Innovation Across the Curriculum: Three Case Studies in Teaching Science and Engineering Communication

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Abstract—*As is true for engineering communication programs nationwide, at MIT curricular and pedagogical reforms have been driven by changes in the kinds of problems that engineers solve and the associated skill sets that engineers must now have in communication and teamwork. This article presents three case studies from communication-intensive classes at MIT that intend to help students develop the advanced communication skills required of professional engineers today. Highlighting classes in biological engineering, aeronautics/astronautics engineering, and biomedical engineering, we explore the following questions: What does it mean for educational practice if professional communication competencies and tasks are the goals? How can students and technical faculty best create the conditions for students to learn to be skilled team members? How can engineering students move from mere display of data to making skilled visual arguments based on those data? The importance of helping students meet the target competencies of professional practice, of teaching effective teamwork and collaboration, and of teaching students to understand and argue with visual data are recognized as widespread needs, and these case studies attest to the possibilities and challenges in meeting those needs.*

Index Terms—*Collaboration, communication across the curriculum, data representation, engineering education, professionalization, teamwork, visual communication, writing process.*

The profession of engineering in the 21st century is undergoing numerous changes, notably in the kinds of problems that engineers solve and the associated skill sets that engineers must now have in communication and teamwork [1], [2]. Current educational initiatives such as communication-across-the-curriculum programs attempt to address these changes by integrating communication instruction in engineering courses rather than teaching writing and speaking in “stand alone” technical writing courses [3]–[6]. Many such communication-intensive (CI) curricular changes throughout American universities have been driven by Accreditation Board for Engineering and Technology (ABET) accreditation and by calls for change by the National Academy of Engineering [7]; however, MIT’s new communications curriculum was driven almost entirely by alumni feedback. A 1997 survey revealed that while MIT alumni felt that they had received top-notch technical educations, they believed that their lack of training in writing and speaking was a significant hurdle to their professional success [8].

Given this feedback, MIT faculty passed the Communication Requirement, an institute-wide faculty initiative with the intention to integrate “substantial instruction and practice in writing and speaking into all four years and across all parts of MIT’s undergraduate program” [8]. Under the Communication Requirement, students are now required to take four CI classes during their undergraduate years, including two CI classes in their majors. CI classes in the majors emphasize communication in the learning of disciplinary content and are taught collaboratively by technical and writing faculty.

Our initial goal at MIT in designing CI instruction was to work with engineering and science faculty to design meaningful, well-defined assignments, use revision and peer review to improve student writing, develop learning goals, and effectively assess student writing. What has also emerged, however, is a move beyond these initial steps to writing and speaking activities that resemble the more advanced challenges of engineering communication that occur in the practice of **doing** engineering [9]. In this way, we have been able not only to ask “What forms of writing should students be doing?” but also to inquire “What activities encourage students to work and think like professional engineers?” Our particular interest is helping students move from general academic writing or novice approximations of disciplinary writing to internalizing the communication-thinking practices of professional engineers [10]. Thus, our CI classes are not “one size fits all,” but rather they are tailored to fit the communication practices of the young professionals in the particular discipline in which we are working. Our collaborative work with engineering and science faculty blends our understanding of writing pedagogy with the expectations of the specific discipline. Currently, every department at MIT offers CI classes in the major, and more than 25 full-time writing

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instructors work with faculty to help implement writing and speaking instruction in those classes.

One might argue that this considerable commitment of resources makes MIT unique in its approach to integrating communication instruction in engineering classes. However, institutions ranging from large state universities such as North Carolina State University to smaller institutions such as Presbyterian College have active "communication-intensive" programs, albeit using quite different approaches. At some institutions, interested faculty are offered workshops in how to create communication- and writing-intensive instruction. At other institutions, communication-intensive instruction has been added to general education requirements and is supported through writing fellows or writing center tutors. The integrated model we use at MIT is also used effectively at other institutions, although on a smaller scale. As we describe in the MIT case studies that follow, the on-the-ground realities of working with faculty, staff, and students to help them achieve communication and course goals can be easily applied to a wide variety of settings. The importance of helping students meet the target competencies of professional practice, of teaching effective teamwork and collaboration, and of teaching students to understand and argue with visual data are recognized as widespread needs, particularly in the framework of ABET's "engineering criteria" [11]. We believe that our examples attest to the possibilities and challenges in meeting those needs both inside and outside of MIT.

The case studies that we next present describe several key issues that partner with communication tasks. The first case, Learning to Write as a Biological Engineer, examines the ways in which undergraduates in biological engineering may be introduced to the professional writing practices of their emerging discipline. Addressing Teamwork Challenges in Collaborative Communication, the second case, studies the challenges of collaborative communication in aeronautical/astronautical engineering and the ways in which students learn the team skills so central to collaboration. And, finally, Data-Driven Arguments in Biomedical Engineering examines the ways in which biomedical engineers use data and ways to teach students to select data as evidence in visual arguments. In each case, we explain how we rationalize the communication focus for each class, how we implement instruction in each class, and how we assess its effectiveness.

CASE STUDY 1: LEARNING TO WRITE AS A BIOLOGICAL ENGINEER

Rationale for Professional Competencies as Goals The instructional goal of teaching students to learn to write and speak as engineers implies several things: a certain amount of imprecision as students strive to take on the identities of professionals (and a reminder that they have not yet done so); the acceptance of professional competence as an ultimate goal; the role of a professional mentor to model and teach professional competencies; and a set of fairly defined, "real-world" tasks based on the work that professionals are already doing. In the case study that follows, each of these factors potentially affects the learning that a student might achieve.

Many of the current classes designated as CI at MIT have been mapped on to pre-existing laboratory classes. On one level, this decision makes logistical sense as students have long presented their laboratory work in written or oral forms; the CI requirement offers a structure and instructional support for these established practices. On another level, the tying of communication activities to students' laboratory work represents the ways in which professional practices are a driving force in curriculum and teaching. In other words, the ideals of research and the ways to inculcate students into those ideals have long shaped the undergraduate curriculum at MIT. And these competencies—the ability to undertake independent research or solve problems through sustained inquiry and the ability to communicate the results of those endeavors—are essential to the success of a professional in any science or engineering discipline.

A key component of professionalism as a driving force is the notion of students developing identities as scientists or engineers. The close relationship between identity and learning is theorized under several names, whether called "situated cognition" [12], "cognitive apprenticeship" [13], or "situated learning" [12], and these theories help explain why professionalism can be a powerful curricular and instruction goal as well as a complication for student learning. For instance, Gee sees learning as always rooted in particular sites of practice and says, "Knowing is a matter of being able to participate centrally in practice, and learning is a matter of changing patterns of participation (with concomitant changes in identity)" [12, p. 181]. What this means for students who are learning in laboratory or other professional settings is that tasks need to be as close as possible to those attempted by professionals and that instruction needs to take into account the "communities of practice" that define individual disciplines

[14]. This conception of learning leads to a far more dynamic environment than a traditional transformation-of-information model from “knowing” professor to initiate student. Instead, according to Lave, “‘Knowing’ is a relation among communities of practice, participation in practice, and the generation of identities as part of becoming part of ongoing practice” [14, p. 157]. Essential to this process is the presence of a mentor to guide student practice toward professional norms. In short, classrooms and laboratories are examples of environment where true professional practice can be found and offer much promise as models for enacting these theories of learning.

When students are writing in these laboratory and classroom contexts, by no means is the trajectory from novice to professional a smooth one. In her study of mechanical engineering students working in groups toward tasks typical of professionals in their field, Dannels found that “students ultimately acted in ways that suggest the prevalence of the academic context” [15, p. 25]. In other words, the group members’ identities (and the need to fulfill an assignment in an academic context) strongly determined outcomes. As Dannels notes, “students may have learned how to be professionals in theory, but they did not translate that theory to actual design practices in the classroom” [15, p. 25].

Social theories of learning help explain some of the complications for developing professional identity in engineering education [16]–[18]. The term “discursive identity” [19] can be used to explore “the relationship between language, identity, and classroom learning” in science classrooms. According to Brown, Reveles, and Kelly:

> science learning involves learning to construct one’s discursive identity in order to participate in science and its associated discourse. The appropriation of a scientific identity is demonstrated through students’ engagement in the classroom conversations, as well as the broader discursive practices that lead to the development of new conceptual knowledge. [19, p. 790]

For undergraduates in a biological engineering class at MIT, these discursive practices include the writing that they are assigned based on the laboratory work they are performing, a context we describe next.

Context for Studying Students’ Development of Professional Competencies Biological Engineering is the newest major course of study at MIT, welcoming its inaugural class in the fall of 2005, and it has proved to be a popular option, with the number of applicants in 2005 exceeding the number of available slots by 50% [20]. Laboratory Fundamentals of Biological Engineering (or 20.109 in MIT’s numeric language) is the first of two required laboratory classes for students in the major, and as such, offers as an explicit goal that it will help prepare students for subsequent laboratory work, whether in classes or in research labs. Also explicit is the goal of preparing students to be professional biological engineers. For example, the first of four content modules conveys the following to students:

> One major goal we have for this module is to establish good habits for documentation of your work, in your lab notebook and on the [class] wiki. By documenting your work according to the exercises today, you will
>
> - be better research students (in 20.109 and in any research lab you may join)
> - be better writers since a clear record of what you’ve done will improve your data analysis
> - be better scientists, since you’ll eventually train others to document things this way, too. [21]

This act of consistently placing the work done in this class in terms of larger professional preparation makes the activities key to students’ development of professional identities. In a sense, the class is structured so that students will have some exposure to the “hot” areas of research in biological engineering. The four content modules for the spring 2007 semester were genome engineering, biophysical signal measurement, expression engineering, and biomaterial engineering. Each module was led by a faculty member or department researcher, and the lab activities were essentially an opportunity for students to see what it was like to work in that particular lab on that particular topic, albeit under more controlled conditions than independent researchers would find.

Another key aspect of the context for this class and for its assignments is the emerging disciplinary identity of biological engineering itself. The particular focus for much of the student research is in the field known as “synthetic” biology, a line of research that the *New York Times* characterized recently as “an effort by engineers to rewire the genetic circuitry of living organisms” [22]. In more fundamental terms, the approach in synthetic biology is based on using what is known about the genome or genetic code of particular organisms—how particular elements of that code function, what happens if a sequence is missing or is altered—and using what is known to build organisms from the ground up or from the nucleotides that make up DNA.

These tools of synthetic biology provide a key context for the writing students are doing. The first writing assignment (Appendix A) asks students "to write a thoughtful, researched essay exploring how a foundational engineering concept ... can be applied as a design tool for biological engineering." The research for this essay comes from students' lab work in which they are applying these "foundational" concepts to a virus in an attempt to modify it as it currently exists and build a synthetic version [23]. Thus, the laboratory work acts to generate evidence to support the argument that synthetic biology is a line of research worth pursuing—an argument that was essentially given to the students as they worked from a prewritten abstract.

The second writing assignment in 20.109 (Appendix B) during the spring 2007 semester was a much more conventional write up of students' laboratory work on the manipulation of a protein complex in yeast. This writing task followed the IMRD pattern (introduction, methods, results, discussion), and for many students its familiarity provided a welcome counterpoint to the first writing assignment. Nevertheless, the perceived familiarity of the genre was not necessarily an ally, as the template form of the laboratory report that students have largely followed in high school laboratory experiences is not the expectation in 20.109. Instead, students are asked to write about their research as scientists would do as they prepare a manuscript for publication. The rhetorical act is thus far more sophisticated than the high school lab template, and students' technical and rhetorical expertise is certainly challenged as they strive to write as biological engineers.

The following student's case study comes from a semester-long research project that examined students' experiences with learning to write in 20.109. Based on an initial survey (Appendix C), one-to-one interviews, observations of class and lab interaction, and examination of written materials, the study looks in particular at students' development of professional identity in a classroom/laboratory context. While the larger study examined four students' experiences in Laboratory Fundamentals of Biological Engineering, what follows focuses on one particular student. In this case, Maxine (not her actual name) represents an engineering student who initially projected a career for herself in the business world rather than in science or engineering. Thus, the professional competencies for writing and speaking have a certain amount of abstraction as mapped onto Maxine's career goals. This lack of direct connection is perhaps more the norm for undergraduates, particularly as career goals shift over time and as class communication assignments can only roughly predict the actual tasks that students will encounter in their futures. Thus, for Maxine the challenges of learning to write like a biological engineer are perhaps emblematic of many engineering students' paths toward professional competencies.

Case Study: Maxine's Struggle to Write like a Biological Engineer At the time of this study (spring 2007 semester), Maxine was a sophomore at MIT, part of the second cohort of students to be biological engineering majors. She chose to pursue biological science while in high school after rejecting physics and computer science as possibilities and after reading a great deal on the research in bioinformatics that was being done at MIT. However, both at the start and at the end of the semester, Maxine stated that her future goal was not necessarily to be a research scientist, but instead to work in finance or with a venture capital firm that funds biomedical research. She felt that this type of work would fit well with her self-described attributes: "I really like giving presentations; I love talking. ... I'm more of a thinker than a hands-on experience [type]. ... [Laboratory work] is interesting, it's fascinating, but I couldn't do it for a living." This class was also Maxine's first real scientific laboratory experience.

In her answers to a start-of-semester survey on writing experiences and expectations and in her first interview, several responses indicated that Maxine had a fairly sophisticated understanding of what scientific writing might entail and ample experience as a scientific writer. For example, she describes her experiences with writing up scientific content in high school:

> *As part of my high school International Baccalaureate program, I was required to write a 22-page mathematics paper. I have also written numerous physics lab write-ups for this same program.*

When she gave more specifics on a paper that she identified as a "significant" writing experience, she easily offered technical language:

> *I wrote a paper about the kalting problem of Turing's thesis. I took a very mathematical approach to this problem and solved it using Gödel's proof by falsification theorem.*

Maxine's sophistication also shows in her response to why she believed 20.109 had been designated as a CI class:

> *Biology has a lot of "holes" in it and thus requires the students to constantly question

> *the validity of their research. I think this class has been made a CI to teach students how to properly do that.*

In terms of writing goals for the class, Maxine offered the following:

> *I hope to analyze large amounts of data and draw logical conclusions, which I can then concisely put down on paper. I hope also to learn to think more creatively, especially in areas such as re-engineering viruses.*

Maxine also described a fairly ordered approach as typical to her writing process, one that involved being a "logical writer" but that also met difficulty with getting started (as she searched for a logical framework) and a tendency to be brief or not descriptive enough. In Maxine's words, "I don't like writing a sentence and then describing it for three sentences. I'm not a fan of that."

When it came to the first essay on the genome engineering laboratory work, Maxine struggled to conform to the expectations of the assignment and the time allotted to complete it. As she described, "I was crunched for time and had to just turn something in and hope for the best." Students' first drafts were graded by the writing instructor assigned to the class (who responded in depth to all student writing produced), and Maxine's received a C−, the lowest grade of all students. In his comments to Maxine, the instructor noted that "in revision you need to work on the presentation and logical structuring of the material." In particular, her draft lacked a clear focus, and her examples to frame her argument seemed only loosely connected. In an interview after she had submitted the draft, Maxine described that she had shown the draft to her father, a mathematician, who

> *couldn't get past the first page. When I was rereading it, I couldn't believe I wrote it. It had no argument to it. It just flowed here and there and wasn't a very focused argument.*

Part of the issue for Maxine and for other students in the class was that the assignment itself, though highly structured, left little potential room for the students to formulate an argument that they were comfortable with and could build on. One of the two faculty instructors for this module noted that the assignment

> *was too proscribed ahead of time; the coupling of that structure to the newness of the* [lab work] *led to essays and a writing experience that . . . I don't know how exciting it was; I know it wasn't that exciting for me* [to read].

In a sense, then, the key professional move of culling an argument from the data itself was lost on Maxine. She did feel strongly about the point she wanted to make in this essay: that completely refactoring a genome was a better method for achieving the promise of synthetic biology than other ad hoc approaches to genetic manipulation. However, she admitted that the "problem with arguing for refactoring is that technology hasn't caught up to that yet; it is kind of primitive." This writing task presented several challenges then. First, it required her to argue for a relatively abstract concept based on laboratory work that was not going particularly well. Second, the final faculty reader and grader is a pioneer in this type of research, though the imagined reader was to be fairly broad. As Maxine described,

> *Anyone with access to PubMed should be able to read it. There's a lot of scientific information in there that may not be clear to someone who's from a purely mathematical background, but they should still be able to follow through and logically understand what's going on.*

The assignment was challenging in that it was very specific and detailed in terms of how to structure the essay and what to include. That detailed structure did not necessarily work well for a writer like Maxine, who needed to figure out a particular focus before she could proceed in a "logical" manner. With the logic of organization already given and the material itself relatively abstract, creating a focused argument was difficult. The content-form relationship was predetermined in a way, unlike a professional scientific writing situation in which the two elements ideally work together. As described by the other instructor for this module,

> *The nature of the assignment wasn't polished initially; it was just an awkward assignment where the voice wasn't really all that clear. They just weren't ready to say something.*

In Maxine's words:

> *I haven't written a paper like the first one before. It was very structured but at the same time it was kind of "Make up your own ideas" and "We want to know what you think." I've actually never had to write such an abstract paper. You don't have very much data backing your arguments in the first place, so your arguments have to be very concise, very precise.*

Maxine did feel that her revision to this essay was a success. She noted that "Once my dad was able to follow the entire essay, it was okay." She received a final grade of B.

The second essay also presented challenges for Maxine. This task was to write up the research she had done investigating a protein complex in yeast. However, Maxine realized that this writing was not like the "technical lab reports" she had done in high school. Instead, this was writing a "journal article." As she noted in an interview, "I've never written a biology paper before, especially with the data analysis and writing about yeast and trying to figure out what's going on there."

The technical instructor for this lab module also noted the conflict between these expectations and experiences that students brought from their previous laboratory work, noting that

> *I'm surprised that they don't know that what they are trying to do is write a paper that you would find in a journal. For them, I think they still think they are writing a high school laboratory report.*

One way to address these expectations was to have students write the sections as homework assignments, which they would submit for instructor feedback. Maxine liked this strategy, noting that "even though the final copy looked nothing like the drafts I submitted, I learned what not to do, and the grades got better and better."

While the technical instructor was a bit surprised by students' expectations of what a "journal article" might entail, she was extremely mindful of the context for this assignment: Students were not writing an article to be submitted for publication; they were writing a research report in which demonstrating mastery of content and mastery of the rhetorical form was key. As she described,

> *We try to give them something legitimate that they're writing about, but they don't have a chance to repeat the experiment. I think it is just moving through that realism to artificial framework that's most awkward about the student writing. It is what it makes sound most like student writing to me.*

Thus, in the "semiprofessional" context of the classroom, it is essential to remember that student learning is the ultimate goal, not necessarily the advancement of knowledge in a field based on its published research. In this school-based context, however, grades do act as a motivating device and also present some level of disparity for students imagining their instructors as readers/graders. Maxine noted that one instructor was "a very big picture man. As long as you can step outside and see what's going on, he'll give you a good grade." In contrast, she saw the instructor/grader for the lab report as "picky on the details." Nevertheless, that instructor noted that

> *I appreciate that this is a student effort; I'm not the editor of* Nature *trying to accept this for publication. It is a little scary to have to say something intelligent about something that someone knows much more than you do.*

Writing Assessment in Laboratory Fundamentals of Biological Engineering As was previously noted, both technical faculty members felt that the first writing assignment would need to change for future semesters. They agreed that the intent of the assignment was sound—to write a focused argument based on the novel research of genome engineering—but indicated a need to find the right balance between structure and openness. The second assignment will largely remain as is: a report, styled like a journal article, about students' lab work; however, the lab content will likely change as faculty try to give students experience with emerging areas of biological engineering research. In addition, faculty note the need to help students better integrate primary literature into their papers, particularly as they discuss unexpected findings or put the research questions themselves into the context of previous research. This sort of professional discursive move is a challenge in this particular environment when students, most of whom are sophomores, simply have not had the experience of reading primary literature, much less mastering the specific body of research in this field.

Nevertheless, the intent of both of these writing assignments was to offer students an opportunity to experience the discursive life of a biological engineer. One of the two faculty members consistently talked about this future outcome and framed her language in terms of students' identities as researchers. In describing the ideal outcome for students learning to write up their research, she said:

> [Students need] *to critically evaluate data and to pull loose ends together in a story they can argue—that they can make an argument, an articulate idea that they can express and try to make sense of the work that's in front of them—because that's something they'll have to do; they'll get data back, and they'll say, "What does it mean?" If it has some familiarity, I don't even know if they'll think back to this class, but if the next time that they do it, it feels familiar, that's great. They would have it as part of who they are.*

This sense of "who they are," then, is a mix of student and professional identity. Students become novice researchers learning from mentors and from each other. Key elements for this learning in Laboratory Fundamentals of Biological Engineering are lab experiences that approach “authentic” activity. In their lab experiences, students work on new and relevant issues in a new and relevant field, and they have ample opportunities to write up this research, to receive feedback, and to rewrite. These practices fit well the essential conditions for learning that has been described as “cognitive apprenticeship” [13], of which laboratory learning is one type:

> First, students come to understand the purposes or uses of the knowledge they are learning. Second, they learn by actively using knowledge rather than passively receiving it. Third, they learn the different conditions under which their knowledge can be applied. ... Fourth, learning in multiple contexts induces the abstraction of knowledge, so that students acquire knowledge in a dual form, both tied to the contexts of its uses and independent of any particular context. [13, p. 487]

In Laboratory Fundamentals of Biological Engineering at MIT, the conditions for learning as “cognitive apprenticeship” or as professional experience were certainly present. The experiences of Maxine show the relatively uncertain route toward those goals, hazards that must be recognized and attended to, if the experience is to be successful.

CASE STUDY 2: ADDRESSING TEAMWORK CHALLENGES IN COLLABORATIVE COMMUNICATION

Rationale for a Focus on Teamwork in Collaborative Communication Engaging in specific writing and speaking tasks, as explored in Case Study 1, introduces students to the criteria of their discourse community. Learning how to produce that communication collaboratively is yet another professional skill they must learn. For engineers, the ability to work successfully in teams is a cornerstone skill that supports high-quality technical work. Of course, engineering students are not strangers to teamwork. By the time they reach their undergraduate courses, they have been active in co-curricular activities, academic projects, and multiple organizations. Yet many of them have not had instruction about team skills, and many of them may not have used those team skills in such fast-paced or complex settings to solve such challenging problems. Although some professors assume that putting students in a group and assigning a project will provide the necessary learning, other faculty understand that, as Lewis, Aldridge, and Swamidass point out, “Students ... do not appear ... to acquire teaming skills in the absence of structured experiences designed to develop these competencies” [24, p. 149].

Engineering and science education literature on teamwork abounds in articles, books, and conference papers. Improvement of team skills has been clearly specified in engineering accreditation criteria [25]. Yet even a quick and partial review of that literature demonstrates that educators use the term “teamwork” easily and variously. While it is likely that most educators are referring to the same general abilities, it is worth observing that in some settings, “teamwork” connotes entrepreneurship and creativity, while in other contexts, it connotes leadership or conflict resolution. In some institutions, the emphasis is on understanding learning styles and their effects on interpersonal dynamics and project management [26].

Student definitions may vary as well. In one study that surveyed two groups of students (N = 2,777 and N = 1,157), findings indicated five factors that contributed to students’ understanding of effective teamwork and subsequent behaviors: contributions to the team’s work; interactions with teammates; keeping the team on track; expectations of quality; and possession of relevant knowledge, skills, and abilities [27]. Yet in one focus group at MIT, students could not agree on central teamwork skills other than leadership.

Moreover, while some researchers provide a useful starting place for defining teamwork (e.g., [28]), engineering and science faculty may persist in their particular definitions of effective teamwork. Investigating whether or not their definitions and those of their students converge is necessary for efficient interaction and meaningful assessment.

Team skills are important not only because engineers commonly work in design teams or research labs but also because nearly 90% of engineering professionals report collaborative writing and speaking as part of their jobs [29]. Therefore, in the MIT Department of Aeronautics and Astronautics, documents and presentations are often collaboratively created and given, and the team skills that support that work are the subject of discussion and assessment.

In addition to the emphasis on collaborative work, the Department of Aeronautics and Astronautics also preserves the benefits of learning to compose individual documents and presentations because we believe that effective collaboration must be based on strong individual contribution as well as a clear understanding of writing process.

Thus, in an effort to achieve this objective, each capstone course in the department includes individual writing or presentation preparation that then contributes toward a collaboratively written document and/or presentation that reflects the work of the design or research team. Individual faculty members and teaching teams interpret this goal flexibly to meet the pace and scope of the particular project. While some capstone courses work with large design teams, in the case study described here, we focus on a capstone course structured around small teams.

Context and Implementation for Teaching Teamwork in Aeronautics/Astronautics

Experimental Projects Lab I and II (or 16.62x in MIT's numeric language) illustrates one implementation of CI and team-oriented learning objectives. This two-semester course begins as teams of two (and sometimes three) students choose partners, a project, and a project advisor. The projects are primarily proposed by various members of the department faculty although sometimes a student team will create its own project proposal and invite a faculty member to advise them. Generally, the experimental projects are ambitious and rigorous, and time constraints require student teams to work efficiently together.

To define precisely the terms used in this case study description, we use "faculty" to mean the leading professor, an engineering professor in the department. We also use the term to mean the communication instructor who consults on both writing and presentation, and the graduate teaching fellow. The faculty members run the course, give lectures, hold conferences with students, and assign grades. By "advisor," we mean the department member who advises the project because she or he is a subject-matter expert in the area. At times, an advisor is recruited from another discipline, but chiefly the advisors are from the Department of Aeronautics and Astronautics. The advisor meets with the team approximately once a week and advises the members on their experimental process. The technical staff comprises the personnel who run the laboratory and shop facilities and consult on fabrication and implementation issues.

The goal of the first semester is to design a research project to the level of specificity that makes it possible for the team to implement successfully the project during the second semester. The learning objectives for the two semesters are for students to be able to complete the following:

- formulate the success criteria and objectives for an experiment that allows the team to assess a hypothesis;
- develop, as a team, the strategy for the design of the experiment and for data analysis procedures to achieve these objectives;
- implement, as a team and on schedule, the detailed design of the experiment and data analysis;
- execute, as a team and on schedule, the experiment that will assess the hypothesis;
- communicate, orally and in writing, the results of the design process and ultimately the key aspects of the overall project. [30]

Both semesters are based on teamwork, and students collaboratively produce five out of the seven communication products. Students begin with individual writing and individual writing conferences that lay a solid base for collaborative communication work. Lectures given by the communication instructor help students through the writing process. Lectures are grounded in active learning and in the examination of models of past proposals.

In Experimental Projects Lab I, students keep individual lab notebooks, and they individually write two iterations of a design proposal. However, their project work, their meetings with one another and their advisor, and their meetings with the faculty are all done as a team.

Students begin their first semester by collaboratively developing a hypothesis but individually writing design proposals. The collaborative writing of the hypothesis ensures that team members and their project advisor (who is not a member of the teaching team) clearly understand and can communicate their thoughts to one another and to the faculty. After the collaborative hypothesis, students then write individual design proposals in iterations:

(1) The first iteration of the proposal includes an introduction, background, and significance section; the hypothesis; a short literature review; and a technical description of what the experimenters plan to do. Engineering faculty comment on and support the instruction in writing. Before the due date for the first iteration, each student also brings a draft to a 30-minute conference with the communication instructor. The first iterations of the proposal are turned in, commented upon by the communication instructor and by the engineering faculty, graded, and returned to the student. The expectation is that comments on this version will be incorporated into the next revision.

(2) In the second iteration of the proposal, each student adds sections on experimental design; data analysis and error mitigation; project planning (scheduling, budget, facilities

needed); and a summary and conclusion. Again, students meet for writing conferences with drafts of their final proposal. The documents are submitted, commented upon, and graded. These final iterations are high stakes writing for the students since their experimental design section must be deemed sound and specific enough for the team to go forward into their second semester.

For the teaching team and the project advisors, the design proposals give a perspective on the ability of each student to conceive of and design experimental research. However, the ability of the team to converge on the design of an experiment also emerges. By reading one student's articulation of the project against his or her partner's proposal, the faculty gain an expanded sense of team functioning. As Loughry, Ohland, and Moore observe, a "major factor accounting for project success [is] the effectiveness of various team processes" [27]. Likewise, other researchers have observed that team difficulties and project problems are linked, but these researchers also conclude that the quality of student written reports is correlated negatively with poor project performance and team dysfunction [31], [32]. Thus, the design proposals and the iterative writing process, along with the periodic team meetings, provide a way not only to mentor students in technical prowess and writing ability but also to investigate potential gaps in team functioning.

The team's first collaborative communication project comes at the end of the first semester when students make a short presentation of their design proposal. Again, the model is that students begin individually on elements of the presentation although they are encouraged to then merge their work. They hear short lectures from the communication instructor. The team practices the presentation with the communication instructor and one or two other teams and receives feedback from both the instructor and their peers. Then, the team makes its presentation and receives questions and comments from the faculty, their advisor, and sometimes their peers. The teaching team grades the oral presentations, and the team members share the grade equally.

In the second semester, Experimental Projects Lab II, the student teams spend little time in the classroom because they are at work in the lab or the shop. The two oral presentations in this term are completed collaboratively, and the final report that describes the entire two-semester experiment is collaboratively written. Again, students receive support through short lectures and writing conferences with the communication instructor.

The challenges in teaching students about collaborative communication divide into issues around content and around process. High-quality content is at the heart of all technical writing and speaking. As students begin to put together a document or a presentation, they often find that the content lacks specificity or is unfocused or (not uncommon) missing. Teasing out the reasons behind these content problems quickly foregrounds team issues around task assignments, lack of consensus, points of confusion, lack of needed skill sets, documentation and scheduling problems, difficulties with responsibility, responsiveness, and basic interpersonal communication. Thus, an early learning objective for students in Experimental Projects Lab I is to understand not only that substance is at the heart of all technical writing and presentation but also that this content is most often produced by strong teamwork. The insistence on substance is reinforced through lectures, through weekly meetings with advisors, through the periodic grading of lab notebooks, and through team meetings with the team members, their advisors, the technical staff, and the faculty. Feedback to the students is explicit, and student teams who are not working in a substantive way find themselves in close conversation with their faculty members and project advisor until the problems are addressed. Team dysfunction that may have produced these difficulties is also a topic of discussion.

Next, collaborative communication also requires composing processes that may be unfamiliar to students. Student interviews document that most of our students have strong individual writing processes, but collaboratively produced communication involves multiple authors who are completing technical work as they simultaneously represent those technical advances in words and graphics. Several drafts are usually necessary to capture accurately the fast-moving work, yet undergraduate students often tend to avoid the drafting and revision process that is necessary to collaborative work. Moreover, most students have only been recently introduced to technical writing, so they may be unfamiliar and perhaps awkward with the conventions of that style of writing or the organizational demands of a large technical report or presentation. In addition, one or more of the team may have significant writing deficits. To complicate matters, student writers and speakers in teams often struggle to achieve a collective, professional voice.

Lastly, collaborative writing in the 21st century brings additional challenges since student writers working on a collaborative document or presentation may be producing it in an asynchronous and distributed manner. Information and partially completed drafts of the document move between writers and editors via email or wikis or through academic management sites. While students may be comfortable with communicating electronically, asynchronously and at a distance, their existing composing and editing practices may not be robust enough to stand up to the organization of a communication with complex information. Moreover, the challenges of electronic, asynchronous, and distributed collaboration expand along with numbers of writers and the scope of the project.

Students faced with collaborative writing tasks need help structuring this interaction to achieve greater coordination [33]. They also need to be guided in adopting a composing style that best fits their team or their work [29]. Because they are unfamiliar with possible ways to divide composition work (horizontal, sequential, stratified), students often fall back on their individual abilities and the linear model [33]. One member assumes the responsibility for writing large parts of and editing the presentation slides or the final report. This style is usually ineffective, inefficient, and inequitable, but it is familiar.

In Experimental Projects I and II, the communication instructor gives guidelines on how to put together a collaboratively written report or presentation and leads a discussion on conflict resolution strategies. Emphasis is placed on more precise documentation, use of style guides, careful division of labor and responsibility, and more realistic scheduling. Additionally, there is discussion about which method or model of composition best fits the team's process. In addition, the communication instructor also reviews presentation slides, organizes "dry runs" or rehearsals, and meets with students and teams for individual writing conferences. Moreover, the communication instructor is available to review presentation slides at any time during the second semester, although many students feel confident in their abilities at that point. Students share the grade for collaborative documents and presentations, so usually students invest a good deal of energy in the collaborative communication process. However, there are instances of "social loafing" and "hitchhiking" that are troublesome for the student teams, detract from the general level of professional accomplishment, and pose problems in assessment for the faculty.

Assessment of Students' Team Skills in Experimental Projects Lab Assessment of team skills is an important part of helping students develop their skills. Not only is development of team skills part of departmental and institutional accreditation, assessing the effectiveness of team skills also allows faculty to measure those skills and assess their own pedagogical outcomes. However, this is the more challenging task when faculty use collaborative writing and presentation strategies; separating the assessment of team skills from technical and communication ability is not easy.

Faculty want to help each student develop his or her team abilities and to ensure that each student contributes equally to the project. A number of questions arise. Should assessment of team skills be summative or formative? Should assessment of team skills be part of the student grade or not? Self-assessment and student reflection are important, but do these measures qualify as rigorous and valid assessment of team skills? How helpful are self-assessment and peer-assessment to a student? Effective assessment of team skills is challenging, and the need for confidentiality is also demanding; consequently, when working with small teams as in Experimental Projects Lab I and II, team assessment can be so general that it is not truly useful to the students. Some researchers suggest that short, specific peer assessment instruments are most useful in summative rather than formative assessments and when tempered by the professor's own observations (e.g., [27]). But it is not easy to apply this recommendation to large student groups with subsystem design teams that may or may not work closely together. Nor is this conclusion applicable in smaller teams, such as those in Experimental Projects Lab I and II, where confidentiality is difficult to preserve.

Moreover, what do students need to know about team skills? And do team styles vary between disciplines, such as science and engineering? Most students in end-of-semester debriefing sessions in this course have said that lectures on team skills have not been helpful while just a few students have said that learning more about the stages of team formation was useful. In focus groups in a larger three-semester capstone course, students said lectures and readings about teams were not helpful, but students did want some specific advice on how to schedule their technical work. What becomes evident from discussion with student groups is that their definitions of team skills vary widely. Some students focus on conflict resolution, leadership, interpersonal abilities, and others focus on documentation, scheduling, and division of labor strategies.

How students learn about team skills is not clear either. In a recent focus group, students responded that they learned most from modeling the behavior of more experienced students and from the one-on-one mentoring of their project advisor or professor. Again, this group of students reiterated what an earlier group had said: didactic teaching is not useful to them in developing team skills.

It seems likely that effective teamwork in engineering and the resulting collaborative communication about that work do not arise from a simple list of behaviors to be memorized in a lecture hall but rather from a set of evolving and complex practice-based skills that accompany professional development. A lecture would be easier to give, but it is possible that what is required is ongoing and specific interaction with students who are trying to learn the complex and interlocking elements of effective engineering teamwork. Nor is assessment easily encapsulated. For some contexts, quantitative assessment may be effective; in other contexts, the qualitative and reflective approach may be more useful to young engineers.

Yet for all the challenges, teaching, mentoring, and assessment in teamwork are necessary because of the strong connection between high-quality teamwork, successful research, and sound design work and the collaborative communication in which they are represented. Our students need team skills that range from interpersonal sensitivities to pragmatic project-management abilities. With a comprehensive set of team skills and the awareness that collaboration is a common element of engineering, our students will be able to apply those skills no matter what the specific disciplinary challenges may be.

CASE STUDY 3: DATA-DRIVEN ARGUMENTS IN BIOMEDICAL ENGINEERING

Rationale for Studying How Students Learn to Make Visual, Data-Driven Arguments With its integration of engineering, medicine, and science, the field of biomedical engineering presents novel research challenges. From technology-development projects that focus on designing and verifying the validity of a new optics imaging device to hypothesis-driven projects that focus on understanding cellular-level changes in tissue scaffolds, the field of biomedical engineering includes perspectives from audiences across many disciplines [34]. Considering this “interdisciplinary challenge,” biomedical engineering students must be taught quite varied skills in communicating their research to readers from both science and engineering disciplines.

A central communication skill that is at the core of biomedical engineering research is the effective presentation of data. On one hand, in technology-development projects, researchers use data to convince readers that their design is optimal and feasible. On the other hand, in experimental research, biomedical engineers use data to provide accurate explanations of research findings with detailed explanations of those findings [34]. For experimental researchers, weighing various kinds of data evidence and providing alternative critiques of experimental research findings are central to the practice of conducting research [35], [36]. Furthermore, given this value placed on data argument in experimental research, the effective design of visuals is critical [37], [38].

Nevertheless, when students write research articles, they often do not fully understand how to select and design meaningful plots for their audience [39]. Students tend to make two common errors in their presentation of data: (1) They select poor figures to represent their findings, or (2) they offer little guidance to readers on how to interpret those figures through descriptive captions or supporting textual explanations. As a result, many students mistakenly assume that raw data or a series of similar-looking plots are effective. What students do not yet realize is that pages upon pages of raw data are not only unreadable, pages of raw data also do not guarantee that the research findings are valid. Students may also assume that the “data speak for themselves,” and thus, they may offer sparse textual explanations of their designs or findings [40]. However, visuals need meaningful captions and other supporting features to guide readers to the thesis, the main point, of a figure.

In the process of learning to think like professional biomedical engineers in communicating their research results, students must internalize that it is the job of the writer to provide thorough, concise, readable explanations of research findings through visual representations of findings. Scientists and engineers read articles strategically and are unlikely to spend time deciphering overly complicated plots (or prose) [41], [42]. In fact, it is not uncommon for readers to skim the visuals of a research article after reading the title and abstract of the article. In such instances, the visuals presented in the results section are read first, and then the supporting text and other sections of the article are read [43], [44, pp. 30–31].

Overall, the need to argue from data is aligned with the contexts of cases 1 and 2, with professional competencies as a driving curricular force and teamwork/collaboration as an instructional process toward those goals. Through the process of learning how to present research data in clear, readable figures, students must learn how to think and read like professional biomedical engineers, determining how their audience will process visual presentations of data. In their own writing, whether alone or in teams, students must learn how to “translate” raw data into meaningful syntheses of their findings so that readers are given an accurate synopsis of research results. In both writing and visual representation, students must be taught to be mindful of their ethical responsibilities to data collection and analysis. In reading research, students must also learn how to discern the accurate representation of data from potentially fallacious misrepresentations. This last point is particularly important for students to learn if they are to become professional reviewers and journal editors [45]–[47].

In the biomedical engineering course described in this case study, our goal is to teach students how to create meaningful representations of original research findings. Many students who come to this course already know the general structure of a research article. What they lack is an understanding of how to **use** that form to make a valid case for their research findings. Specifically, they lack an understanding of how to read, design, and critique the visual representations of data that are the centerpiece of research articles in biomedical engineering.

Context and Implementation for Teaching Argumentation from Visual Data Quantitative Physiology: Cells and Tissues (or 6.021J in MIT’s numeric language) is a large-lecture, undergraduate course in biomedical engineering. In the course, students study the principles of mass transport and electrical signal generation for biological membranes, cells, and tissues. The course also has several communications-learning goals, including the following: (1) Students will learn to integrate the research and writing processes, and (2) through learning the storyboard approach to selecting and representing quantitative findings, students will learn to present more concise and accurate presentations of their data that give readers confidence in their experimental research.

In Quantitative Physiology, writing is associated with two projects: an experimental project in a wet lab and a theoretical study using computer simulation. Each project lasts approximately five weeks and is carried out in parallel with lectures, recitations, and homework assignments.

Students are introduced to the first project assignment, a microfluidics experiment, approximately three weeks into the course. After selecting a research partner, students write a proposal that describes their proposed lab research. The purpose of the proposal is to ensure that students have well-defined projects before they enter the lab. Without well-defined projects, students will likely gather poor data and, thus, the process of trying to present that data in a meaningful fashion will be frustrating. Even in the proposal stage of the class, the lead technical professor reminds students that the goal of their research is to convey research data accurately, not to make data fit a particular theory:

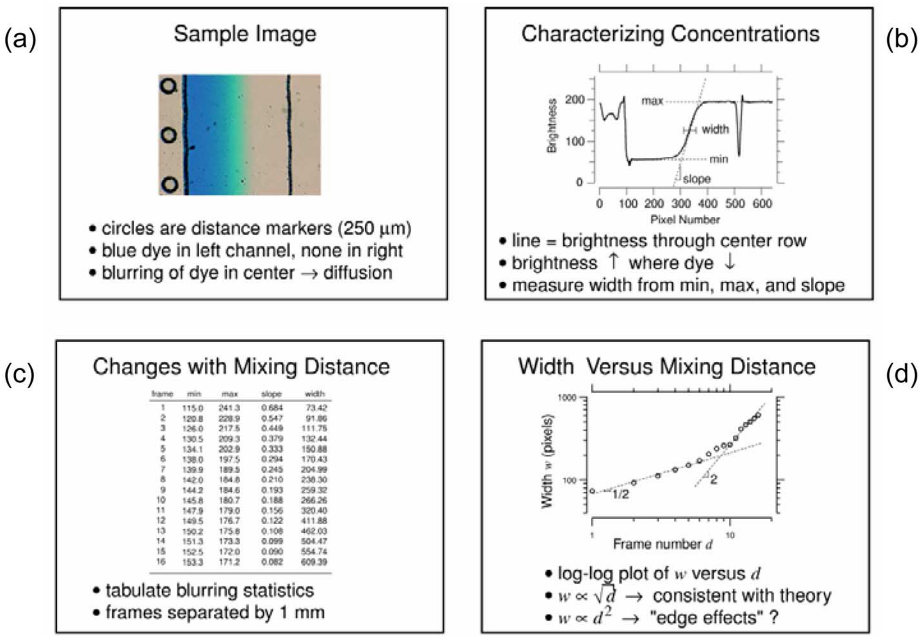
> When you do your experiment, you may get unexpected results.... You should explore unexpected results and try to understand their bases. Your aim should be not simply to reject or accept your hypothesis, but to develop insight into the phenomena.... Keep in mind that this is an **experimental** project. Your goal is to characterize **what** happens, not **why** it is happening. Theoretical analyses may support your experimental findings. However, your grade will be primarily based on the reliability of your data. [48]

Within one week, students submit their proposals for review. Initially, approximately 75% of proposals are rejected because the students’ research approach is too broad or their methodology is unfocused. After receiving substantial feedback, students revise and resubmit their proposals until their research approach is approved.

While students are in the process of gathering lab data, we provide a lecture on how to take the data they gather in the lab and prepare a written presentation of their findings. This lecture is given collaboratively by the lead technical professor and writing program instructor. In this lecture, we model how professional biomedical engineers think about communicating their findings throughout the data-gathering process.

Given the limited scope of the projects in Quantitative Physiology, we suggest that their principal results can be refined into five or six specific figures, whether hard copies of data obtained in an experiment or simply hand-sketched figures of expected results. The point is to assemble the five or six specific figures into a storyboard, or narrative of the research. The point that we want to stress to students here is that often researchers cannot present every finding within the limited space of a research article. The tension for a researcher is to select meaningful figures without misrepresenting their results.

By developing a storyboard, students also focus on what information is, or is not, important in each of the figures. For each figure, students are asked to identify the two to three points that are most important for the audience to understand.



(a) Sample Image

- circles are distance markers (250 µm)
- blue dye in left channel, none in right
- blurring of dye in center → diffusion

(b) Characterizing Concentrations

- line = brightness through center row
- brightness ↑ where dye ↓
- measure width from min, max, and slope

(c) Changes with Mixing Distance

frame	min	max	slope	width
1	115.0	241.3	0.684	73.42
2	120.8	228.9	0.547	91.86
3	126.0	217.5	0.449	111.75
4	130.5	209.3	0.379	132.44
5	134.1	202.9	0.333	150.88
6	138.0	197.5	0.294	170.43
7	139.9	189.5	0.245	204.99
8	142.0	184.8	0.210	238.30
9	144.2	184.6	0.193	259.32
10	145.8	180.7	0.188	266.26
11	147.9	179.0	0.156	320.40
12	149.5	176.7	0.122	411.88
13	150.2	175.8	0.108	462.03
14	151.3	173.3	0.099	504.47
15	152.5	172.0	0.090	554.74
16	153.3	171.2	0.082	609.39

- tabulate blurring statistics
- frames separated by 1 mm

(d) Width Versus Mixing Distance

- log-log plot of w versus d
- $w \propto \sqrt{d}$ → consistent with theory
- $w \propto d^2$ → "edge effects" ?

Fig. 1. Sample storyboard, used with permission from Dennis Freeman.

If the list for one figure contains more than three important points, we suggest that the student consider whether the points might be more clearly made with more than one figure. Similarly, if there is only a single interesting point associated with a figure, it might be possible to merge figures to more meaningfully show trends in the findings. The goal in this step is to incorporate all of the interesting results into a logical presentation of the research findings. Fig. 1 is a storyboard that we use as an example of research from a microfluidics project. It includes the key figures selected for a research article: (a) a figure for the methods section that would be included with a schematic diagram of the microfluidics device; (b) a plot that synthesizes the main findings; (c) data provided in tabular form; and (d) a regression analysis of the findings.

After explaining this model storyboard, we give students a challenge—analysis of several problematic storyboards. The students work with a partner to figure out the problems with the various example storyboards. The challenge has the effect of ensuring that students gain, at least, a rudimentary understanding of the storyboard concept. We revisit the storyboarding concept multiple times after this lecture so that students have multiple opportunities for learning.

After two weeks of lab work by the various groups, students are ready to write a draft of their final report. Once students have completed their research, the teaching assistants review the students' lab notebooks to ensure that the storyboards are suitable. Students then work together to draft a 3,500-word scientific paper. Students submit three copies of their reports, one copy each for the technical staff, writing staff, and peer. We then reconvene one week later at a writing clinic. At the writing clinic, papers are returned, and students speak with reviewers about their comments.

As we review the student drafts, we often find that some students do not grasp the storyboard approach that we outline in our communications lecture. As a result, these students' report drafts display little coherence across figures, lack textual explanations, or are poorly designed. We address these issues in our written comments on student papers, our peer-review guidelines, and in a general letter to the class from the lead professor. For example, a comment by a teaching assistant or writing reviewer might point to a problem across several images (e.g., "All of these plots seem to be making the same point but at different concentrations. Can you condense these 8 figures into 4 or even 1 meaningful figure that shows a clear trend in your results?").

The lead technical professor also returns to the idea of the storyboard in summary comments to the class. For example, in fall 2006, the professor wrote the following, along with other comments on how to improve the report drafts:

> **Create a Storyboard:** The most important section of your report is the Results section (this is true for all technical reports). Think

> of the Results section as a presentation of technical findings that is intended to lead the reader to some set of conclusions. Construct the presentation using figures that build upon each other. The first figure should be close to the raw data (e.g., images, calibration results, etc.). The later figures should show more highly processed results that build on the earlier figures.
> **Storyboard Method:** Start with your figures. Assemble your figures into a storyboard. Associate 2–3 bullet points with each figure. Arrange the figures and bullet points so that each flows naturally into the next.
> **Common failure modes:** The Results sections of many of the first drafts seemed to be collections of relatively independent figures that did not build on each other to convey a higher level message. Many Results sections had little text, suggesting that little thought had gone into the purpose of the figures. The first figure in many of the first drafts showed highly processed results (e.g., ratio of swelling in six conditions as a function of concentration of X) that is the main result of the study. This is a bad strategy. Why should a reader believe that the ratio of swelling is the important thing to measure? Why not the difference instead of the ratio? You should show individual swelling relations first, so that the reader can independently come to the conclusion that computing the ratio is a good thing. [49]

After receiving comments from the reviewers, students revise their reports and submit their final manuscripts, along with comments from their peer reviews, within one week. Students' revised, final manuscripts are graded by the same writing and technical faculty who graded their draft reports (Appendix D).

What are the challenges in teaching students how to make arguments with data? The first challenge is having students design projects that will yield useful data. We strongly believe that the best educational research experiences are ones in which students gather original research. Because there are no "right" answers with original research findings, students cannot rely on the faculty to give them the "correct" answer or specific instruction to get the right answer. To ensure that students yield useful data in their lab work, they need help defining their projects. Although the proposal-writing process in Quantitative Physiology requires additional time on the part of the faculty and teaching assistants, the initial time spent reviewing student proposals saves time later in the lab. Rather than helping struggling students redefine poorly defined projects once they are in the lab, the teaching assistants can dedicate more of their time in the lab to helping students decipher their data and to answering more substantive questions about the research process.

Another challenge is getting students to make plausible interpretations of their findings. Students often cling to the idea that they must **prove** a particular theory or that anomalous data mean that their experiment was a failure. By repeatedly reinforcing the idea of the storyboard, we encourage students to move beyond these simple conceptions of scientific research to see how their own data, even if messy or inconclusive, require an explanation that a reader can follow. This approach also helps us remind students that the responsibility of the researcher is to give data a thorough and accurate explanation, not to merely dismiss problematic findings as equipment failure or shoddy research.

A third challenge is getting students to evaluate each other's data critically. Students must be given explicit advice on how to critique data in a peer report and must be rewarded for those efforts. This process includes looking at plots and tables as well as supporting text. As one student observed last year, sometimes it's useful to look at a plot and ask, "Is there anything really useful there?" In order to accomplish this goal of engaged peer review, peer review efforts should be included in the final report grade.

Finally, teaching students to make visual arguments with data in the 21st century brings some specific technological challenges. Plots generated in programs like MatLab do not easily import to Microsoft documents, and students who work across platforms often have difficulties sharing figures because images become easily corrupted. We encourage students to generate multiple output forms of their data and to use PDF files. We have also designed specific programs to help students output data from MatLab so that they can focus on data collection and analysis.

Assessment of Student Learning in Quantitative Physiology In order to understand more about student learning in Quantitative Physiology, we conducted a qualitative study of student learning in the class. Our goal in this small study was to investigate how students' understanding of the research process changed over the semester. We interviewed eight students six times over the course of the semester. Five of the interviews were conducted while students were completing the microfluidics lab project, and one interview was conducted at the end of the semester. We interviewed students five times during one experiment, so we could identify key moments in the learning process. We asked students questions about collecting data, reporting results, collaborating with a partner, and giving/receiving peer review. We also asked them general questions about the scientific research process.

After interviewing students, we coded the data thematically to reveal general trends in the interview responses. At the end of the semester, students saw the research and writing processes as more interrelated. Students no longer thought about research occurring only in the lab and about writing as crafting grammatically correct sentences. Students also learned that analyzing data, creating compelling arguments, and revising their written work require much more time than they originally thought. For example, when we asked students if they discovered any limitations or new possibilities in their data while writing their report, students reported that they found new insights in their data analysis. One student responded:

> *I learned that the data can be analyzed in many different ways, with differing results. The important part of data analysis is to objectively analyze the data in a way that is logical and independent of the actual results. I also learned the importance of analyzing seemingly insignificant deviances in the data. You can't just assume that the theories are always correct.*

The peer review process was also a valuable way for students also to gain new insights into making arguments with data. For example, another student said this:

> *One of the things I realized from the peer review especially is that there are many ways to take data and analyze data, so it is important to justify to the reader why you took a specific approach and why you think it's valid—particularly because it might not seem that obvious to someone else. Also, data presentation matters—both in terms of tables versus figures and text description in Results. Our first draft, we primarily just threw the data at the reader, in the final we tried hard to present it more pointedly.*

These comments support our general observations about student writing in Quantitative Physiology. When students revise their reports with feedback from multiple reviewers, the average grade from draft to final increases by approximately one letter grade. From a qualitative assessment perspective, we have found that students' reports are better organized, that the figures they select better convey their research findings, that their figures are clearer because we have addressed issues in visual design such as axes and captions, and that their data analyses include greater attention to detail. As a result of these improvements, we can focus our efforts on further clarifying and refining student understanding of concepts rather than correcting major misunderstandings in report organization and presentation of findings. This has also allowed us to deepen our assessment of student writing to address issues of novelty and conceptual correctness (Appendix D).

We have also found that the focus on storyboarding translates well to oral presentations. For their second project, students give an oral presentation rather than submit a written report. Using the storyboard approach, students are able to design more focused oral presentations of their findings without the common errors found in PowerPoint presentations.

In the field of biomedical engineering, the effective presentation of research results in visual form is an important element in research writing; using reader-expected standards for data representation allows readers from varied disciplinary backgrounds to understand and assess the validity of the findings. Thus, in biomedical engineering classes students need data representation skills that go beyond basic information design. By learning to select key figures of their research findings, integrating those figures into a cohesive storyboard, and critiquing the data in peer manuscripts, students learn one of the most important ways that professional researchers think about communication and research.

CONCLUSION—AND RECURRING QUESTIONS

This article highlights various approaches used in MIT's CI curriculum in trying to generate methods that help students develop the advanced communication thinking skills required of professional engineers today. Using identity as a central concept in a CI course such as Laboratory Fundamentals in Biological Engineering reveals how students struggle to develop a professional identity, even within the space of seemingly simple writing activities in the disciplines and, thus, reveals how we must constantly revise and update our approaches to help students gain a professional identity in that discipline. Using teamwork as a central concept in a CI course such as Experimental Projects Lab I and II has allowed us to explore the connection between successful collaboration in design and communication. Finally, using arguments with data as a central concept in a CI course such as Quantitative Physiology has allowed us to explore the relationship between writing and the data representation and, thus, to change how we teach the process of writing up original research findings.

It is important to note that it is not our intent to create a divide between what is possible at a resource-rich institution such as MIT and other institutions not similarly fortunate. If anything, the questions we raise in these case studies and the limits of our instruction are applicable to many institutions struggling to create meaningful educational opportunities in engineering communication. One significant limit is raised by the very presence of a large cadre of WAC instructors with specific expertise in teaching writing and the subsequent potential for a perceived split between teaching “writing” and teaching “content.” Getting engineering faculty more involved in these processes and applying concepts of teamwork and collaboration to the larger enterprise of CI classes at MIT are ongoing challenges.

Our research and the case studies we present here raise other widely applicable questions: What does it mean for educational practice if professional communication competencies and tasks are the goals? How can students and technical faculty best create the conditions for students to learn to be skilled team members? How can engineering students move from mere display of data to making skilled visual arguments based on those data? By no means have we figured out the complete answers to those questions, but we hope that the case studies we present show some potential paths to finding those answers, as well as obstacles in those paths.

Additionally, our inquiry into the teaching of communication at MIT represents “teacher-research” or “action-research” [50] meant both to improve practice and to broaden our knowledge of what it means to learn to communicate as a scientist and engineer. Thus, the sustained research in which we continue to engage—via surveys, focus groups, individual interviews, and analyses of students’ work, all in the context of contemporary theories of teaching and learning—are essential activities for communication professionals in any setting.

It is also not our intent for the case studies presented in this article to be the final word on the redesign of communication instruction in engineering education. Our intent, instead, has been to highlight the ways that a commitment to teaching communication within disciplinary frameworks at MIT has brought to the fore three key aspects that require attention: professionalization, teamwork/collaboration, and argumentation. Each of these aspects is present in some degree to all of our CI classes, and each reveals the opportunities and complications for designing communication instruction.

APPENDIX A

20.109(S07)—GENOME ENGINEERING ESSAY

Assignment You are asked to write a thoughtful, researched essay exploring how a foundational engineering concept (e.g., abstraction, modularity, insulation, standardization, decoupling) can be applied as a design tool for biological engineering. Your lab work with M13 will provide the context for your argument.

Abstract This has been written for you to clarify the assignment. You can include this abstract as your own.

> To engineer novel biological systems, we need to change the genetic code of existing biological materials, not by making a few changes as current methods allow us to do but rather by making lots and lots of changes in a fast, cheap, and reliable way. Just as “plug-ins” provide new or improved functions to existing computer programs, the current tools of molecular biology allow for piecemeal modification to genetic programs, adding functionality but often complexity and clumsiness as well. In this essay I will describe two approaches to biological programming, ad hoc adjustment, and complete refactoring, as applied to the simple genome of the bacteriophage M13. With both approaches, I will show how the application of a foundational engineering concept, namely (abstraction, insulation, standardization, decoupling, modularity...choose one), enables more reliable and elegant genetic programming and can give rise to a platform with more flexibility and fewer restrictions.

Introduction From your introduction, your readers expect to find out why your topic is important and why they should be interested in it. To do that, you need to describe the larger context for the work, the ways it’s important, and the specific areas your paper will address. There’s no need to hide your main point or approach. At the end of the introduction, the reader should want to learn how the foundational idea you've chosen (abstraction, modularity, insulation, standardization, or decoupling) serves a useful purpose and affords great opportunity if incorporated among "best practices" for biological engineers, expecting M13 to be the test case they'll follow.

Launch this section using one of the following quotes, or a personal favorite.
- Today, most software exists, not to solve a problem, but to interface with other software. (I. O. Angell)
- Programming languages should be designed not by piling feature on top of feature, but by removing the weaknesses and restrictions that make additional features appear necessary. (Anonymous, Revised Report on the Algorithmic Language Scheme)
- Programs for sale: Fast, Reliable, Cheap: choose two. (Anonymous) Think (design) globally; act (code) locally. (Anonymous)
- Think twice, code once. (Anonymous)
- Weeks of programming can save you hours of planning. (Anonymous)
- Any fool can write code that a computer can understand. Good programmers write code that humans can understand. (M. Fowler, "Refactoring: Improving the Design of Existing Code")
- A program like Microsoft's Windows 98 is tens of millions of lines of code. Nobody can keep that much complexity in their head or hope to manage it effectively. So you need an architecture that says to everyone, "Here's how this thing works, and to do your part, you need to understand only these five things, and don't you dare touch anything else." (C. Ferguson "High Stakes, No Prisoners; Times Business Press")

Explicitly describe what problem or issue the quote you've chosen highlights and how the point applies to genetic programming as well.

Next...well, it's really up to you. You could
- allow one of the more familiar software disasters to illustrate comparable design problems that can be encountered when making biological materials;
- describe some (but not all) current practices in genetic programming and their limitations;
- introduce M13 as the example you've chosen to hack and debug.

Some ideas you may want to introduce are listed but this list is neither exhaustive nor mandatory:
- complexity;
- simplicity;
- refactoring;
- features of good/bad computer programs;
- features of good/bad genetic programs;
- standardization;
- decoupling;
- abstraction;
- usefulness;
- discovery.

Body: Parts 1–3 In these sections you will build off of your introduction to present M13 as an example of the issues you've highlighted. Your readers expect to learn something from what you present; thus, you'll need to supply ample description as well as an analysis of your lab results. Remember your goal is to make a persuasive argument for the concept of abstraction (or modularity, insulation, standardization, decoupling...) with evidence from your laboratory experience.

Part 1: How it's built: M13 as a test case

At the conclusion of this section, the reader should have a good understanding of
- the prevalence and diversity of bacteriophage;
- the M13 life cycle (include a figure if you like);
- the size and organization of the genome;
- the proteins encoded by the genome structure (include a figure or table if you like);
- any natural variations to the genome.

End this by highlighting how "engineerable" the natural example seems, and how (abstraction, modularity, insulation, standardization, or decoupling) are key to reliably and predictably accomplishing this.

Part 2: Build to learn: M13 and piecemeal fixes

At the conclusion of this section, the reader should have a good understanding of
- the application of M13 for phage display, cite at least one successful application of this technique;
- the limitations/variations of phage display;
- the modification to the genome that you performed in lab and what useful purpose it could serve;
- your plaque assay and Western data, be it positive or negative (include a figure and table).

End this part by commenting on how fast, cheap, and reliable this approach proved to be. On the scale of other engineering feats, how ambitious was it? How much expertise was required? How can you imagine making it an easier and more robust engineering task?

Part 3: Learn to build: Refactored M13

At the conclusion of this section, the reader should have a good understanding of
- what refactoring is;

- what the rough draft of refactored M13 tried to do;
- which gene (gII, gIX, etc.) you refactored and how you approached/solved the specifics of that problem;
- your plaque assay and Western data, be it positive or negative (include a figure and table).

End this part by commenting on how refactoring compares to ad hoc tweaking and how much or how little promise it holds for building fast, cheap, and reliable biological systems.

Conclusions or Summary In this section, your readers expect you to tie up the concepts you raised in your introduction with the specific examples you've described in terms of M13. Most important, you need to supply some "future thinking" about the implications of what you've presented, whether for future experimental work or the larger field.

APPENDIX B

20.109(S07)—EXPRESSION ENGINEERING REPORT

Assignment You are asked to write a formal lab report detailing your work in this module. Specifics for each section of this report are detailed below. General information about formatting the report are mostly addressed here.

Abstract

- Please keep the number of words under 250.
- Do not include references in the abstract.
- Try drafting this section after you've written the rest of the report.
- If you're stuck, start by modifying one crystallizing sentence from each of the sections of your report.
- Please do not plagiarize (accidentally or other) the class wiki. This applies to your entire report.

Introduction

The homework you wrote after the first day of this new module will serve at the heart of your introduction. You should add (at least) one final paragraph to narrow the information "funnel," ending your introduction with a clear description of the problem you're studying and the method you are using. If you would like to preview for the reader your key results and conclusions in the last sentence of your introduction, you may.

Materials and Methods

If you used any kits for any of the manipulations, it is sufficient to cite the manufacturer's directions, e.g., "yeast were transformed according to the Q-biogene transformation kit protocol." Subdivide this section into the following:

(1) Yeast strains and plasmids
  - list genotypes and plasmid names when known.

(2) PCR
  - include primer design info here;
  - include primer sequences, for knockout and for candidate verification;
  - include PCR cycling conditions.

(3) Yeast transformation
  - include how you selected for transformants;
  - include what you did to verify that URA3 was integrated where you thought.

(4) Yeast Microarray
  - mention kits as relevant, including any deviation from published protocol if any;
  - mention how many yeast and how much RNA was used;
  - describe array analytical methods in results section rather than in Materials and Methods.

Results: Figures

You should include but are not limited to the following figures and tables:

Figure 1: panel A: table describing transformation results; panel B: agarose gel verifying URA3 insertion.
Figure 2: Spot test images.
Figure 3: Microarray analytics.
Figure 4: Microarray conclusions.

Each figure should be numbered, and should have a title and legend text

- In paragraph form, describe each figure and the observations you made.
- As much as possible, reserve conclusions about your data for the discussion section. Clearly an exception to this will be which of your deletion candidates was correct, as this information is critical for the next steps in the experiments.

Discussion

You should include but are not limited to

- conclusions you can draw from your work, including any uncertainties;

- other data (published or personal communications) that support or contradict your conclusions;
- limitations of your work, e.g., what kinds of experiments/controls would have been great to include;
- next experiments you would like to try to extend your findings and strengthen your conclusions.

APPENDIX C

START OF SEMESTER STUDENT SURVEY FOR CASE 1—LABORATORY FUNDAMENTALS OF BIOLOGICAL ENGINEERING

Your name: ____________________________________
Class standing (check one): ___FR ___SOPH ___JUNIOR ___SENIOR
Gender: ___M ___F
Age: _________

1. What is your primary language for writing and speaking? _________
2. What other languages do you write and speak? _________
3. What have been some of your experiences with writing up scientific content (whether research, lab reports, review articles, etc.)?
4. Describe a significant writing experience, whether in or out of school:
5. What do you struggle with most in your writing?
6. What are your strengths as a writer?
7. What kinds of reading and writing do you do outside of school?
8. What kind of writing do you expect to do after graduation from MIT?
9. Why do you think 20.109 has been designated as a Communications-Intensive class?
10. What are your writing goals for 20.109?

APPENDIX D

MULTIDIMENSIONAL SCORING RUBRIC USED TO GRADE STUDENT REPORTS IN QUANTITATIVE PHYSIOLOGY

10%	**First draft of report** A: Complete report, professionally written. B: Significant work, but report needs further clarification before final submission. C: Incomplete descriptions, missing sections, or poor figures. D: Few results, few figures, few discussion points, report not complete.
5%	**Critique of peer report** A: Several helpful high-level suggestions (e.g., suggesting major restructuring, new figures,...) plus probing questions (could your result be caused by...?) plus appropriate low-level comments (e.g., on grammar or graphics). B: At least one helpful high-level suggestion or probing question plus low-level comments. C: Helpful low-level comments. D: Few helpful comments.
15%	**Report Structure** A: All information is present and is well organized in proper sections, using standard scientific report structure. Appropriate use of source materials. Reader can easily follow from section to section of report. B: All information is present but poorly organized in no more than one section. Reader may have difficulty following one section of report but generally understands overall report structure. C: All information is present but multiple instances of misplaced information, and/or repeated minor organizational problems that interfere with report coherence. D: Information is missing from report, report does not follow standard scientific report structure and/or misuse of source materials. Reader cannot follow overall structure of report.
10%	**Clarity and Conciseness of Exposition *** A: Content of each paragraph is readable with clear, simple prose and appropriate use of technical language. Each graph clearly supports the prose. B: content is readable with minor slips in clarity or a single unclear passage/graph. C: Major slips in clarity and/or multiple unclear passages/graphs. D: Repeated wordiness or lack of clarity, poor presentation of visual information, and/or accumulation of stylistic errors that interfere with readability. * Grades may be reduced for reports that unnecessarily exceed the 10 page (3,500 word) limit.
10%	**Technical Clarity and Conciseness** A: Methods, Results, and Conclusions are technically clear and concise. B: Minor lapses in technical clarity or occasional extraneous technical points. C: Significant lapses in clarity and conciseness, but clear enough to assess results and conclusions. D: So unclear that results or conclusions cannot be assessed.
20%	**Conceptual Correctness** A: Thorough investigation of at least one topic, authors demonstrate a clear understanding of this topic, and there are no technical errors. B: Thorough investigation of at least one topic, and no technical errors. C: Thorough investigation of at least one topic, but one or more minor technical errors. D: Investigations are insufficiently thorough (e.g., measured too few cases to support a trend) or contained major technical errors.
30%	**Insightfulness** A: Clever experimental design, compelling experimental results, and imaginative analysis. B: Clever experimental design, compelling experimental results, or imaginative analysis. C: Acceptable experimental design, adequate experimental results, and acceptable analysis. D: Unacceptable experimental design, inadequate experimental results, or unacceptable analysis.

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