Benchmarking the Integration of Complex Systems Study in American and Australian Mechanical Engineering Programs

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I. Introduction

A. Background

As engineers are increasingly required to solve problems involving complex physical, biological, and social systems, engineering education needs to respond to meet these emerging needs. As educators, we must become aware of the changing needs of undergraduate mechanical engineering students to master an ever-increasing amount of content knowledge and to develop an ability to think critically and holistically across complex systems. This awareness of the shortcomings of engineering education is the first step to implementing a change.

As powerfully stated by William Wulf, president of National Academy of Engineers, "Many of the students who make it to graduation enter the workforce ill-equipped for the complex interactions, across many disciplines, of real-world engineered systems."[11] Wulf suggests that engineers are increasingly required to solve problems involving complex physical, biological and social systems. Recently, NAE has responded to this awareness by establishing the Engineer of 2020 Project.[9] This project addresses the growing need to pursue collaborations with multidisciplinary teams of experts, because of the increasing complexity and scale of systems-based engineering problems. According to the latest publication these teams must have the following attributes: "excellence in communication (with technical and public audiences), an ability to communicate using technology, and an understanding of the complexities associated with a global market and social context" [6]. These attributes are in alignment with the attributes of a complex systems thinker.

The leaders from many prominent professional engineering societies have also addressed the need for engineers to solve problems involving complex physical, biological, and social systems.[1][2][3][4][5][7] In response to this need, the American Institute of Chemical Engineers, the American Society of Civil Engineers, ASME, and the Institute of Electrical and Electronic Engineers are collaborating to offer "Excellence in Engineering Education" teaching workshops for engineering and engineering technology faculty.[4] The American Society of Mechanical Engineers (ASME) have responded to this need by promoting a "shared vision of the future of mechanical engineering education in the context of new and rapidly emerging technologies and disciplines, national and global trends, societal challenges for the 21st century, and associated opportunities for the profession" [1]. As an awareness of the current state of engineering education and of the changing needs of undergraduate mechanical engineering students matures, change can begin to be implemented.

A closer look at the engineering education programs in America and Australia will provide two distinct perspectives. Engineering education in America has been heavily influenced by the cold war. This strong defense-related influence has encouraged a mechanistic, simple systems approach in the way that engineers are educated. Australia has a different history; their engineering educational program has been driven by social and environmental systems, which are inherently much more complex.

Before change can be implemented, a reexamination of the content of current undergraduate mechanical engineering programs is necessary. The authors are examining how current engineering educational programs in the United States (US) and Australia equip engineering students to practice at the intersection of complex systems.

B. Complex Systems Discussion

Complex systems study refers to the study of a holistic system and how it interacts with other systems. In the realm of engineering, complex systems study requires that the engineer not only consider the technical aspects of a system, but also the social, environmental, economical, and global aspects as well (See Figure 1). Industry and the broader society are responding to this concern, but engineering education is lagging behind. As this concern is brought to the engineering education community's attention, possible solutions to this complex problem can result.

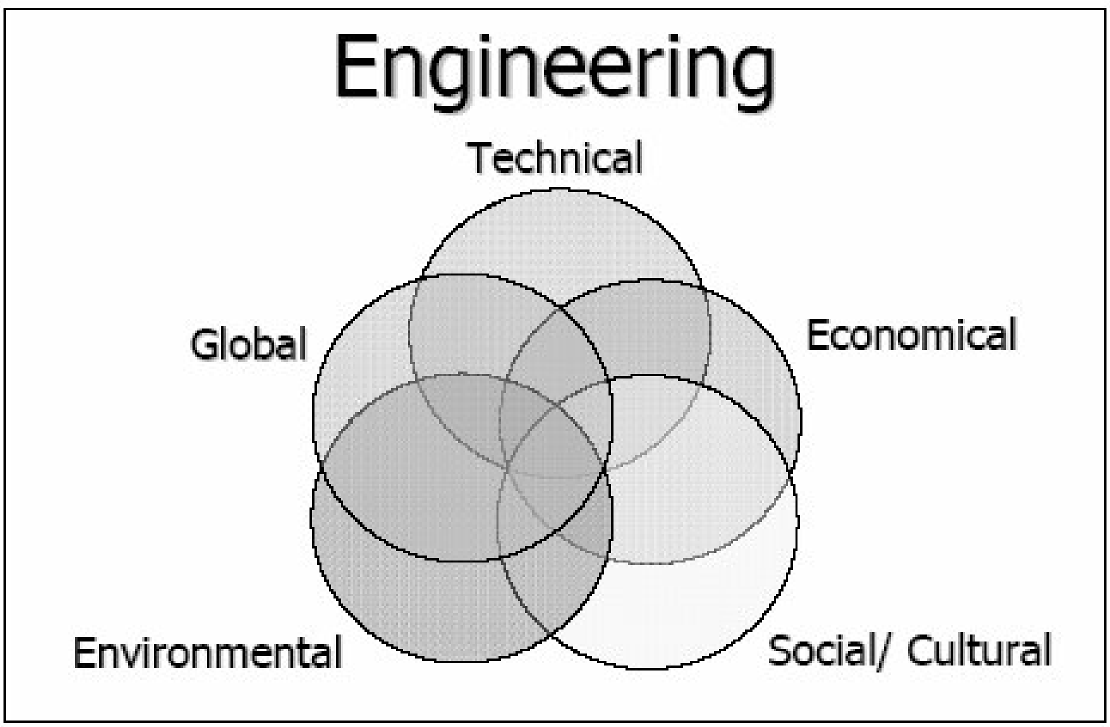

Figure 1: Complex Systems Illustration

II. Research Questions

This study seeks to find answers to the following questions:

1. What is the state of complex systems in Australian and American mechanical engineering educational programs?

2. How does the state of Australian and American mechanical engineering educational programs compare?

3. Are there any programs that embrace this concept of complex systems?

III. Research Design

Online surveys were designed to provide answers to the above research questions. These surveys were developed and administered to undergraduate students. To administer the online survey, the research team emailed a letter to the chairs with a link to the online survey. The chairs were instructed to forward the survey to undergraduate students.

A. Sample

Included in the Australian study sample were all colleges and universities that are "Group of Eight" Universities (or Research I Universities).

Included in the American study sample were colleges and universities that a) are Research I Universities, b) offer a bachelor's degree in mechanical engineering, and c) were one of the seven randomly selected universities or the University of South Carolina.

B. Methodology

The online survey was developed using CTL Silhouette featuring the FlashlightTM Current Student Inventory Version 2.9. The survey questions were developed cooperatively by the research team (See Appendix). The survey utilized check boxes, a 6-point likert scale (options ranging from "Never" to "Completely or "Strongly Disagree" to "Strongly Agree"), open answer formats, and radio buttons.

Special precautions were taken in order to ensure the validity of the survey. One author, Wally Peters, is an expert in the area of complex systems, while Michelle Maher is an expert in education. These authors helped develop and approve the content of the survey. Dr. Robert Johnson is a survey expert who reviewed the survey and made changes to the structure of the survey. Americans developed this survey. Due to cultural and linguistic differences, the responses to some of the questions may have misleading results.

C. Study Variables and Analysis

1. Research Question 1: What is the state of complex systems in Australian and American mechanical engineering educational programs?
The student survey response data was analyzed to determine the state of complex systems according to undergraduate students in American and Australian mechanical engineering programs. The survey data was displayed graphically so that subtleties between the data sets could be seen. The normalized average of the checklist style questions was taken for each response and displayed graphically with a bar chart. The mode of the likert scale responses was calculated and displayed graphically with a bar chart for each question. The open-answer responses were put into categories according to whether the students agreed or disagreed, and according to how well they appear to understand the concept of complex systems by their responses.

2. Research Question 2: How does the state of Australian and American mechanical engineering educational programs compare?
To compare Australian and American mechanical engineering educational programs, the student survey results were compared. The checklist style questions were considered to be significantly different if the unpaired T-test results were less than 0.1 (90% confidence interval). The likert scale responses were considered to be significantly different if there was a difference of at least 2 points in the modes of the Australian and American student responses. For the open-answer responses, a confidence interval of 90% was used to determine whether the two data sets were significantly different.

3. Research Question 3: In what ways do programs embrace this concept of complex systems?
To determine the programs that embrace this concept of complex systems, the open-answer questions were analyzed. The respondents that showed that they had an understanding of complex systems from the first two open-answer questions were used as the sample for this research question. From this sample, the answers to the third question, *"Describe any projects, courses, or extracurricular activities in which you have participated that use this concept of complex systems,"* were categorized as projects, courses, extracurricular activities, work, research, or none. These results were graphed. They were normalized according to the number of students in the sample.

IV. Results

A. Research Question 1: What is the state of complex systems in Australian and American mechanical engineering educational programs?

The state of complex systems in Australian and American mechanical engineering educational programs is described by the undergraduate student survey response data.

The results of the question "At this point in my college education, I have received a basic foundation in the following areas (check all that apply): English, Humanities and Social Sciences, Life Sciences, Math, and/or Physical Sciences" are presented in Figure 2. The bar that denotes the combined results of American and Australian students shows that the students have a basic foundation in the typical areas of emphasis in an engineering curriculum: Math and Physical Sciences. Around 45% of the students indicated that they have received a basic foundation in English, and humanities and social sciences. Only 38.7% of students indicated that they have a received a basic foundation in Life Sciences. Concepts of complex systems are the groundwork of life sciences. This low percentage of students that indicate that the basics of life sciences are covered in their engineering coursework is an indicator that complex systems may not be prevalent in engineering educational programs.

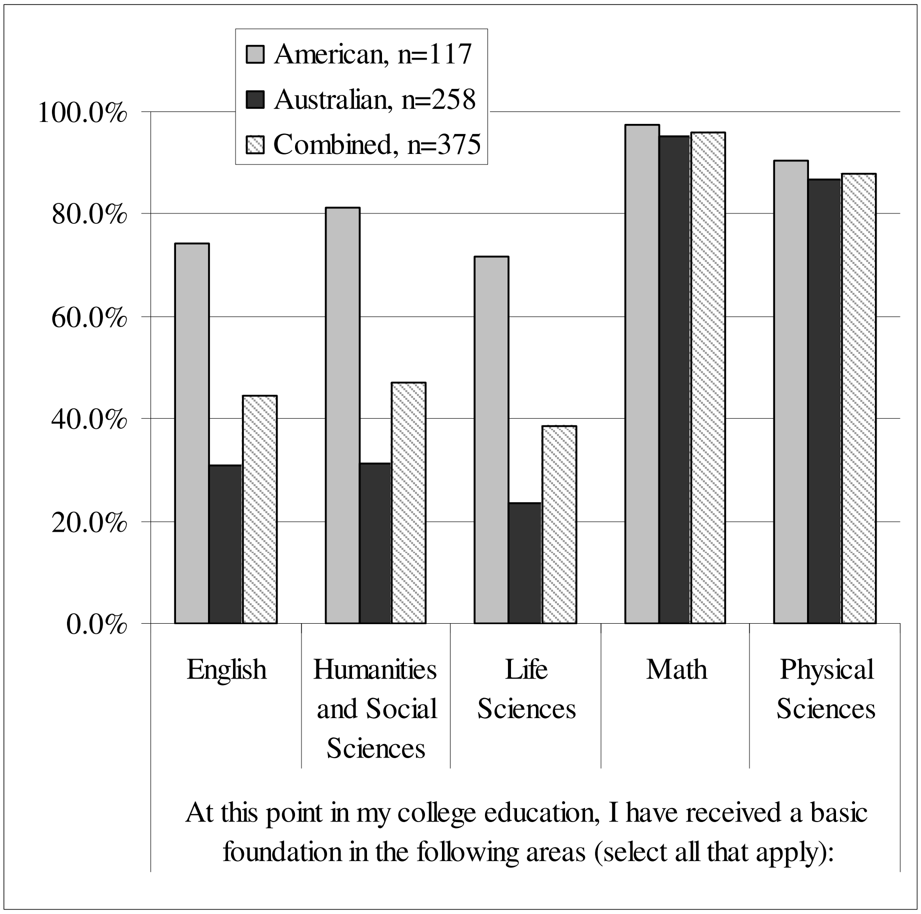

Figure 2: Normalized average of the responses to the question, *"At this point in my college education, I have received a basic foundation in the following areas (select all that apply):…"* in the student survey

Overall, the responses to the question, "How frequently have the following areas been addressed in your courses," indicate that technological areas that embrace complex systems study are not being stressed in undergraduate engineering courses (See Figure 3). The bar that denotes the combined results of this question indicates that only one area, information technology," is addressed "often." Four areas, "transportation systems, alternate energy systems, advanced/ intelligent materials, and advanced manufacturing," are addressed "sometimes." The remaining five areas, "nanotechnology, micromechanical systems, critical infrastructure, bioengineering, and bioelectrics," are never addressed in undergraduate engineering courses.

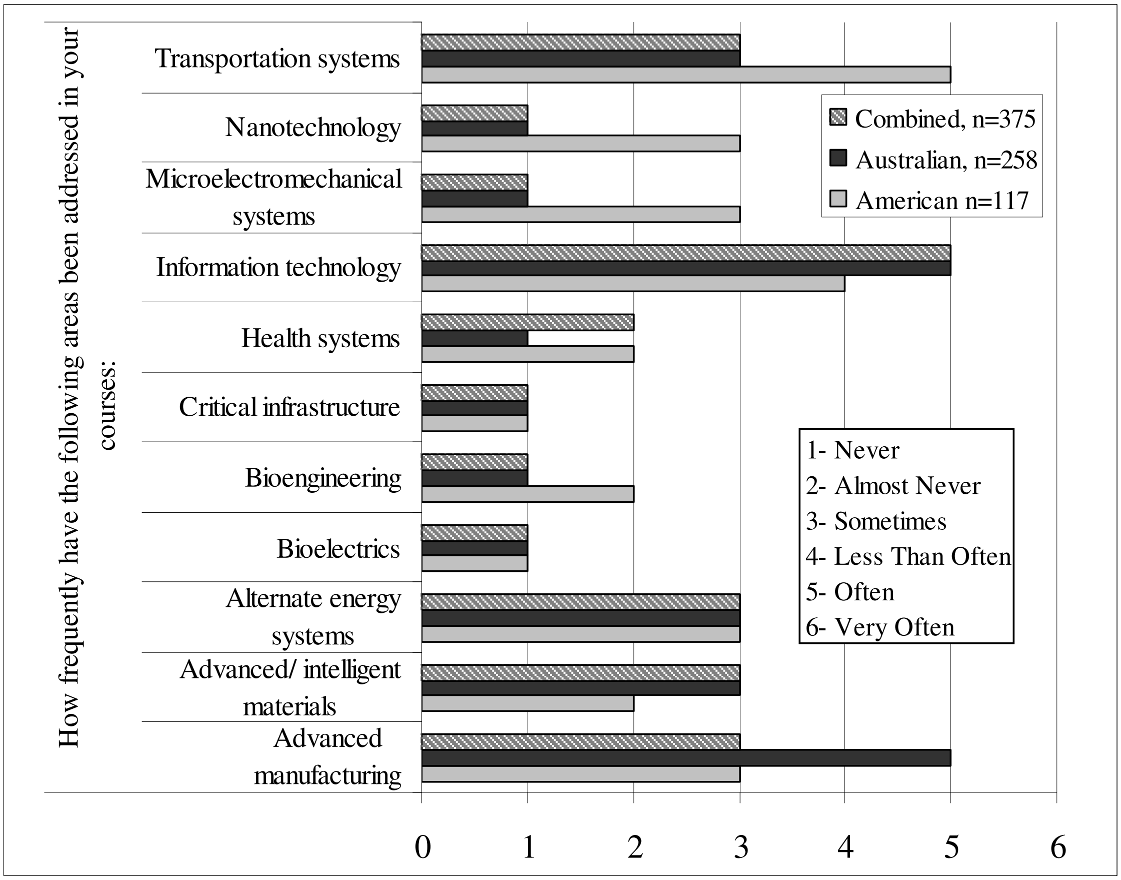

Figure 3: Mode of the responses to the question, *"How frequently have the following areas been addressed in your courses,"* in the student survey

The responses to the question, "How often has your program addressed the interrelationship of engineering with…," indicates that some aspects of complex systems are being addressed in engineering educational programs (See Figure 4). The students indicated that their program has addressed the interrelationship of engineering with ethics, earth systems/ environment, and economy "often." The interrelationship of culture and aesthetics are addressed "sometimes," while social norms, politics, and law are "almost never" addressed. These findings are important, because they show that the current state of engineering educational programs is embracing some concepts of complex systems. Engineering educational programs are not only stressing the technical aspects of a system, but also the ethical, environmental, and economical aspects of an engineered system as well.

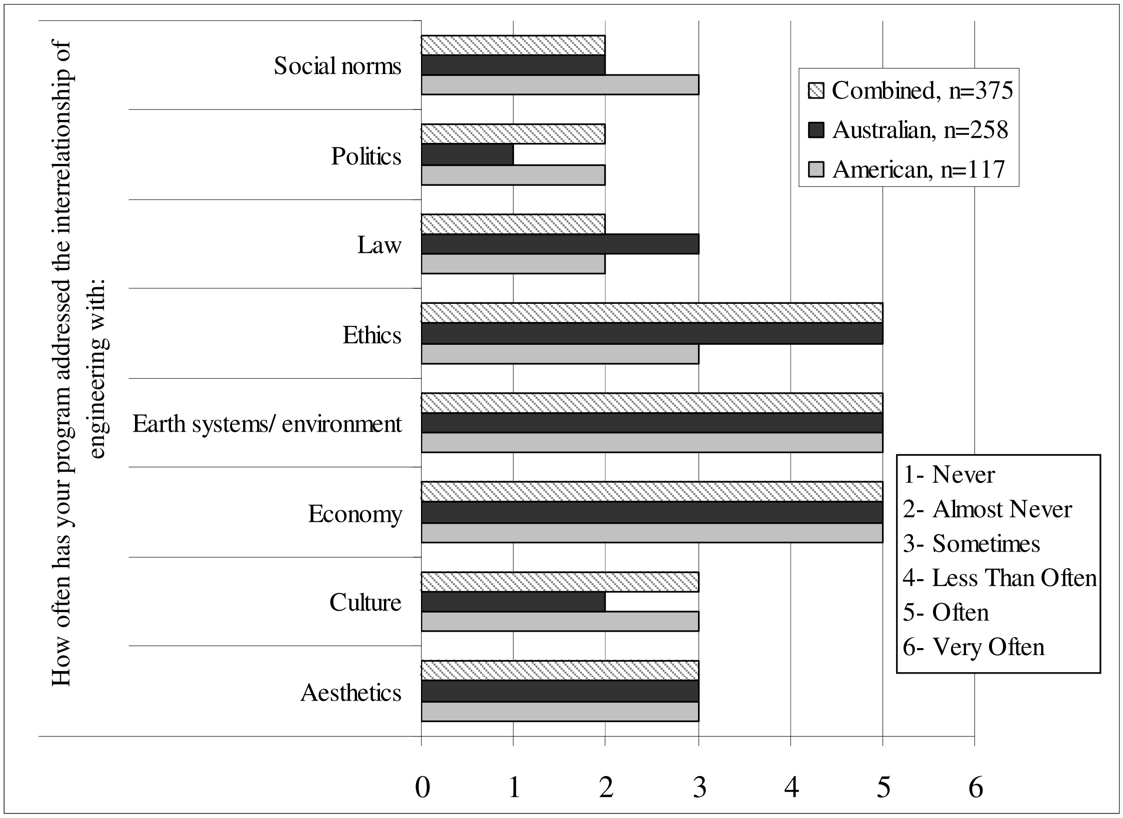

Figure 4: Mode of the responses to the question, *"How often has your program addressed the interrelationship of engineering with…,"* in the student survey

The responses to the question, "My engineering educational experience to date has equipped me to do the following…" indicates that there is an emphasis in complex systems skills in engineering educational programs (See Figure 5). The combined results indicate that the most common response (the mode) was "agree" to each of the characteristics (work in multi-disciplinary teams, work in multi-cultural teams, tolerate uncertainty, think critically, solve complex and open-ended problems, engage in life-long learning, communicate effectively, apply what I have learned to "real world" situations, and analyze and synthesize complex systems. This is significant, because it shows that undergraduate engineering students are acquiring the skills to become complex systems thinkers.

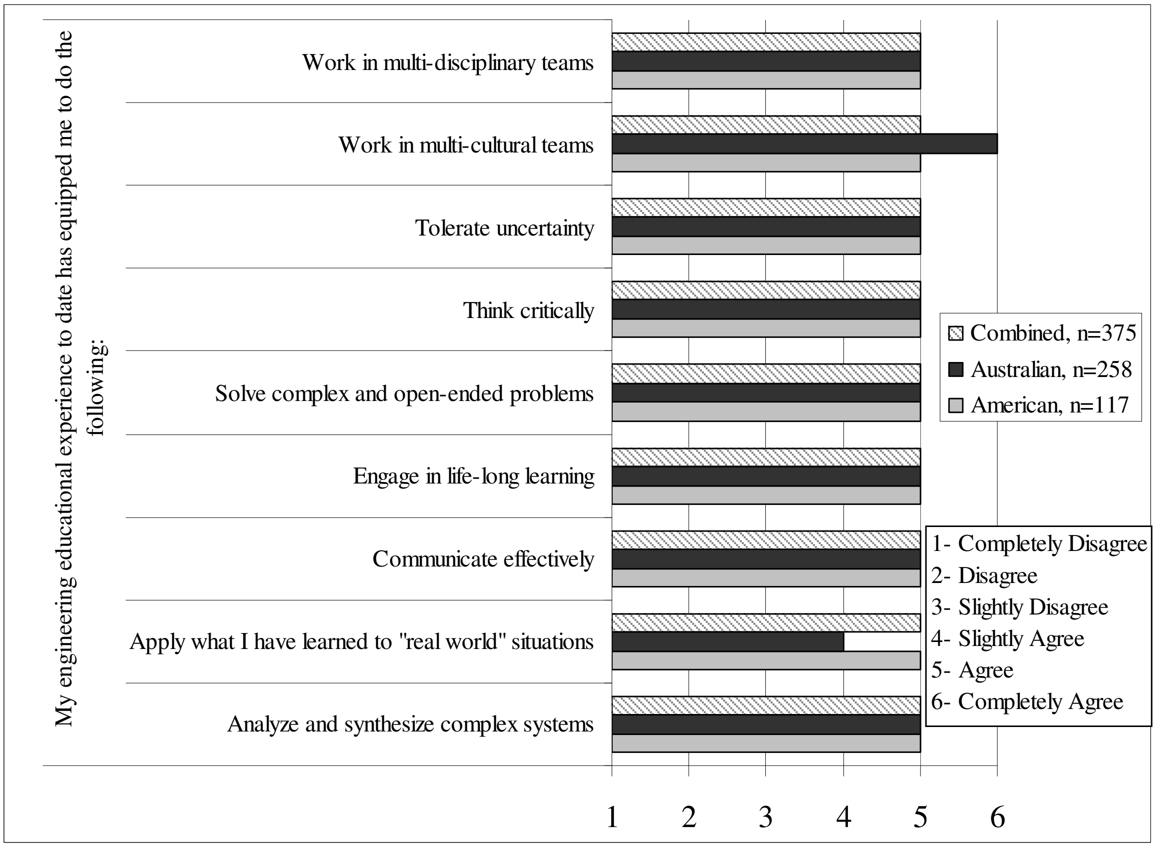

Figure 5: Mode of the responses to the question, *"My engineering educational experience to date has equipped me to do the following…"* in the student survey

The responses to the question, "The engineering educational experience should equip engineers to do the following…" indicate that undergraduate engineering students believe that integrating complex systems study into their educational development is important (See Figure 6). The students' most common response to each of these questions was "completely agree." This is significant, because it shows that undergraduate engineering students believe that it is important to integrate complex systems skills into their educational experience.

It is interesting that almost completely across the board, the engineering students indicated that they *agreed* with the question of whether their educational experience to date has *equipped* me to do the following, and they indicated that they *completely agreed* with the question of whether their educational experience *should* equip engineers to do the following. This subtle difference in the responses to this question may indicate that there is some discrepancy between what is present in their educational experience and what should be present.

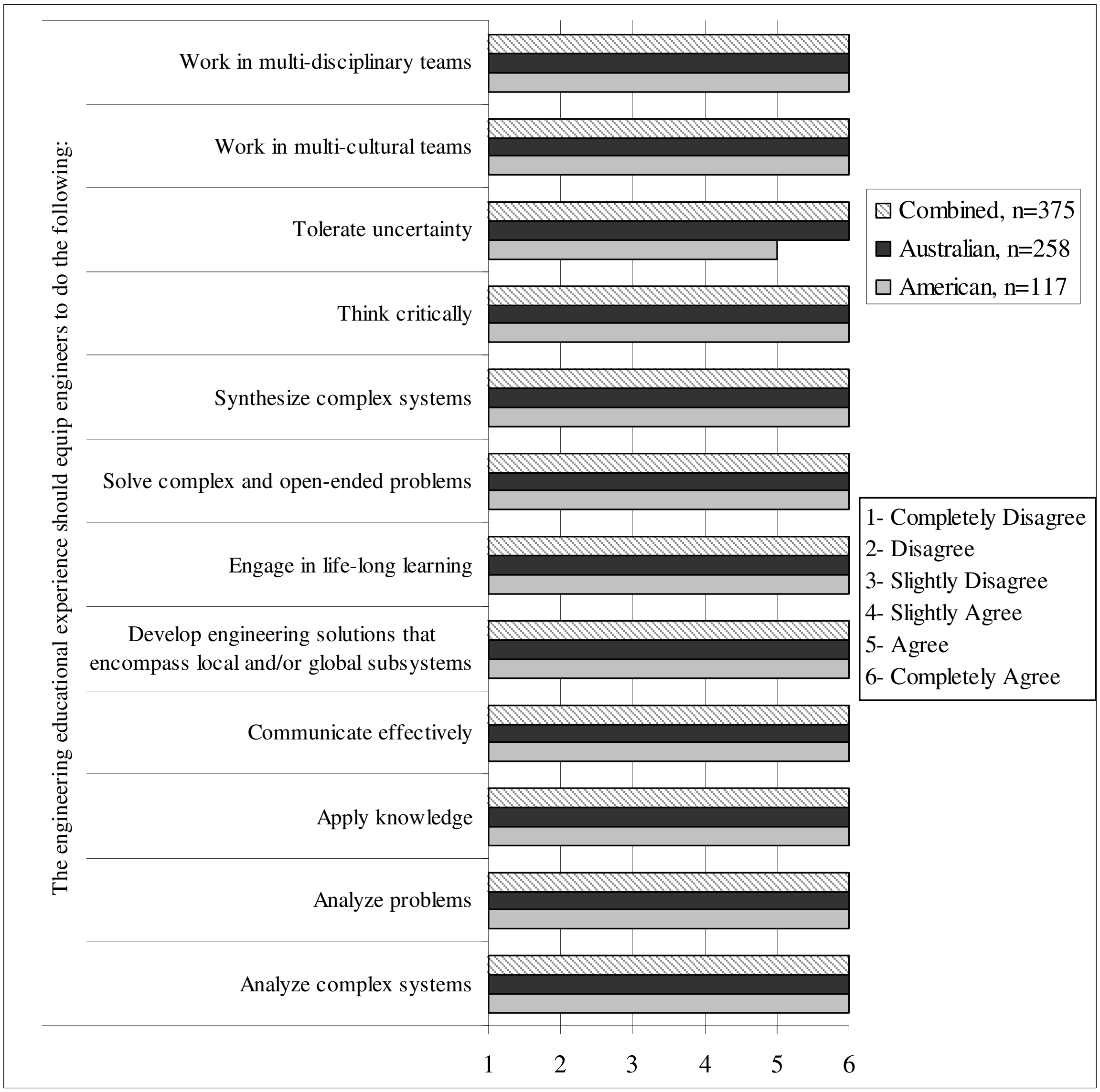

Figure 6: Mode of the responses to the question, *"The engineering educational experience should equip engineers to do the following…"* in the student survey

The questions with an open-answer format gave the authors a clearer picture of the students' understanding of complex systems, and a clearer view of their opinions involving the integration of complex systems into their educational experience.

The first open-answer question, "Describe how your engineering educational experience has helped you deal with the concept of complex systems" elicited responses that either agreed or disagreed that their engineering educational experience has helped them deal with the concept of complex systems, and elicited responses that showed an understanding or misunderstanding the concepts of complex systems (See Figure 7). Many of the students agreed that their engineering educational experienced has helped them deal with the concept of complex systems (66%), but a large percentage (39%) of these students had a misunderstanding of what encompasses complex systems. An overwhelming majority of the students that misunderstood complex systems believed that complex systems were complicated problems that can be broken down into smaller parts to be analyzed and then can be put back together (the sum of the parts equals the whole). In complex systems, the sum of the parts is greater than the whole. Only a small percentage of students disagreed that their engineering educational experience has helped them deal with the concepts of complex systems.

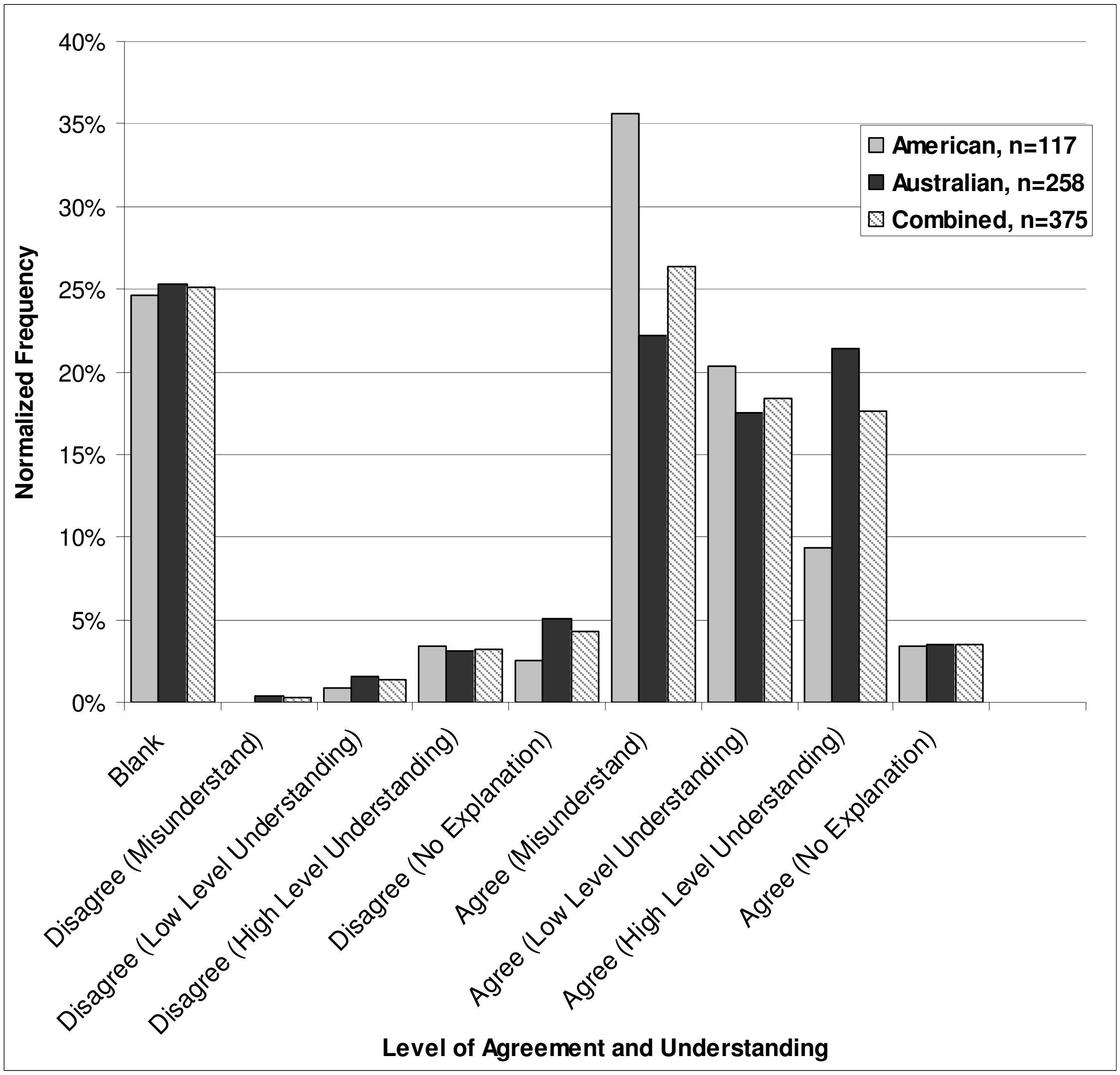

Figure 7: Survey respondents' level of agreement and understanding to the question, "*Describe how your engineering educational experience has helped you deal with the concept of complex systems*."

The responses to this question were grouped according the responses that a) understood complex systems, b) misunderstood complex systems, c) had no explanation, and d) were blank (See Figure 8). The results show that 40.5% of the respondents understood the concept of complex systems. This shows us that at some point in these students development, they are being exposed to the idea of complex systems. Assuming that all of the respondents that gave no explanation and left their response blank misunderstand the concepts of complex systems, then the remaining 59.5% of the students do not understand the concept of complex systems.

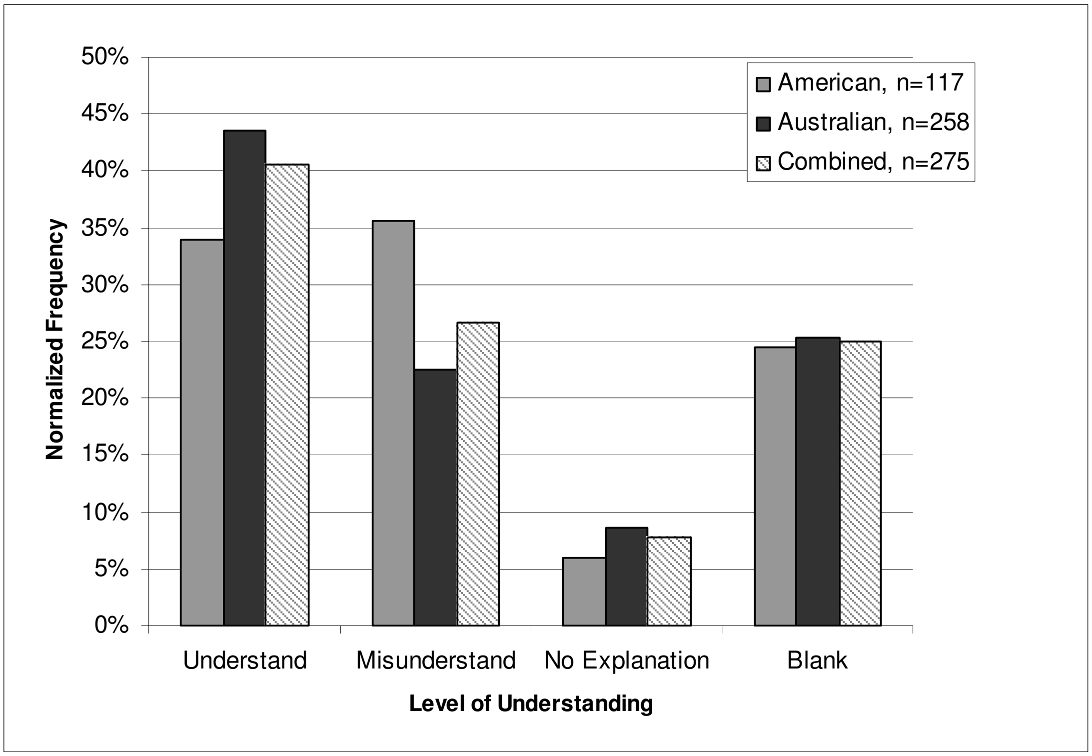

Figure 8: Survey respondents' level of understanding to the question, "*Describe how your engineering educational experience has helped you deal with the concept of complex systems*."

The next open-answer question, "Is it important to integrate complex systems into the engineering educational experience? Tell us why or why not" elicited yes and no responses, and explanations for each of these responses. The explanations were analyzed to determine how well the respondents understood the concept of complex systems. The results show that 98.1% of the respondents that understand the concept of complex systems believed that it was important to integrate complex systems into the engineering educational experience.

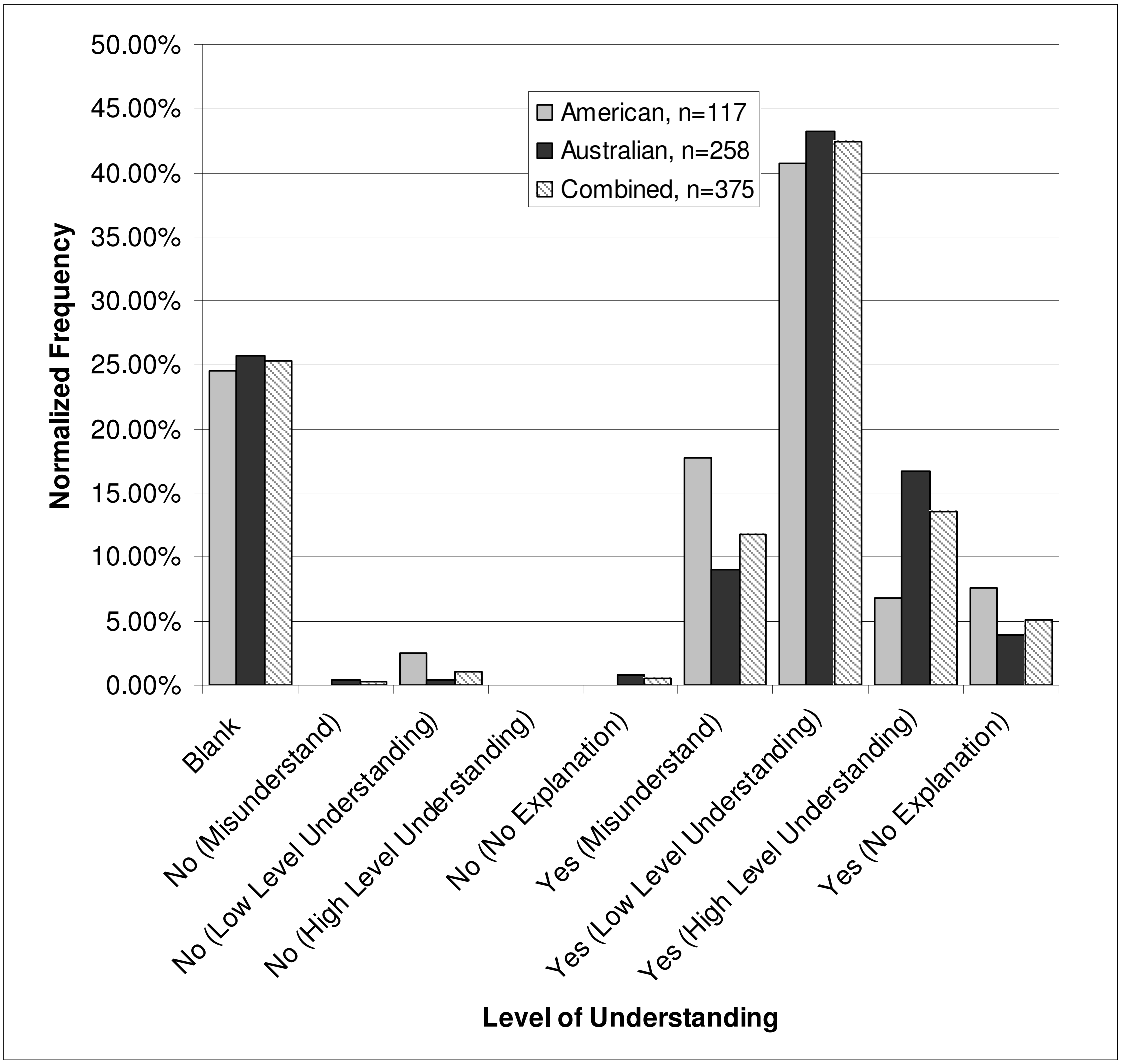

Figure 9: Survey respondents' level of agreement and understanding to the question, "*Is it important to integrate complex systems into the engineering educational experience? Tell us why or why not.*"

The responses to this question were also grouped according to the responses that a) understood complex systems, b) misunderstood complex systems, c) had no explanation, and d) were blank (See Figure 10). The results show that 57.1% of the respondents understood the concept of complex systems. This shows us that at some point in these students development, they are being exposed to the idea of complex systems. If all of the respondents that gave no explanation and left their response blank, then the remaining 42.9% of the students do not understand the concept of complex systems. More students appeared to understand the concept of complex systems on this question (an increase of 16.6% from the previous question).

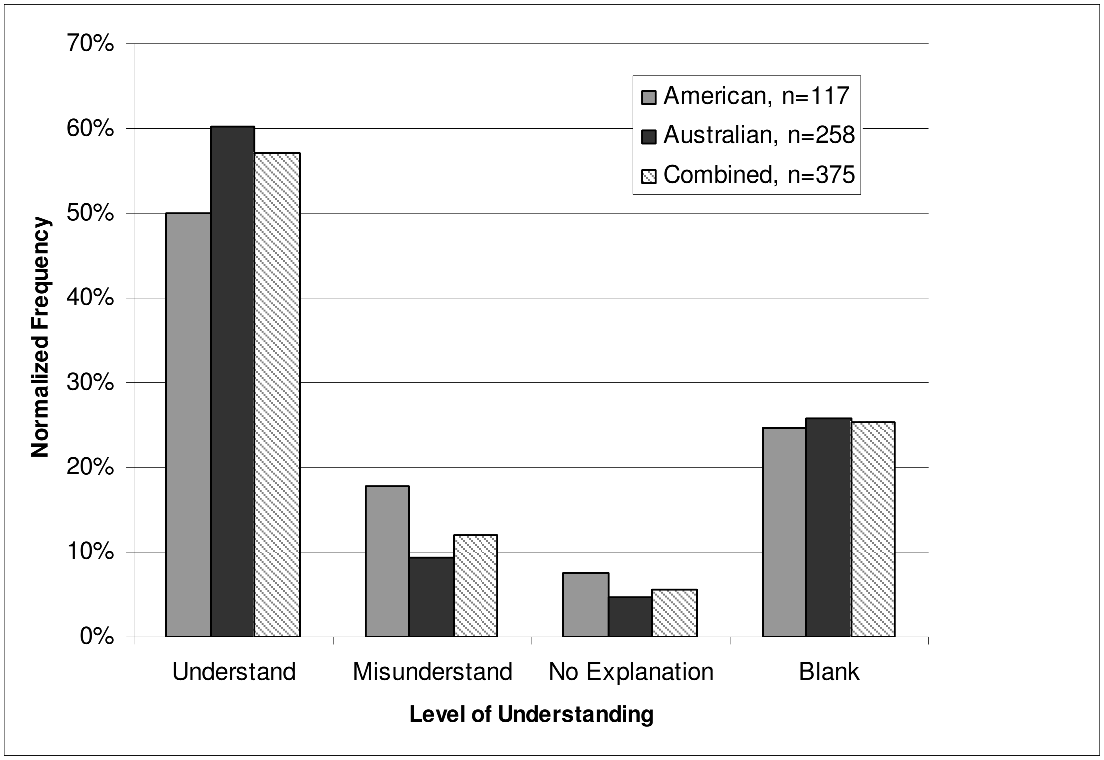

Figure 10: Survey respondents' level of understanding to the question, "*Is it important to integrate complex systems into the engineering educational experience? Tell us why or why not*."

The results from the first two open-answer questions may be misleading due to the way that the author determined whether the student understood complex systems. Many of the students mentioned "real-world" in their discussion, which elicited a category of yes, low level of understanding. This could mean that they understand complex systems, or that they think that complicated systems are in the real world.

Complex systems are present to some degree in American and Australian engineering educational programs. Many of the students believe that it is important to integrate complex systems into the engineering educational development. Next we will look at the differences between the state of American and Australian engineering educational programs.

B. Research Question 2: How does the state of Australian and American mechanical engineering educational programs compare?

The results of the question "At this point in my college education, I have received a basic foundation in the following areas (check all that apply): English, Humanities and Social Sciences, Life Sciences, Math, and/or Physical Sciences" are compared using a two-tailed paired t-test. The samples were assumed to have equal variances. The results of this test indicate that the American and Australian results of this question are statistically different for the responses English, humanities and social sciences, and life sciences (the t-test results were less than 0.1 for these areas, a 90% confidence interval) (See Table 1). The American undergraduate students indicated that they received a fundamental grounding in these areas much more than the Australian undergraduate students. The normalized average responses can be seen visually in Figure 2. These results are in line with the curriculum differences in

America and Australia. In America, the undergraduate engineering degree consists of a basic liberal arts education, which includes English, and humanities and social sciences. In Australia the curriculum consists of a larger variety of engineering courses that occur over their 4 year educational experience. Life sciences are becoming more and more important in many emerging areas of engineering, such as bioengineering and nanotechnology. Concepts of complex systems are the groundwork of life sciences. This high percentage of American students that indicate that the basics of life sciences are covered in their engineering coursework is an indicator that complex systems may be prevalent in American engineering educational programs.

Table 1: T-test results of the question *"At this point in my college education, I have received a basic foundation in the following areas (select all that apply): English, Humanities and Social Sciences, Life Sciences, Math, and/or Physical Sciences."*

	Normalized Average		
	America	**Australia**	**T-test Results**
English	74.4%	31.01%	8.18E-11
Humanities and Social Sciences	81.2%	31.40%	1.62E-21
Life Sciences	71.8%	23.64%	3.69E-21
Math	97.4%	95.35%	0.58
Physical Sciences	90.6%	86.82%	0.29

The likert scale responses were considered to be significantly different if there was a difference of at least 2 points in the modes of the Australian and American student responses.

The differences of the American and Australian undergraduate student responses to the question, "How frequently have the following areas been addressed in your courses," indicate that the areas of transportation systems, nanotechnology, and microelectromechanical systems are addressed more often in American students' courses, while advanced manufacturing is addressed more often in Australian students' courses (See Figure 3). This difference may be due to more of a focus on technology in American engineering universities. This could mean that more complex systems are present in American engineering classrooms because many of the technologies encompass complex systems. Or it could mean that there is more of a focus purely on technology and not on complex systems. It could also be due to cultural and linguistic differences. These results may be misleading because Americans developed the survey. The implications of this question needs to be explored more with open answered survey questions, one-on-one interviews, or focus groups.

The differences of the American and Australian undergraduate student responses to the question, "How often has your program addressed the interrelationship of engineering with…," indicates that the interrelationship of ethics with engineering is addressed more in Australian engineering educational programs (See Figure 4). The American students responded "sometimes" to this question, while the Australian students responded "often." Professional society codes usually address a micro-ethic, an ethic that applies to the behaviors of an individual engineer. However, ethics is an area that can embrace this concept of complex systems when viewed from a macro-level.[10] Wulf points out that macro-ethical concerns are very different from the traditional micro-ethical concerns and the reason lies in the complexity and the inherent uncertainty of problems with which engineers are currently dealing.[10] Depending on whether a micro-ethic or macro-ethic is being presented in engineering educational programs, the results to this question could imply that Australian engineering students are being more exposed to complex systems through ethics, or they could simply be more exposed to a simple systems view of ethics—a micro-ethic. The implications of this question need to be explored further by additional research.

The responses to the question, "My engineering educational experience to date has equipped me to do the following…" and "The engineering educational experience should equip engineers to do the following…" are not significantly different for American and Australian engineering students (See Figure 5 and Figure 6).

For the open-answer responses, a confidence interval of 90% was used to determine whether the two data sets were significantly different.

The first open-answer question, "Describe how your engineering educational experience has helped you deal with the concept of complex systems" elicited responses that either agreed or disagreed that their engineering educational experience has helped them deal with the concept of complex systems, and elicited responses that showed an understanding or misunderstanding of the concepts of complex systems (See Figure 7). When a contingency table was developed, the chi-squared test could not be performed because more than 20% of the values were less than 5. By comparing the normalized frequency of American and Australian engineering student responses, two groups stand out as being different. The percentage of students that indicated that they agreed that their engineering educational experience has helped them deal with complex systems, but had a misunderstanding of the concepts of complex systems was much higher (by 13.4%) for American students than for Australian students. The percentage of students that indicated that they agreed that their engineering educational experience has helped them deal with complex systems, and had a high level of understanding of the concepts of complex systems was much higher (by 12.1%) for Australian students than for American students. This indicates that the Australian students have a better understanding of the concepts of complex systems. When the responses were grouped according to the level of understanding only, a chi-squared test was appropriate (See Table 2). The results of this test indicate that at the 90% confidence interval level, there is a statistically significant difference between American and Australian responses. These results concur with the above results. The Australian students understand the concepts of complex systems more than American students (9.7% higher understanding) (See Figure 8). The American students misunderstand the concepts of complex systems more than Australian students (13% more misunderstanding).

Table 2: Chi-squared goodness-of-fit test results

CHI-SQUARED GOODNESS-OF-FIT TEST				
	First Open Answer Question		Second Open Answer Question	
Null hypothesis, H0	Distribution fits the data		Distribution fits the data	
Alternate hypothesis, HA	Distribution does not fit the data		Distribution does not fit the data	
Distribution	Normal		Normal	
SAMPLE:				
Number of observations	375		375	
Number of cells with values less than 5	14		14	
Number of parameters used	0		0	
Test:				
Chi-squared test statistic	7.754		7.630	
Degrees of freedom	3		3	
Chi-squared CDF value	0.051		0.054	
Alpha Level	Cutoff	Conclusion	Cutoff	Conclusion
10%	6.251	Accept H0	6.251	Accept H0
5%	7.815	Reject H0	7.815	Reject H0
1%	11.341	Reject H0	11.341	Reject H0

The second open-answer question, "Is it important to integrate complex systems into the engineering educational experience? Tell us why or why not" elicited yes and no responses, and explanations. The explanations were analyzed to determine how well the respondents understood the concept of complex systems (See Figure 9). When a contingency table was developed, the chi-squared test could not be performed because more than 20% of the values were less than 5. By comparing the normalized frequency of American and Australian engineering student responses, two groups stand out as being different. The percentage of students that indicated that they agreed that it is important to integrate complex systems into the engineering educational experience, but had a misunderstanding of the concepts of complex systems was much higher (by 8.9%) for American students than for Australian students. The percentage of students that indicated that they agreed that it is important to integrate complex systems into the engineering educational experience, and had a high level of understanding of the concepts of complex systems was much higher (by 10%) for Australian students than for American students. This indicates that the Australian students have a better understanding of the concepts of complex systems. When the responses were grouped according to the level of understanding only, a chi-squared test was appropriate (See Table 2). The results of this test indicate that at the 90% confidence interval level, there is a statistically significant difference between American and Australian responses. These results concur with the above results. The Australian students understand the concepts of complex systems more than American students (10.3% higher understanding) (See Figure 10). The American students misunderstand the concepts of complex systems more than Australian students (8.5% more misunderstanding).

C. Research Question 3: In what ways do programs embrace this concept of complex systems?

The respondents that showed that they had an understanding of complex systems from the first two open-answer questions, were used as the sample for this research question. Of the American respondents, 23.7% showed that they had an understanding of complex systems from the first two open-answer questions (n=28). Of the Australian respondents, 25.3% showed that they had an understanding of complex systems (n=95). From this sample, the answers to the third open-answer question were categorized as projects, courses, extracurricular activities, work, research, or none. These results were graphed after being normalized according to the number of students in the sample (See Figure 11).

When the results were combined, the courses (39.0%) and the projects (37.4%) were the most frequently mentioned in the response to the question, "Describe any projects, courses, or extracurricular activities in which you have participated that use this concept of complex systems." The third most common response is "none," (21.1%).

When the American and Australian results are compared, Australian students list projects much more often than American students (a 39.2% difference). The American students list courses much more often than Australian students (a 23.5% difference). These differences in results may be indicative of more projects being conducted in Australian engineering educational programs. Or, the projects that are present in Australian engineering programs could embrace this concept of complex systems more than for the projects in American engineering programs. It should be noted that some of the lines between courses and projects are unclear. For instance, if a student listed a "Senior Design Course," it would be considered a course, however if a student listed a "Senior Design Project," it would be categorized as a project.

Another difference between the American and Australian students is the larger percentage of American students listing work as a place that this concept of complex systems was embraced (an 8.9% difference). This could be due to more students working while attending American universities, or returning to school after work experience.

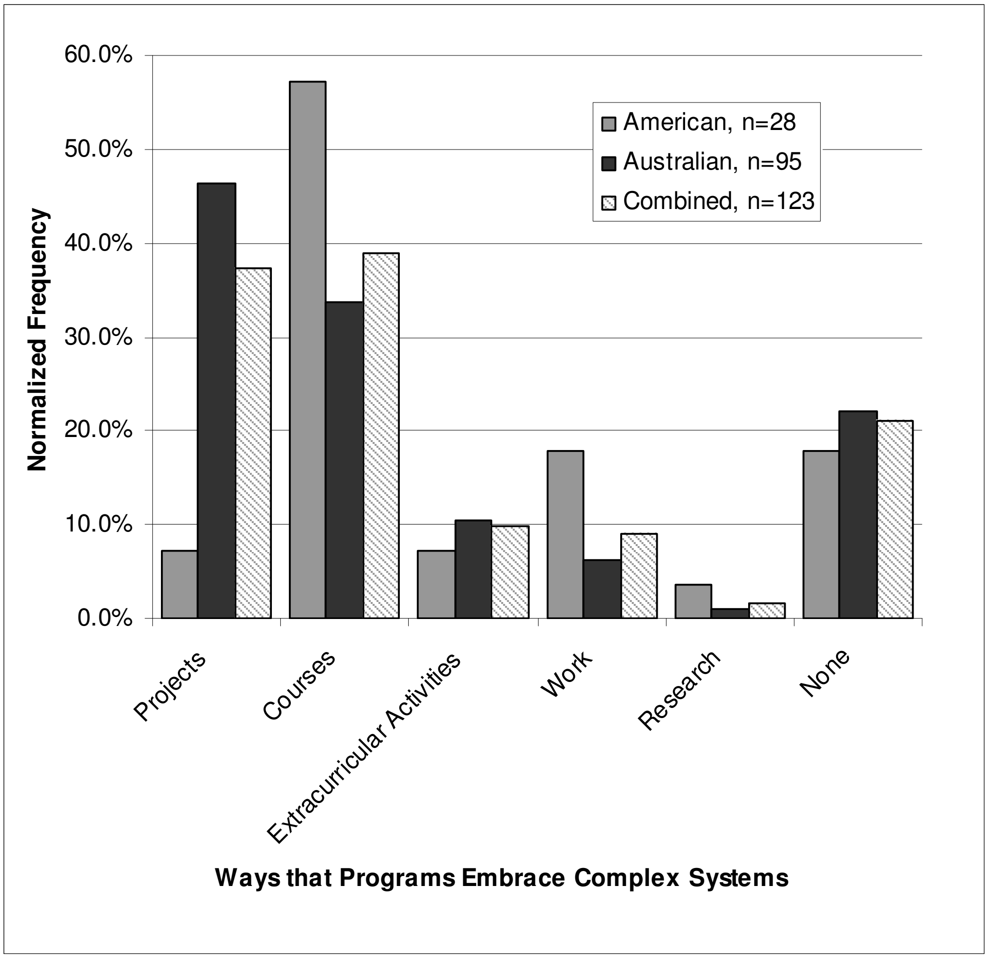

Figure 11: Describe any projects, courses, or extracurricular activities in which you have participated that use this concept of complex systems.

V. Conclusions

This study benchmarked the state of complex systems study in engineering educational programs in America and Australia. The authors feel that engineering graduates need to have a holistic understanding of engineering and how engineering influences and is influenced by the world around it.

A move towards achieving engineering graduates that have a holistic understanding of engineering and how engineering influences and is influenced by the world around it will not only attract people to the engineering profession, but will also help retain the students that are already interested in engineering. The attributes of an engineer that embraces the concepts of complex systems is described in the closing paragraph of the *Engineer of 2020: Visions of Engineering in the New Century* [9]. "What attributes will the engineer of 2020 have? He or she will aspire to have the ingenuity of Lillian Gilbreth, the problem-solving capabilities of Gordon Moore, the scientific insight of Albert Einstein, the creativity of Pablo Picasso, the determination of the Wright brothers, the leadership abilities of Bill Gates, the conscience of Eleanor Roosevelt, the vision of Martin Luther King, and the curiosity and wonder of our grandchildren."

VI. Acknowledgements

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VII. Biography

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VIII. Appendix