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Teaching Undergraduate Aerospace Engineering Students to Reason and to Communicate about Complex Design Choices

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Abstract: Undergraduate engineering students who are enrolled in capstone design courses are introduced to the multi-dimensional tasks of complex design. The capstone design course also is often the student's introduction to the ways that engineers both reason and communicate about design choices in their professional community. The undergraduate engineering curricula can offer the technical and theoretical knowledge and computational methods that are necessary to engineering students but still not be sufficiently explicit about which pieces of evidence or methods are more reliable in a making a complex design choice. Without the clarity of reasoned thought that optimal design requires, high quality communication is not likely. The paper describes a pedagogical strategy designed and implemented to strengthen student reasoning about design choice.

Introduction and background: In the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology, aerospace engineering students complete their undergraduate degrees with one or a combination of capstone design courses that involve complex design assignments or experiments. In these courses, students are introduced to the multi-dimensional design space with its constraints and requirements and also to experimental protocols. The written design proposals and reports and formal presentations that are required are less like the usual undergraduate problem sets and more like the communication deliverables that professional engineers produce. Faced with the higher order critical thinking tasks as well as the demands of communicating their thoughts both in writing and orally, students frequently report frustration. “What exactly is it you want?” they ask.

Teaching undergraduates to work in a multi-dimensional design space and to communicate about that work is challenging. Just as the increased complexity produces a greater demand on student performance, it produces a greater demand on engineering and communication faculty to teach and mentor students in this phase of their professional development. And professional development is, in fact, a significant element of this capstone work. In addition to the desired student outcomes and all the assessment of those student skills, what we also hope to see at this culminating phrase of their education is their readiness to join the professional community of engineers.

How do we teach students to be professional engineers? We can lecture them on ethics and help them find internships. We can organize complex experimental and design courses. Yet for the most part, we teach them professional behavior by modeling it for them or hoping that they absorb this from internships or summer jobs. Thinking like an engineer is implied in our expectations, but could we teach this more explicitly? Would teaching students explicitly about the ways in which engineers think and reason and argue improve the students’ abilities in design and writing and speaking?

This paper suggests that thinking (speaking, writing, designing, experimenting) like an engineer includes not only a body of technical knowledge but also the rhetorical ability to argue and reason with evidence in the ways that are accepted in the engineering community. This paper also describes a pedagogical model developed to strengthen those rhetorical abilities in students who are working on complex design problems. Assessment of this strategy is ongoing, and data will be presented at the ASEE Annual Conference 2006.

A thorough discussion of how knowledge is constructed and agreed upon in the engineering profession is beyond the scope of this paper. But clearly professional identity is based not only on what one knows but also how one comes to know it and how that knowledge is tested and accepted and discussed in the context of time. Dorothy Winsor notes in *Writing Like an Engineer* "one has to use language as others do in order to be accepted as a group member, and one has to think like a group member in order to use language as the group does. [1] Solomon widens the range of ways in which professional identity is established. "Identity is experienced through . . . sharing a common enterprise, values, assumptions, purposes, and rules of engagement and communication." [2] She goes on to argue that the transition from being a student (which she describes as compliant, not deeply reflective, intent on the "right answer") to being professional is based on observing and understanding common behaviors and activities and seeing ourselves actually creating work within those patterns.

Perhaps the rhetorical challenge for an engineering student in a design course comes in two parts. Assuming that s/he can reach the point of assembling rational design choices, s/he then must understand the quantitative (and perhaps qualitative) criteria in order to make a final design choice. The first part of the challenge may be assembling the evidence for this choice and being able to argue for it. But the second and less easily discerned challenge is knowing which methods of proof are valid and which may not be quite as persuasive. "Claims are seen to be grounded through the process of argument---relating imaginative conjectures. . . to evidence. . . which itself needs to be open to scrutiny in terms of the way it is framed conceptually and the trust that can be placed in it (due to) its reliability and validity." [3]

John Robinson in "Engineering Thinking and Rhetoric"[4] describes engineering rhetoric as "explaining why a particular solution to a problem is best." He divides engineering problems into simple (the constraints and criteria for evaluating the solution are all qualitatively similar) and compound (the evaluation criteria are not qualitatively similar and cannot be joint optimized). He goes on to note that a common strategy for solving compound problems is to divide the problem into parts that can be solved more simply, but some simple solutions to simple problems don't quite solve the compound problem.

Then, Robinson claims, the engineer's thinking is closer to that of a lawyer who argues from analogic situations or precedence and claims their relevance.

Thus, Robinson concludes, an engineering student learns as much from his engineering mentors' experiences in design and fabrication and experiment as s/he does from the calculations taught in the classroom. In the latter instance, the student learns how to arrive at the precise values that provide important support for design choices, but in the former instance, s/he learns about the implicit assumptions that allow an engineer to know which calculations to perform.

Implicit assumptions, it appears, are hard to define if only because they are "understood" and not directly expressed or not readily apparent. Yet they are an important part of what makes pieces of engineering knowledge cohere, and they allow experienced engineers to analyze design problems swiftly and then begin to design and evaluate precise solutions. Undergraduate students generally have not had enough experience to develop intuitive approaches to design problems, but working with experienced and talented engineering professionals can be a beginning.

The Model: In fall 2005 and winter 2006, the faculty team teaching a three semester capstone design course, Space Systems Product Development, designed and implemented a pedagogical model that explicitly focused on helping students to learn to argue for design choices or design processes. We always expect students to be able to speak and to write about their rationale for design choices or design processes, but these incidents of speaking and writing usually occur in long, multi-student, formal oral presentations or in lengthy written design documents. Our students usually excel in these forms, but in effect, we felt that we had been looking at the evidence of the design work that had been completed. The point of meaningful intervention had passed. And, working in teams, individual student work was difficult to distinguish, so that students who were not so strong did not receive the necessary support.

Instead, what we wanted to focus on were the “teachable moments” in which students’ learning could be deepened or refocused by faculty query. We wanted to focus explicitly on the evidence for specific design choices, and we wanted to create a dialog with students at critical points so that they could ask their mentors about engineering assumptions and strategies. We intended to structure our model so that all students benefited from the strengths of the learning group but also so that individuals who needed more support received that attention.

This model left in place the larger formal oral design reviews and the formal written documents at middle and end of the term. These deliverables gave a valuable representation of the state of the design at certain points and were key places in which sub-team work was integrated. They also provided students an opportunity to practice their professional presentation and writing skills.

However, to complement these, the faculty added three informal sub-team briefings and two short individually written engineering analysis papers that were coupled with individual reviews with the student’s mentors.

Informal sub-team briefings: The cycle began with an informal briefing in which sub-teams of four students met with their mentor (s) and often a communication faculty for 45 minutes. Half of this time period was taken up with a few viewgraphs outlining the sub-team’s work. The rest of the time was devoted to an active question and answer period. Students got immediate feedback on their work and were also given suggestions about how to proceed with greater success or focus. In turn, students asked questions of their mentors and took extensive notes.

Individual engineering analysis papers: After the informal sub-team briefings, each student chose a piece of design work that s/he had been pursuing and wrote a three page analysis of that work. They were expected to be explicit and also specific about their approach, their conclusions and their evidence or reason for those conclusions.

These engineering analysis papers were graded and commented on for communication elements by a communication instructor. Then the student and his/her mentor both received a copy of this graded paper.

Individual Review with Mentor: The student then met for a twenty minute discussion with his/her mentor in which the focus was strictly on the student's design choices or process and the reasons for that. The individual review was not a presentation or a briefing but an active dialog between student and mentor. The mentor then scored the student's technical work but did not comment on the communication elements.

There were two full cycles of the sub-team briefings, the engineering analysis and the individual reviews, and we concluded with a final informal briefing leading up to the final design review.

Summary: None of the pieces of this model were unfamiliar to our faculty team, but what was new for us was the sequence in which the elements were combined and also the tighter feedback loop between students and engineering or communication mentors. Putting the sub-team informal briefing first allowed the students to leverage group knowledge to pull their ideas together in an informal setting. It also gave the mentor (s) a first look at this smaller team and a sense of student capabilities. The written analysis targeted the individual student again both from the perspective of the communication instructor and of the engineering mentor. Students received written feedback on their communication practice within days of submitting the paper; conferences with the communication instructors were available both before the submission of the paper and after the student had received comments. Moreover, students met with their mentor within a week in the individual review where the focus was on the technical work.

Assessment of the model: Assessment of the model took place after the first and after the second cycles. A short survey gathered student assessment of interaction with engineering mentors, the difficulties they faced in complex design work, and the effectiveness of the briefings, the written analyses and the individual reviews. Engineering mentors completed a parallel but not identical survey.

Lessons Learned to Date:

- This model can scale to large classes with the addition of engineering mentors.

We originally designed this strategy for a class size of around 20-25, but 66 students enrolled in the course. Three professors led this course (necessary in order to cover the wide range of subject matter), but we quickly added other mentors including graduate students (doctoral and master's), post-doctoral research scientists, visiting professors, experienced technical instructors and other subject matter experts. We also added another communication instructor for a few hours a week. The expectation for all but the three lead professors and lead communication instructor was only a few hours a week devoted to mentoring, and thus we had the coverage we needed to get students face-to-face with engineering mentors. However, we also learned that this model coupled with a larger number of students and engineering mentors did require a great deal of organization in order to meet our goals for timely feedback to the students.

- Even before assessment, students began to volunteer their "discovery" of how engineering assumptions help the design process.

For example, a student describes an experience in the early part of the first semester: *I was supposed to come up with a mass budget for the battery system for the rover, but I really didn't know where to start. Then Professor W. 's graduate student sat in with the team and came up with a figure and just reeled off how he got it. And I realized he made all these assumptions that I didn't think to make! It was an estimate, but still it was pretty close.*

- Engineering mentors are quick to focus on the kinds of engineering analysis students need to do, and students readily enter into dialog with mentors who showed them how to go further in their design thinking more quickly.

For example, a student on another team tells us: *I was trying to figure out what kinds of methods of locomotion would work for the rover and its missions, so I did a* *literature search in a database of journals. I found several recent articles, but this is a new area. And the articles were more theoretical. I got the best information from a technical report database on a government Web sites that Mr. W (a guest speaker) listed, but then Professor K suggested I search industry sites to see if any of the components were commercially available. I found some that seem as though they'd work and now I have the specifications for those components, too.*

- Students have more substantive and specific information to write about and they are eager to write it, but they still need instruction and feedback in how to write with organization and coherence.

Conclusion: This pedagogical model is in its early stages. Future work includes an ongoing and thorough assessment not only of student responses but also of the responses of engineering mentors and a quantitative assessment of differences in student writing grades between the first analysis and the second. Since the course extends over three semesters, this model will be tested and assessed over a period of eighteen months.

Sources:

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