Improved Student Independence Through Competitive Tinkering

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***Abstract*—Two recent trends in engineering education are gamification and application of makerspace concepts. We have combined these to develop multiple open-ended competitive active learning activities. Assessment data show that relative to a baseline offering, the treatment group developed a marginal improvement in attitude and motivation but a significant improvement in student confidence and self-assessed abilities. Student self-assessed independence rose 9% across the baseline offerings and 16% in the treatment offerings, with at least 18 respondents per group. This manuscript discusses the course structure, the activities, the assessment data, and lessons learned from student focus groups and instructor observation. The focus groups reported that the factors that improved their skills and motivation the most were the competitions, the use of small teams for projects, and the open-ended nature of the projects; whereas the most detrimental factors included not enough live lecture time (a flipped classroom was employed so that contact hours focused on the projects) and not enough example problems were covered for the students to learn the mathematical mechanics. We conclude that a balance must be struck to let students learn sufficient basic skills through more traditional approaches while still providing some open-ended activities to inspire them.**

I. Introduction

The traditional "chalk-and-talk" lecture format is pervasive, but it has increasingly been shown to be ineffective at engaging student interest. Educational research has pointed to student-centered, active learning to improve student comprehension, interest, and retention – particularly within under-represented groups [1]. This paper evaluates a combination of active learning activities that were implemented in the authors' signal processing and communications classes. Since signal and communication theory rely heavily on probability and mathematical representations of signals, most popular textbooks emphasize abstract mathematics and omit hands-on activities, and most course offerings are lecture-only without active learning components. Active learning, in which the student is an active participant in the learning experience, leads to the student being engaged in the classroom [2]. Most approaches to active learning in engineering take the form of collaborative problem-solving [3] or design projects [4], [5] and the use of student-centered inquiry-based activities has been recognized as an important active learning tool [6].

Two active learning approaches which have recently attracted attention include *tinkering* [7]–[11] and *gamification* [12]–[15]. While these two approaches are distinct within the educational research community, they work together naturally in local hackathons, drone competitions, and robotics competitions. Such events appeal to a wide age range from K-12 and up, regularly feature industry participation, have high public interest, and are scalable. This paper presents activities for bringing these approaches into signals courses. While tinkering and gamification have been studied independently in other disciplines [9]–[14], to the best of our knowledge no previous work has combined these two *complementary* approaches nor applied them to signals-related courses. In order to free up contact hours, the courses can be "flipped," wherein a portion of the lectures are pre-recorded and then viewed by students outside the class period [16]–[18].

Tinkering is adapted from the concept of "makerspaces" – do-it-yourself, grassroots organizations focused on designing, building, and hacking [19], [20]. Makerspaces have become popular as vehicles for exciting people about science and engineering [19], [20]. The explosion of makerspaces around the country – made possible in part by the democratizing effect of widely available low-cost electronic equipment and instrumentation – has created entire communities of self-motivated learners who have acquired significant knowledge about a wide range of technical concepts. These non-traditional "learners" are actively developing and innovating with low-cost single-board computers (e.g. Arduinos or Raspberry Pi's), DSP boards, and software-defined radios (e.g. RTL-SDR's) without theoretical background or formal training in signal processing and communication systems. In the context of signals, there appears to be a gap between traditional learners (who may grasp some theory, but rarely do any "making" or "hacking" in signals courses), and the makers/hackers (who build, but may not understand the underlying theory or optimal approach to a given problem), leading to an opportunity for cross-fertilization between these two communities. We seek to leverage the excitement and tinkering ethos adopted by the maker movement, bringing that approach into the classroom, and nurturing students' learning trajectories as an extended process of making and tinkering. For example, makers have embraced $20 USB dongles (RTL-SDR's) intended for digital television reception which can be re-programmed as software-defined radios to eavesdrop on a wide range of signals with security implications – from airplanes flying overhead (sending ADS-B signals), to readings from neighborhood electric meters. A wide range of exercises can be developed around such tools, prompting students to adopt a maker mindset, employ improvisational problem solving, and get motivated to learn signal theory concepts while actually building something. Other low-cost materials which can be used for tinkering include acoustic hardware (speakers, microphones); DSP boards and single-board computers which are already available in many institutions; and the ubiquitous nature of high-quality digital cameras via cell phones, which can be used for projects ranging from image processing to machine learning to autonomous navigation and mapping.

It is important to note that in the maker community, extrinsic motivation and interest in the subject matter induces the participants to tinker and create; whereas in a classroom environment, a requirement to tinker and create is induced, with the goal of providing extrinsic motivation and interest in the subject matter. That is, the cause and effect are unavoidably reversed, so a perfect correspondence cannot be made. As will be shown later in the paper, this reversal of causality is evident in a somewhat limited improvement in student motivation; however, it had the side effect of greatly improving student independence instead. We will return to this point later, but it is important to keep in mind that herein the tinkering is the driving force rather than the effect of pre-existing interest.

Gamification (a.k.a. game-centric curriculum design or game-based learning) [12], [13] has recently been popularized in academia and industry, for various reasons. First, games can provide extrinsic motivation and encourage students to work hard of their own accord [21] – a University of Texas study found students voluntarily did three times as much work when it was presented as a game [22]. Second, in terms of Myers-Briggs personality types, 54% of faculty are Introverted and 64% are iNtuitive, whereas 70% of students are Extroverted and 70% are Sensing [23], [24]. Thus, while faculty prefer calm, intimate problem-solving groups, students are more likely to respond to boisterous, public activities centered on facts and data. Third, research by Kolb has shown that over time, students in the sciences become more analytical and less creative (and students in the arts are the opposite) [24], [25]. Games can counter this effect by forcing students to think about the course concepts more creatively, by using game rules that require students to interpret, explain, and demonstrate course concepts in non-traditional ways [26]. Games can also engage more regions of the brain than traditional lecture, by incorporating verbal interaction, visual interaction, and motor skills. Finally, games provide an alternative model for student progress. McGonigal notes that games provide a series of carefully constructed obstacles which allow players to learn by *rapidly failing and improving* – thus mastering the challenge at hand [27]. Indeed, gamification has shown promising results in research across many higher education disciplines including civil engineering [28], engineering graphics [29], [30], geoscience [31], English [32], and business [33]–[35]; as well as proven to effectively improve learning across all demographics and most age groups [36]–[38]. Much of the research has compared traditional pedagogical approaches, such as lectures or even general group work in contrast to approaches which are supplemented to varying degrees by the use of games, with generally positive findings.

In [21], Kapp goes into more detail on what he considers good gamification techniques, again highlighting the ways in which the added challenge and context of a game encourages students to work hard of their own accord – evidence of this can be found in a study from the University of Texas which found students voluntarily did three times as much work when their work was presented as a game rather than a traditional assignment [22]. Likewise, [21] discusses the importance of good design of gamification for educational purposes, meaning that any game created for learning should employ the qualities of other good games yet still be suitable for conveying everything the educator needs – in short, it must be fun with meaning. Several of the learning activities we will discuss in this paper achieve this by mimicking popular party games to achieve meaningful learning outcomes.

The remainder of this paper is structured as follows. Section II describes the institutions and the structure of the treated courses. Section III provides details about the specific activities that were implemented. Section IV discusses the assessment data that was collected, including pre- and post-surveys, focus groups, and course evaluations. Section V provides instructor reflection. Section VI concludes the paper.

II. Course Structure

For context, we provide here an overview of these institutions. Western Washington University (WWU) is a public master's granting institution located in Bellingham, WA. It is the third largest university in the state of Washington. While WWU formerly offered degree programs in engineering technology, the newly formed Department of Engineering and Design graduated its first class of electrical engineers in 2016. Currently, the electrical engineering program is a purely undergraduate degree program. In contrast, the Air Force Institute of Technology (AFIT) is a military-focused graduate-only school, forming a graduate analog of the U.S. Air Force Academy. 68% of the students are in the U.S. Air Force, and another 10% are officers in other services or are officers in allied international militaries. The enrollment is 56% MS, 23% PhD, 16% certificate program, and 5% non-degree-seeking.

The AFIT courses that were studied were EENG580, Introduction to Signal Processing; and EENG663, Signal Detection & Estimation. EENG580 is a first-quarter graduate class. Many of the students have already had undergraduate Fourier theory, though some have not; as such, no pre-requisites are assumed, and the course covers a hybrid of undergraduate and graduate concepts within basic signal processing. EENG663 is a third-quarter graduate class, and it is fairly advanced and rigorous. The WWU courses that were studied were EE360, Communication Systems; EE361, Signal Propagation; and

EE460, Digital Communication Systems. These are required junior and senior-level undergraduate courses.

In order to free up time for the proposed active learning activities, the classes were “flipped” [16]–[18], i.e. most lectures were pre-recorded and viewed by students at home. The WWU courses were flipped during both the baseline and treatment offerings, and the AFIT courses were flipped only during the treatment offering. At both institutions, the 7 to 15 minute videos were recorded on tablets using the “Explain Everything” app. When the assessment data is discussed in Section IV, efforts will be made to segregate the effects of simply flipping the classroom from the effects of the active learning activities.

AFIT and WWU are both on a quarter system, with ten weeks per quarter plus an exam week. The AFIT courses met for four hours of lecture per week, while the courses at WWU met for three hours of lecture and two hours of lab per week. The WWU courses used a combination of tinkering and gaming activities throughout the duration of the course, both during the lecture periods and the lab periods. Some activities occupied as little as 30 minutes of class time, while other project-focused activities occupied multiple lab sessions spanning two weeks. The primary topics covered in EE 360 included significant review of continuous linear time-invariant systems and frequency-domain concepts, sampling and interpolation in discrete-time systems, amplitude modulation, quadrature modulation, and pulse-amplitude modulation. The primary topics covered in EE 361 included transmission lines, RF impedance matching, RF signal propagation, wireless channel modeling, and basic concepts in antenna theory.

For lecture periods at WWU which did *not* make use of tinkering/gaming activities, the students were instructed to take notes and formulate questions on the video lectures they had watched in advance of the class period. These classes began with the instructor giving a short problem to work while walking around the room to “check off” that each student had compiled notes from the videos. Next, several students were randomly selected in turn to ask questions from their notes, which typically lasted about 10 minutes. The instructor then opened the floor to accept questions from any students with lingering questions. About half of the time, the question-asking portion led to an engaging discussion lasting the duration of the assigned lecture period. Other times, the Q&A lasted approximately half the lecture period, and the remaining class time was used to work homework problems.

III. Activity Overview

Our intent here is to provide enough context for the reader to understand the activities, but not to provide exhaustive details. Full descriptions of the activities have been posted at [39]. As such, we provide a short description of a few of the projects, the material each covers, the tinkering elements, and the competitive elements.

EENG580, transform properties: Students use properties of the 2D Fourier and Mellin transforms to efficiently realign multiple images that have been translated, rotated, and scaled. The associated course material was transform properties and how they vary between the 1D Fourier transform, the 2D Fourier transform, and the 2D Mellin transform (a.k.a. the Fourier transform in log-polar coordinates). To incorporate tinkering, the students were given a list of potential applications and asked to use the method they developed for as many applications as possible. Options included detecting subtle changes between successive images of a scene, mosaicking of many overlapping images into a larger image, de-jittering of a video, and super-resolution. To provide a competitive aspect, students were asked to present the results from each application they attempted, and the class voted on the most impressive solution for each application.

EENG580, filtering: Students design an audio filter to remove narrowband interference from an audio signal. This is a fairly straightforward and common laboratory exercise in signal processing classes. The tinkering aspects were somewhat minimal, consisting of determining the spectrum of the interfering signal so as to determine filter specifications, and adjustment of the filter coefficients through standard methods. The competitive aspects involved developing a robust design process: students competed to find the least computationally complex design that would meet specifications and to redesign the filter to meet new specifications in as small a time as possible.

EE360/EENG580, radio transmission: This unit covered an array of topics related to radio systems, primarily sampling theory, mixing/modulation, and correlation. Students design an end-to-end digital communication system using audio hardware in a way that mimics radio hardware. Very little information about existing communication systems was provided to the students in advance, so the tinkering aspect involved determining a mapping from bits to waveforms, methods for deciding which bits were sent, and maximization of performance by considering the frequency response of the environment and audio equipment. An unintended tinkering aspect arose from the fact that all of the cheap audio hardware we tried tended to produce significant harmonics (in some cases comparable to the fundamental frequency), wreaking havoc on designs that used frequency-division protocols; and the students had to identify and correct for this issue while on a time line. To add a competitive aspect, students competed to maximize bit rate (subject to a maximum bit error rate), maximize transmission distance (with minimum bit rate and maximum bit error rate requirements), and minimize the computational complexity per received bit.

EENG580, verbal game: One hour of class time is used for concept review near the end of the course to play a verbal game similar to Taboo, Catch Phrase, Unspeakable, Battle of Words, or Word Charades. Students divide into teams, and one player must get teammates to guess a word, but the clue giver cannot say any of a list of forbidden words (see Fig. 1). This can be an effective learning tool if used carefully, since students must prepare by learning the meaning of each course concept rather than memorizing a verbatim definition.

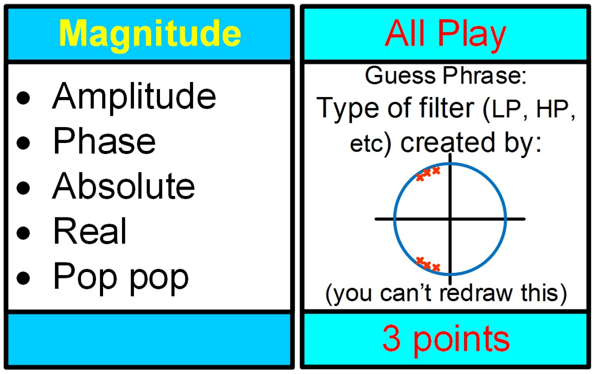

Fig. 1. Example EENG580 game cards, as presented during the game. Left: in the verbal game, teammates must guess "magnitude" but the cluegiver cannot say "amplitude," "phase," etc. Right: in the drawing game, the cluegiver must first determine that the guess phrase is "band stop filter" and must then sketch it well enough for teammates to guess it.

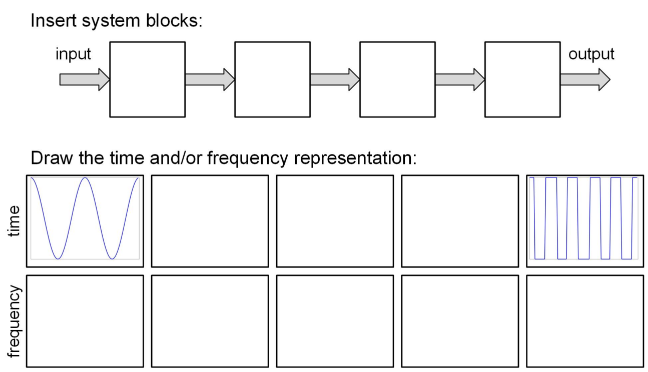

Fig. 2. EE360 signal elements gameboard. Plot axes are omitted for readability.

EENG580, drawing game: One hour of class time is used for concept review near the end of the course to play a drawing game similar to Pictionary; Win, Lose or Draw; Fast Draw; Draw Something; or iSketch. Students divide into teams, and one player must get teammates to guess a word using only sketches (see Fig. 1). Traditionally, no characters can be written, but we allowed a small list of characters to be used given that the course content is so mathematical in nature. Again, this can be an effective learning tool because it forces students to think about and explain course concepts in a non-traditional way.

EE360, graphical convolution: Students are given 16 simple plots (e.g. delta function, rectangle, triangle) on transparency film and a set of 20 mystery shapes that were produced by convolving the simple shapes. One student on a team picks a mystery shape and determines which two simple shapes were convolved to produce it, making use of the transparencies to try out the convolution. Then a teammate takes just the two simple shapes and redraws what he/she thinks the mystery shape is. This allows students to practice deconvolution and convolution and assess their understanding.

EE360, signal elements: Each group is given a gameboard (shown in Fig. 2) signal cards, element cards, and frequency tokens, an erasable marker and a 10-sided die, and a list of recipe cards. Each recipe lists the input and output signals, the available system elements, and the frequency values available. Taking turns, each student arranges the elements into a correct order and places the frequency tokens onto the appropriate signal blocks. Another student fills out the sketches at each point along the gameboard. An example might consist of the starting and ending signals shown in Fig. 2; an element list consisting of a high pass filter, a low pass filter, two mixers, and a one-bit quantizer; and frequency options (for filter cutoffs or mixers) of 1 kHz, 9 kHz, 10 kHz, and 11 kHz. For this example, there are 60 possible element arrangements and 24 ways to assign frequencies to each arrangement, leading to 1440 possible configurations; so students must proceed methodically rather than via a brute-force approach.

IV. Assessment Data

A. Pre/post surveys

Table I shows student survey responses from the baseline and treatment course offerings at WWU, the undergraduate institution in this study, and Table II shows the responses from AFIT, the graduate institution in this study. Fig. 3 shows the same data in visual form. There were four categories of questions: student interest in the subject matter, perception of its value or significance, abilities at various tasks, and level of independence at various tasks. Multiple questions were averaged within each category. The full survey instrument is available at [39]. The goal is not simply to promote growth in each category, but to promote more growth in the treatment offerings than in the baseline offerings.

The most noticeable point is that the "abilities" category grew the most, both in baseline and treatment years and both at WWU and at AFIT. With the already high level of growth in the baseline WWU offering, it is perhaps not surprising that the WWU treatment offering did not exhibit additional growth. However, there was a slight increase in growth in the AFIT treatment offering. The "interest" and "perception" categories behaved similarly to each other. In the baseline offerings, WWU growth was small and there was even a small decrease at AFIT. In the treatment offerings, growth increased slightly at WWU and the the drop at AFIT was reversed to produce some growth. The "independence" category improved as well, with a modest improvement in the treatment offering (over the already significant baseline growth) at WWU, and with a doubling of growth at AFIT. In summary, in terms of absolute growth, "abilities" and "independence" grew the most in the treatment year; but relative to the baseline offering, "interest" and "perception" exhibited the most improvement in growth in a relative sense.

Despite the improvements in the treatment offering, growth in student interest remains low, even though this category was expected to improve the most when this study was conceived. Our hypothesis for this behavior is that there were perhaps too many assignments, and they may need to be streamlined since these were the first offerings of most of the assignments. The activities will be refined and the workload will be dropped in

TABLE I
UNDERGRADUATE STUDENT SURVEYS FROM WWU. IN EE360 & EE361, 50/50 RESPONDED ON THE BASELINE PRE-ASSESSMENT, 46/50 RESPONDED ON THE BASELINE POST-ASSESSMENT, 26/26 RESPONDED ON THE TREATMENT PRE-ASSESSMENT, AND 22/24 RESPONDED ON THE TREATMENT POST-ASSESSMENT.

WWU data	interest (1-5)	perception (1-5)	ability (1-5)	independence (0-100)
baseline pre	3.88	3.97	2.49	63.6
baseline post	4.00	4.19	3.82	75.4
baseline change	0.12	0.22	1.33	11.8
treatment pre	3.80	4.01	2.68	64.7
treatment post	4.12	4.39	3.93	80.5
treatment change	0.32	0.38	1.25	15.8

TABLE II
GRADUATE STUDENT SURVEYS FROM AFIT. IN EENG580 & EENG663, 31/34 STUDENTS RESPONDED ON THE BASELINE PRE-ASSESSMENT, 15/34 RESPONDED ON THE BASELINE POST-ASSESSMENT, 26/27 RESPONDED ON THE TREATMENT PRE-ASSESSMENT, AND 18/26 RESPONDED ON THE TREATMENT POST-ASSESSMENT.

AFIT data	interest (1-5)	perception (1-5)	ability (1-5)	independence (0-100)
baseline pre	3.88	3.82	3.18	65.5
baseline post	3.71	3.63	3.69	73.0
baseline change	-0.17	-0.19	0.51	7.4
treatment pre	4.13	3.91	3.38	68.3
treatment post	4.16	4.25	3.94	84.8
treatment change	0.03	0.34	0.56	16.5

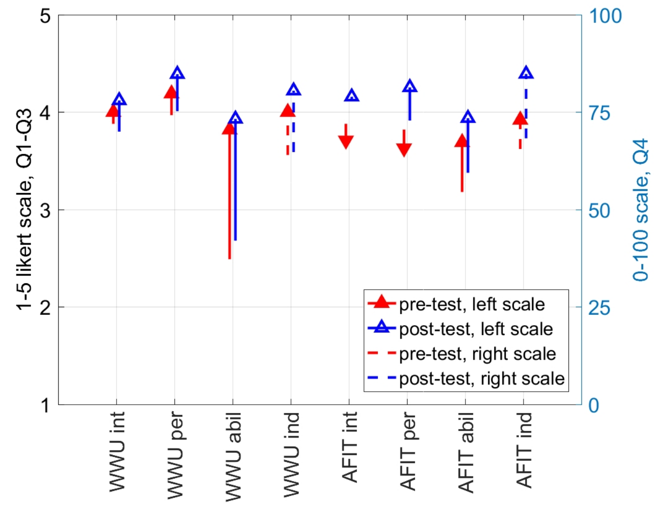

Fig. 3. Visual representation of survey data from Tables I and II. Arrowheads indicate an increase or decrease. Since the four question groups use different scales, two axes were used, but the axes were scaled such that their minima and maxima coincide, allowing relative comparison of the data from different question groups.

the final year of this study, and we will reassess at that time. The growth in student confidence in their abilities and level of independence was not the targeted outcome, but in retrospect it does not seem that surprising given that the various activities were designed to let the students *do* something rather than just solve homework-style problems.

B. Focus groups

At the end of each course, an hour was set aside for a voluntary focus group session. The instructor left and a student moderator ran each session. The students were given three questions to answer: (1) What aspects of the course were most helpful in developing new skills? (2) What aspects of the course affected your self-motivation, and how? (3) What suggestions do you have to improve the learning process for students in the course next year? Students discussed possible responses in small groups, then amalgamated a list of the responses from the entire class. The students then individually scored each response from 1 to 5, with a 5 indicating that the student fully agrees with that response. The median, mean, and standard deviation of these scores for the highest-averaging responses are listed in Tables III and IV.

The **baseline** year focus group top responses are listed in Table III. There were several recurring themes throughout the session:

- Examples: Practical and/or applied examples were cited as positively influencing both students' self-motivation and their development of new skills. (1A,1B,2C)
- MATLAB practice: Students were pleased with development of MATLAB skills at the same time that they offered suggestions for making increased use of MATLAB including possibly meeting in a computer lab so that examples could routinely be worked along with lectures. (1A,1C,3B)
- Assignments: Project and homework both positively influenced students' self-motivation and skill development. Students cited the logistical benefit of only having to submit one homework problem per assignment but acknowledged that having additional required submissions might help them develop skills even more. (1A,1B,2B,2D)
- Textbook: Students' lowest rating for any item was for the impact of the textbook on their motivation (i.e. it had a negative impact) and replacement of the textbook was suggested as a way to improve the class (though this was not one of the top suggestions). (1E)

TABLE III
FOCUS GROUP TOP RESPONSES DURING THE BASELINE OFFERING OF EENG580 AT AFIT. 12 STUDENTS PARTICIPATED. FOR BREVITY, ONLY RESPONSES AVERAGING ABOVE 4/5 ARE LISTED. Q1 RELATES TO SKILL DEVELOPMENT, Q2 RELATES TO MOTIVATION, AND Q3 RELATES TO FUTURE IMPROVEMENTS.

AFIT baseline top responses	Med	Mean	σ
1A) Project provided matlab/writing skills	5.0	4.33	0.98
1B) Homework examples were practical	4.0	4.25	0.75
2A) Professor helpful in office hours	4.5	4.50	0.52
2B) Project & homework were interesting	4.0	4.25	0.75
3A) Post lecture notes in advance	5.0	4.58	0.67
3B) Hold class in a computer lab	4.0	4.08	1.00

The **treatment** year focus group top responses are listed in Table IV. Recurring themes differed from the baseline year:

- Activities: the open-endedness and competitive nature of the activities were said to significantly improve skillsets and motivation. (1A, 1B, 1D, 1G, 2A, 2C, 2I)
- Videos: the use of videos to enable a flipped classroom

TABLE IV

FOCUS GROUP TOP RESPONSES DURING THE TREATMENT OFFERING OF EENG580 AT AFIT. 14 STUDENTS PARTICIPATED. FOR BREVITY, ONLY RESPONSES AVERAGING ABOVE 4/5 ARE LISTED. Q1 RELATES TO SKILL DEVELOPMENT, Q2 RELATES TO MOTIVATION, AND Q3 RELATES TO FUTURE IMPROVEMENTS.

AFIT treatment top responses	Med	Mean	σ
1A) Open-endedness of projects	5.0	4.62	0.65
1B) Project competitions	5.0	4.50	0.65
1C) Teams for the projects	5.0	4.50	0.76
1D) Flexible due dates	5.0	4.50	0.65
1E) Lecture videos	4.0	4.07	0.65
2A) Competitions	5.0	4.64	0.50
2B) Videos: rewatch, pausing	4.0	4.07	1.21
2C) No strict lab procedures	4.5	4.07	1.07
3A) Solve some problems in lecture	5.0	4.64	0.74
3B) Have some lecture re-cap	5.0	4.50	0.65
3C) More examples in videos	4.0	4.29	0.61
3D) Fewer assignments	4.5	4.14	1.03

improved skillsets and motivation, and students enjoyed being able to pause and re-watch video segments. (1E, 2B, 1H)

- Time management: having flexible deadlines and submission requirements improved student motivation. (1D, 2D, 2H, 2J)
- Most of the criticisms asked for more examples and/or re-cap of the videos during lecture. (3A, 3B, 3C)

In both offerings, students seemed to like *doing* things. The primary criticisms from the baseline year were both alleviated in the treatment year, since the use of videos removed the need for rapid note-taking and the need for a computer lab was removed as all the students brought in laptops daily to work on their projects. However, the use of a flipped classroom may have swung the nature of the class to make students feel too directionless since in two of the criticisms, the students asked for some in-class lecture to be brought back. As noted in Section IV-A, they also felt that the new approach had a bit too much work, so care must be taken when adding in-class projects to the existing homework structure. The homeworks are still needed to teach the mechanics, but perhaps they could be pruned a bit.

C. Student evaluations

The student evaluation questions are standardized by the school and were generally not targeted at the assessment questions of interest to this study. As such, we have not included the full numerical data here, but we have included qualitative data in the form of relevant student prose that was included in some of the survey responses from the treatment offering of EENG580 at AFIT. The responses most directly relevant to this study are:

- "The structure of the course (inverted class), the assignments (labs and homework), and the teaching tools (games) made this one of the best courses I have ever taken. I feel that I understand DSP on a level I never have before."
- "I thought some of the ideas [from the focus group] were good. Especially the idea to have a high level overview of the relevant videos at the start of each class. Just a presentation of the concept and important equations. The examples and derivations can be left for the videos."
- "I did not think the reverse classroom thing really works at all. I felt like I was taking two classes at once. The labs consumed so much time and effort, that they really became a course of their own. I would recommend lecturing at least once a week. The videos were helpful, but I don't think you can call them a substitute for a lecture."
- "With videos being the lecture, I found it difficult to remember the information presented. If I had a question, I had to remember to write it down for future class times instead of having the benefit of classroom discussion on the theory with the immediate lecture on a topic."
- "It was very useful having the video to be able to watch [a] section multiple times when I did not understand something."
- "This really turned into a lab class. It was fun but I'm not sure I took a lot away academically. I'm still not sure I could successfully do a DFT on my own. Whether that is needed with computers I don't know."
- "He didn't provide many instructions, but I think that was intentional. The freedom we had with the projects was unusual but I think beneficial. I was never really sure what to expect from the exams though."

There was a wide range of responses. Note that the responses to the flipped classroom (i.e. the use of videos) was particularly mixed. There was less resistance to the assignments themselves, though the next-to-last response suggests that the student is more comfortable with by-hand computation than the extensive reliance on computers used in this course. In aggregate, the responses support earlier data indicating that in the final year of the study, there should be fewer assignments and a bit more in-class lecture during contact hours.

V. INSTRUCTOR OBSERVATION AND REFLECTION

When offering open-ended activities, one potential stumbling block is that students will try a wide variety of approaches to solve many different extensions to the original problem, and it is difficult to anticipate all of these approaches in advance. In activities which permit students to use a wide range of hardware, much of the instructor's in-class time can be spent debugging hardware-related issues. This can be time consuming for instructors and frustrating to students, since progress is halted until the instructor can help or until the students resolve the issue on their own. Arguably, achievement of the latter outcome is a desired learning objective for the students, but this issue can cause significant stress for students worried about assignment deadlines. It is recommended that instructors test out as many possible implementations on as many computing platforms as possible to mitigate this issue. If the activities across the course are constrained to only one or two sets of hardware (e.g. audio hardware and cameras), that can help as well. Having a graduate student test-run each activity and verify that a solution can be easily implemented on that student's platform is generally not sufficient to ensure that the activity will proceed smoothly in class.

It can be all too easy to make fun projects that have minimal relation to course content. Instructors should keep the course learning objectives in mind when designing activities. In several of our projects, we added course videos covering extension content beyond the usual course scope, with such content tied to applications within the activities. For example, the Mellin transform is not usually covered in introductory signal processing classes, but we included a video on implementing it in discrete time in two dimensions, which allowed us to extend the Fourier properties activity from simple image translation to rotation and scale alignment.

Many students complained about the workload when they had activities to complete and write up along with traditional homework-type assignments. We tried to mitigate that in EENG580 by only grading homework based on completion and being very liberal with due dates, but that was insufficient. In EENG663 which was offered in the current term that just completed, we scaled back from 5 activities to 4 and from 6 homework assignments to 4. This lead to coverage of fewer concepts, but hopefully with greater understanding of those few concepts. The students also felt a bit adrift when they spent so much time viewing videos on their own; as such, in future offerings, we will add a small amount of live lecture time to the start of most classes.

Equipment cost is an issue. Most universities do not provide much funding for educational equipment. The activities listed in this paper generally use low-cost equipment such as audio hardware (available on most laptops for free, or cheap external devices can be bought for $10 per item for standardization), cameras (readily available on smart phones), software radios (RTL-SDR dongles are available for $20 each), and homemade manipulatives such as transparencies and laminated cards. Additional gaming materials could be created virtually as MATLAB software if the department is willing to use teaching assistant funds to hire a student as a programmer.

The treatment offering did seem to improve student participation. In traditional lecture formats, many of the students are reluctant to ask or respond to questions, or to volunteer to solve problems on the board. In the treatment offering, these more "reserved" students were as engaged in the activities as the more "boisterous" students. Both types of students appeared to be very invested in the activities. Even though most of the activities only required students to complete a fraction of questions, many students opted to complete more than the required minimum.

On generalization: versions of all of the courses discussed above are taught at universities in electrical engineering programs around the world, so the specific activities could be implemented at most universities with minimal modification. However, the context may need to be considered in the course design. This refers to the maturity of the student body, their incoming programming skills, their prior experience with hardware, and how common group work is at a given institution. The simplest way to adjust for the student population is to provide them with more resources or time as needed. For example, a younger or more academically diverse student population could be given some starter code or examples; and a weaker student population could be given more time to complete each activity. The activities can be modified for more sophisticated student populations by adding challenge problems or even asking them to implement techniques from the literature. There may be some administrative considerations to be accounted for as well. Specifically, there can be a challenge in finding class time to do these activities. This is most easily accomplished by adding/repurposing a dedicated lab slot, by flipping lectures, or by making them optional after-hours gaming help sessions (perhaps run by a teaching assistant). However, there is considerable research on the benefit of these sorts of "active" learning approaches, and so even if adding these activities to class comes at the expense of some other course content, perhaps the students are learning more overall.

On competition: Thoughts on the influence of the competitive aspects of the activities are somewhat speculative, since we did not perform offerings without the competitions. The students seemed to enjoy the competition, but it is still a form of evaluation and thus an added emotional burden for the students. However, if the competitive aspect was removed, it might reduce the impetus for the students to explore and to go beyond the minimum guidelines for each activity. This in turn might reduce the students' growth in independence. A subset of our effort focused on collaborative versus competitive work was documented in [40], which showed that both aspects have value, and nether aspect should be marginalized relative to the other.

VI. Conclusion

Gamification and embracing the makerspace ethos are two current trends in engineering education. In this study, we combined these two approaches to develop classes centered on multiple open-ended competitive active learning activities. We implemented these classes at one undergraduate-only institution and one graduate-only institution, and evaluated the students via surveys and focus groups. A flipped classroom was used to enable the use of the new activities during contact hours. Relative to a baseline offering, the treatment group developed a marginal improvement in attitude, motivation, and self-assessed abilities; and a significant improvement in independence. The latter metric rose from 9.2% growth to 16.2% growth, averaged across the two institutions. The focus groups said that the aspects of the course that improved their skills and motivation the most were the competitions, the use of small teams for each project, and the open-ended nature of the projects; whereas the most detrimental course aspects included not enough live lecture time and not enough example problems were covered for the students to learn some of the mathematical mechanics. The students also seemed beaten down by the workload; when adding activities such as these, time and effort must be reduced in other areas so that the students can adequately complete all assignments. We hypothesize that the high workload in the treatment offering is the cause of the minimal improvement in student morale, and this will be addressed in the final year of this study.

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