MAKING AND GAMING IN SIGNAL PROCESSING CLASSES

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ABSTRACT

Signal processing, communication systems, and estimation and detection theory are important concepts in electrical engineering, and are taught in most graduate and upper-level undergraduate electrical engineering programs. Students often struggle with the abstract concepts of signals, however, largely because the courses are very theoretical. Traditionally, these theoretical courses are delivered in a lecture-based format which provides little opportunity for students to attain a concrete understanding of signals. Occasionally, signals courses have an associated lab, but they often rely heavily on numerical simulations, which leaves students struggling. In this paper we lay out an active learning framework for engaging students using the "tinkering" concept used in the emerging maker movement and the idea of "gamification." We present baseline data, course structure, activity lists, and details of a specific activity.

Index Terms— Education, tinkering, maker movement, gamification, active learning

1. INTRODUCTION

The traditional "chalk-and-talk" lecture format is pervasive, but it has increasingly been shown to be ineffective at engaging student interest. Table 1 shows student survey responses from the four baseline course offerings; the full survey instrument is available at [1]. Student interest and perception either declined or only slightly increased from the pre-assessment to the post-assessment, even though their self-assessment of abilities and independence markedly increased. The AFIT instructor has won five student-selected teaching awards and scores in the top 40% of instructors in student course evaluations, suggesting that the drop in interest may be due to the traditional class format and content rather than student dissatisfaction with the instructor.

Educational research has pointed to student-centered, active learning to improve student comprehension, interest, and retention – particularly within underrepresented groups [2]. 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 [3]. Most approaches to active learning in engineering take the form of collaborative problem-solving [4] or design projects [5, 6] and the use of student-centered inquiry-based activities has been recognized as an important active learning tool [7].

Table 1. Baseline student surveys. In EENG580 & EENG663 at AFIT, 31/34 students responded on the pre-assessment and 15/34 responded on the post-assessment. In EE360 & EE361 at WWU, 50/50 responded on the pre-assessment and 46/50 responded on the post-assessment.

	interest	perception	ability	independence
AFIT pre	3.88 /5	3.82 /5	3.18 /5	65 /100
AFIT post	3.71 /5	3.63 /5	3.69 /5	73 /100
WWU pre	3.88 /5	3.97 /5	2.49 /5	64 /100
WWU post	4.00 /5	4.19 /5	3.82 /5	75 /100

Two active learning approaches which have recently attracted attention include *tinkering* [8–10] and *gamification* [11–13]. 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, 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 [8–13], 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 at home [14–16].

Tinkering is adapted from the concept of "makerspaces" – do-it-yourself, grassroots organizations focused on designing, building, and hacking [17, 18]. Many "makers" are actively developing and innovating with low-cost platforms (e.g. Arduinos, Raspberry Pis, DSP boards, or software-defined radios) without theoretical background or formal training. However, there is a gap between traditional learners and makers, leading to an opportunity for cross-fertilization. We seek to leverage the excitement and tinkering ethos of maker culture by bringing them into the classroom. For example, makers have embraced $35 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 materials which can be used for tinkering include acoustic hardware (speakers, mi-

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crophones), and DSP boards and single-board computers which are already available in many institutions.

Gamification [11, 12] has recently been popularized in academia and industry, for various reasons. First, games can encourage students to work hard of their own accord [19] – a University of Texas study found students voluntarily did three times as much work when it was presented as a game [20]. Second, over time, students in the sciences become more analytical and less creative [21]. Games can counter this by requiring non-traditional interactions with the course content. Finally, games provide an alternative model for student progress. McGonigal notes that games provide a series of "unnecessary obstacles" which allow players to learn by *rapidly failing and improving* – thus mastering the challenge at hand [22]. Indeed, gamification has shown promising results in research across higher education [23–25] and industry [26, 27].

2. COURSE STRUCTURE

This section discusses overall course structure; details of a few specific activities are provided in Section 3. Due to limited space, the intent is to inspire comparable course design by other instructors rather than to provide step-by-step instructions, though eventually more detailed instructions will be available at [1].

Table 2 lists "tinkering" or makerspace-style activities that have been developed and alpha-tested for the authors' courses. Most activities use four contact hours each and the majority of students' out-of-class time across two weeks, within the context of a course with four contact hours per week. The use of a flipped classroom allows expenditure of contact hours on the activities. The remaining four contact hours from each two-week unit can be used for problem working sessions or elaboration and answering of questions about the video lecture material. The hardware required for each activity is stated in Table 3. Due to typical instructor budget constraints, most of the activities were designed to use inexpensive equipment, such as a USB speaker/microphone set, a pair of monaural microphones synchronized using a mono-to-stereo connector, a camera (available to most students via their phone), and a cheap software radio. The exception is the angle of arrival estimation activity, which uses a more expensive radio with multiple synchronized receive antennas. However, suitable radios such as the USRP E310/E312 are fairly common in departments that engage in communications research.

In order to "gamify" each activity, the following approach is endorsed. Baseline completion of a set of minimum requirements will be sufficient to earn a passing grade, and a higher grade can be earned with a more complete, accurate, and well-written report, and/or by completing additional activities. These additional activities will take the form of competitions, as listed below. This provides students with autonomy and some degree of control over the learning process, which is an important component to learning [28]. Subjective competitions will be voted on by the class, which will also allow students to showcase their results to their peers.

Impulse response: Students will transmit and receive an audio signal and measure the acoustic response of an environment. Competitions will include finding an impulse response with the longest-delayed non-line-of-sight component, finding a response with the most frequency nulls, and characterizing the most distinct environments. **Graphical (de)convolution:** Students will be given a collection of "shape cards" as well as a "mystery signal" sketched on transparency sheets, and will be asked to select a set of shape cards that, when convolved, recreate the mystery signal. Deconvolution exercises can be performed by additionally giving the students a starting "shape card". **Position tracking:** Students will use a pair of microphones to track a speaker who is known to be on a line 2 feet from the whiteboard, using time-difference-of-arrival. Competitions will include least position error, fewest computations required to meet a prescribed error threshold, and most visually impressive real-time tracking performance. **Image registration:** Students will align multiple images that differ by a translation. Competitions will include best demonstration of various extensions, such as adding rotation and/or scale differences, super-resolution, de-jittering video frames, mosaicking, change detection, and dealing with illumination differences. **Filter design:** The goal here is to remove narrow band noise from an audio recording by designing a stop-band filter. Competitions will include the shortest FIR filter that meets the filter specifications, the first group to successfully re-design the filter after specifications are changed, and the best implementation of a technique from the literature (e.g. design of a filter with quantized coefficients). **Communication system design:** Students use a speaker and a microphone to transmit bits from one laptop to another. Competitions include maximizing the bit rate, maximizing the transmit-receive distance that maintains a target bit rate, and minimization of receiver computational complexity. **Communication system mix-n-match:** Students will be given cards containing various communication system blocks (oscillators, mixers, filters, quantizers, samplers) as well as various input signals. Students will then "create" systems by ordering and connecting the system blocks in varying configurations, and will be asked to sketch the time and frequency domain signals between each connected block. **Multiuser Communication Systems:** All student teams are given a microphone which acts as a receiver. Students are tasked with collaboratively sharing a single speaker which acts as a transmitter (e.g., in FDMA or TDMA) to transmit the maximum amount of data to each receiver. Competitions include maximizing sum rate, maximizing worst case rate, and minimization of receiver computational complexity. **Geolocation:** Students will use a cheap software radio to measure signal strength of an FM radio station, and will use multiple measurements to estimate its position. They will compete to locate as many stations as possible (within some position error); and to locate a station as accurately as possible with 10, 20, or 30 measurements. **Frequency estimation:** This project involves applying common frequency estimation algorithms; alternatively, the frequencies can be pre-specified, making this an M-ary detection problem. Students will compete based on estimation error, minimum computational complexity, and real-time tracking performance of a frequency-hopping signal. **Angle of arrival:** Students will use a software radio with 2-4 synchronized input terminals to estimate the bearing to a radio transmitter. Students will compete to demonstrate performance in as many methods as possible (e.g. MUSIC, ESPRIT, ML, etc.) and to minimize estimation error. **Spectrum sensing:** The goal is to use a simple software radio to detect the presence or absence of a radio emitter in a given spectrum band. Students will compete based on accuracy, on minimization of complexity, and best real-time visual display. **Pixel classification:** Students will use their cameras to collect a large database of photos of multiple material types as viewed from a distance (e.g. grass, trees, brick, siding, pavement, clouds); then they will develop probabilistic models and algorithms to use when classifying a photo of an unknown material within the existing classes. Competitions will include best accuracy, lowest complexity, and smallest training database.

Meta games are also possible. Some researchers have implemented a virtual "trophy case" (e.g. "perfect score on a quiz"), mirroring Xbox and Playstation video game communities [11]. Similarly, [11] did an excellent job of unifying a variety of activities into a single theme, using experience points, leaderboards, and achieve-

Table 2. Tinkering activity suggestions. The various equipment sets are detailed in the text. "DSP" means digital signal processing, "comm" means communication systems, and "D&E" means detection and estimation.

Course	Activity	Equipment	Topics
DSP	Impulse response measurement	Audio1	LTI systems, impulse/freq. response
DSP	Graphical (de)convolution	Office	convolution, deconvolution, LTI systems
DSP	Speaker position tracking	Audio2	Fourier properties, the DFT, sampling
DSP	Image registration	Camera	Fourier properties, the DFT
DSP	Filter design	Audio1	FIR/IIR filters, sampling
DSP/comm	Communication system design	Audio1	filters, the DFT, sampling
DSP/comm	Communication system mix-n-match	Office	oscillators, mixers, filters, sampling
DSP/comm	Multiuser Communication systems	Audio1	FDMA, TDMA, CDMA, interference
D&E	Signal strength geolocation	SDR1	MLE, CRLB
D&E/comm	Frequency estimation	Audio1	MLE, CRLB
D&E	Angle of arrival	SDR2	MLE, linear algebra
D&E/comm	Spectrum sensing	SDR1	Neyman Pearson detection, ROC curves
D&E	Pixel classification	Camera	M-ary detection

Table 3. Equipment. Cost estimates assume each group already has two laptops running MATLAB and a cell phone with a camera.

System	Description	Example	Cost/group
Audio1	Speaker and microphone	laptop, or USB peripherals	$0-$30
Audio2	Synchronized microphone array	Audio1 x2 plus mono-to-stereo adapter	$50-$100
Camera	Standard camera	Phone camera	$0
SDR1	Software radio receiver	RTL-SDR, HackRF, AirSpy	$30-$300
SDR2	Radio receiver array	USRP E312	$3000
Office	Basic office supplies	markers, transparency foils	$20

ments. However, some research has shown that leaderboards can be demotivating to all but the top performers, with most students plateauing mid-way through the course as the leaders pull increasingly ahead [29]. For that reason, we have avoided a leaderboard; but in order to unify the course units, the students will play two review games near the end of the course. First, they will play Taboo®, which is a word game in which a cluegiver must get teammates to say a word, but the cluegiver cannot say a handful of select words related to the guessword. Then they will play Pictionary®, in which a student must sketch each course concept and have teammates guess it. Both games require custom-made cards for each course. One suggested rule change is to allow a handful of selected mathematical symbols in Pictionary®, wherein characters are normally forbidden. These two games force students to understand course concepts beyond the literal definitions, forcing creativity rather than regurgitation [30]; and one appeals to verbal learners, while the other appeals to visual learners. In past offerings, we have found that students often rely on shared experiences of the concepts with their study group, which helps foster a sense of camaraderie. Sample custom cardsets and templates are available at [1].

With this course arrangement, it is critical that students view the video lecture material and any pre-reading before class. There are several approaches that may encourage this. Standard approaches include occasionally having a short pop-quiz at the start of class, or collecting a written pre-lab assignment. However, these impose significant additional work on the instructor and tend to dampen student morale. Another approach is "warmcalling," wherein students are informed that each day, several students will be randomly selected and asked to formulate an intelligent question about the day's activities.

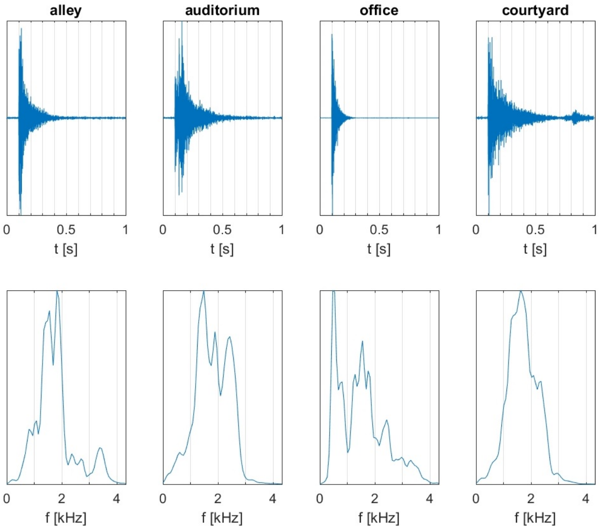

Fig. 1. Student-generated examples for the audio impulse response activity. Top: impulse responses. Bottom: frequency responses.

3. ACTIVITY DETAIL

This section details two specific activities from Table 2 that have been tested in a preliminary form by the authors. As an additional example, the "audio communication" activity from Table 2 was fully classroom-tested in a pilot study, as detailed in [31].

3.1. Impulse Response Measurement

Herein, students are to use the "Audio1" equipment from Table 3 to measure and compare the acoustic impulse response of several environments. We recommend providing each group with the same audio peripherals to level the playing field; this can be done for about \$20 per group. For the first half of the activity (week 1), the students are expected to view the following material in advance: discrete time signal notation and building blocks (notably a delta function), system properties such as linearity and time invariance, and characterization of a system by its impulse response. For week 2, the students must view the basics of the discrete Fourier transform. Since this is the material typically presented at the start of a DSP course, this is a good introductory activity. The students are also given a brief tutorial on using MATLAB to interface with the speaker and microphone – useful functions include "sound", "audiorecorder", "record", "stop," and "getaudiodata." Aside from that, the students are left to explore.

Tinkering challenges the students must grapple with include: (i) How do you generate an audio impulse? (ii) What environmental features will generate interesting effects in the impulse response? (iii) How do we deal with an asynchronous transmitter and receiver? (iv) How do we generate a "smooth" frequency representation from noisy data? (v) Does the inherent response of the audio equipment limit what can be measured? Game-based challenges can include: (a) Find an impulse response with a significant (say, at least 10% of the maximum) coefficient at the longest delay possible, and geometrically show why that coefficient arose in the recording environment. (b) Find a frequency response with as many nulls as possible (e.g., distinct valleys that dip by 3 dB relative to local peaks), and relate it to the geometry of the environment. (c) Depict as many unique responses as possible – as this is subjective, the winner can be determined by a class vote after each group presents their findings. The instructor may also encourage the students to consider speaker phones from cell phones or teleconference suites as interesting environments.

The student authors of this paper field-tested this activity and collected the data shown in Fig. 1. The amount of effort required to learn the hardware and software, develop a methodology, and collect the data was appropriate for a two-week activity.

3.2. Multiuser Communications

This inquiry-based activity intends to model the downlink in a communication system, and requires a group of students (each with their own receiver) to collaboratively share a single transmitter. The activity is conducted using simple acoustic hardware, and is designed to be a follow-on activity to the "communication system design" activity listed in Table 2 and described in detail in [31].

A wireless *acoustic* transceiver design is useful because it can be implemented very economically with two computers, a speaker, and a microphone. Fortunately, while the acoustic transmission medium and hardware have little similarity with RF transmission, the mathematical descriptions of signals and concepts such as modulation in acoustic communication are identical to those in conventional electromagnetic RF wireless communication. Thus, by conducting experiments using acoustic hardware, the students are able to hear the signals they create, which provides a less abstract observation of the operation of wireless communication systems. In addition, since acoustic frequencies are much lower, the activity can be completed with much slower sampling rates, and with readily available hardware without sacrificing learning.

The materials used for this activity consisted of very inexpensive, off-the-shelf components including: (i) PCs with standard onboard soundcards, (ii) installations of MATLAB, (iii) a 28mm 0.25W 8 ohm speaker intended for use as an internal PC speaker (\$1.85 ea), and (iv) a General Electric 98950 detachable desktop microphone (\$11.00 ea) for each student. We note that Octave would work just as well in place of MATLAB. Our choice of speaker was driven purely by cost, and virtually any speaker or microphone would suffice.

The single speaker was plugged into one PC (acting as a transmitter), and each of the students was given a microphone to be plugged into their PCs (acting as receivers). Since the chosen speaker was intended for use as a "PC speaker" that conveys BIOS error codes by beeping, its frequency response was highly frequency selective; the added complication of a frequency selective transmitter made for a useful learning opportunity. Again, as this is a follow-on exercise to a single user transmitter/receiver design exercise [31], the students had already characterized the frequency response of the microphone and speaker, and had previously created their own scripts for transmitting and receiving bits.

Adopting an inquiry-based approach, the activity description distributed to the students was purposefully lacking procedural details, and instead succinctly gave the students a design goal of collaboratively building a single MATLAB transmitter with multiple receivers to send and reliably decode at least 10 bits of binary information in 10 seconds or less at each receiver. The students were left to decide for themselves as a group how to implement the multi-user aspect of the activity. For example, some groups realized that their previously-developed single-user transmitters each used different frequencies for conveying information, so they employed FDMA. Other groups realized that they could split the 10 seconds of transmission time into time slots, and subsequently employed TDMA.

To encourage collaboration, the entire group of students was given a bonus that was a function of the worst performing receiver. This appeared to encourage students to collaborate heavily, and help one another to make sure that all receivers were as robust as possible.

Another variant of this activity involved students sharing the transmitter *competitively*. In this scenario, each student provided a signal to be transmitted (subject to a peak power constraint), and the transmitted composite signal was the sum of all students' transmissions. In this variant, the design goal was for each student to maximize their own rate while minimizing that of their peers, with bonus scores being given to the students with the highest bit rate.

4. COMMUNITY INTERACTION

In order to foster the "maker" spirit in the students, we will be meeting in a local non-profit makerspace during the contact hours for several of the activities. The relevant background theory and project handouts will be made available to the regulars of the makerspace, and they will be invited to partake in the competitions. The goal is for this interaction to further the tinkering mindset of the students and to give them the opportunity to explore a makerspace. Similar interactions are most likely possible in the readers' home cities; even though Dayton, OH and Bellingham, WA are fairly small metropolitan areas, they each have a variety of makerspaces. Near Dayton, there are Dayton Diode (daytondiode.org), Proto BuildBar (protobuildbar.com), FabSpace (fabspace.net), and Tinkr Tech (tinkrtech.com); and near Bellingham, there are The Foundry (bellinghamfoundry.com), The Hive (makedolearn.org), Spark Museum (sparkmuseum.org), Metrix Create:Space (metrixcreatespace.com), and Jigsaw Rennaissance (jigsawrenaissance.org). Many universities and small towns also have clubs that can serve this purpose, such as amateur ham radio operators clubs.

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