in UREs were better prepared than graduates who had not participated in a URE in terms of problem solving and critical thinking skills.

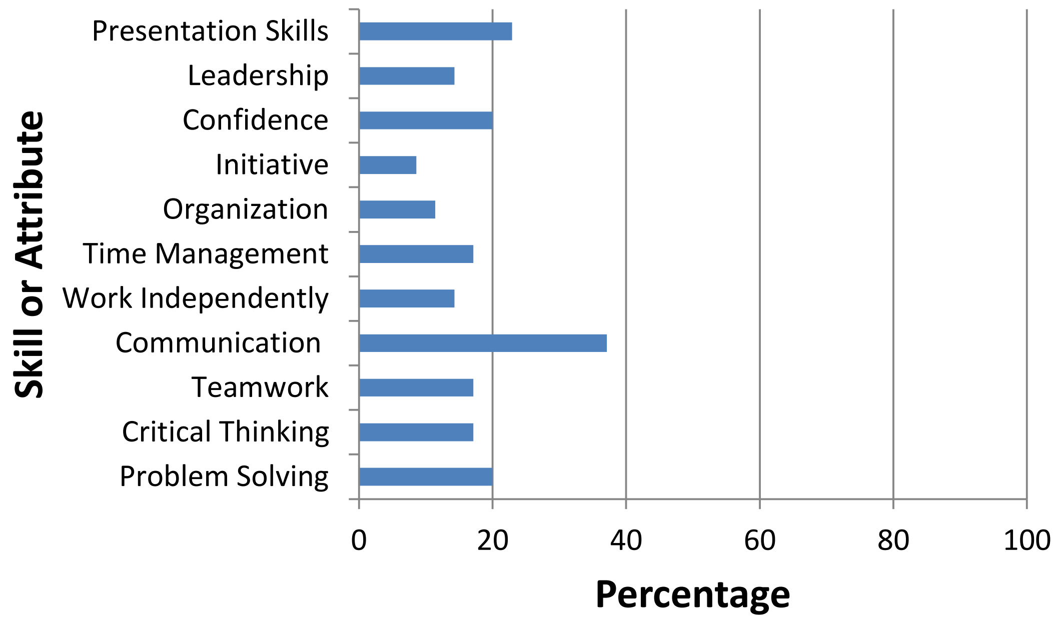

Figure 4: Percentages of industrial representatives who identified a particular skill or attribute as lacking in recent engineering and computer science graduates.

Revisions to the Definition of a Successful URE

The faculty survey and interviews, as well as the industry survey, mostly confirm the preliminary definition of a successful URE for average engineering and computer science students. As noted, the faculty input indicated that some consideration of the development of self-sufficiency is necessary in the definition. In addition, the greater importance placed by faculty and industry on teamwork indicates that that should be considered of greater importance than independent work. With these factors in mind, the definition of a successful URE for average engineering students is now proposed as follows.

The goals for a successful URE for average engineering students are

1) The URE should develop applied engineering, problem solving, and critical thinking skills of the students to help prepare them for a career as an engineer, likely in industry.

2) The URE should improve the communication skills of the student.

3) The URE should increase the confidence of the student in their abilities, their independence and self-sufficiency, and help clarify their career goals.

4) The URE should help the student learn to work as part of a team.

5) The URE should provide the students with an understanding of how to conduct a research project.

While the fifth goal was not seen as important by many representatives from industry, it is still important for students considering graduate school and can give some students an advantage when seeking some industrial jobs. Therefore, it was decided to keep it as a goal of a successful URE.

The faculty and industrial input indicates that many faculty need to reconsider how they are designing a URE for average engineering students. There does appear to be a need to consciously work on developing communication skills as part of a URE, and there also appears to be a need to be certain that students are gaining teamwork skills while they work on a URE. The fact that more students identified development of independent work skills than teamwork skills runs contrary to the order expected by faculty and industry, indicating that the UREs are not filling this need as often as desired.

Summary

In this paper, the results of a previous survey of undergraduate engineering and computer science students who participated in undergraduate research experiences in CEAS were supplemented with the results of a faculty survey and interviews on student UREs as well as an industrial survey on their expectations of graduates. With this additional information, some modification of the defined goals of a successful URE for average engineering students were made, but on the whole the new information confirmed the preliminary definitions developed from student input. In addition, some areas that may need more focus when faculty are developing and overseeing UREs were identified.

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