# MIT'S INTRODUCTION TO BIOLOGICAL ENGINEERING: A LONGITUDINAL STUDY OF A FRESHMAN INQUIRY-BASED CLASS

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## ABSTRACT

*We describe an introductory class in biological engineering that uses project-based and mentored inquiry to create a supportive, exciting, and effective learning environment. Freshman students at MIT work in small teams and with senior MIT students to design a biotechnology that addresses a real-world challenge of their choosing. Students gain familiarity with the tools and vocabulary for biodesign first through some hands-on experiences with synthetic biological systems and later by working in teams to define, present and then refine their ideas. A multi-year study of the class experience and impact included postsurveys and semistructured interviews of two freshman cohorts and a retrospective survey of three freshman cohorts. Data support the claim that students perceive academic gains through their project-based classroom*

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*experience. Freshmen reported they are better able to understand content in some of their other MIT courses, are better able to read scientific articles, and now think differently about biology. Moreover, they indicated the class was valuable in learning technical content and synthetic biology. We find this project-based class helps students make meaningful connections to scientific ideas, to personal goals and to a vision of their future selves.*

Early in their academic careers, freshmen students at Massachusetts Institute of Technology (MIT) are hard pressed to identify anything, anything at all, that they don't like about MIT. When explicitly asked by the Dean of Undergraduate Education about disappointments or let-downs, a look of confusion comes to their faces. "What's not to love?" is the implied or explicit answer they give. They feel that the people are great, the excitement is palpable, and they can't wait for classes to start. Yet poll those same students a year later when they return to campus for the sophomore year, and we find they have a slew of misgivings and a ready list of discontent. And while some change in attitude is reasonable to expect, given the rigor of MIT's freshman curriculum and the personal growth that most students experience in college, there is clearly a culture shock for most students and a perceptible deflating of the spirit in many.

All of MIT's freshmen take General Institute Requirements in their freshman year including a year of Physics and Calculus, and a term of Chemistry and Biology. These classes usually enroll several hundred students in the lecture portions and so are often far larger than the students experienced in high school. The classes are also considerably more academically challenging. On MIT's admission blog (MIT Admissions Office, 2008), one student who struggled in an accelerated freshman Physics class wrote,

> You know, people say that physics is only learned through practice, but I quickly realized that I had an issue. The class was moving too fast for me to practice. The lectures didn't teach ANYTHING. They consisted entirely of PowerPoint presentations that talked about theories, general concepts, and information that never actually taught me how to do physics.

The disconnect between theory and practice is evident in this student's description of his experience, and many students are surprised by the dramatically elevated expectations as they move from high school to college. The happy ending for this freshman's story is that he switched to a slower-paced section of physics and ultimately earned a "B" in the class.

But believing that his story is representative of the culture shock most freshmen experience at MIT during their first year, MIT's Task Force on the Undergraduate Educational Commons wanted to improve the freshman experience, and they recommended our Institute experiment with project-based (PB) classes designed for freshmen as a way to sustain their motivation and enthusiasm for learning (Healey, 2005). Informed by some successful PB-classes MIT teaches for upperclassmen and with financial support from the d'Arbeloff Fund for Excellence in Education, six new PB-classes for freshmen were taught for the first time in the 2006–2007 academic year (Freeman, Cooper, & Lucas, 2007). These were "add-on" classes to the standard collection that freshman enroll in. The home departments offering these classes ranged widely, from Mechanical Engineering to Architecture and Urban Planning. However the PB-classes had unifying goals that included design-motivated cross-disciplinary learning, synthesis of ideas and techniques, and the use of real-world problems to drive disciplinary knowledge. Students in these classes had an opportunity to develop solutions that met personally meaningful challenges. The solutions were devised through their own informed decision-making process rather than by their work towards a single-solution that had been prescribed in advance.

Coincident with these initial offerings of freshman PB-classes, MIT's Department of Biological Engineering was established. Offering the first new undergraduate major at MIT in nearly 30 years, the Department of Biological Engineering was undertaking a number of educational experiments of its own. In particular, the new Department designed several classes whose the explicit goal was to define Biological Engineering as an engineering discipline and to distinguish this new major from existing programs in Biomedical Engineering and in Biology. The tagline used by our new department, "creating biological technologies, from discovery to design," was broad enough to incorporate many ideas and approaches. It was also so broad that it articulated little about our educational mission or approach. To help freshmen students understand MIT's new undergraduate major and this new field, Professor Drew Endy and I (NK) taught a freshman PB-class starting in the Spring of 2008. We named the class "Introduction to Biological Engineering Design," and it was given the MIT course number of 20.020 (Kuldell, 2013b), which is read aloud as "twenty-twenty."

We liked this number a lot since it reflected our hope that the class would help students perfectly envision the roll that Biological Engineering could play in their MIT education, in their future careers and in the world. Though Professor Endy left MIT in 2009 to teach at Stanford University, the class has been taught for 12–20 students by one of us (NK) and evaluated by another of us (RM) each Spring since 2008.

20.020 gives students the opportunity to design a biotechnology that is responsive to a real world need. Over the 14-week term, we guide the class through different "phases" transitioning from whole group activities (labs, videos, role-playing etc.) and teacher-led discussions in phase 1, to work in small teams, student presentations and consultations with technical experts in phase 2. We mentor the freshmen students in multiple ways while they discover their interests and as they take increasingly more ownership and responsibility for the project they've devised. Meaningful learning comes through this process of authentic, mentored inquiry (Donovan & Bransford, 2005; Freeman et al., 2014). Inquiry-based classrooms avoid the "mental slavery" that John Dewey cautioned against nearly a century ago (Dewey, 1938/1997), and directly support student interest and engagement (Boyer, 1998). Inquiry-based classrooms are inherently authentic, interdisciplinary, and reflective because students ask their own questions (Cummins, Green, & Elliott, 2004; Luckie et al., 2012), a skill that is viewed by some as the single most valuable thing we can teach them (Rothstein & Santana, 2011).

## CLASS STRUCTURE

### *Phase 1: Provide a Conceptual Framework for Synthetic Biology*

At the start of the term, 20.020 is taught through short interactive lectures, and with hands-on activities intended to give students direct experience with engineered living systems. These lectures and activities establish the basic techniques, strategies, and vocabulary for biological engineering. For example, the first few lecture hours emphasize an abstraction hierarchy that is used in a subfield of biological engineering called synthetic biology. The abstraction breaks complex systems into manageable and distinct levels of detail. At the highest level, called "Systems," a plain language description of the biotechnology is required. For example, "I want a cell that can detect arsenic and turn red when it detects unsafe levels of the contaminant" is one system-level description we use in the class that meets an environmental grand challenge. At the other end of the abstraction hierarchy is the DNA sequence that encodes the genetic parts to build the living system. The students are shown where such sequences can be found on the Internet, and they come to appreciate how modern scientific understanding and their own grasp of it enable the engineering of living systems. We return to this aspect of the class later in this chapter because, according to our assessments, its impact on their experience is tremendous.

The engineering strategies and vocabulary the students hear about in lecture are reinforced by direct experimentation. We provide some prototypical examples of engineered living systems for them to measure, manipulate, and test. These hands-on activities include smell tests of bacteria engineered to smell like bananas, and introduction of DNA into bacteria to turn the cells purple or green. There are activities in which students use computers to model and simulate the behavior of unnatural DNA circuits. We also set up roll-playing activities in which they anticipate public reaction to biological engineering as an emerging technology. The variety and charisma of these activities really "hook" the students on the potential of engineering the living world, as well as raise their awareness of science and engineering in society. During interviews of the students conducted by one of the authors (RM), we hear comments that echo this student's (caseFL) comment, "When you are doing hands-on stuff, everyone is pretty much excited. I think that is just the nature of the work. And everyone is like, 'Oh, this is really cool to see as the end result'." The activities requiring microbes are sourced from our bioengineering teaching laboratory that is physically near the PB-classroom, but all the activities can be carried out in a traditional (non-laboratory) classroom with impervious and paper-covered tables to keep the reagents, and after Biosafety Level 1 training of the students by our office of Environmental Health and Safety.

### *Phase 2: Design a Biotechnology*

The activities and vocabulary that are central to "Phase I" of 20.020 provide a platform and common experience that students draw on as they move into the design phase of the class. One student, caseTL, noted how, "We started by designing our general idea of the system, an abstract version of it. Natalie had taught us about black-boxing things. [We first identified] what we wanted the system to do. Then we focused on how we would actually get it to do that."

Intentionally, the Phase I lectures and activities apply equally well to any of the challenge areas that students are considering for their own projects. Topic areas such as "food and energy," "health," or "environment," are deliberately kept broad, and students have the freedom to choose which topic area to work in. We could have chosen to focus the class so that all students address a common goal, such as clean water one year, and sustainable fuel the next. However, since we wanted students to feel genuine investment in their project, we allow them to choose the challenge area and to set their own goal. Furthermore, because they are freed from the obligation of implementing their final designs in a lab, they are happily unencumbered by the voices that say "it won't work" or "that can't be done here." One faculty member emailed, after hearing about a project idea that aimed at remylenating neurons, to say, "Sounds exciting. I would argue that not knowing what is possible in the brain, however, can be useful for the synthetic biologist – maybe something new can be created, from scratch!"

### *Project Management*

If shepherding a classroom full of open-ended student-selected projects seems daunting, there are at least three aspects that we've implemented in our PB-class that we find make the effort manageable. The first of these aspects is class size, admittedly the one aspect that teachers cannot easily control. Scheduling conflicts, interest level and who knows what else typically keeps 20.020 enrollment to two dozen students each spring, with approximately three-quarters of them ultimately completing the class. Another aspect that keeps our open-ended PB-class manageable is that students generally group themselves into a small number of project areas, five or fewer, with anywhere from two to seven students in each group. Why this happens isn't clear.

The aspect of our class that has the greatest impact on its management is an unusual overlay we've designed in which a second class runs as a companion class with the freshman PB-class, a seminar course called "20.385: Current Research in Synthetic Biology" (Kuldell, 2013a). This class runs with anywhere from six to 12 students who are generally juniors or seniors majoring in biological engineering at MIT. Students in this advanced class not only read and discuss the current primary literature each week, but they are also assigned as a mentor to one team of freshman, working with them during the long block of "studio time" that is set aside for the freshman to develop their project ideas. Such interactive, constructive activities have been shown to increase student learning outcomes (Menekse, Stump, Krause, & Chi, 2013; Mohamed, 2008). Indeed, our assessments have invariably indicated positive outcomes for both the freshmen and the advanced students when grouped to collaboratively develop project ideas. For example, one freshman, caseSN, noted how the mentors are helpful but not prescriptive, saying "they have seen other things that we have not, and can offer their perspectives. At the same time, they are not trying to impose little stuff on us because we actually have more raw knowledge on the topic than they do." Mentors invariably know more about the ups and downs of their team's project development and the team's interpersonal dynamics than the course instructor. One freshman student, caseNA, made the following reflection.

> Our mentors are just like friends. They are like big sister and big brother .... They help us polish our slides, to make our slides better. When we present, they are in the room and listen to our presentation. During the rehearsal, they ... help us to prepare. They pretend to be the other students and raise questions.

## MILESTONES

Once the teams are formed and their mentors are assigned to them, the freshmen work towards a presentation to the class of three project ideas in their grand challenge area. These "3 ideas" presentations are given six weeks after the term begins, and they address high-level aims, not implementation ideas. For example, students explicitly discuss how large a problem they are focusing on, how much their project could help, if other technologies exist to address this challenge and if there are things that are unknown or unknowable about this challenge. In the area of "food" one year, the team's three ideas were (1) tartar controlling "Bacto-gum," (2) protein-enriched rice, and (3) cells that remove toxins from clay in places where "geophagy" (literally "earth eating") is practiced. Feedback on each team's three ideas helps them decide which of the three projects to pursue for the rest of the term. For example, the teams frequently must decide between designing a solution that makes a large impact on a relatively small problem or another solution that has a small impact on a gigantic challenge. Both outcomes are equally valued in this class. Feedback also points the teams in the direction of similarly themed projects that may exist and they are given additional articles to read if there are publications that relate to their ideas.

Within one week of their three ideas presentation, the teams are required to narrow their three ideas down to one, a decision that frequently stresses team dynamics for the first time. Students often grow attached to one of the three ideas, especially if it is the one they initially proposed to the group. This winnowing from three ideas to one can also be a first-experience with evidence-based argumentation. For example, one student, caseEE, reported the following.

> In my high school, I was one of the smarter people. And here, everyone was top of their (sic) class in high school. In high school, everyone would agree with me. They would go with what I said …. Even if I were wrong, they would agree with me …. But here, everyone has [his/her] own opinions, own ideas. And sometimes we conflict because everyone has [his/her] own ideas. Everyone is really smart here. So definitely, working in groups has been a little more challenging than it was in high school because you are not really the one in charge anymore.

To help with the dynamics at this junction of their work, the freshmen teams rely on their senior mentors and on as many published journal articles they can find and understand quickly. On rare occasions, teams can't choose and so two of the three ideas remain viable, but in most cases one idea seems the most appealing for the team to pursue at the next, more technical level. The engagement of students in this choice is evidenced by comments such as that of caseFL, "I liked the project idea that my team decided to go with. It was very easy for me to do research on it and get involved with because it was something I was passionate about."

The "Tech Spec Review" is the next milestone in the team projects, and is reached intentionally quickly, just three weeks after the three ideas presentation. The team's initial technical specification requires they provide a preliminary outline using the abstraction hierarchy that was presented in the lectures and activities earlier in the term, an initial simulation of their biotechnology using a modeling tool, and, most importantly, a list of open questions that they are trying to address. For the "food" team's three ideas listed above, they decided to pursue the "bacto-gum" project, specifying a bacteria-infused chewing gum that would detect other bacterial cells that were growing in high population numbers and in the low pH environment around teeth, and then release an anti-inflammatory agent to improve gum health. Unknowns for the team at this point were things like, "how would the bacteria in the chewing gum sense pH in the mouth," and "would the system work only in the mouth and not in other places in the body where anti-inflammatory compounds would be undesirable." Teams must commit to a "GO/NO GO" decision on their project at this point in the term, and most, including the "food" team described here, feel sufficiently confident in their ability to further define and describe their project that they give their work a “GO”. The rare “NO GO” teams move to a “runner-up” project from their three ideas presentation.

The final five weeks of the term are dedicated to refining the design and specification of their projects. Lectures and hands-on activities are rare but important in this home stretch of the class because they help students polish their projects. Short lectures present tips for things like measuring reliability of different systems or for giving powerpoint presentations. Teams meet in class and often outside of class research and to develop their project idea into one that could be implemented in a lab.

In addition to the guidance provided by the team mentors, the final few weeks of the project development cycle include “consultations” with two or three experts in the team’s area of study. These consultations not only “up the game” for the freshmen, who are anxious about presenting their ideas to someone whose journal or news articles they’ve read, but the consultations also prevent the students from putting off the final push of hard work it takes to fully refine their idea. The “bacto-gum” team, having changed their project to a yeast-based one after the Tech Spec Review, met with a yeast geneticist, with a student from Harvard Dental School, and with an immunology expert, Professor Hidde Ploegh from the Whitehead Institute. Our assessment of 20.020 as a freshman PB-experience consistently shows how important these meetings with consultants are for the students.

The range of final project ideas from this PB-class is tremendous. Freshman biodesign teams have proposed living systems for accelerating composting, stemming the red-tide algae blooms, harvesting lithium from ocean water, replacing defective genes in patients with muscular dystrophy, regulating iron levels in the blood of female athletes, and many, many more blue-sky project ideas. The ideas are based on extensively researched scientific understanding, but the teams are also granted some liberty in their designs, with imagined “black boxes” to mask the complexity of genetic functions that are, as of now, incompletely understood or as yet undiscovered. As the term ends, students leave the class wishing they could extend their work to a laboratory setting. In addition to their intellectual eagerness, students have also learned to work with each other in healthy, deadline-respectful ways and they are sad to break up their teams as the term ends.

## METHODOLOGY

Since 2008, one of the authors (RM) has conducted a study of the course with the 2008, 2011, 2012, and 2013 cohorts. Each cohort consists of freshmen enrolled in the spring semester of the course. For each cohort, Dr Mitchell conducted semistructured interviews; for the '12 and '13 cohorts, a postsurvey was added. In spring, 2014, a post-postsurvey was administered to the '11, '12, and '13 cohorts. In this chapter we review results from the combined '12 and '13 cohort surveys and interview data, as well as data from the post-postsurvey. The fifteen-minute, online postsurveys explored learning activities, class atmosphere, and impact, and consisted primarily of statements for which students expressed their level of agreement by means of a 7-point Likert Scale (1 = strongly disagree and 7 = strongly agree). Survey data were analyzed using IBM SPSS Statistics, version 22 (IBM Corp., 2012).

Students from the '12 and '13 cohorts participated in the interviews that were conversational, informal, and ranged in length between 20 and 30 minutes. By means of several open-ended questions, the interviews explored students' view of the experience, its impact, and their attitude toward the experience. The interviews were audio taped, and transcriptions were made of each session. A content analysis was performed on the responses (Corbin & Strauss, 2008; Maxwell, 2012; Weiss, 1994). In this chapter, two letter codes serve to distinguish participant comments.

## RESULTS

Twelve of the 2012 cohort and eighteen of the 2013 cohort completed the post survey (response rate = 63% and 90%, respectively). 30 students completed the post-postsurvey (response rate = 73%). Survey links failed to reach six students who should have been surveyed with the post-postsurvey instrument, limiting the opportunity to participate to only 41 of the 47 possible respondents.

Analysis of the survey data of the interview responses (Mitchell, 2014) supports the claim that students perceive academic gains through their PB-classroom experience. For example, in their responses to the 2012 and 2013 postsurveys, for which Tables 1 and 2 provide greater detail, freshmen reported they are better able to understand content in some of their other MIT courses ($M$ = 6.10), are better able to read scientific articles ($M$ = 5.97), and now think differently about biology ($M$ = 5.90). In responding to the post-postsurvey, students indicated the class was valuable in learning technical content ($M$ = 5.76) and synthetic biology ($M$ = 6.03). During the interviews, several students identified intellectual connections to

***Table 1.*** Descriptive Statistics for Combined Data from 2012 and 2013 Postsurvey Items that Relate to Team Experience and Class Atmosphere.

| Items | *N* | *M* (SD) | neg% | neut% | pos% |
|---|---|---|---|---|---|
| Q4e. Working in a team was an important part of my experience in 20.020 | 30 | 6.43 (1.22) | 3 | 3 | 93 |
| Q4f. The senior mentors were an important part of my experience in 20.020 | 30 | 5.53 (1.41) | 7 | 7 | 87 |
| Q6a. I found 20.020 fun to attend | 30 | 6.63 (0.49) | 0 | 0 | 100 |
| Q6b. I found the class exciting | 30 | 6.53 (0.57) | 0 | 0 | 100 |
| Q6c. I found myself looking forward to class | 30 | 6.43 (0.68) | 0 | 0 | 100 |
| Q6d. I felt inspired by this class | 30 | 6.07 (1.14) | 0 | 13 | 87 |
| Q6e. I felt like sharing my ideas in this class | 30 | 6.20 (0.81) | 0 | 3 | 97 |
| Q6f. I felt I could take intellectual risks in class | 30 | 6.23 (0.68) | 0 | 0 | 100 |
| Q6h. Our team ran into challenging problems | 30 | 6.73 (0.45) | 0 | 0 | 100 |
| Q6i. Our team successfully worked through or around challenging problems | 30 | 6.23 (1.01) | 3 | 0 | 97 |
| Q6j. Our team successfully worked through frustrations related to designing our system | 30 | 6.27 (0.91) | 3 | 0 | 97 |

*Note*: Neg = negative, neut = neutral, pos = positive. The negative category represents the percentage of students who indicated they *strongly disagree*, *disagree*, and *slightly disagree* with statement. Neutral category represents the percentage of students who indicated they were *neutral* toward the item. The positive category represents the percentage of students who indicated they *slightly agree*, *agree*, and *strongly agree* with the statement.

***Table 2.*** Descriptive Statistics for Combined Data from 2012 and 2013 Postsurvey Items that Relate to Impact.

| Survey items | *N* | *M* (SD) | neg% | neut% | pos% |
|---|---|---|---|---|---|
| Q9f. I was better able to understand content in some of my other MIT subjects (e.g. 7.01x) | 30 | 6.10 (0.99) | 0 | 10 | 90 |
| Q9g. I am better able to read primary scientific literature | 30 | 6.03 (0.96) | 0 | 10 | 90 |
| Q9h. I feel that I can better explain ideas to others | 30 | 6.17 (1.02) | 0 | 10 | 90 |
| Q11d. As a result of 20.020 I now think differently about biology | 30 | 5.90 (0.84) | 0 | 7 | 93 |
| Q11e. As a result of 20.020, I am a better problem-solver | 30 | 5.83 (1.23) | 7 | 10 | 83 |
| Q11f. As a result of 20.020, my confidence in defending my ideas increased | 30 | 5.90 (1.03) | 0 | 13 | 87 |
| Q11g. As a result of 20.020, my confidence in interacting effectively as part of a group increased | 30 | 5.97 (1.03) | 3 | 3 | 93 |
| Q11h. As a result of 20.020, I am better able to read scientific articles | 30 | 5.97 (1.00) | 3 | 3 | 93 |

*Note*: Neg = negative, neut = neutral, pos = positive. The negative category represents the percentage of students who indicated they *strongly disagree, disagree,* and *slightly disagree* with statement. Neutral category represents the percentage of students who indicated they were *neutral* toward the item. The positive category represents the percentage of students who indicated they *slightly agree*, *agree,* and *strongly agree* with the statement.

other subjects they studied at MIT, as evidenced by quotes such as caseDM's. "We are doing a project right now that is really hands-on … soaking in knowledge that 7.013 (Introductory Biology) could not pump into me. I am doing this myself." Or that of another student, caseJC, who said "the kind of things I learned in 18.03, differential equations …. It was like, 'Oh my God, I have never seen this explained in biology classes. This is really cool.' The idea that you can engineer biology is fascinating." Students credit the class structure as well as their classmates for their meaningful learning, for example one student (caseDM) made the following comment.

> [When] you are looking at articles, understanding the material, and putting a system together with your team … you learn a lot. I have learned more from the four members of my group than I have from the research online. They have [taught] me different things … or maybe something that I did not hear in bio or did not grasp.

The students' appreciation for the PB-framework goes beyond their increased knowledge of technical content. Students consistently remark on the intellectual energy and ownership they feel for their projects, for their teams and for their learning. They identify several aspects of the class atmosphere that evoked this emotional impact, aspects including their feelings of safety, the classroom's emphasis on openness, and the absence of excessive amounts of stress. One hundred percent of the freshmen felt they could take intellectual risks in class ($M = 6.23$) and 97% were willing to share their ideas in class ($M = 6.20$). The inter-relatedness of these aspects of the classroom atmosphere is emphasized in caseDM's comment, "It is not like … if you mess up this little bit, … you are going to fail. It is laid back. We are learning at our own pace. You are learning the stuff that pertains to your project." Several students commented how the instructor (NK) made high quality work and learning the priority for students. One student, caseJT, noted, "It is her supportive guidelines, the outline for the class expectations, as well as her demeanor when she is talking to us …. It is very clear she … wants us to learn above everything else, which we are definitely doing!" In the postsurvey responses in both 2012 and 2013, 100% of the freshmen viewed the class as exciting ($M = 6.53$) and fun ($M = 6.63$), and found themselves looking forward to the class ($M = 6.43$). For 87%, the class inspired them ($M = 6.07$). Fig. 1 compares how positively students viewed different aspects of the class which were reported in the post-postsurvey. Even a year or more later, 100% of the students who responded to the post-postsurvey indicated how much fun the class was ($M = 6.67$). One commented on the post-postsurvey instrument, "My group from

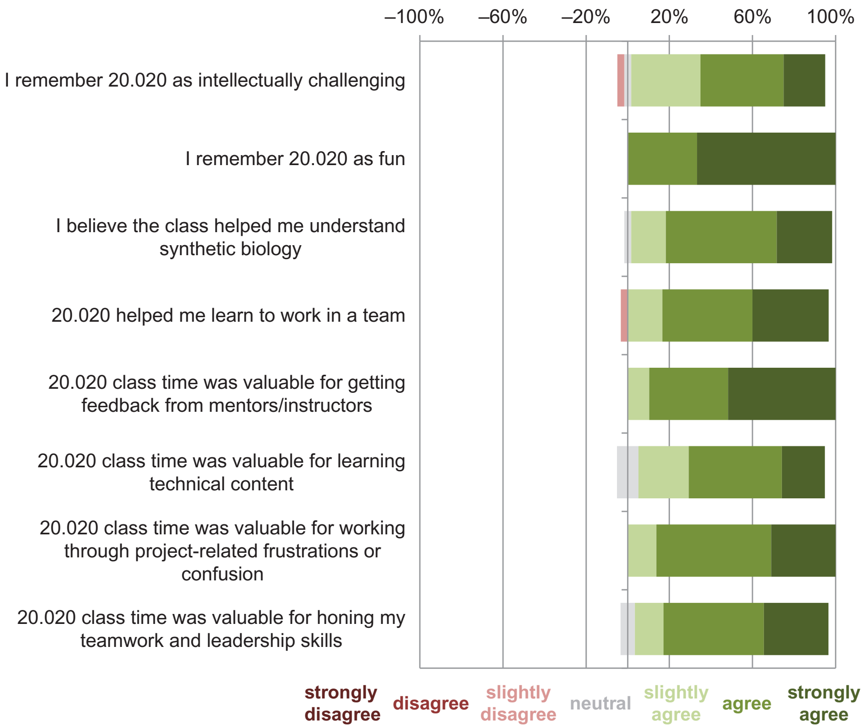


*Fig. 1.* Distribution of How Students Viewed the 20.010 Experience One-to-three Years after Completing the Course, Views They Reported by Means of a 7-point Likert Scale (1 = strongly disagree and 7 = strongly agree) to Statements on the Post-postsurvey. *Note*: The survey was administered in spring 2014 to the 2011, 2012, and 2013 cohorts. Thirty students completed the post-postsurvey (response rate = 73%). Survey links failed to reach six students who should have been surveyed with the post-post survey instrument, limiting the opportunity to participate to only 41 of the 47 possible respondents.

20.020 still keeps in touch and occasionally has dinner together!" and another wrote, "I really enjoyed/remember fondly all of the experiments we performed to visualize the concepts that we talked about in class!"

The emotional connection that students feel for their team and their project extends to the relationship students developed with their team mentors, the advanced students in the companion class for 20.020 who facilitate freshman teams' project development. The mentors were seen as resources for content, as able teachers, and, at times, as mediators. For example, when projects or individuals were following unproductive paths, the freshmen in 20.020 could rely on the mentors to refocus the work.

> They kept us on track. They would ask us, "Oh, how is it going? Is everything working?" Then, we would have to stop whatever we were doing and make sure that everything was working, and usually [we would] find problems. So, they were definitely useful. They did not solve problems for us, but they helped us to solve our problems. (caseAC)

With the 2012 and 2013 postsurvey data, we found 87% of the freshmen viewed the mentors as an important part of their 20.020 experience (mean = 5.53); in the post-postsurvey, 100% of the students valued their work with the team mentors (mean = 6.41).

Personal resiliency in response to setbacks and frustrations is one of the most surprising aspects of the class for the students interviewed. The safe classroom atmosphere and the support they felt from their teams and the team mentors encouraged the freshmen students to work through the challenges they faced.

> I never had to do anything like this before. So it was a new experience. It was harder than I thought it would be to [put] things together that would work to achieve our purpose, and not interfere with each other or have all sorts of horrible things happen …. Kind of frustrating … Searching for what we needed was hard …. Once we found articles, reading through them and trying to figure out if they were actually relevant, which most of them were not, was difficult. (caseAC)

The projects posed challenges, and the challenges were compounded by the freshmen sometimes underestimating the difficulties of the design task. As one freshman, caseFL, explained,

> The [abstraction] was very helpful for me because when we first started, we just black-boxed it, like this is a device. And I was like, "Oh, this is really cool. This is the input. This is the output." I [thought,] "That is really easy." And then, when I got into it, I am like, "Okay, that is a lot more work."

Along similar lines, caseHM commented,

> In the beginning, we are working on a project, thinking "Oh, yeah, sure, that project seems pretty simple … we can do it." But, as we read more and more, more unknowns came up, getting more complex every day …. Having [to think up] the design was not very difficult …. But finding the parts so that we can make it [work] was very challenging.

In the 2012 and 2013 postsurvey responses, 100% of the freshmen indicated they ran into challenging problems ($M$ = 6.73), and 97% reported working successfully through or around the challenging problems, or through frustrations related to designing their systems ($M$ = 6.23). They reported that as a result of this class, they are better problem-solvers ($M$ = 5.83) and have gained greater confidence in defending their ideas ($M$ = 5.90). In the post-post data, students remembered the class as intellectually challenging ($M$ = 5.70) and valuable for working through project-related frustrations or confusion ($M$ = 6.17) with 93% reporting it challenging and 100% reporting it valuable to working through their confusion.

Students relied on the literature and on each other to meet the challenges and frustrations arising from their work. The findings indicated that each student group moved its project forward based not on ego or personality, but based on research findings. One student, caseDM, offered this insight into the team's dynamics.

> It is kind of interesting because we do not disagree on where the project is going. [If a student] pulls up an article that says this, X, Y, and Z, I read the same thing she is reading. I am like, "Okay. That makes sense. Let us try to implement this in our project." We are not so much giving opinions. This project, we want to make it as realistic as possible. So we just go by the rule that the article we are reading is correct .... Let the research, let the articles do the talking.

Postsurvey data revealed that 93% of the freshmen reported that working in a team was an important part of their 20.020 experience ($M$ = 6.43). In the post-postsurvey, students reported the class helped them learn how to work in teams ($M$ = 6.10). They found class time valuable for honing their teamwork and leadership skills ($M$ = 6.03). In every year we have taught the class, students self-identify personal improvements in teamwork as one of the most profound and satisfying aspects of the class. CaseDN's comment is typical:

> I am really close with my project group. We work really well together. Even if there were people [with] whom you did not work very well, ... [early in the semester] you learned how to work together, which I think is really important, especially in [Biological Engineering]. ... [This] is a very collaborative field and we are going to be doing a lot of group projects ... in the next three years. So, it was really important to get exposure to that.

## DISCUSSION

We find that this PB-class is a supportive, exciting, and effective learning environment that helps students decide their academic and personal path.

Year after year our assessment of this PB-class reveals that the students make meaningful connections to scientific ideas, to personal goals and to a vision of their future selves.

If MIT students, who are arguably among the most STEM-oriented teenagers in the world, credit their PB-experience in 20.020 for improved understanding of technical material and as a lasting realization of their professional and interpersonal skills, then what could such a classroom experience do for students who are less inclined to study science and engineering? Asked another way: could a PB-class such as the one described here reveal for non-STEM students how creative, interdisciplinary and optimistic science and engineering can be and reveal that there is a place in this effort for them? The complex problems that engineers address have multiple solutions, and we have shown that such complexity can engage students as contributors. Open discourse around challenges in a safe environment factor into their learning, as does mentored inquiry. Fully adopting the framework we've outlined here presumes some things about class size, time, and leadership as well as resources for teaching. However there isn't any classroom that is too large, too pressed for instructional hours or too poor that couldn't adopt elements of it.

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