Teaching High Performance Computing:
Lessons from a flipped classroom, project-based course on finite element methods

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***Abstract*—High Performance Computing (HPC) is an area that requires students to acquire knowledge in a wide range of topics. At the same time, HPC is not a theoretical subject and is best learned through non-trivial projects. Teaching HPC therefore lives with the tension of having to cover many small, disconnected areas while wanting to provide more feedback on student projects.**

This paper considers the lessons learned from teaching MATH 676 "Finite Element Methods in Scientific Computing", a course one of us teaches at Texas A&M University as a project course with a flipped classroom.

The contribution of this paper is to describe a practitioner's approach to using principles of reflective writing and journaling to connect the material of the video lectures to student projects. We will discuss our experience with this approach, in particular regarding (1) helping students engage deeply with course content, (2) increasing motivation, independence, and perseverance, and (3) facilitating more communication with the course instructor. We will also share our experiences with the technology options for electronic journals and report on what worked and what didn't.

Keywords-HPC education, flipped classroom, teaching and technology, journaling, reflective writing, practitioner's report of experience, qualitative research, experiential learning, student engagement.

I. Introduction

High Performance Computing (HPC) is a subject requiring students to learn material from a broad range of topics that do not necessarily all build on one another. For example, typical HPC curricula – often geared at STEM students without much background in computer science – include matters such as

- "Computer literacy": Using compilers, command lines, editors, build tools, integrated development environments
- Programming and algorithm design, data structures
- Parallel computing, pthreads, message passing paradigms such as MPI; theoretical considerations about limits to parallelization
- Version control
- Debugging
- Basic numerical methods such as quadrature, Gauss elimination, finite difference approximation to derivatives
- Iterative methods such as Newton's method for nonlinear systems; Jacobi and Gauss-Seidel solvers, the Conjugate Gradient and GMRES methods for linear systems; preconditioning
- Finite element/difference/volume methods
- Fast Fourier Transform (FFT) and fast multipole methods

Many HPC courses in interdisciplinary programs also include sections on mathematical modeling and overviews of the kinds of models and applications one encounters in applying HPC to problems in the sciences and engineering.

Given the disparity of these topics, teaching an HPC course therefore presents challenges and opportunities different from many other science, technology, engineering, and mathematics (STEM) classes. In particular, a linear arrangement of material throughout the semester or year is, at best, not natural and, at worst, not useful for student learning. Rather, since HPC is an integrative subject, an obvious approach is through comprehensive student projects that rely on many of the topics outlined above. As with other project-based courses, there is competition between the need to present new material and providing feedback to students.

We have addressed this challenge in our graduate course MATH 676, "Finite Element Methods in Scientific Computing," by using a flipped classroom model with extensive video lectures posted on YouTube (see [4]), and supported by student reflective writing in electronic journals as a means for them to document their project progress, their learning process, and practice how scientific work functions.

This paper discusses our approach to teaching this course and our experiences based on self-evaluation and student feedback. In the following, we will first describe the background and context of the course (Section II), present the instructional approach (Section III), followed by self-evaluations and student perceptions of the course (Section IV). We conclude with recommendations for those instructors who might wish to apply similar strategies to their own teaching of HPC courses.

All student data, including any direct quotes, is presented with students' informed consent, obtained in a manner approved by the Institutional Review Board of Texas A&M University.

II. MATH 676: "FINITE ELEMENT METHODS IN COMPUTATIONAL SCIENCE"

The course MATH 676, "Finite Element Methods in Scientific Computing," taught by one of us every other year at Texas A&M University, is the context of this paper. The primary purpose of the course is to familiarize students with the practical applications of the finite element method (FEM); a FEM theory course is a prerequisite. The course is a hands-on, project oriented HPC course covering all of the subjects listed in the introduction above. Typical enrollment consists of 15–20 students representing most science and engineering programs (including mathematics). Students taking this course generally have some background in numerical methods from a theoretical, but rarely from a practical, perspective. Few students have programming experience beyond brief Matlab scripts and none have worked with software systems as large as deal.II, the widely used open source finite element library that serves as the foundation for this course [2, 3].

To provide students with a deep understanding of and experience in HPC, the course is structured around individualized projects in the spirit of engineering "capstone" courses, i.e., students work on semester-long projects that include intermediate milestones, a final report and a final presentation. (The present course differs from a typical engineering capstone classes in that it cannot rely on only integrating the knowledge from different classes taken in previous semesters, but needs to provide much knowledge as part of the course.) The course meets twice weekly for 75 minutes in a computer lab to allow students to work on their projects and receive guidance during class time. As these are graduate students, projects are created and assigned individually based on their respective research areas, with students developing a code that in most cases forms the basis for their thesis research. However, the remainder of this paper equally applies to any other method of assigning projects and, in particular, we believe that all of its conclusions are equally valid for undergraduate HPC courses as well.

The challenge presented by the context of this course is the conflict between covering and applying a large amount of material with which few students are familiar, while simultaneously providing students with adequate assistance and feedback on their projects. This challenge is easily explained through a simple calculation: if one were to spend half of each class period presenting new content (which certainly would not allow an instructor to cover all of the topics previously mentioned), then only 30–40 minutes per class period would remain for one-on-one interaction with students, or approximately two minutes per student. Clearly, this amount of time is inadequate to give meaningful feedback and guidance.

In the first three iterations of the course, we taught MATH 676 as a traditional lecture-based course and encountered the challenges outlined above. Insufficient guidance for students resulted in overcrowded office hours and students required to be prematurely independent, consequently wasting time on dead-end approaches when a quick faculty consultation could have kept them on track. We therefore set out to revise the method by which we teach the course, as motivated and explained in the following.

III. APPROACH

In our search for a strategy to resolve the challenges of time management, broad content, and intensive student projects, we redesigned the course to incorporate three new components: a flipped format, research journals, and reflective writing. We will discuss each of these three aspects individually in the following subsections.

A. *A Flipped Class Format*

A flipped format class is an emerging but increasingly popular instructional design that requires students to watch content videos or otherwise engage with the course material before coming to class, thus freeing time in class for direct contact between the teacher and students. Several recent articles summarize the format and its components [5, 19], but, in short, the basic premise is that a teacher's time is best spent interacting with students, whereas content delivery – such as the traditional lecture at the whiteboard with its primarily unidirectional flow of information – can be left to technical means. This course structure is gaining traction in both K-12 and higher education based on the growing availability of quality content-based videos generated and presented through sites such as the Khan Academy [14], Coursera [8], MIT OpenCourseware [22], and iTunesU [12]. Some instructors view the flipped class format as a means to better reach students with diverse learning styles or preferences [16], while others subscribe to the research-based evidence that increased interactivity in the classroom improves student learning outcomes [10]. Regardless, flipping a course seems to be a solution for many instructors dissatisfied for whatever reason with a traditional lecture-based model.

In the following subsections, we will outline our approach to implementing the flipped format, followed by a discussion of our experience with it.

1) *Technical considerations and implementation*

We came to the decision to try flipping MATH 676 after asking ourselves the question "What is the most important element of this class for student learning and how can the instructor best address it?" The answer was that student projects are the most important component and the best way for the instructor to support those projects is by providing timely and individualized feedback. Therefore, all other aspects of the course design needed to support students building robust and high-quality projects. The only way to increase student-teacher interaction was to remove the lectures from class time. Others have drawn similar conclusions regarding instructional priorities and the best use of class time [6, 10].

To present the course material to students, we have recorded 48 video lectures [4], each between 30 and 60 minutes long, that individually or in groups cover most of the topics outlined previously. Students are then assigned to watch these lectures outside class, with a relatively heavy load of foundational topics towards the beginning of the semester, and fewer, more specialized lectures assigned towards the end when students' focus is on their projects. Not all lectures are relevant to all students, and some videos are assigned on an as-needed individual basis for each student's project.

The videos recorded for this class are freely available on YouTube [4] and have proven to be surprisingly popular. They collectively gather some 1,000 views per month, regardless of whether MATH 676 is taught or not, and are consequently a resource not only for our students but also for HPC developers elsewhere. Indeed, other institutions in the United States, Europe and Africa are teaching their FEM courses using our videos.

While recording 35 hours of videos may be a prohibitive aspect of the flipped course model for many instructors, there are numerous resources available for those who may wish to apply the format without the burden of video production. In the HPC arena, this includes our own lectures [4] as well as similar ones on related topics, such as Gilbert Strang's lectures on linear algebra [24], Tim Davis's on direct solvers for linear systems [9], or Randy Leveque's on HPC [17].

2) Experience

Creating the videos was, without a doubt, far more work than we would have spent on this course under any other circumstance. We recorded our videos in a local television studio but did not have the possibility of post-recording video editing. We were therefore required to have all of the material prepared well in advance and needed to incorporate the questions one might expect to get if there had been an actual audience. Then the recording needed to be right the first time around. Showing up with only a rough idea what one is going to talk about – as all of us undoubtedly do occasionally when teaching a class we have taught many times before – is insufficient. On the other hand, the meticulous preparation undoubtedly led to better lectures. Additionally, videos have the advantage that they only need to be recorded once and then may be reused indefinitely.

Students did comment on the quality of lectures during class discussion, as well as in their journals (see below). However, the more common comments were that they appreciated the interactivity during class time and, frequently, about how they learned from the video lectures differently than they would learn from in-class lectures. The following are representative comments from student journals (here and throughout, quotes retain the original spelling and grammar of students' writing):

"Video lectures was one of the important aspects for the course like this. I have gone back many time to the previous lectures in case of some doubts. Also I can refer them in the future."

"[A]s far as class structure, I found it very useful that we got one-on-one time with the professor to give guidance with our projects during the class period, so I completely agree with the decision to have most lectures done as video lectures outside of class. Also, I like video lectures because we can re-watch them when we need them. This is especially helpful in a class like this because some of the lectures demonstrate how to use software, so the visual component is useful, as opposed to just writing notes to read later."

In terms of the benefits to students, quotes like those above, as well as our personal interactions with students, indicate that students demonstrated more motivation and independence because they had control over the flow of information. Our findings, based on our practitioner perceptions of student learning and qualitative analysis of the journals we will discuss below, align with the quantitative research conducted by others [10]. Engagement during class time, in this case practice with authentic problem solving as supported by direct interaction with faculty, resulted in deeper student learning.

B. Research Journals

In response to the flipped course format, many instructors ask the question "How do you know if students watch the videos outside of class?" The obvious answer is: you will know! While broader issues of student motivation and accountability are beyond the scope of this paper, let it suffice to say that students who do not watch the assigned videos quickly find themselves lost during class time. Most graduate students and upper level undergraduates are uncomfortable with being lost – in particular considering that they get several minutes of individual attention during every class period – and the situation quickly resolves itself. However, in our planning, we wanted a more concrete measure of students watching the videos and so instituted a research journal. In the following subsections, we discuss the design of these journals and our experience with them.

1) Technical considerations and implementation

The primary goal we originally had for these research journals was as a means to document and digest what videos students have watched and how the content relates to their work. Students were required to maintain the following elements:

- A table of contents, including entry titles and dates.
- A record of the lecture videos they watched. These entries needed to include a summary of the three most important points from the lecture and two or three questions they still had. The entries then served as the foundation for class discussions. Often, we began class by asking "What questions do you have after watching the assigned video(s)?" We also frequently reviewed student journals before class to preemptively identify common questions and provide prompts if necessary.
- A project log that showed, with dated entries, when students worked on which parts of their projects, progress (or lack thereof, both often illustrated by copy-pasting formulas or visualizations of results), and notes for what they want to try next.

For the research journal, we used Google Documents. This platform has a number of advantages that made it useful for our purpose:

- We were already familiar with it.
- Students by and large already have Google accounts, making shared document creation easy for them.
- It allows simultaneous editing so the student and instructor might both work in the document at once, and it has some attractive features, like the means to create a table of contents automatically linked to section headings of the document.

- As an instructor, one sees the documents shared by students in a single place. Furthermore, the document overview shows which documents have been edited since they were last viewed, allowing the instructor to immediately see who is working, who is not, and which new journal entries need to be reviewed.

Most learning management systems, e.g. Blackboard, have similar functionality to implement student journals and could be used equally well for faculty to read and grade journals. We have used other systems with similar success.

2) Experience

Through the research journal, we were able to judge who was watching the videos as assigned and address students' common questions or points of confusion. The journals also helped us to synthesize and resolve common misconceptions, an important point given that video lectures were recorded without an audience and therefore lacked the immediate instructional feedback of students reacting to the new material. The journals therefore provided an important means of feedback from students that we incorporated by offering additional information and errata for each video, as the videos can no longer be easily modified.

Although accountability for watching lectures was the initial and primary purpose of the journals, their actual use diverged significantly from our expectations. First, reviewing these journals proved to be a surprisingly addictive activity. We checked the highlighted overview of shared documents at least once per day, on average, and then reviewed new journal entries, providing advice and answers to student questions in differently colored text. Reading journals was so addictive because of the opportunity to provide immediate feedback and seeing students learn as they are typing, connecting theory to practice, formulating questions, and formalizing their knowledge. We were able to watch words appear on the screen as students type, then disappear as they backspace through sentences and entire paragraphs after realizing their own mistakes. This opportunity to observe student learning in the moment is exceedingly rare and never so clear as it was for us in the electronic journals. This may be due in part to the fact that Google provides an indication of who currently has a document open, but students cannot tell whether someone is actually watching at any given time and, mostly correctly, may assume that nobody is watching unless the instructor is typing as well. Regardless, reading student journals provided a much richer source of feedback than reading only the final, polished reports students must submit in other project-based course formats.

Given how we, as instructors, frequently read the journals (i.e., close to when they were written, rather than once a week or even less often), students quickly realized they could use journals as a tool of communication. This unexpected use was a significant advantage of the course format for students who took advantage of the journal to ask questions in addition to documenting their video watching. One student commented on his use of the journal as a help forum as follows:

"[T]he most helpful tool for my learning was by asking questions and receiving answers […]. This is extremely useful because when having a face-to-face class, it was difficult for me to ask questions due to cultural differences. I tend to be shy when asking questions in front of other class mates. However, this journal entries allowed me to ask as many questions I can without a fear."

Writing to learn, such as in the student research journals, is a recognized instructional strategy for deepening students' content learning. For example, Zinsser [27] promoted writing throughout the breadth of college degree programs and suggested incorporating writing into all courses, not just the traditional writing venues of the humanities. Many universities, including our own, now require writing-intensive courses across all majors. In science and mathematics education, writing to learn is a generally accepted means to deepen content learning and improve scientific inquiry skills [1, 7, 13, 25]. We observed this deeper learning first hand, from the deep questions posed within the journals, to the increasing ability of students to articulate their research topics, strategies, and results. Learning journals supported students making connections among course content, their semester project, and their broader thesis research agenda.

Indeed, this inference is reflected in what students wrote about writing a journal in their reflective writing essays (see below). The following are representative quotes:

"Keeping journal of learning is one good experience I have had for this course. Initially it felt like berdon but then gradually, mainly after spring break I got into the habit that whenever I worked for the project I kept my journal open so that I can record what I am doing. Also the responses, I got […] was very helpful and quicker way, I would say, to get my doubt answered. Also, when I watched the lecture video, I thought I understood everything and then I sat to write the summary for that made me think what I really have learn and what was the most important points in the same. Some time I have seen lectures twice or thrice to write it down."

"During this period, since entry is one of the necessary work of this course, I started to write entries to record what job and tries I already did. Although the contents are still very coarse, I am now getting used to it. This one helps me to see what I have tried without wasting my time. I will keep on using this in the future."

"From taking this course and participating in a reflective exercise, I found what I was missing: To really understand the material at a deep and intuitive level the student needs to think very hard about "why" questions. I feel like this exercise […] helped me to gather my thoughts […] and really understand the processes that lie deeper than the surface. I plan to continue using a reflective journal through my PhD study and have found a nice tool that will help me do this."

Several other students also commented that they will continue to keep journals or that they would prefer more classes using journals as a learning tool. While some of their positivity may be the result of attempting to meet faculty expectations, we believe there is still sincerity in these comments as the prompts for the essays from which these quotes were taken did not require students to write about their journaling experience in particular. Indeed, when we told one of the students that we were working on this paper, his response was that he is still writing a journal, more than a year after the end of the class.

In summary, requiring students to keep a journal was much more beneficial than simply evaluating whether students indeed watched the online lectures. Rather, it proved to be a much greater than expected advantage by (1) engaging students more deeply with course content, for example by summarizing what they thought the important lessons from a lecture were, or by formulating what progress they have made in their projects and where obstacles lie, (2) ensuring students work on their projects throughout the semester, and not just immediately before the deadline, and (3) facilitating a much deeper level of communication with the course instructor.

C. *Reflective Writing Exercises*

In addition to the use of the journal as documentation of students' engagement with the lecture videos, students were also required to complete periodic reflective entries. The goal of reflective writing is to engage students with the larger picture of their experience in the course, beyond course content or semester projects. In effect we asked them to write, and thereby learn, about their own learning.

Reflection on learning experiences is well established in the educational literature, beginning with Dewey in 1933 [11], who claimed strong thinking skills could best be developed through reflection upon experience. Kolb's [15] model of experiential learning built on Dewey's work, proposing that, to learn effectively, students must work repeatedly through a cycle of exposure to new experiences or information, reflection on the new information, analysis of the information, and decision making with regards to how the new experience or information can be integrated into their existing knowledge base.

In the context of our class, reflective writing therefore acts as a learning support mechanism for the lecture videos and student projects, facilitating student movement through the experiential learning cycle. Despite reflective writing's long presence in the literature, it is rarely utilized in STEM courses. While Parsons [23] used writing for metacognitive growth in a precalculus course, and some pre-service teacher training programs [20, 21] apply reflective writing to influence student motivation and learning behaviors, little literature exists for reflective writing in STEM and we are not aware of any at the graduate level (for two examples of its use with undergraduates, see [18,26]). We were therefore in uncharted waters with respect to the reflective writing element of the course. The following subsections outline the design of and our experience with these writing exercises.

1) *Implementation*

Students were asked to use the reflective writing as an opportunity to read back through their research entries, look for patterns and develop insights that might otherwise go unnoticed. This could include the realization that they had understood and corrected an initial misconception and are now able to correctly describe where they went wrong; or to realize that they keep making the same mistake over and over, and consequently provide them with an opportunity to rethink their approach and the underlying foundations.

As part of the course's requirements, students needed to submit a one to two page essay both halfway through the semester and at the end, summarizing an important insight they had regarding the class and how they arrived at that insight. We had hoped for student responses to include statements about understanding a new technique to debug programs; discovering another reason why version control systems are useful; or that not all linear systems are equally difficult but can instead be classified by matrix structure or properties such as positive definiteness or symmetry. Students were asked to provide their essays as separate journals entries.

2) *Experience*

Despite our hopes, the reflective writing essays were not as obviously a success as the journals as a whole. In particular, for the first essay, many students used their writing assignment to just summarize the topics the video lectures had covered so far, their previous journal entries, or what they had done so far for their project. Many essays contained a lot of quite technical details. Typical sentences from midterm essays read like this (information that could identify students based on their specific projects has been removed):

"To create [my] solver, I broke the problem up into several steps: […] The [X] problem needed the gradients of the [Y] solution but the [X] solver's DoF handler could not interpolate a scalar function since it is a vector valued DoF handler. This meant that the [Y] solver needed to compute the gradients and pass the gradients to the [X] solver rather than the [Y]. […] At the moment, I have the one way coupling without time dependence using the method I have described. I have begun writing the single DoF handler version of the problem, but it is not complete. Clearly this is the direction the design should be driven, since the benefits greatly outweigh the disadvantages."

"The project is to develop a [solver for student project]. By the middle of March, we had tested the mesh with a realistic permeability field using step-6 as well as the functionality of adaptive mesh refinement. The critical step in setting up the model was to […]. This idea did not work out for me since […]. Nevertheless, we found an alternative approach to tackle this problem, i.e., instead of working on […] we could actually create […]. The resulting value is still around 65,000 for the coarse mesh."

On the other hand, we also got comments such as the following, demonstrating insight how what they had learned connected with previous experiences:

"Initially, when I looked in to the documentation of deal.ii, it seemed very hard to learn honestly speaking. […] I thought, writing my one code might be easier than this. This thought has obviously has changed as the classes passed by. Some day before, as part of my project, I have written a program to solve the heat conduction equation for spatially variable conductivity, for which I took one of the tutorial program and did that program in less than three hours. I had done this same problem in MATLAB before in my master's which took me a week to write the code. Although that was also a good experience […] I am almost ten times faster."

"One of the most important tools I've learned to use this semester is revision control software, more specifically, subversion. On a day-to-day basis, I work on three to four computers, and I need to be able to keep an up-to-date

version of all my files. […] When dealing with remote files […] I need some other way to keep my files synchronized between my computers. Subversion provided the solution to this problem."

Yet, comments such as these were rare in the midterm assignment, coming from at most one third of students. We hypothesize that there are two underlying causes for students' inability to write reflectively about their own learning process (and, consequently, for their inability to benefit from the deeper learning opportunity this provides them):

- All participants in this class are graduate students in the sciences and engineering. In these disciplines, the entire education process emphasizes processes, techniques, and – mostly – inanimate objects. Many documents in these disciplines are in fact written in passive voice. Writing about themselves, their experiences and how they act as individuals is something our students had not done since at least high school and were simply not prepared to do. Despite clear instructions, only a small fraction of students were able to successfully write about their learning experience.

- Of the 16 students we report on here, only four were native speakers of English. The remaining twelve were from Central America, the Middle East, and the Far East. These students struggle with the English language to begin with but at least in some cases their prior education and cultural backgrounds may also have influenced their desire and ability to write about themselves. As an example, recall the quote provided earlier about cultural inhibitions to ask questions in class.

Seeing students' inability to write reflectively after the first assignment was submitted prompted us to reconsider our approach. Clearly, written instructions alone were not effective in prompting students to accomplish the task. It occurred to us that students may simply not know how a successful essay might look. We therefore started to write our own journal in which we wrote about our own learning process trying a new class format, what elements we found successful or lacking, and, generally, showing ourselves as learning individuals, including the doubts and insecurity that often come with trying something new. By demonstrating how a reflective learning journal looks, we hoped to set an example of our expectations for them.

This approach showed immediate effect. Students informally reported that they read our journals as religiously as we read theirs, and that they learned a great deal about how one approaches reflection on learning. They were also generally very appreciative of the opportunity to observe others learn, in particular someone with much more experience than they. For at least some students, this resource translated into a greater ability to write about their own learning in the end-of-semester assignment. At the same time, for a significant fraction of students, the effect of observing the instructor write reflective writing assignments had little effect on their own ability to do so.

In summary, we had hoped to inspire a deeper form of learning by requiring reflective writing essays of our students. Such assignments have been shown in the existing literature to increase motivation, independence, and perseverance, and deepen content learning [24]. However, not all students were able to derive benefit from the assignment, due to what we believe to be issues relating to their educational and cultural backgrounds. Providing an example by writing a journal of our own improved the situation somewhat, though we will need to do so starting at the beginning of the semester in future iterations of the course.

IV. DID IT WORK?

The success of a new approach to teaching a class lies in whether students learn more, learn more deeply, retain more knowledge or understanding, or simply enjoy class more. We have neither a sufficient sample size nor a sufficiently elaborate method of evaluation to answer these questions quantitatively. Of course, the difficulty of providing experimental designs to quantitatively support conclusions underlies much of educational research, and the current study is no exception: Given (i) the effort necessary to support individualized projects, (ii) the consequently small number of students taking the class, (iii) the difficulty in quantitatively evaluating course formats in which every student works on a different project, and (iv) the fact that we cannot go back in time to evaluate the old format, one cannot expect concrete measures of the new format's success. However, we can provide other, qualitative evidence of success that supports the use of these strategies and indeed have already done so in previous sections. Here we summarize the main points of our qualitative data.

First, from the perspective of an instructor, the flipped format was very successful. In particular, one of the largest stressors of the previous traditional lecture-based format was the inability to spend more than two or three minutes with each student per class period, and constantly needing to cut short interactions to move on to the next student. Dealing with 16 students individually each 75-minute class period is still a lot and more than one might ideally choose, but it is a major improvement over the previous situation.

The new format was also clearly more enjoyable. As is likely apparent from the description above, reading student journals and seeing how student progress in their projects in real time presents a view of *learning* that teachers rarely have the opportunity to experience in such vivid detail. There is a certain satisfaction in being able to witness this. As anyone who has gone through college will attest, there is certainly a correlation between a teacher enjoying a class and student enthusiasm for the subject.

Students enjoyed the format as well. Even though the course (similar to other capstone-like courses) has a reputation of being far more work than most other classes, significantly more students want to enroll than we can accommodate. This was already the case with the "old" format, but if student comments in their final reflective essays and student evaluations of the class are any indication, student demand for the course will not diminish:

"This semester has been a unique experience for me. I have often wondered what education is going to look like in

a few years. I see all these online education classes popping up at many schools and have a hard time seeing how they can compete with the classes on campus. I have had to work with students in those types of classes before and have found that learning was not really happening at all. I don't see them lasting very long. I really enjoyed this semester and found myself wishing more classes were structured in a similar pattern. I liked having the lectures available online and then having class where we could practice and get our hands into the material. It fit my learning patterns perfectly. I could see many more classes successfully patterned in this manner."

"At first, the reflective journal writing felt like a burden. But its benefits are clear now. Journal writing clarified my thinking."

"Enrolling in this course has exposed me to much more material than I expected. Most of all, the instructor has changed the way I approach problems. His exercises of self-reflection have made me become a more thoughtful student."

Furthermore, practically every student's class evaluation (which are text-based rather than quantitative for mathematics classes at Texas A&M University) mentioned that they thought how useful the journals were; none criticized the format. In other words, the quotes provided above are not selected to make the setup of this course look particularly good. Rather, it is truly difficult to find negative statements in the more than 100 pages of reflective student writing and class evaluations we had available, as well as the over 600 combined pages of journals.

Finally, the most important point of the class is to support students as they grow by tackling large, meaningful semester-long projects. Spending a significant fraction of the time at the whiteboard presenting new material is a suboptimal use of a teacher's time. Although some elements, such as the reflective writing essays, need to be adjusted for future use, the flipped format, coupled with the interaction possible through the journal, felt like a much more appropriate and successful method of teaching.

V. Conclusions

We have employed a class format that differs significantly from that used in most STEM classes in that we pre-recorded video lectures and assigned them to students to watch outside of class. Class time was then used to briefly discuss important points of the lectures and common questions, leaving the remainder of each class period for individual interactions relating to student projects. We augmented this "flipped" format with student journals and reflective writing.

The approach to teaching this way is intended to provide at least the following three, important benefits: (1) helping students engage deeply with course content, (2) increasing motivation, independence, and perseverance, and (3) facilitate more communication with the course instructor. As outlined in the previous sections and supported by student quotes, we believe that the format succeeded in realizing these benefits.

The experience we have with this class format is therefore largely positive and we will continue to use and refine it. In particular, this pertains to the use of reflective writing, which we continue to believe to be a very useful tool if used appropriately. Providing students with good examples of reflective writing should help overcome the educational and cultural issues that we believe have hampered its usefulness during the first time we taught the class in the way reported here.

Acknowledgment

This work was supported in part by the National Science Foundation through Award No. OCI-1148116, as well as the Computational Infrastructure in Geodynamics initiative (CIG), through the National Science Foundation under Award No. EAR-0949446 and The University of California, Davis.

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