

Barry Van Veen

Flipping

Signal-

Processing

Instruction

The conventional approach to university education, prevalent for hundreds of years, involves a lecture by the professor during the scheduled class period and students working on exercises outside of class. *Flipping* a classroom refers to reversing the traditional role of in- and out-of-class activities. This instructional approach is sometimes also called *inverting* a classroom. In a flipped paradigm, the students are introduced to topics and basic concepts using video lectures or other means during their time outside of the classroom and spend the scheduled class period working on exercises under the supervision of the instructor. Instead of being a “sage on the stage” the instructor now becomes a “guide on the side” [1]. The conventional paradigm treats the student as an empty container into which knowledge is poured, while the flipped paradigm treats the student as an active learner who reconstructs knowledge from information. The flipped classroom began to receive increasing attention in the early 2000s (e.g., [2] and [3]) and has become much more accessible to instructors recently with the advent of low-cost screencasting software, e.g., [4], and Web-based course and video management tools. My institution, the University of Wisconsin-Madison (UW-Madison), recently opened a new teaching facility in 2011 called WisCEL [5] that is specifically designed for interactive, student-centered approaches to teaching and is perfectly suited for the flipped classroom format.

In the fall of 2012 and spring of 2013, I flipped two different signal-processing classes. This experience has convinced me that the flipped classroom is an extremely

effective paradigm for teaching signal processing. It has altered my core view of teaching and led me to raise my expectations for mastery of signal-processing concepts by all students.

MY FLIPPING JOURNEY

I decided to try flipping my signal-processing classes late in 2011 after watching the development of active learning strategies for around ten years and having an increasing number of conversations with colleagues about potential student learning gains. I had been regularly teaching two classes: a senior-level signal-processing class that covered sampling, the discrete Fourier transform (DFT), z-transform analysis, and finite/infinite impulse response filter design, and a graduate-level class that I had developed for students with no prior signal-processing background. In the graduate level class we begin with the definition of a signal, progress through sampling, the DFT, multidimensional signal-processing concepts, filter design, wavelets, random signal representations, and introduce estimation theory and hypothesis testing. This fast-paced class is application oriented and focuses on properly using MATLAB and standard signal-processing methods rather than developing theory. It is quite popular with graduate students in a diverse set of fields, e.g., biomedical engineering, neuroscience, psychology, materials science, geology, and computer science. My initial plan was to develop a flipped version of the graduate-level class because of its intensive use of MATLAB. However, I was able to schedule the senior-level signal-processing course in WisCEL for the fall of 2012 and decided to flip this course first.

In the spring of 2011, I had experimented with capturing my traditional

classroom lectures on video and making them available to the class through the Web. While the students in the class found this quite helpful for review or when they had to miss class, I concluded that these types of lectures were not well suited for a flipped classroom. The videos were long (75 min), sometimes had topics spilling over a lecture boundary, often had multiple topics in one lecture, and also contained information relevant to that particular semester. I decided—underestimating how much work this would involve by almost an order of magnitude—to record a series of modular, topical lectures on the order of 10–15 min each that would cover the contents of the senior-level signal-processing class. (A video describing the equipment and procedure I converged on for creating video content is available in [6].) When the fall 2012 semester began, I had recorded the first three weeks of content. By the end of the semester, I was frantically trying to finish lectures a few days before the corresponding class exercise.

I recruited an adventurous teaching assistant (TA), Joseph Karls, to join me on this teaching experiment during the fall semester. His main responsibility was to assist with developing the exercises that the students would complete each class period. He also assisted as a coach during class and held limited office hours. He voluntarily spent far, far more time on the class than his teaching appointment specified. He proved to be indispensable, as I had also underestimated the challenge of designing in-class exercises that were interesting and could be completed within the allotted class period by students having a range of backgrounds and strengths. It took several weeks to achieve this balance. In the first two weeks, it was common for no one to have finished our

planned exercise even after 90 min, despite the scheduled class time of 75 min. A significant number of students arrived early and stayed for the entire 2 h I reserved the WisCEL facility. The students were incredibly patient and an invaluable source of feedback as we worked toward finding an appropriate balance for the in-class exercises.

CLASS ORGANIZATION

The class was run through UW-Madison's version of the Moodle open-source course management system (CMS). The CMS hosted the video content, exercises, solutions, MATLAB files, and relevant articles. Figure 1 depicts a screenshot of the class Web page for the second week of the class. For each class period there is a list of the videos that were to be watched in advance along

with a list of relevant reference sections in the textbook. There were typically three 10–15 min videos assigned for each 75-min class period. The exercise for the period was released 15 min before the official start of class, due 45 min after the scheduled class end time, and solutions were posted later in the day. Twelve weekly homework exercises were assigned over the course of the semester. The homework assignments built on the classroom exercises. They were intentionally shorter than the weekly assignments I had used in the conventional paradigm. There was a midterm exam and a cumulative final exam. The final grade in the class was based on the classroom exercises, homework, and exams.

There was no penalty or explicit incentive for the students to watch the videos before coming to class, other than the fact that they would be applying the lecture material in the exercises. I did spot-check compliance through the CMS several times throughout the semester and found that nearly all of them were watching lectures prior to class. It was unusual for me to encounter a student in class that was unprepared for the exercise.

The WisCEL classroom space is organized in pods of six seats/tables arranged in a circle, as shown in Figure 2, to encourage interaction between students. Each seat has a laptop computer with access to MATLAB and the campus network. I let the students choose their seats each class period. While I verbally encouraged them to discuss the exercise with their classmates, I did not require any formal group

interaction to limit the number of changes they experienced.

The classroom exercises typically contained a mix of MATLAB and theoretical (pen and paper) problems. For example, an exercise on aliasing involved using MATLAB to downsample the sound produced by a saxophone playing a single note and using theory to calculate where the various harmonics should appear in the spectrum based on their original frequencies and the sampling rate. The students also listened to the sound at different sampling rates to hear the distortion due to aliasing. Their in-class work was formatted using MATLAB's "Publish" feature to produce a single file containing their code, plots, theoretical predictions, discussion, and analysis of the results. We learned that providing a MATLAB starter file with the layout for the exercise and key commands—especially complicated code sections not central to the concept under study—was key to facilitate completion of the exercise in a timely fashion. This scaffolding enabled greater focus on the signal-processing concepts at hand and avoided wasted time due to subtle coding issues. They completed the starter file by inserting MATLAB commands directly relevant to the concept under study and by recording their observations and analysis.

During the class period, the TA and I circulated throughout the classroom space both responding to questions and asking questions. For example, I might approach students with a plot on their computer screen and ask them what they were seeing and why it looked that way. Or I might ask how the assignment was going and if they had any questions. Occasionally I provided a brief clarification to the entire class upon observing widespread misunderstanding or a typo in the assignment. I intentionally tried to interact with each table at least once or twice during every class period. The support the students received from peer collaboration allowed the TA and I to focus on the most difficult issues they encountered and spend significant chunks of time with students that were really struggling with a problem or concept.

The screenshot shows a Moodle course page for 'Week 2'. It lists two class periods: Sept 11 (Videos 7-9) O&S 4.1, 4.2 and Sept 13 (Videos 10-12) O&S 4.3, 4.4. Under Sept 11, there are three lecture items: 'Fourier Representation Properties Lecture', 'Intro to Sampling Lecture', and 'Freq Domain Interp of Sampling Lecture'. Under Sept 13, there are three lecture items: 'Reconstruction and Sampling Theorem Lecture', 'Sampling - Examples Lecture', and 'Equivalent Analog Filtering Lecture'. Below these are 12 numbered items, each with a video icon and a document icon, representing lecture videos and notes. At the bottom, there are sections for 'Period 3 Exercises' (with a restriction notice), 'Period 4 (9/13) exercises' (with a restriction notice), and 'Homework 2 Specification' and 'Homework 2 Solution'.

[FIG1] A screenshot of the class Web page for the second week showing assigned reading, video lectures, notes, class exercises, homework, and solution files.

STUDENT REACTION

A variety of methods were used to obtain student reactions. Simple student feedback (keep it/change it format) was solicited in the third week. Formal student feedback of the course and teaching environment was obtained in the 14th week as part of the WisCEL program evaluation process. An evaluation of my teaching performance was requested in the last (15th) week of the semester to fulfill my department's teaching evaluation policy. I received informal verbal feedback over the course of the semester from a significant portion of the class. None of the students in the class indicated that they had previously participated in a class taught using the flipped format.

On the first day of class, I explained that they were part of an experiment in flipping the classroom, that the goal of this new format was to improve their learning of the material, and that I wanted their feedback. The feedback early in the semester was consistent with respect to the in-class exercises taking much too long, but somewhat mixed with respect to the new format. Students generally liked the video lectures, but some also missed the conventional lecture format. This changed over time. Less than 10% of the class indicated a preference for the traditional lecture format in the end-of-semester evaluations, although some of those felt very strongly. For example, one anonymous student remarked, "New class format ruined the great teaching ability of the professor." Another wrote, "Class activities were helpful, but I think more clarity would be gained if there were lectures traditionally." There were a much larger number of enthusiastic, positive comments about the flipped approach at the end of the semester. Examples include "The set up of the class was extremely conducive to my learning and allowed me to interact with the professor on a more personal level.," "Kudos for active learning environment. I learn by doing, not listening.," and "In here it's easier to ask good questions. You're working problems yourself and you realize you have a question and you just ask someone or ask the professor. He shows you



[FIG2] The WisCEL facility. (Photo courtesy of Mark Riechers, Engineering External Media Relations, UW-Madison College of Engineering.)

what you're doing wrong or how to do it and you're working again. You know you get it. In a lecture you're just watching someone else do it. You might think you get it but you might be missing things. Here you know if you get it."

Quantitative assessment of my teaching performance by the students is typically near the top of the available range and their numerical ratings did not change in any identifiable manner for the flipped offering.

It took a few weeks for the students to adapt to the new classroom environment—initially many of them were reluctant to talk to their peers or ask me questions, but with time the classroom became active and lively. A grouping started to be evident. Students clustered with peers that appeared to prefer similar work styles. Some of the more active groups could be found discussing problems together at a white board. Occasionally, students would bring a chair and their own laptop to a "full" table of six and work in even larger groups. The quieter groups tended to be smaller and less interactive but equally focused on the assigned task.

A small subset of students indicated there was too much homework/out-of-class work in this new paradigm although a much larger percentage thought the balance was appropriate. Some expressed concerns with keeping up with the regular pace of the class and noted it was difficult to do the class exercise if they hadn't taken time to watch the videos beforehand. The flipped classroom does require more

regular, active involvement by the student and it seems a minority of students do not like this aspect.

LEARNING GAINS

My impression, based on interactions with students throughout the semester, was that a much greater percentage of them understood the material and concepts than when I had previously taught the class in a conventional format. This impression was confirmed when I graded the final exam. I had never seen an overwhelming majority of a class perform at such a high level. Figure 3 depicts the mean and median scores on the final exam for the flipped offering and the previous three times I taught the course in a conventional manner. Figure 4 presents histograms of final exam scores for conventional (pooled across the three previous conventional offerings) and flipped paradigms. There is a clear increase in performance with the flipped paradigm. In the flipped paradigm, 90% of the class had final exam scores exceeding 70/100, while only 55% exceeded 70/100 in the conventional approach. A Wilcoxon rank sum test rejects the hypothesis that the conventional and flipped paradigm final exam scores are from identical distributions with equal medians with a p -value of $p = 0.0052$.

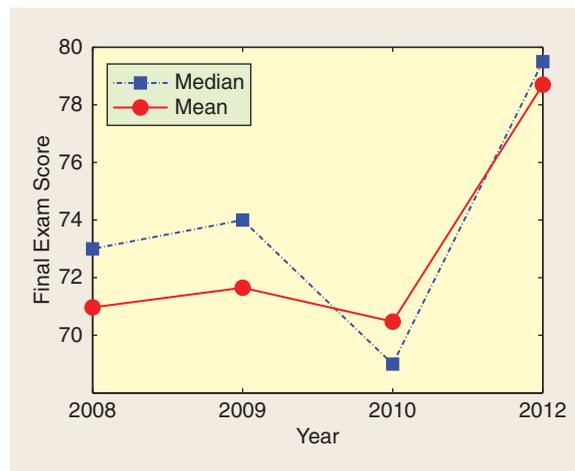
The format and coverage of the exam for each class offering remained the same, but the questions differed, so one possible explanation for the performance difference is that the exam in 2012 was much easier than the other years. However, my

impression was that the 2012 exam was the most difficult of the four exams. This is supported by the fact that the high score of 94 was less than the high score on any of the others. Also, the errors I observed when grading were much less significant than to what I was accustomed, consistent with the impression I had formed of each student's mastery based on extensive individual interaction. Another possible explanation is that this class had a much greater percentage of high-performing students. This seems extremely unlikely given that the class consisted of 30 students. While it is impossible to definitively rule out an alternate explanation for

the performance improvement, the overall experience convinced me that the flipped format made a very significant contribution to gains in student learning. As suggested by Figure 4, the gains were greatest for the traditional lower-performing students. The number of students with exam scores below 70 was reduced to a very small percentage of the class.

FLIPPING A SECOND CLASS FOR GRADUATE STUDENTS

In the spring of 2013, I followed a similar format teaching the graduate-level course for students with no prior

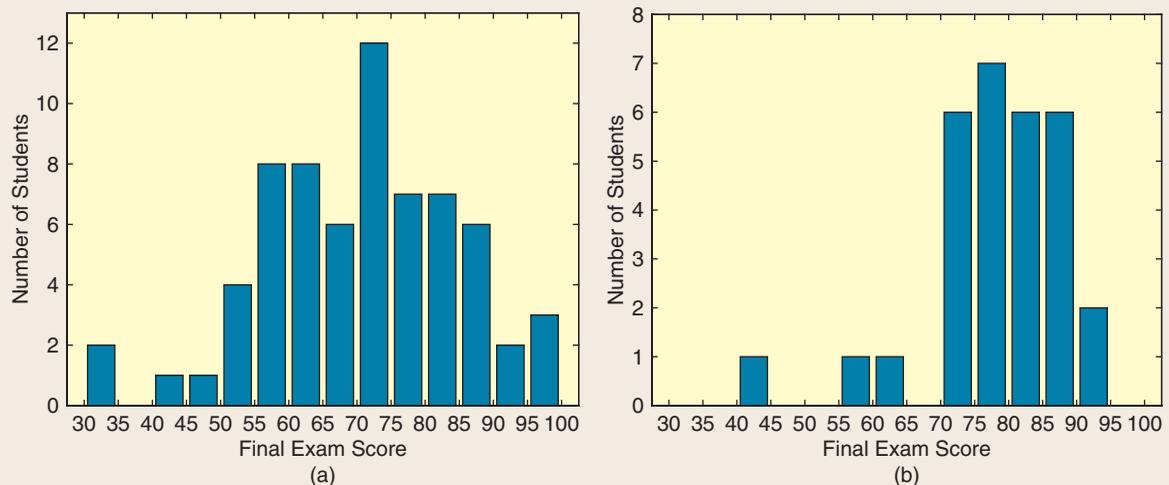


[FIG3] Median and mean final exam scores for the conventional lecture-based approach (2008–2010) and the flipped paradigm (2012). Exam scores are out of 100 possible points.

signal-processing background in the WisCEL facility. They watched lectures before the scheduled class period and then during the class period worked on MATLAB exercises designed to teach high-level concepts and how to properly apply signal-processing methods in various problems. Twenty-five students completed the semester. There were nine out-of-class homework assignments that built on the in-class exercises. There were no exams. Instead, the final evaluative component was a project that was chosen by the student and went into greater depth on a signal-processing topic of interest to them.

Overall, the flipped format resulted in the students spending much more supervised time applying signal processing than in the conventional format. In addition, they had the immediate opportunity in class to ask questions of their peers and myself. My impression, based on my interaction and the quality of their homework assignments and final projects, was that they learned far more than students who had previously taken this course in a conventional lecture format. They were much better prepared to work independently on the homework and presumably to correctly apply signal

processing to problems in their research and career. Formal student feedback on end-of-semester evaluations supported my observations and indicated nearly universal support for the flipped paradigm. For example, one student wrote, "I liked the hands-on learning approach. I feel that I will be more likely to use what I have learned with this method in the future because of the better understanding of the material I obtained with this class format." Another stated, "This was the first course I've taken on signal processing. I brought absolutely nothing, but am leaving with great 'hands-on' exposure to signal



[FIG4] The histogram of final exam scores contrasting conventional lecture-based and flipped paradigm. (a) pooled scores from 2008, 2009, and 2010 for conventional lecture-based approach. (b) Scores from 2012 for flipped paradigm. Exam scores are out of 100 possible points.

processing.” During one week of the semester I fell behind recording lectures and preparing exercises due to travel and gave two conventional lectures, which one anonymous student described at the end of the semester as “brutal” compared to the hands-on format we normally used.

In previous offerings of the course, I relied heavily on a TA during the first half of the course to help students adjust to the basic concepts of signal processing and become comfortable with MATLAB. The flipped offering did not need this additional TA support since the students received enough supervised practice with MATLAB in the classroom and I was able to directly address questions one-on-one.

SUMMARY

Developing and implementing the flipped paradigm required much greater effort on my part than teaching with a conventional format. The greatest effort was recording the videos followed by creation of in-class exercises. However, the effort put into developing the videos and exercises directly contributed to the success of these classes and the value perceived by the vast majority of students. I expect to benefit from this initial investment in subsequent offerings of these courses since the majority of videos and exercises can be reused with relatively little modification. The high workload was compensated on a personal level by the enjoyment I received from experimenting with new approaches and by achieving a professional development goal of learning to create online instructional content. Most of all, it was extremely rewarding to see the increase in student performance.

Initially, I missed the lecture. Like many professors, I enjoy performing in front of a group. In the flipped classroom, I no longer had the opportunity to put on a show in front of a somewhat captive audience. However, as the semester went on, the rewards of the flipped classroom environment outweighed the loss of the spotlight in lecture. For example, the barrier between student and professor was much lower in the flipped classroom. I was able to interact with and get to know the students at a depth that I had not experienced in a conventional lecture

format. I learned which students I could joke around with and those who preferred more formal interaction. I also learned which students tended to struggle and those who were capable of extending the ideas in new directions. I felt personally invested in their success as their coach—much more than I did as the “fountain of information” in the lecture format. The investment I was making in this coaching relationship may also have inspired many students to take their performance in the class more seriously than they would have with the more distant professor-student relationship typical of the lecture paradigm.

I BELIEVE THAT PASSIVE LISTENING TO A LECTURE IS NOT AN EFFICIENT LEARNING TOOL FOR MOST STUDENTS—ACTIVE HANDS-ON WORK WITH THE MATERIAL IS WHERE THE REAL LEARNING TAKES PLACE.

Some have argued that the technology-assisted flipped paradigm is more cost effective than a traditional lecture approach. At the time of this writing, I am not yet convinced this is true, especially if one accurately accounts for faculty time developing a flipped course. However, the approach certainly improves the quality of the learning experience and should scale to larger numbers of students at reduced cost. My experience suggests that a single faculty member can adequately coach around 30 senior-level signal-processing students during a classroom session. Increasing the number of students requires additional coaches, but the time required of the additional coaches is limited to a few hours per week in the classroom. For example, a class of 55 students likely requires an additional coach, such as another instructor or TA. I did not see value in holding a discussion/recitation section since the students were already getting plenty of problem-solving experience in class. The improved in-class

learning environment likewise reduces the need for TA office hour support.

The high-effort barrier to implementing the flipped classroom could be greatly reduced by adoption of a textbook-type model for video lectures and classroom exercises. The vast majority of us do not write a textbook for every course that we teach. Similarly, it seems very inefficient for every teacher to record their own video lectures and develop in-class exercises. An instructor could easily customize a course to their particular needs given a well-done library of videos and exercises, in the same way that we now select a subset of sections and problems in a textbook. I have placed my lectures on YouTube [7] as a small step in this direction. Using lectures produced by someone else does not diminish the role of the instructor. To the contrary, I believe the instructor in a coaching role has a much bigger potential impact on student learning than one who lectures.

A second barrier to successfully flipping a class is the “row-column” arrangement of the desks in a typical university classroom. This setting makes it difficult for the students to interact with each other and almost impossible for the instructor to circulate among the class. Students should be facing each other in clusters with enough space for the instructor to position himself or herself immediately adjacent to each student.

My view of the importance of the lecture in teaching has undergone a significant shift. I believe that passive listening to a lecture is not an efficient learning tool for most students—active hands-on work with the material is where the real learning takes place. The primary value of a lecture is to introduce concepts and provide context. For most of my teaching career, I spent a lot of effort trying to carefully craft my lectures. This time and effort is much better spent carefully crafting hands-on exercises. One of my explanations for the student-learning gains that were observed in the flipped classroom is the discipline forced on all students to apply the concepts being taught. I suspect that the traditional lower-performing half of the class were much more engaged with applying the material in my flipped classroom than when the

application is expected out of the classroom, and this forced, supervised extra practice directly translates to improved exam performance. A casual approach to watching video lectures outside of class is likely of much less negative consequence in a flipped classroom than a half-hearted approach to working problems out of class in a conventional paradigm. Even those who are diligent in working on problems on their own are likely to get “stuck” applying new concepts, while they quickly get their questions answered in the flipped classroom.

This flipped classroom experience has changed a subconscious view that I held for 25 years regarding the capability of undergraduate students to master signal-processing material. I had consistently observed a stubborn 40% or so of my signal-processing and signals and systems classes fail to demonstrate what I considered proficient use of the material on the final exam, e.g., the 45% that scored below 70 in Figure 4(a). This happened in spite of my best efforts and the fact that I usually scored very high on student evaluations of my teaching, so I assumed that a significant fraction of students simply were not able to learn signal processing at a high level. This view was manifest in the curve I used for grading, which typically had the top 15% of the class receiving As, the next 30% receiving Bs, and the remaining 50+% Cs or lower with a class average grade

point average below three out of four. My experience with flipping the class has made it abundantly clear that the critical issue is not the ability of the students, but rather the method of instruction. The overwhelming majority of students really are capable of mastering signal processing. My job as a teacher is to engage them in a way that enables them to perform at a high level. The high level of performance I observed led to an unexpected dilemma assigning grades. Following my historical curve would have led me to give different grades based on nearly indistinguishable performance differences. I concluded this was a very good problem to have and decided to assign grades based on my assessment of absolute performance instead of relative performance. Consequently, a very large majority of the class received As or Bs.

There is room for improving the approach used in these first two classes. Specifically, student feedback suggests that the difficulty and duration for the in-class exercises and amount of out-of-class homework requires additional adjustment. I am also adding brief automated quizzes on each lecture using the course management system. They are designed to be completed prior to class, and quiz performance will be a small component of the performance evaluation. The primary goal is to increase retention of key concepts. Quiz performance also provides a near real-time

metric of student engagement and progress, allowing the instructor to quickly identify students that are struggling and initiate intervention.

I have taught at UW-Madison since 1987. Flipping my classes has been the most transformative experience of my career, and I doubt that I will ever be able to go back to teaching in the conventional paradigm, especially for undergraduate- or introductory graduate-level signal-processing classes. I too have flipped.

AUTHOR

Barry Van Veen (vanveen@engr.wisc.edu) is a professor in the Department of Electrical and Computer Engineering at the University of Wisconsin, Madison.

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from the **GUEST EDITORS** (continued from page 19)

The next article by Boashash et al. provides a description of the application of TF methods to the analysis of electrocardiography and fetal movement signals with the aim to develop automatic analysis and classification methods for such signals.

The final article by Bonnel et al. focuses on the use of TF representations in the analysis and characterization of underwater acoustic channels.

We hope that this special issue provides the reader with a broad scope of

theory and applications of TF signal analysis, capturing recent developments and opening the door to new frontiers. The nonstationary nature of ubiquitous biological and man-made signals will continue to fuel the interest in this area and propel future contributions to improved representations that meet problem-solution objectives and are specific to different applications.

We would like to express our deep gratitude to the many individuals who made this special issue possible. We

thank all of the authors who submitted proposals and all of the reviewers whose recommendations significantly helped in improving the selected articles. We are also indebted to *IEEE Signal Processing Magazine* Editor-in-Chief Abdelhak Zoubir and Special Issues Area Editor Fulvio Gini for their support and guidance throughout the solicitation and reviewing process, as well as to Rebecca Wollman for her valuable administrative assistance.

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