On Flipping a Large Signal Processing Class

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Modern academy traces its roots back to the medieval universities established between the 12th and the 14th centuries [1]. Much has changed in the world of academia during the millennium that separates a modern university from a medieval one. Among these changes, there are two that arguably stand out the most. First, university education is no longer considered the exclusive purview of a select few; rather, it has become a basic human right for all. Second, technology has become an integral component of university education, be it the delivery of information through multimedia presentations, the use of email for student–teacher interactions, the reliance on course management systems for submission and grading of assignments, or the adoption of e-books as class texts. But there is one thing in academia that has remained largely unchanged since the advent of medieval university, namely, the *mode of instruction*. *Lecturing*—in which an instructor imparts knowledge to its audience by standing in front of them and reciting relevant information that is recorded by the attendees—was the only mode of instruction in medieval universities [1]. And lecturing *remains* the dominant mode of instruction in modern academy. This is despite the fact that research on learning indicates lecturing is not the most effective means of helping students master the course material [2]–[5]. The reason for the survival of lectures in modern academy is simple: *among all the modes of instruction available to today's instructors, lecturing remains the quickest and cheapest means of educating large numbers of students*. The purpose of this article is to argue, however, that a carefully "flipped" classroom can be used to replace a traditional lecture-based classroom with minimal time, cost, and infrastructure overhead, *even* for large classes with 100's of students. The findings reported in this article are mostly based on the author's seminal 15-week flipped offering of a junior-level signal processing class with final enrollment of 133 students in the Department of Electrical and Computer Engineering at Rutgers, The State University of New Jersey in Spring 2016 Semester.

Anatomy of a Flipped Classroom (Sidebar)

In a traditional classroom, the instructor transfers knowledge to the students by delivering weekly lectures during assigned class periods. The students are then expected to master the covered material *outside* the classroom by working on assigned homework exercises and reaching out to the instructor during assigned office hours for any clarifications. Traditional classrooms, unfortunately, do not work equally well for all students (see "The Case Against the Lecture Format"). A flipped classroom (also referred to as an inverted classroom) literally *flips* the traditional learning paradigm on its head (see Fig. 1) [6]–[12]. Specifically, the knowledge transfer component of the course in a flipped classroom is moved outside the class; this typically involves the use of video lessons (see "Contemporary Alternatives to the Lecture Format"). The freed-up time during the assigned class periods is then used for carefully designed activities and collaborative exercises that help students master the course material. This "flipping" not only helps the students clarify any confusions in real time, but it also enables the instructor to personalize instructions to individual students based on their own gaps in understanding (see "Flipping Digital Signal Processing at Rutgers University").

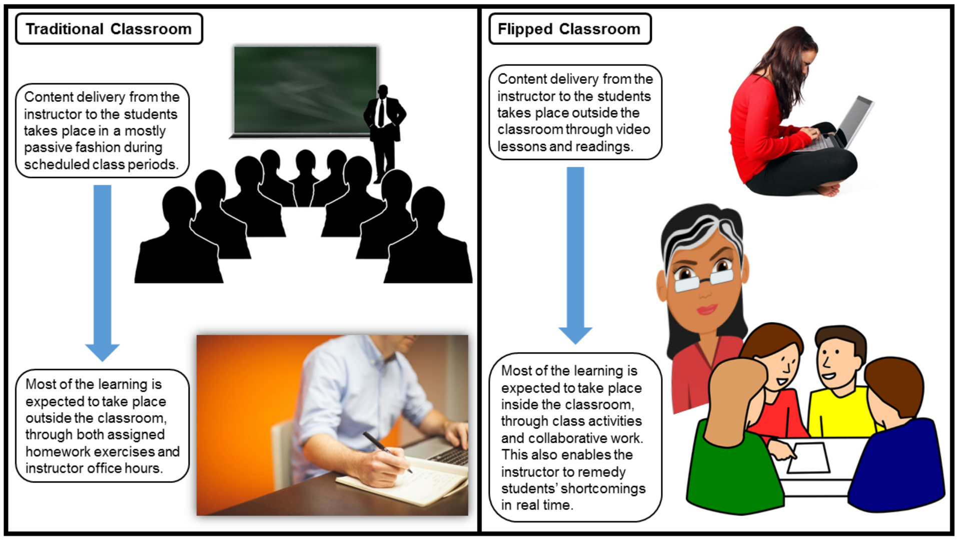


Fig. 1. A side-by-side comparison of a typical lecture-based classroom and a flipped classroom. Because of the nature of these two modes of instruction, lecture-based learning and flipped learning are sometimes also referred to as passive learning and active learning, respectively.

I. The Case Against the Lecture Format

Tens of millions of students graduate from universities around the world in which instructions are centered around lectures. This is proof enough that lecturing works. Recent research, however, makes it abundantly clear that lecturing does not result in the *best* learning outcomes for *all* students [2]–[5]. And this is perhaps more true in science, technology, engineering and mathematics (STEM) disciplines than in other disciplines. In particular, the following limitations of the lecture format in engineering education started the author on his quest to seek more effective, but low-overhead, alternatives to lecturing.

The fallacy of academic equivalence: Engineering instructors all over the world will have no hesitation accepting that "no two students are alike academically." This truism holds regardless of whether one is an instructor at a more- or a less-selective university, and whether one teaches a mandatory introductory course or an advanced elective class. The initial academic variation among newly admitted students can be primarily attributed to their diverse educational, geographic, and socio-economic backgrounds. Afterward, the unavoidable pyramid structure of engineering curriculum begins to amplify this initial variation. But the lecture format ignores the academic variation among students and, instead, makes the fallacious assumption that all students enrolled in a class have required mastery of prerequisite concepts. The unfortunate outcome of this "fallacy of academic equivalence" is that two students, one of whom secured an 'A' and one of whom managed a 'D' in the prerequisite course—receive identical instructions in the classroom.

The fallacy of behavioral equivalence: The lecture format is primarily a *passive* mode of instruction [13], with *active* interactions between the instructor and the students mainly taking place in two scenarios: (i) the instructor probes and/or prompts the students in order to gauge their understanding of the presented material, and (ii) the students ask clarifying questions by interrupting the instructor. An instructor who relies on the lecture format for achieving the learning objectives of the class effectively makes an implicit assumption that students are capable of utilizing the aforementioned avenues for turning a passive lecture into an active one. Unfortunately, this is another fallacious assumption; just like academically, no two students are behaviorally alike! Indeed, for every student in a classroom who is apt at interacting with the instructor during a lecture, there are tens of students in the same classroom who either hesitate to engage in or outright dislike such interactions. While there are myriad explanations for this, ranging from social shyness and the fear of appearing clueless to one's peers to the inability to quickly articulate one's challenges with the presented material [13]–[16], the end result of the "fallacy of behavioral equivalence" is that the instructor can seldom, if ever, take real-time remedial actions to correct students' understanding of the course material.

The fallacy of learning equivalence: Much of the learning in engineering classes takes place through problem solving. In most—if not all—engineering classes, however, the lecture format leaves little time for in-class problem solving. Engineering instructors try to overcome this limitation of the lecture format by assigning homework and practice problems to students. In doing so, the instructors make an implicit assumption that all students are equally capable of learning through out-of-class problem solving. But this too is a fallacious assumption. Consider, for example, what happens when a student gets stuck on an assigned problem due to conceptual challenges. The common thinking is that such students would reach out to the teaching staff (instructor, teaching assistants, etc.) for help. This, however, does not happen for a great majority of students due to reasons that range from their inability to approach the teaching staff during the assigned hours[1] to the inefficacy of email as a medium for discussing mathematical concepts [17], [18]. The unfortunate consequence of this "fallacy of learning equivalence," especially in large classes, is that students' learning begins to go out of lockstep with each passing lecture.

II. Contemporary Alternatives to the Lecture Format

The limitations of the lecture format, especially in the case of engineering education, are well known to the academic community. And several alternatives have been proposed and experimented with in recent years to overcome these limitations. Three modes of instruction that in particular stand out among these alternatives are *project-based learning*, *(massive open) online course*, and *flipped classroom*. While each one of these alternatives has its own sets of pros and cons, the author decided to experiment with the flipped classroom based on the following observations.

- Project-based learning helps students gain a deeper understanding of the course material by presenting them with a real-world problem and guiding them toward a possible solution in a structured manner [19]–[22]. It is perhaps one of the most engaging modes of instruction and research has shown it to be highly effective in

[1]Engineering instructors, for example, can often be heard complaining about students' lack of participation in office hours discussions.

overcoming limitations of the lecture format [22]. Project-based learning, however, has its own set of challenges when it comes to its adoption for engineering education. It is not straightforward to design a project-based learning curriculum for the majority of core engineering courses. Further, project-based learning requires specialized active learning classrooms (see Fig. 2), which are typically in short supply on most university campuses. Finally, the human resource overhead (in terms of man hours and student–faculty ratio) associated with project-based learning deters cash-strapped academic departments with large student enrollment from fully embracing it as a scalable alternative to traditional lecturing.

Fig. 2. One of the active learning classrooms at Rutgers University; facilities such as this are often recommended in education circles for use in project-based learning, flipped learning, etc. (Photo courtesy of Rutgers Digital Classroom Services.)

- Online courses in general, and massive open online courses (MOOCs) in particular, are often put forth as scalable alternatives to the lecture format [23], [24]. The single biggest advantage of online courses is that video archiving of instructor's presentations enables students to digest new material at their own pace by pausing, rewinding, and fast-forwarding parts of videos. Strictly speaking, however, online courses (MOOCs or otherwise) are pedagogically near-identical twins of lecture-based courses. Similar to the lecture format, they revolve around passive transfer of knowledge from the instructor to students and implicitly assume behavioral and learning equivalence of students. In fact, if anything, the lack of face-to-face interactions with the instructor only make it more challenging for some students to achieve the learning objectives of online courses. And the astronomical dropout rates of MOOCs [25], [26] seem to confirm this impression that online courses are pedagogically challenging for all but the most resolute of students.
- Flipped classrooms (see "Anatomy of a Flipped Classroom"), popularized in K–12 education by the advent of *Khan Academy* [27], appear to strike somewhat of a balance between the high-overhead of project-based learning and the overly passive nature of online courses in engineering education. Similar to online courses, a flipped classroom makes use of video-based instructions that allow students the flexibility of revisiting key concepts at later stages in the course. Similar to project-based learning, a flipped classroom uses class time for activities that not only help students recognize deficiencies in their understanding of course material, but

also enable the instructor to take *real-time* remedial steps that can address these deficiencies. It is no surprise then that flipped classrooms have been adopted by a number of engineering instructors in recent years [28]–[33]. Notwithstanding these adoptions, the conventional wisdom among engineering instructors has been that a flipped classroom—similar to project-based learning—is not scalable to core engineering courses that enroll 100's of students. There are two main reasons for this perception. First, it is a common belief that flipped offerings also require active learning classrooms. Second, positive learning outcomes in flipped classrooms are often linked to low student–faculty ratios. The fact that flipped classrooms in engineering education have mostly been adopted for small (sometimes elective) classes seems to strengthen this perception.[2]

III. Flipping Digital Signal Processing at Rutgers University

A. Background and Motivation

ECE 346: Digital Signal Processing is a required course at Rutgers for students majoring in electrical engineering. It is offered every year in spring semester, with an average final enrollment of 100+ students in the last five years. Traditionally, more than two-thirds of the students enrolling in this course are juniors who took *ECE 345: Linear Systems and Signals* in the immediately preceding semester, while the rest are seniors who did not or could not enroll earlier in the signal processing course for various personal or academic reasons. The author has been teaching this course since Spring 2012, with his first offering very much in the mold of traditional lecture and chalkboard format. This first offering would be considered a success by most academic standards; the course quality received an average rating of 4.33 (out of 5) from 56% of the enrolled students and there were more than a handful of students who had truly mastered the course material by the end of the semester. Despite its seeming success, this first offering also laid bare to the author many of the limitations of the lecture format, especially in relation to large core courses. In particular, the struggles of students who did not conform to the assumptions of the lecture format (see "The Case Against the Lecture Format") were all too palpable during the semester.

The author made several tweaks to his first offering in the ensuing semesters in an attempt to make his offerings more equitable to students. These tweaks included experimenting with presentation slides in lieu of chalkboard text, video archiving of class lectures, grade-based incentives for class participation, and different attendance policies. Some of these tweaks appeared to be helpful to students' learning (e.g., video archiving), while other tweaks seemed to have either little effect (e.g., mandatory attendance) or negative effect (e.g., presentation slides) on students' learning. And none of the tweaks seemed to directly confront the challenges of academic, behavioral, and learning variations among students. It was during this time, when the author was exploring different means of teaching signal processing, that an interesting development took place. Prof. Van Veen taught flipped version of a senior-level elective signal processing class to 30 students at the University of Wisconsin-Madison in Fall 2012 and shared his (highly positive) experience in [29]. The term "flipped clasroom" entered in the author's lexicon in 2013 as a result of [29]; and he spent the next two years discussing with other educators (including the author

[2]Among the documented flipped classrooms in electrical engineering, [29], [30], and [31] had 30, 115, and 40 students, respectively.

of [29]) means by which large core engineering courses could possibly be flipped using minimal time, cost, and infrastructure overhead.

B. Ingredients of Flipping on a Shoestring

There were three major challenges that came to the fore when the author carefully examined the possibility of flipping the mandatory junior-level signal processing class at Rutgers. First, and this is perhaps the most daunting aspect of flipping a course for any instructor, the author needed a plan to create engaging video lessons in a cost- and time-effective manner. Second, and as noted by other instructors of flipped classes [29], [30], flipping a course for 100's of students requires more than one person to guide students during in-class activities. A general rule of thumb for student–guide ratio in flipped classes is 20–30 students/guide, which means the author needed a strategy to involve four to five additional guides in his flipped classroom without creating a budgeting crises for his department. The third challenge, often considered one of the biggest hurdles to adoption of flipped learning for large engineering courses, is that the largest active learning classroom at Rutgers has a capacity of 90 students. Since enrollment in Digital Signal Processing at Rutgers often exceeded 100 students, the author needed a plan that would enable students to reap the benefits of a flipped classroom in a lecture hall setting. The different ways in which the author addressed these three challenges are described below.

Low-overhead video lessons: Short, self-contained video lessons are the key to creating a flipped classroom. But planning, recording, and production of professional-looking videos can overwhelm even the most committed of instructors. The author, being cognizant of the risks of overcommitting, opted for an acceptable compromise between overhead and quality of the video lessons for his flipped offering. This compromise involved: (i) delivering lectures to students enrolled in his traditional offering of the signal processing class in Spring 2015 using a pen tablet (Wacom Bamboo Tablet) connected to a Windows laptop and Microsoft OneNote, (ii) capturing laptop's screen using a screencasting software (Camtasia Studio 8) and recording voice using an external mic (Logitech HD Webcam), and (iii) stitching, slicing, and deleting the recorded material using Camtasia Studio 8 to produce a set of 27 videos, each one of which covered a single topic and excluded classroom interactions and discussions with students. These videos, which are further divisible into subtopics of durations ranging from 10 minutes to 30 minutes, are publicly available on the author's YouTube channel [34]. This piggybacking on traditional lecturing allowed the author to limit the time overhead of these video lessons to an average of approximately 2.5 hours per video. (This figure excludes both the lecture preparation and the lecture delivery times since the author would have spent this much time regardless as part of the Spring 2015 offering.) The monetary overhead of these video lessons was also quite manageable, enabling the author's department to absorb the entire cost; in particular, an equivalent system comprising a pen tablet, an external mic, and screencasting and video editing software can be built as of this writing for approximately 400 USD.[3]

Low-cost in-class assistants: While having a person assisting every 20 to 30 students for in-class activities is critical to the success of a flipped classroom, most universities cannot financially afford such a high ratio of students

[3]This figure excludes the costs of a laptop and note-taking software, both of which are considered integral for today's educators.

to teaching assistants. The junior-level signal processing class at Rutgers, for instance, has historically been assigned one graduate teaching assistant (GTA). In order to balance the needs for financial prudency and in-class assistants, the author resorted to the use of *peer* learning assistants (LAs) for in-class activities. Specifically, the author—along with the help of *Rutgers Learning Centers*—recruited five students from his previous (Spring 2015) offering of the signal processing class to serve as LAs for in-class activities. Each one of these LAs spent two hours per week preparing for in-class activities and three hours per week assisting students during class times. These LAs were formally coached at the start of the semester in the art of pedagogy by Rutgers Learning Centers, and each one of them received a total of 1500 USD for the 14 weeks of instructions. Thus, for a meagre monetary overhead of 7500 USD (split among the university and the department), the author's flipped offering resulted in a student–guide ratio of 22 (five LAs and one instructor for 133 enrolled students).

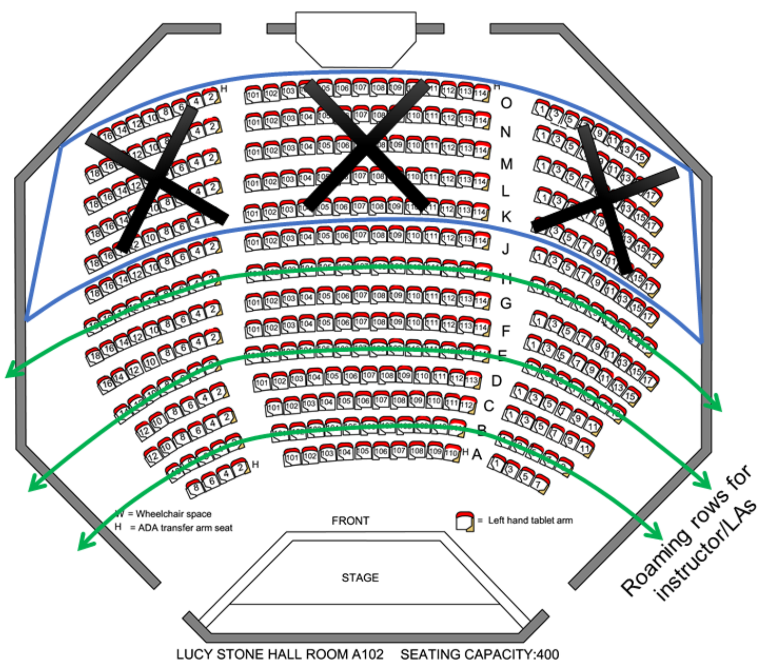


Fig. 3. A possible seating arrangement in a lecture hall for students in a large flipped classroom. This arrangement, which is being used by the author in his Spring 2017 flipped offering at Rutgers, prohibits students from sitting at the very back of the hall (black crosses) and in three rows (green arrows), and enables instructor(s)/LA(s) to reach individual students by moving within the (green) restricted rows. This particular seating arrangement can accommodate up to 161 students, while it is scalable up to 257 students.

Flipping in a lecture hall: While an instructor should ideally have access to an active learning facility for a flipped offering [29], [30], the capital cost associated with construction of such facilities—especially the ones that can accommodate 100's of students—means this is not always possible. The author faced this very challenge for his flipped offerings at Rutgers. Rather than being deterred by this challenge, the author retooled his flipped offerings for large lecture halls. This retooling involved: (i) reserving a lecture hall for the flipped classroom whose capacity was at least twice the maximum expected course enrollment, (iii) dividing the lecture hall into contiguous groups of three rows each, and (iii) prohibiting students from sitting in the middle row of each group of rows. These empty middle rows enabled the instructor and the LAs to freely roam around the lecture hall, be able to physically approach all students, and assist them during in-class activities (see Fig. 3). While such a seating arrangement cannot be considered a replacement for an active learning facility, in which students themselves can also roam around and can utilize resources such as computers and writing boards (see Fig. 2), mid- and end-of-semester feedback from students (see “Reflections on the Flipped Offering”) suggested that the solution was an effective compromise between idealism and realism.

C. Course Organization

The author’s seminal flipped offering of the signal processing class physically met for 80 minutes each at 8:40 a.m. on Mondays and Thursdays. In addition, enrolled students were divided into three recitation groups, with each group attending one 80-minutes recitation (led by the GTA) per week. There were three main categories of activities within this offering that fundamentally differentiated it from a traditional offering (see Table I for a bird’s-eye view of these activities). These categories, referred to as *home activities*, *in-class activities*, and *recitation activities* in the offering’s parlance, accounted for 29% of a student’s final grade. In order to achieve the learning objectives of this offering, which included comprehensive understanding of sampling theory, discrete-time processing of continuous-time signals, discrete Fourier transform, spectral analysis, and design of digital filters, the author organized the three sets of course activities as follows.

Home Activities: The category of home activities comprised tasks that students were required to complete outside the classroom. These tasks, the graded portion of which accounted for 7% of a student’s final grade, were further subdivided into three groups. First, the students were regularly assigned *video lessons*, ranging in total duration from 30 to 70 minutes, and *textbook reading* that had to be watched and completed, respectively, before each class period. Second, each set of assigned video lessons and textbook reading was associated with an *online assessment* on a course management system (CMS) that the students had to complete by 7 a.m. on the day of the respective class. These online assessments comprised the simplest of short-answer, true-false, and multiple-choice questions and served as one of the main motivating factors for the students to watch the assigned videos and complete the assigned reading. There were two other aspects of the online assessments that gave students the opportunity to remedy some of the shortcomings in their understanding of the covered material. These involved giving ample time to the students to complete an online assessment (typically, an average of three to five minutes per question) and allowing students to retake an online assessment (with a different set of questions) in the case of unsatisfactory performance on the first attempt. The author’s flipped offering in Spring 2016 had a total of 20 online assessments, which accounted for 67% of the grade for home activities. The final group of tasks that constituted home activities mostly consisted of paper-and-pencil exercises meant to reinforce students’ understanding of the course material. The reader is referred to Fig. 4 for a graphical representation of home activities in author’s flipped classroom.

In-Class Activities: The author divided each 80-minutes class period into two components. The first component, which typically lasted for 10–15 minutes, was used for a brief review of key concepts covered in the assigned video lessons. The second component, which covered the remaining class time and accounted for 15% of a student’s final grade, comprised activities that helped students reflect on their understanding of the assigned video lessons and

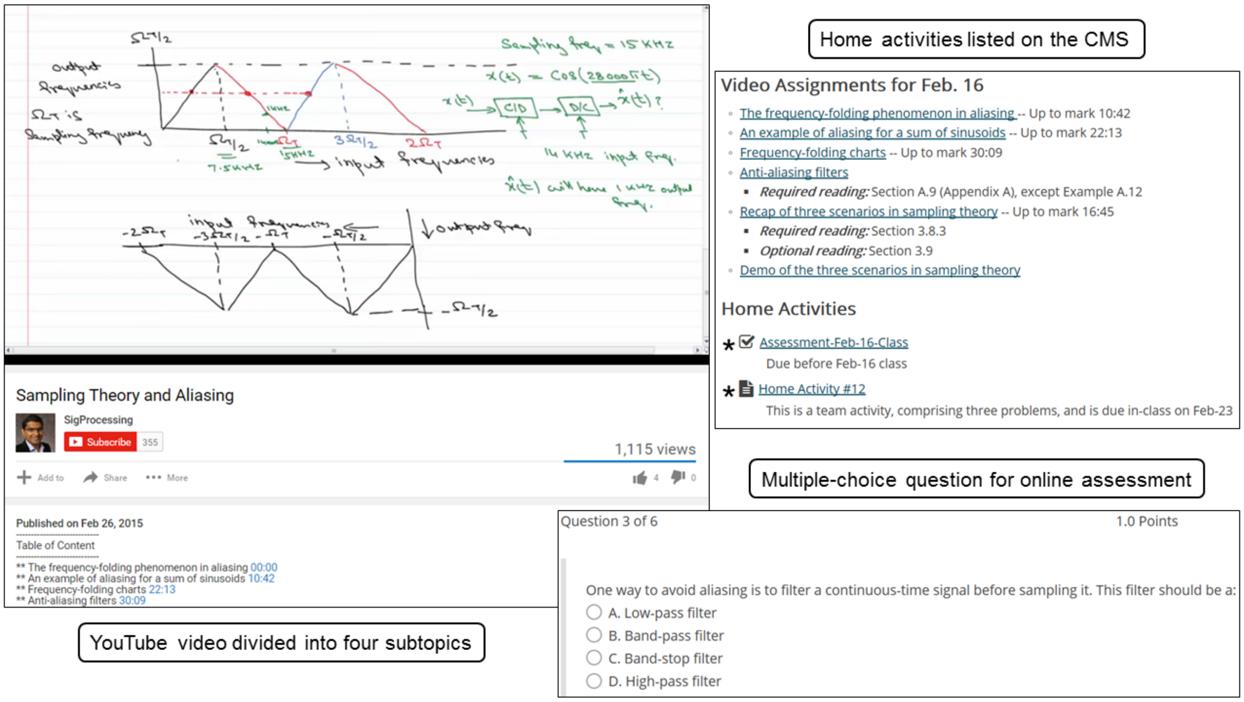


Fig. 4. A graphical representation of the three main groups of tasks comprising home activities in author's flipped classroom. The CMS screenshot corresponds to the author's Spring 2017 flipped offering.

enabled the author take real-time remedial actions in response to widespread confusions. To this end, these activities were split into two categories, namely, *polling questions* and *paper-and-pencil exercises*. The polling questions part of in-class activities involved sequentially displaying short conceptual questions to students on a presentation slide and recording students' responses in real time using an online polling platform (see Fig. 5(a)). (The author used *Poll Everywhere* platform [35] in his class, which allows participants to respond using mobile devices.) The paper-and-pencil exercises part of in-class activities involved sequentially assigning longer problems (see Fig. 5(b)) to students and collecting students' works on loose sheets of paper. A typical class period consisted of 2–5 polling questions and 1–3 paper-and-pencil exercises, with each polling question worth two points, each exercise worth anywhere between four and twelve points, and the students guaranteed 25% of the points for attempting an activity. The author and the five LAs helped the students during each ongoing activity by roaming around the lecture hall and providing cues to struggling students. This looking over the shoulder of students and, in the case of polling questions, instantaneous access to students' responses (see, e.g., Fig. 5(a)) gave the author real-time insight into students' understanding of the covered material. This insight, which is one of the most important differences between a lecture-based offering and a flipped classroom, was then used to deliver a focused set of clarifying instructions to students at the end of each activity.

Recitation Activities: Each one of the three recitation groups in the class attended one weekly 80-minutes recitation period led by the GTA. The activities in these weekly recitations were designed to enhance students' problem-solving skills. To this end, each recitation period was divided into two components. The first component,

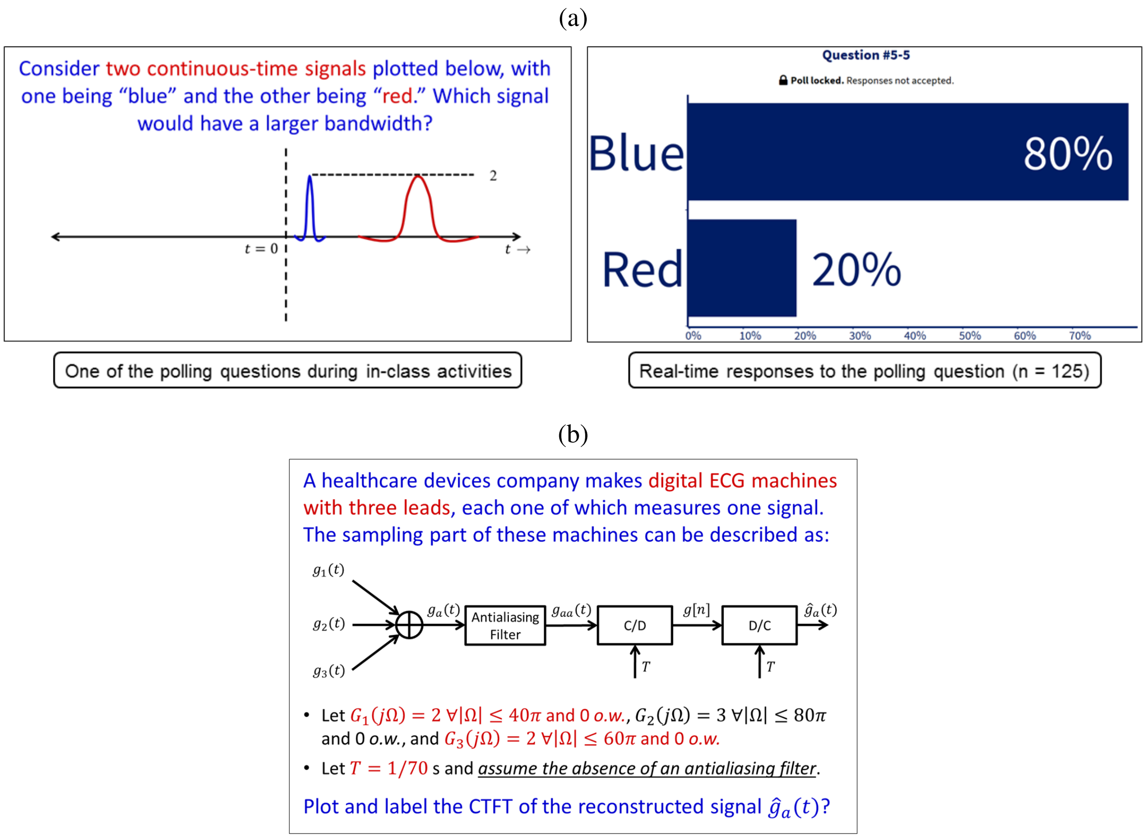


Fig. 5. Illustrative examples of (a) a short conceptual question and students' responses to that question in author's flipped classroom, and (b) a longer paper-and-pencil exercise that the students solved within the class period.

which typically lasted for 30–35 minutes, involved the GTA solving 3–5 problems on a chalkboard that reinforced the concepts covered in the last two sets of video lessons. The second component, which primarily distinguished the recitations in the flipped offering from those in a traditional offering, covered the remaining recitation period and accounted for 7% of a student's final grade. In this component, students were sequentially assigned 3–5 paper-and-pencil problems that specifically helped them master the *mechanics* of problem solving.[4] The students were given anywhere between four and ten minutes to solve each one of these problems on loose sheets of paper, with each problem worth anywhere between four and ten points. Further, the students were guaranteed 25% of the points for attempting a problem. The GTA, after assigning a problem to the students, roamed around the recitation room and helped students struggling with the problem. In addition, the students were encouraged to discuss the problems among themselves. Finally, the GTA capped off the assigned problems with collection of students' works and brief discussion of solutions of the problems.

The rest of the flipped course's structure—apart from the aforementioned home, in-class, and recitation activities—followed a traditional offering, with the remaining 71% of a student's final grade divided among a pre-requisite quiz, two in-class exams, a term project, and a final exam. There was, however, one additional aspect of the author's

[4]This should be contrasted with the in-class paper-and-pencil exercises that focused on students' basic understanding of the course material.

TABLE I

SUMMARIZATION OF THE MAIN ACTIVITIES THAT COMPRISED THE AUTHOR'S FLIPPED OFFERING IN SPRING 2016.

Step #	**Activity Category**	**Activity Details**	**Grading Details**
1-1	Home Activity	Viewing of assigned YouTube video lessons (∼30–70 minutes per class)	Ungraded
1-2	Home Activity	Completion of assigned textbook reading (if applicable)	Ungraded
1-3	Home Activity	Completion of online assessment (due by 7 a.m. on the day of each class)	∼5% of the final grade
2-1	In-Class Activity	Review of key concepts by the instructor (∼10–15 minutes per class)	Ungraded
2-2	In-Class Activity	Short polling questions (∼2–5 questions, with each worth two points)	15% of the final grade
2-3	In-Class Activity	Paper-and-pencil problems (∼1–3 problems, with each worth 4–12 points)	(25% points for an attempt)
3-1	Home Activity	Paper-and-pencil problems (∼1–3 problems assigned after some classes)	∼2% of the final grade
4-1	Recitation Activity	Problem solving by the GTA (∼30–35 minutes and ∼3–5 problems)	Ungraded
4-2	Recitation Activity	Paper-and-pencil problems (∼3–5 problems, with each worth 4–10 points)	7% of the final grade

flipped offering that *seemed* to enhance students' learning experience. In the second week of the semester, after the enrollment transients died out, the author divided his class into teams of three students (with at most two teams with four members each). The idea here being that students on the same team would not only sit together during each class period and collaboratively work on in-class activities, but they would also work together on home activities comprising paper-and-pencil exercises. The success of this idea in terms of its impact on students' learning experience, however, depended on the creation of *balanced* teams. The author accomplished this goal through the use of *CATME Team-Maker* tool [36], [37], which allows an instructor to gather various pieces of information from students and then assigns students to different teams according to the criteria and weighting specified by the instructor.[5] The author, in particular, configured the CATME Team-Maker tool such that the final set of teams brought together students with different levels of academic preparation, but similar (self-described) commitment levels, schedules, and class years; see Fig. 6 for a sampling of the particular criteria and weighting used by the author for his Spring 2017 flipped offering.

IV. REFLECTIONS ON THE FLIPPED OFFERING

The discussion in "Flipping Digital Signal Processing at Rutgers University" makes it abundantly clear that the author's flipped offering was substantially different from a traditional lecture-based offering. *But did this offering result in better learning outcomes for the students?* Unfortunately, there are too many variables that affect students' learning abilities and a definitive answer cannot be given for this question without having the ability to control these variables. Some of these variables include students' academic preparation and command of pre-requisite material, their learning styles, their work habits, and their intellectual abilities. Since none of these variables could be controlled by the author in his flipped offering, only anecdotal evidence from the perspectives of the instructor and the students can be provided to ascertain the effectiveness of the flipped offering.

[5]The CATME system has historically been free for use by the academic community. Starting July 1, 2017, however, there is expected to be a nominal license fee per unique student in an academic year that will help defray the system's annual maintenance costs.

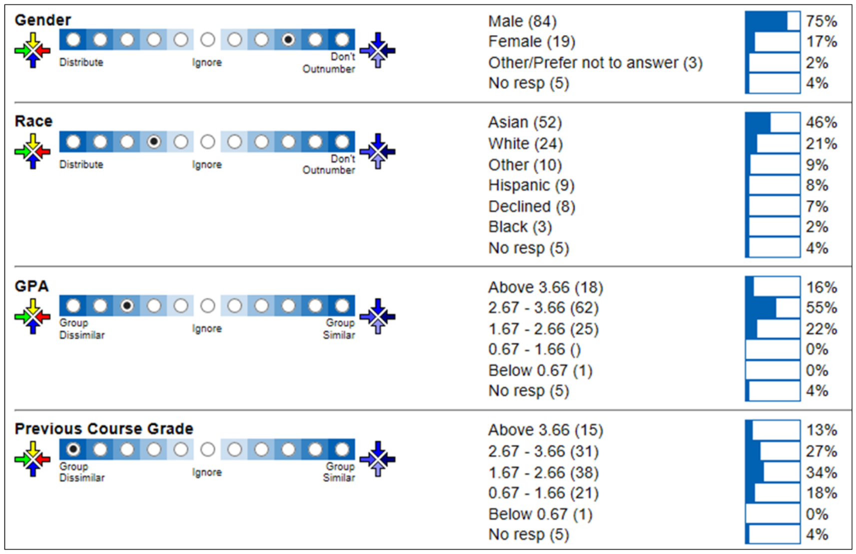


Fig. 6. Partial screenshot of the CATME Team-Maker tool used by the author to distribute the students in his flipped classroom across different teams. This particular configuration of criteria and weighting corresponds to the author's Spring 2017 offering with an enrollment of 111 students.

A. Instructor's Perspective

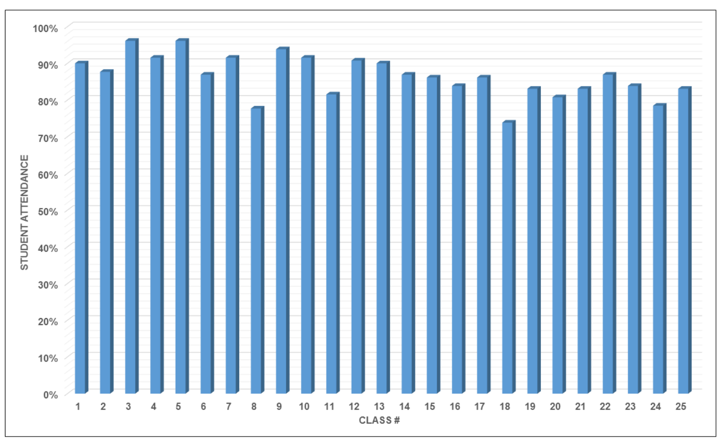


Fig. 7. The percentage of students attending each class period of author's Spring 2016 offering (average attendance = 86%). This data corresponds to the use of in-class activities grades as proxy for students' attendance, ignores the three class periods used for one review session and two in-class exams, and excludes the three students who withdrew from the course after the "drop" deadline.

There are four data points from the perspective of the author that seem to suggest that the author's seminal flipped offering was a success. First, the number of students attending each scheduled class period (see Fig. 7) as well as the general body language of the students seemed to suggest the students were—on average—much more engaged in the flipped offering compared to the author's previous four traditional offerings. Second, the students' performance on in-class activities as well as the depth of their in-class queries suggested that the students internalized the course material better than in the author's previous offerings. Third, the sophistication of students' term projects in the flipped offering, on average, exceeded that of the projects in the author's traditional offerings. A possible explanation for this improvement is that students enrolled in the flipped classroom mastered the material better than in previous years. Finally, it used to be relatively straightforward for the author in previous years to map students' numerical grades to letter grades. But the assignment of letter grades in the flipped offering became quite a chore for the author due to the lack of significant gaps in the distribution of students' numerical grades. A possible explanation for this phenomenon, which has also been pointed out in [29], is that fewer students were being left behind in terms of their understanding as part of the flipped offering. In particular, the most noticeable aspects of the author's flipped offering—in comparison to the previous four years—are the significantly higher percentage of A grades and the significantly lower percentage of D grades; see Fig. 8 for grade distributions of author's 2012–2016 offerings.

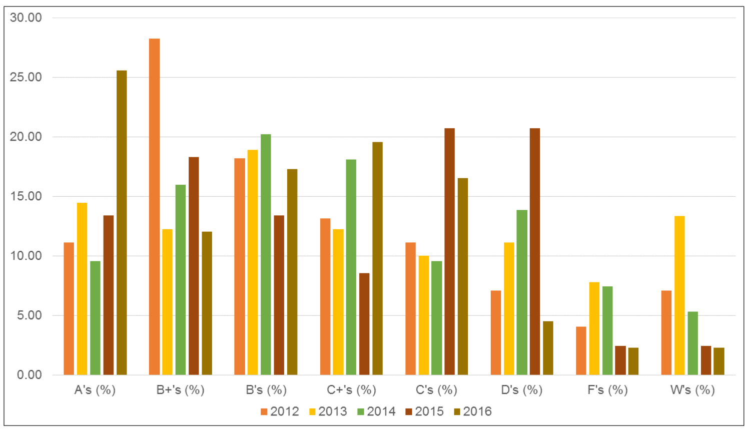


Fig. 8. Grade distributions for author's (spring) offerings of the signal processing class from 2012 to 2016. In terms of significant changes from year to year, presentation slides were used in lieu of chalkboard text for the 2013 offering, lecture archiving on YouTube was started from the 2014 offering, and a fully flipped class was offered in 2016.

B. Students' Perspective

Students' perspectives on this seminal flipped offering were formally obtained in two different manners. First, midway through the semester, the author solicited anonymous feedback from the students on his flipped offering through a comprehensive survey of 24 questions. This survey, which had questions that ranged from numerical ratings (e.g., "*Strongly Disgree*" (1) to "*Strongly Agree*" (5) for "*The traditional, lecture-based format of engineering education needs to be reformed*") and multiple choice (e.g., "*Yes*," "*No*," and "*Not Sure*" for "*If given an opportunity, would you rather have ECE 346 in the traditional, lecture-based format?*) to open ended (e.g., "*What is one thing you would change if you were to offer ECE 346 as a flipped class?*"), was completed by 63% of the enrolled students ($n = 84$). Among the survey takers, there were 75 students who had no prior experience with a flipped classroom. Table II summarizes responses of students to five main questions in the survey that reflected this cohort's opinion of engineering education, while Table III summarizes students' responses to four key questions in the survey that can be interpreted as evaluation of the author's flipped offering. It can be seen from these two tables that—midway through the semester—an overwhelming majority of the students preferred the flipped classroom over the traditional

TABLE II

STUDENTS' RESPONSES TO FIVE QUESTIONS ON A MID-SEMESTER SURVEY IN SPRING 2016 THAT SOUGHT THEIR PERSONAL OPINIONS ON THE STATE OF ENGINEERING EDUCATION ($n = 84$).

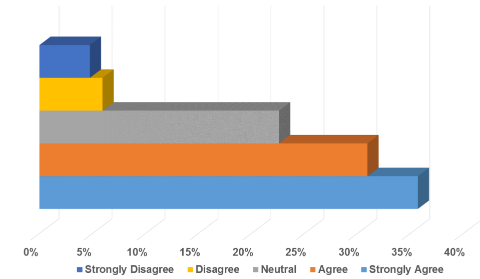
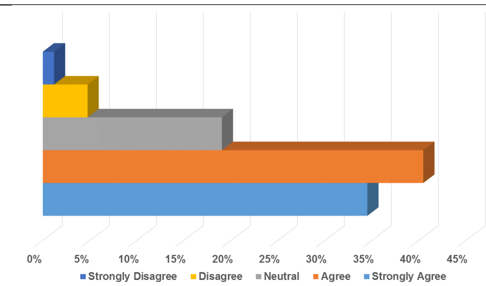
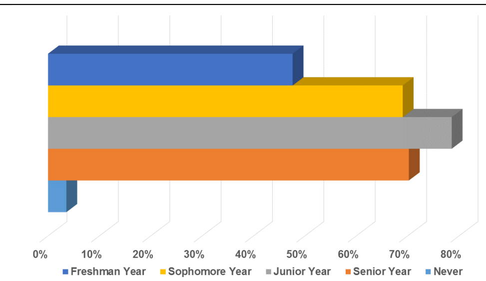
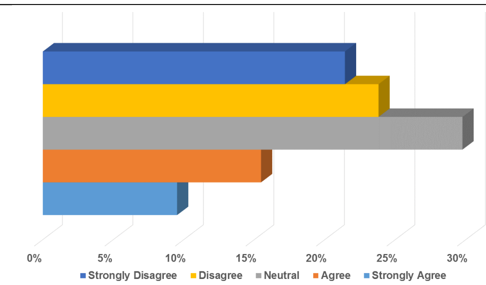
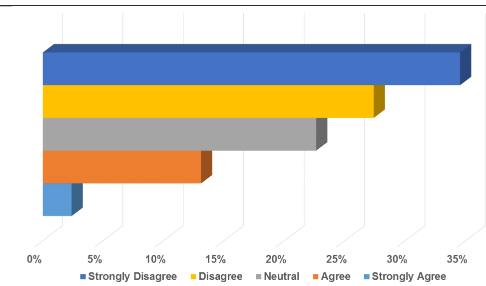
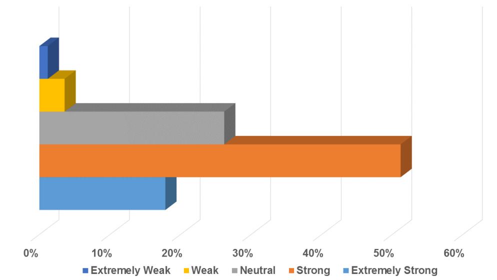
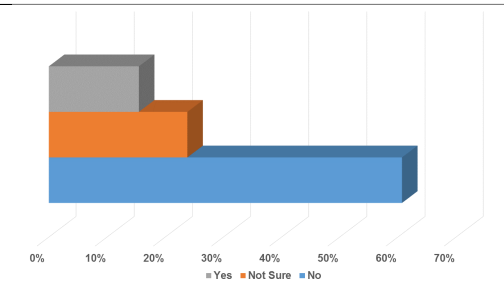
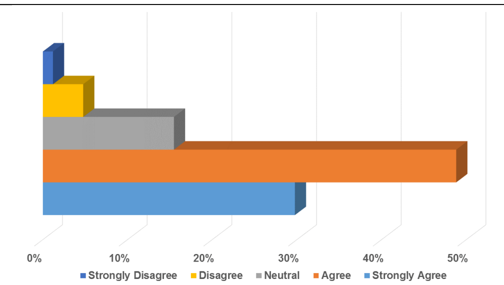
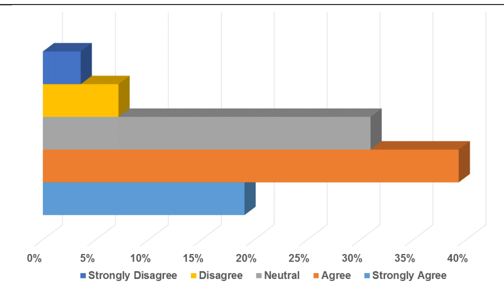
#	Survey Question	Survey Response
1	The traditional, lecture-based format of engineering education needs to be reformed.	
2	A flipped classroom can be a good alternative to traditional, lecture-based format of engineering education.	
3	In engineering education, flipped classes should only be offered at the following levels (select one or more options).	
4	Flipped classes in engineering education should only be offered for small-sized (< 20–25 students) courses .	
5	Flipped classes in engineering education should never be offered in lecture halls, even if it means reverting back to traditional, lecture-based instruction.	

TABLE III

STUDENTS' RESPONSES TO FOUR QUESTIONS ON A MID-SEMESTER SURVEY IN SPRING 2016 THAT CAN BE INTERPRETED AS EVALUATION OF THE AUTHOR'S FLIPPED OFFERING ($n = 84$).

#	Survey Question	Survey Response
6	What kind of a student you consider yourself to be in relation to mathematically intensive courses?	
7	If given an opportunity, would you rather have ECE 346 in the traditional, lecture-based format?	
8	In your opinion, the flipped offering of ECE 346 enables you to better learn the material.	
9	The flipped offering of ECE 346 will help you get a better grade than the traditional offering because it enables you to better understand key concepts.	

lecture-based classroom. Students' responses to the open-ended questions in the survey shed some light onto a few of the reasons for this preference. According to one student, "*I enjoy the overall aspect of watching the videos at home and then solidifying the information in class.*" Another student responded, "*[It has given] me a chance to see what I do wrong when working out a problem [. . .] during the class time[,] instead of working on homework and waiting a month to get it back and not knowing why I did what I did.*" And yet another student stated, "*The flipped classroom method works better (in my opinion) because each student can go at his/her own pace.*"

While the open-ended responses of a number of students taking the mid-semester survey validated the author's initiative, it can also be seen from Table II and Table III that not every student agreed with this initiative. There were, in particular, 13 students who would have preferred to enroll in a traditional lecture-based course (cf. Question #7 in Table III). The responses of these students to Question #4, Question #5, and some of the open-ended survey questions helped explain their opposition to the flipped classroom. Nine of these 13 students responded with either *Agree* or *Strongly Agree* to Question #4, while seven of them responded with either *Agree* or *Strongly Agree* to Question #5. In terms of the open-ended questions, one of these students stated, "*I feel that the flipped classroom is too much work for the amount of credits currently offered.*" Another student responded, "*[. . .] the flipped classroom threw a curveball at me and I was slow to adapt. It certainly demands a higher time commitment [. . .]*" And yet another student stated, "*[I'm] doing very poorly in this course as of right now [. . .] For this reason, I don't like it.*" These, and somewhat similar responses of a few other students, suggest that some of the students who preferred the lecture-based format might have done so for reasons other than pedagogical ones.

The author obtained the next set of feedback on his flipped offering at the end of the semester as part of a Rutgers-administered anonymous course survey that helps students evaluate teaching effectiveness of the instructor and quality of the course. There were a total of 98 students (74% of the enrolled students) who responded to this survey. These students gave the flipped offering an average quality rating of 4.47, which is the highest quality rating the author had received for his signal processing class. Note that the author is all too familiar with the common refrain in some parts of the academy that the course quality (and instructor evaluation) ratings are inversely proportional to the amount of time students have to spend on the course. However, the author's flipped offering was nothing but a highly demanding class. One of the students, for example, noted in his end-of-semester survey, "*The work load was extremely high[,] which helped with learning the material [. . .]*" Similarly, another student wrote, "*The flipped classroom was an interesting experience, even though it was more work for students.*" In general, the feedback students provided through the end-of-semester survey corroborates findings of the mid-semester survey and suggests better learning outcomes for a majority of the enrolled students. According to one student, "*The abundance of examples and problems we did in class helped me understand the material more effectively than doing homework problems on my own. Despite being a class at [8:40] in the morning, I seldom felt tired or uninterested during the class.*" Similarly, another student responded, "*The constant cycle of watching the videos, taking the quiz, reviewing in class, doing problems and going to recitation to learn it again and do more problems was a fantastic process. It helped solidify every topic and drill it into my head [. . .].*" These are just few of the many survey responses that suggest students found the flipped offering to be *both* demanding *and* rewarding.

V. Concluding Remarks

A flipped offering is a serious undertaking, both from the perspectives of the instructor and the students. In particular, the amount of work and the additional resources required for successful offering of a flipped course can easily overwhelm the most dedicated of instructors. However, the author's experiences suggest that if one gradually transitions into a flipped offering and also adapts some aspects of a flipped classroom to the resource constraints of the offering university then a flipped offering can be a truly rewarding experience for both the instructor and the students. But before one can do that, one has to be convinced of one thing, namely, if some students are academically struggling in class then it need not necessarily be due to their lack of trying. Once that realization sets in, only then can one go ahead and investigate pedagogical techniques that work better for those students. And when instructors try to answer the question of what works, they must be cognizant of the fact that the top-performing students cannot be used as a yardstick for success of a pedagogical style. Indeed, there are always going to be students in every class who would succeed regardless of the pedagogical techniques adopted in the class. But an instructor's duty is to reach out to all, and not just the top few, students. The seminal flipped offering of the author has him convinced that an appropriately adapted flipped classroom is one way to reach out to more students. After having experimented with the flipped classroom and having seen the outcomes of this experiment, the author is not planning to revert back to the traditional lecture-based format for his undergraduate signal processing class. And he hopes that this article, along with the experiences of other engineering instructors, will inspire others to begin their own quest for the elixir of scalable effective teaching.

Acknowledgements

The author owes the success of his seminal flipped offering to both discussions with numerous educators as well as support from several sources. He would, in particular, like to acknowledge the support of the National Science Foundation CAREER Program, Rutgers Electrical and Computer Engineering, National Academy of Engineering Frontiers of Engineering Education, Rutgers Learning Centers, Rutgers Digital Classroom Services, and Rutgers Scheduling and Space Management. He would also like to thank Susan Albin, Helen Buettner, Mary Emenike, Lawrence Rabiner, Barry Van Veen, and Roy Yates for many helpful discussions, and the anonymous reviewers for several helpful comments.

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