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First Steps in Strengthening the Connections Between Mathematics and Engineering

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First Steps in Strengthening the Connections Between Mathematics and Engineering

It is well-documented that students have difficulty transferring their knowledge between the domains of science, mathematics, and engineering.[1-3] This lack of transfer can lead to friction between these departments. Some engineering professors are tempted to blame their colleagues in math and science for not teaching effectively or not even addressing the proper content. Conversely, colleagues in mathematics and science have been known to say that engineering students do not actually try to learn the material and just plug numbers into equations. Believing that neither case is an accurate portrayal of the situation, the director of the Engineering Education Innovation Center at The Ohio State University formed a task group to address these concerns. The group currently has representation from mathematics, physics, and 3 different engineering departments (mechanical and aerospace, electrical and computer, and the first-year engineering program). Many members of the group already participate in weekly discussions focused on coordinating the math, physics, and engineering fundamentals courses that are part of Ohio State's Fundamentals of Engineering for Honors program.

As the task group considered various approaches to making the connections between math, science, and engineering coursework more apparent to students, it was quickly determined that faculty buy-in would be crucial. The group constructed and distributed a survey to faculty throughout the College of Engineering. This survey focused on the use of mathematics in engineering classes, first asking faculty to rate the importance of core mathematical topics in their disciplines. It also asked for a rating of how well prepared students tend to be in these areas when entering their major courses, along with how skilled they are in these areas upon graduation. The results of this survey will indicate to the task group the areas in which faculty believe coordination efforts will have the most impact, helping determine the next steps.

This paper describes the preliminary efforts of the task group to frame the problem.

Sample

The survey was developed and distributed using the college's on-line Qualtrix system. All of the college's approximately 275 departmental teaching faculty (professors, clinical faculty, and lecturers) were requested to take the survey. These instructors are distributed over 11 instructional units. The survey was available for approximately 3 weeks near the end of the autumn 2012 semester. Two reminders were sent during this time. The resulting response rate was 77 (28%), and the responses reflect a fairly representative sample of departments and job titles.

Tables 1 and 2 depict the distributions of the sample with respect to department and job title.

Table 1. Representation of Departments by Faculty Completing Survey

Department	Percentage of Survey Respondents
Mechanical/Aerospace	22
Biomedical	13
Computer Science	12
Electrical/Computer	12
Civil/Environmental/Geodetic	10
Food/Agricultural/Biological	8
Integrated Systems	8
Chemical/Biomolecular	5
Other	5
Materials Science	3
Architecture	1
Center for Aviation Studies	0

Table 2. Distribution of Job Titles of Respondents

Job Title	Percentage of Survey Respondents
Professor	37
Associate Professor	32
Assistant Professor	12
Clinical Faculty	5
Lecturer	14

Aggregate Results: Importance of Mathematical Topics and Perceived Competence of Graduates

The first set of questions on the survey sought to identify a) which mathematical concepts are regarded as the most important for success by faculty and b) how successfully they believe their undergraduate programs currently are at building student competence in these same areas. For these questions, a list of mathematical concepts was generated (largely by the mathematician in the task group with input from the rest of the group). The survey asked

1) How important is it for students who graduate from your undergraduate program to be able to competently apply concepts from each of the areas listed?
2) How competent is the average graduate of your program in each of the following areas?

These results are summarized in Table 3. On the survey, the second question was answered on a 5-point scale, but for ease of comparison in this table, those scores have been normalized to a 7-point scale. Note that a "not applicable" option was available as a response for the second question, in case a faculty member had indicated in response to the first question that a concept was not relevant. Text boxes were provided for respondents to further explain or elaborate upon any of their responses.

Table 3. Summary of Faculty Ratings of Importance of and Graduates' Competence With Mathematical Topics. Ratings are on a 7-point scale. Numbers in parentheses are standard deviations.

Topic	Average Importance	Average Competence
Calculus	6.0 (1.5)	4.8 (1.2)
Linear algebra	5.7 (1.4)	4.1 (1.3)
Analysis of nonlinear phenomena	4.6 (1.5)	3.5 (1.3)
Ordinary differential equations	5.4 (1.8)	4.2 (1.4)
Partial differential equations	4.8 (1.8)	3.6 (1.4)
Complex variables/functions	4.5 (1.6)	3.6 (1.3)
Numerical simulations	5.7 (1.3)	4.4 (1.2)
The use of vectors to represent physical quantities	5.7 (1.5)	4.5 (1.2)

Inspection of these responses show that the faculty believe all of these topics to be at least somewhat important. Calculus is the most crucial; complex variables and functions are the least so. The faculty do not perceive that the students graduate with a high level of competence in any of these areas. Interestingly, there is a strong relationship between the rating of importance for a topic and the perceived competence of the students. Thirteen respondents provided additional information in the text boxes. The one trend that emerged from these comments was that some faculty believed that the topics of discrete math, numerical simulations, and statistics should have been included on the list. Some other faculty used this opportunity to make complaints about the level of mathematical (and in one case, scientific) preparation of their students. These data indicate that faculty believe there is room to improve the mathematical competence of engineering students and that there are ample opportunities for the task group to improve the ways in which students develop their mathematical skills during their undergraduate engineering experience.

Aggregate Results: Importance of Specific Skills and Student Preparation

Respondents were given a list of more detailed mathematical skills (again, developed with the expertise of the group's mathematician). They were asked to think about the one or two undergraduate courses they teach most frequently and to rate how important it was that students understood these skills in order to do well in those particular courses. These results are summarized in Table 4, which lists the skills from most important to least important. In looking at these responses, it can be seen that faculty rate nine of the twelve skill sets as important (a 4.0 or higher on a 5-point scale). The only set of skills to be rated at less than 3.5 is creating algorithms, at a 3.3.

Table 4. Summary of Faculty Ratings of Importance of Specific Mathematical Skills
Ratings are on a 5-point scale. Numbers in parentheses are standard deviations.

Mathematical Skill	**Average Importance**
Evaluating solutions/checking work	4.5 (0.8)
Being familiar with units and dimensions	4.4 (1.0)
Knowing how to create and interpret graphs	4.4 (1.0)
Performing algebraic manipulations	4.3 (1.0)
Knowing how to convey & interpret engineering relationships through mathematical expressions	4.3 (1.0)
Using parameters/symbols, rather than numerical values, in analysis	4.2 (1.1)
Interpreting the role of parameters in mathematical expressions	4.0 (1.0)
Formulating mathematical models	4.0 (1.0)
Being familiar with estimation/knowledge of magnitude scales	4.0 (1.1)
Knowing when to differentiate or integrate	3.7 (1.3)
Working with multivariable problems	3.7 (1.2)
Creating algorithms	3.3 (1.3)

Respondents were then asked to rate each of these same skills according to the preparation of the students entering their program. These results are listed from highest to lowest competence in Table 5.

Table 5. Summary of Faculty Ratings of Student Preparation in Mathematical Skills
Ratings are on a 5-point scale. Numbers in parentheses are standard deviations.

Mathematical Skill	**Average Competence**
Performing algebraic manipulations	3.3 (0.9)
Knowing how to create and interpret graphs	3.2 (0.9)
Being familiar with units and dimensions	3.1 (1.0)
Knowing when to differentiate or integrate	2.9 (0.9)
Using parameters/symbols, rather than numerical values, in analysis	2.9 (1.0)
Being familiar with estimation/knowledge of magnitude scales	2.8 (1.0)
Knowing how to convey & interpret engineering relationships through mathematical expressions	2.8 (0.8)
Evaluating solutions/checking work	2.7 (0.8)
Working with multivariable problems	2.7 (1.0)
Interpreting the role of parameters in mathematical expressions	2.7 (0.8)
Formulating mathematical models	2.6 (0.9)
Creating algorithms	2.4 (0.8)

It is apparent in comparing these responses to the importance ratings in Table 4 that the students do not arrive to courses as mathematically prepared as the faculty believe they should be. Looking at the relative rankings further, the skill considered most important, evaluating solutions and checking work, is in the bottom half of the competence list. Students are the least prepared to create algorithms, but this was also ranked least important by the faculty.

Department-Level Results

Remembering that the primary purpose of the faculty survey was to identify the most fruitful areas for the task group to focus, the initial analysis of the data focused exclusively at the aggregate level. However, a deeper probe was conducted to see if responses varied by department. Table 6 summarizes the responses regarding the importance of mathematical topics at the department level.

Table 6. Summary of the Importance of Mathematical Topics by Department
The top number is the average and the bottom is the standard deviation.
Shaded boxes indicate high importance (rated 6 or more on a 7-point scale).

	Calculus	Lin Alg	Nonlin	ODE	PDE	Complex	Num Sim	Vectors
Biomed	6.62	5.79	5.02	6.18	5.90	4.70	5.75	5.77
	0.52	1.41	1.07	1.19	1.12	1.50	1.17	1.55
Chem	6.36	5.34	3.50	5.67	3.86	3.46	3.49	6.02
	0.56	1.52	1.34	1.52	1.51	1.36	1.50	0.99
Civil	5.83	5.17	4.71	4.13	4.11	3.91	6.04	5.97
	1.23	1.27	1.13	1.84	1.84	1.91	1.14	1.50
Computer	5.27	4.98	3.98	3.15	3.07	4.25	4.90	4.53
Sci & Eng	1.31	1.40	1.29	2.20	1.93	1.51	1.38	1.78
Electrical	6.97	6.68	4.78	6.59	5.35	6.22	6.07	6.76
& Comp E	0.09	0.47	1.98	0.82	1.69	1.10	1.12	0.37
Food, Bio,	3.46	4.92	3.24	4.09	3.88	3.26	5.24	3.25
& Agric.	2.20	1.14	1.28	1.56	1.69	1.28	1.51	1.31
Indust &	6.00	6.14	5.50	4.84	4.43	4.07	6.32	6.03
Systems	1.77	1.93	1.37	1.70	1.79	1.50	1.07	2.16
Material	7.00	6.02	5.02	6.02	5.04	4.54	6.03	5.54
Science	0.00	1.39	0.01	1.39	1.42	0.72	1.38	0.73
Mech	6.46	6.03	5.16	6.33	5.74	4.61	6.04	6.45
	0.96	1.39	1.74	0.71	1.12	1.67	1.12	0.95

This analysis excludes the one respondent from architecture, as well as those who did not identify with one of the major departments. The electrical and computer engineering respondents found most topics to be important, rating six of the eight topics at a six or higher. The lowest rating from them was 4.78. Mechanical engineering also placed high importance on most of the topics surveyed. On the other end of the spectrum, food, biological and agricultural engineering, along with computer science and engineering, did not place a particularly high importance on any of the areas.

As in the aggregate data, understanding of nonlinear phenomena was not rated as highly important; neither were partial differential equations. Not surprisingly, the electrical engineers rated complex variables and functions highly, but no other department did so. The two areas that were rated as highly important by the most departments were calculus and numerical simulations, indicating that these might be fruitful areas for the task group to look to in developing connection points between mathematics and engineering courses.

Looking at the responses to the questions about the perceived competence of their programs' graduates, the results are somewhat mixed. These results are summarized in Table 7.

Table 7. Average Perceived Competence of Graduates
With Mathematical Topics by Department (Scale of 1 to 5)
Shaded cells indicate areas of low competence.

	Calculus	Lin Alg	Nonlin	ODE	PDE	Complex	Num Sim	Vectors
Biomed	3.67	2.85	2.84	3.67	2.87	2.56	3.30	3.14
	0.97	0.71	0.73	0.82	0.44	0.59	0.86	0.80
Chem	3.29	1.97	1.49	2.76	1.80	1.24	2.77	2.44
	0.67	0.01	0.69	0.84	0.72	0.34	1.12	1.32
Civil	3.28	2.27	2.86	3.08	2.84	3.72	2.53	2.94
	0.92	1.03	0.93	0.79	0.79	0.39	1.13	1.39
Computer	3.54	3.54	2.22	2.32	2.05	2.56	3.11	2.98
Sci & Eng	0.52	0.67	0.85	1.02	0.85	1.09	0.76	0.81
Electrical	3.64	2.83	2.01	2.84	2.68	2.93	2.61	3.14
& Comp E	0.49	0.91	0.62	0.32	0.54	1.04	0.78	0.81
Food, Bio,	3.14	3.24	2.29	3.11	2.71	2.76	3.64	2.98
& Agric.	0.88	0.95	0.61	0.89	0.65	0.53	0.50	0.83
Indust &	3.48	3.08	3.11	2.86	2.64	2.47	3.68	3.25
Systems	0.96	1.09	0.32	0.95	1.11	0.98	0.65	0.80
Material	2.77	2.81	2.29	2.31	1.81	1.88	3.16	3.41
Science	0.37	0.31	0.43	0.43	1.14	0.53	1.24	0.93
Mech	3.26	2.96	2.24	3.14	2.57	2.19	3.07	3.60
	1.03	0.88	1.07	1.15	1.11	0.96	0.87	0.79

On the positive side, only two departments (chemical engineering and material science and engineering) reported seriously low competence (identified here as an average rating between 1 and 2 on a scale from 1 to 5) in any areas for their students. However, chemical engineers identified four of the eight areas as such, which is of concern. Additionally, no area was given an average rating higher than 3.7 by any department. This indicates that the faculty may well be receptive to the efforts of the task group; certainly they believe there is room for improvement in developing the mathematical competence of engineering majors.

When the faculty responses regarding the importance of specific mathematical skills are analyzed by department, very little is seen that adds to the aggregate picture. Every skill listed on the survey was designated as highly important by at least one department. As might be expected from the aggregate data, the only skill that was rated as highly important by all departments was checking work and evaluating answers. Still, five of the twelve skill areas were deemed highly important by at least two-thirds of the departments: expressing relationships through mathematics, interpretation of graphs, understanding units and dimensions, algebraic manipulation, and using symbols instead of numbers in calculations. The only skill actually rated as unimportant was creating algorithms, by the materials science and engineering department.

The survey data also show that the faculty largely believe students enter their undergraduate courses with adequate preparation mathematically, but do not go so far as to say that they are well prepared or that they are poorly prepared. Sixty-seven percent of the department-level responses fall within a quarter point of the middle of the five-point scale. Materials science respondents identified poor preparation in multivariate analysis, expressing relationships mathematically, and knowing when to differentiate or integrate. Chemical engineers find their students lacking in developing algorithms. Of these, the only one that was identified as an area of high importance was for the materials science students in expressing ideas mathematically. On the other end of the spectrum, the only area identified as having strong preparation was for chemical engineering students in estimations, but that department ranked estimation skills as the next-to-least important of the skill areas on the survey.

Looking at the department-level responses, no areas have been identified where students are seriously lacking in their preparation, but there is plenty of room for improvement. The majority of the skill areas have been identified by the majority of the departments as being important for student success, giving the task force many options for developing approaches with the potential to be well-received by the faculty in general.

Next Steps

In these survey responses, faculty have identified to the task group the mathematical topics and skills that they believe are most important, along with their perception of student ability in these areas. The task group is beginning to explore possible strategies for increasing the transfer of skills from introductory mathematics to engineering courses. By focusing these efforts on the skills that have been identified as both important and somewhat deficient, the task group should achieve meaningful engineering faculty buy-in. It is also hoped that this makes it more likely that there will be a substantive impact on student understanding and achievement. A couple of areas that the data suggest are checking solutions and expressing engineering ideas using mathematics.

It is not clear at this point whether the majority of the effort should be directed at the engineering fundamentals courses taken by all engineering freshmen, departmental courses, or mathematics courses. To help make this determination, a similar survey is being developed and will soon be administered to faculty of introductory mathematics courses at Ohio State. Exploring any mismatches in the perceptions and beliefs of the two groups of faculty is key to developing an effective intervention.

[1]Bransford, J. D., Brown, A. L. & Cocking, R. R. ,ed, *How People Learn: Brain, Mind, Experience, and School* (National Academy of Science, 1999).

[2]Bassok, M. & Holyoak, K. J., "Interdomain Transfer Between Isomorphic Topics in Algebra and Physics," *Journal of Experimental Psychology: Learning, Memory, and Cognition* **15**, 1, 153-166 (1989).

[3]Bassok, M., "Transfer of Domain-specific Problem-solving Protocols," *Journal of Experimental Psychology: Learning, Memory, and Cognition* **16**, 3, 522-533 (1990).