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# What Do We Gain by a Blended Classroom? A Comparative Study of Student Performance and Perceptions in a Fluid Mechanics Course*

DONALD R. WEBSTER
School of Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0355, USA.
E-mail: dwebster@gatech.edu

ROBERT S. KADEL
Center for 21st Century Universities, Georgia Institute of Technology, Atlanta, GA 30332-0765, USA.

WENDY C. NEWSTETTER
College of Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0360, USA.

We conducted a study of student performance in and perceptions of a blended classroom delivery of a 3rd-year-level fluid mechanics course. In the blended classroom pedagogy, students watch short on-line videos before class, participate in interactive in-class problem solving (in pairs), and complete individualized on-line quizzes weekly. The hypothesis is that when the cognitive load attendant on fluid mechanics problems is significant, an interactive learning environment yields greater learning outcomes than the traditional modeling-and-mimicry approach. We analyze this claim in the context of the complexity, ill-structuredness, and cognitive load inherent in navigating fluid mechanics problems. Comparisons are made among traditional and blended classroom deliveries by the same experienced instructor via student surveys and direct assessment of student performance. The results reveal dramatic improvement in student engagement, perceptions, and achievement in the blended classroom pedagogy. Significant differences are found in final course total and the withdrawal/fail/passing (WFD) rate. Further, a regression model explains a strong amount of variation in final course total and the coefficients suggest that the blended classroom pedagogy adds approximately 4–5 points on a 100-point scale. Student surveys reveal significantly greater enthusiasm, stimulation, self-perception of how-much-learned, perception of the value of the course activities, and the overall effectiveness of the course and instructor in the blended classroom. The combined use of the lecture videos, the interactive exercises in-class, and online quizzes provided an opportunity for students to manage their cognitive load while learning the subject of fluid mechanics.

**Keywords:** instructional change; blended learning; collaborative learning; problem based learning; teaching evaluations

## 1. Introduction

Engineers are known and hired for their ability to formulate and solve problems. It is no surprise, therefore, that a significant portion of any engineering class is devoted to the professor modeling a problem-solving method followed by students practicing it in class or as problem sets for homework. The expectation is that this sequence of activities – modeling and mimicry – should lay the groundwork for mastery and transfer to novel problems on exams and to future engineering careers. The participation structures [1] offered in this sequence to the instructor and the student are prescribed and constrained. The instructor writes at the board and the student copies what he or she sees. Both are active, but in different ways. The instructor generates; the student replicates. A sub-sequence in this larger sequence is occasionally initiated by the instructor asking, ''Are there any questions?'' This invitation can be taken up or rejected by students. If accepted, a student in turn poses a question (*generates*) that receives an answer (*generates*) from the instructor. Without this invitation from the instructor, the modeling-and-mimicry progression proceeds until the conclusion or answer is achieved.

In this paper, we challenge this community-sanctioned, ubiquitous classroom practice of modeling-and-mimicry as insufficient and even deleterious to deep learning and mastery. We ground this claim in an analysis of the complexity, ill-structuredness, and cognitive load inherent in navigating problems that arise when subjects such as fluid mechanics are involved. We further ground this claim in illuminating the cognitive processes that are called to action when the participant structures are intentionally altered in the classroom to promote student-to-student generation and negotiation. Finally, we ground this claim in a comparative study of a fluid mechanics course taught by the same experienced instructor with essentially identical content under two conditions: a modeling-and-mimicry approach and a blended classroom approach.

### 1.1 Cognitive Load and Learning

Cognitive science has long posited that learning



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depends on (1) the acquisition of schemas and (2) the transfer of those schemas from controlled to automatic processes [2]. A schema is best understood as a domain knowledge structure that plays a crucial role in how to approach and solve a problem. A schema allows the expert problem solver to recognize a problem statement as belonging to a particular classification of problem types, which in turn requires a specific set of steps and procedures. For example, expert engineers have schemas around applying the principle of conservation of energy that they harness to solve applicable problems. In turn, these solved problems are likely to be categorized with other comparable problems to which the same schema can apply, thereby building cases in long-term memory where this schema is applicable. Novices, bereft of such schemas, frequently resort to surface structures when classifying problems, not deep principles [3]. Because they have yet to develop these schemas, novices cannot recognize or utilize previous problem configurations. They often rely on general problem-solving strategies such as means-ends analysis or working backward from the solution, while filling in the sub-goals and accompanying procedures [4–5].

To further complicate the situation, because the processes, goals, and sub-goals associated with a schema are missing for the novice, there is nothing automatic about the problem solving. Every step requires cognitive activity thereby increasing the cognitive load on working memory [2]. The more difficult the required task, the greater the *intrinsic* cognitive load. If the learning environment is sub-optimal, another load increases – *extraneous* load or the additional cognitive burden brought on in the poor design of the learning intervention. A final load, *germane* load refers to the working memory resources that the student has available to devote to dealing with the intrinsic cognitive load associated with the information as well as the extraneous load inherent in the design of the learning environment. As the germane cognitive load increases, the cognitive resources available for the student to assign to learning correspondingly decrease [2]. Within this framework, if the goal is to enhance learning outcomes, there are two possible strategies for the instructor:

1. Reduce the difficulty of the task, so that fewer cognitive resources are required and the germane load decreases to assign cognitive resources to learning.
2. Maintain difficulty and provide enough scaffolding or support in the learning environment to reduce the extraneous and germane load, thereby freeing cognitive resources for learning to occur.

In engineering education generally, attempts have been made to reduce the difficulty of the task in introductory courses. Evidence of this may be found, for example, in the sequencing of a course in Statics before a course in Dynamics in most engineering mechanics curricula. The strategy is that learning to transform a static mechanical system into a free body diagram and subsequent analysis is an easier task than addressing a system in motion. Once the introductory step is mastered, learning to solve for more complex systems will be easier. While this may be true, what is missing from this formulation is an analysis of task difficulty as the basis for this widely accepted curricular assumption.

### *1.2 Task Complexity*

*What makes a task difficult?* Jonassen [6] posited that difficulty emanates from two sources – internal and external factors. Internal factors can be found in the student. They include such things as prior domain knowledge and previous problem-solving experiences. While very important, internal factors are generally not in the control of the instructor. For our purposes, we are concerned with factors external to the student, but endemic to the task itself. Jonassen and Hung [7] propose two general factors contributing to task difficulty: complexity and structuredness. Complexity characterizes what is *known* in the problem and is impacted by four features: (1) the breadth of knowledge required, (2) the mastery level of that knowledge, (3) the intricacy of the problem-solving procedures, and (4) the complexity of the relationships among the parts. Each of these features impacts task difficulty independently. When taken together, however, task difficulty and intrinsic cognitive load can increase independently, and thus, the summative effect is amplified.

Structuredness, on the other hand, has been delineated as the degree to which elements in the task are known or knowable, predictable or unpredictable, and fixed or dynamic [8, 9]. Five parameters have been identified as characterizing task structuredness: (1) intransparency, (2) heterogeneity of interpretations, (3) interdisciplinarity, (4) dynamicity, and (5) the legitimacy of competing alternatives [7]. The greater the number of unknowns or imperfectly known elements in a task, the greater the intransparency. In the presence of unknowns, the task completer has to make assumptions and generate estimates to make up for intransparency. Moreover, the task becomes more ill-structured as the problem is more open to different interpretations. The problem of making an urban river parkway more sustainable, for example, is open to a number of interpretations in terms of starting points, final goals, and different stakeholder perspectives. Likewise, the more varied the disciplines called to the task, the more open and unstructured the task becomes. Finally, when various states in the problem are in flux and emergent depending on previous states and actions and when the number and variety of possible solution paths increases, the more ill-structured the task.

### *1.3 The Difficulty and Intrinsic Cognitive Load Associated with Fluid Mechanics Problems*

Fluid mechanics, a 3rd-year level course in most engineering curriculum, is challenging for most students (e.g., [10]). Upon completion of an engineering course in fluid mechanics, students should be able to apply fundamental flow analysis techniques to fluid systems. To accomplish this, they will demonstrate an understanding of the basic concepts of fluid mechanics with emphasis on formulation and solution of flow problems. They will build on skills acquired in mathematics, physics, and engineering mechanics courses (i.e., Statics and Dynamics) to solve flow problems of engineering relevance. They must understand basic fluid mechanics concepts comprising fluid properties, shear stress in fluids, and hydrostatic pressure variation. They learn to describe fluids in motion and conduct integral control volume analysis. They need to discern whether and when to apply the principles of conservation of mass, conservation of momentum, conservation of angular momentum, and/or conservation of energy. Students also learn how to analyze the pressure variation in moving fluids. Additional topics include dimensional analysis and differential control volume analysis in addition to flow applications such as boundary layers, flow in pipes, and fluid motion around objects.

While this description of expected knowledge and skills in fluid mechanics provides a general picture, we employed the Jonassen and Hung [7] framework to further articulate task difficulty. Five faculty members, who each have taught the introductory fluid mechanics course on multiple occasions, evaluated the course content by assigning High, Medium, or Low to each of the nine dimensions of complexity and structuredness (Table 1). The assessments by the five instructors revealed a good level of agreement, and a single aggregate rating is reported in Table 1. Five of nine categories are rated as High or High/Medium, whereas only one is rated as Low. This characterization of the course content reveals that learning to solve fluid mechanics problems carries significant intrinsic cognitive burden. To minimize germane load, and thereby enhance learning, either task difficulty needs to be decreased or the learning environment needs to be optimized to reduce extraneous cognitive load. The current study focuses on the design of an optimal learning environment needed for such task complexity.

### *1.4 Varied Modes of Learning Engagement and Associated Cognitive Processes*

Recently, advocates in engineering education have been calling for more active and engaging pedagogies that move beyond the modeling-and-mimicry approach as a way to improve learning outcomes (e.g., [11–13]). But, what do "active" and "engaging" mean? With the goal of getting more precision into words like "active", "passive", and "engaged", Chi [14] and Chi and Wylie [15] developed a taxonomy of possible learning engagements and attendant differential learning outcomes that has come to be known as the ICAP framework. "Each mode of engagement corresponds to several different types of behaviors and to differentiable knowledge-change processes" [15]. In this framework, the categories of engagement are manifest in overt behaviors that are observable in students. *Passive* (P) engagement is receiving information without doing anything beyond listening; *active* (A) engagement is characterized by some kind of motor movement or physical manipulation; *constructive* (C) engagement is when the student generates or produces an output of some kind; *interactive* (I) engagement is when two students engage in constructive dialogue around a product, in which turn-taking is evenly distributed. A hypothesis of this taxonomy is that each mode can be translated into differential learning achievement from minimal understanding, to shallow, to deep, and finally to deepest. Each level presupposes the previous, so that for the interactive mode, students co-construct a product through dialogue leveraging the constructive mode towards a deeper learning outcome. The potential for learning gains for each of these treatments is proposed based on studies in which the particular learning mode was enacted by students. Passive engagement fosters later recall; active fosters application; constructive begets transfer of learning to new products; and interactive culminates in reciprocal co-creation of a product that relies on recall, application, and transfer.

Given the complexity and ill-structuredness of fluid mechanics problems, which learning configuration is best suited to address the inherent cognitive load? In the modeling-and-mimicry model, students *actively* copy what is on the board in class and individually *construct* answers to homework problems out of class. What if we create a learning environment for fluid mechanics in which students were *interactive*? Would this kind of learning environment better support the student by reducing extraneous load and thereby free up germane load?

**Table 1.** Articulating the difficulty of the introductory fluid mechanics course following the framework in Jonassen and Hung [7]. The ratings are a determination of High, Medium, or Low for the particular dimension of task difficulty and consist of an aggregation of the determination of five experienced instructors who regularly teach the course

| Dimension of Task Difficulty | Summary Description of Dimension | Rating | Justification for Introductory Fluid Mechanics |
|---|---|---|---|
| 1. Complexity – Breadth of knowledge required | How much domain knowledge does the problem solver need to solve the problem? | **HIGH** | Fluid mechanics problems require a foundation in Newtonian physics and engineering mechanics. The problems require application of applied mathematics, including differential, integral, multivariate, and vector calculus, as well as differential equations. |
| 2. Complexity – Attainment level of domain knowledge | What is the level of difficulty and abstractness of the needed concepts? | **HIGH** | Fluid mechanics problems often require application of calculus and physics principles. The problems generally involve three-dimensional formulations (with a temporal dimension as well since the material flows), which requires an advanced level of abstraction to describe and understand the problem. |
| 3. Complexity – Intricacy of problem-solving procedures | What is the path length broken down as the number of steps required and the complexity of those steps? | **HIGH/MEDIUM** | Fluid mechanics problems generally involve a significant number of cognitive steps including diagnosing and interpreting the problem statement, translating the problem description into a conceptual model for analysis, application of fundamental principles and domain knowledge to the analysis of the model, and accurate application and calculation of the appropriate applied mathematics. |
| 4. Complexity – Relational complexity | What is the number of relations that need to be processed in parallel during a problem solving process? | **MEDIUM/HIGH** | Fluid mechanics problems rarely have one single, simple, straightforward solution path, but this aspect is constrained in the course by dividing the content into finite, focused modules. Nevertheless, students often have choices about the conceptual model design, the principles to include in the analysis, and the level of complexity of the analysis to apply. |
| 5. Structuredness – Intransparency | To what degree is the problem description unknown or uncertain? | **LOW** | The subject of fluid mechanics has substantial unknown or uncertain aspects that require assumptions to be made. However, this is constrained due to the defined learning outcomes of the course. In particular, problem-solving exercises in the introductory course and corresponding textbooks are designed to be focused on a particular principle with reduced ambiguity. |
| 6. Structuredness – Heterogeneity of interpretations | To what extent is there variation in the interpretations and perspectives for understanding or solving the problem? | **LOW/MEDIUM** | The design of the course focuses the interpretations because topics are presented in sequenced well-defined modules. Some variability in interpretation remains, however, due to the uncertainty in the applicability of various principles (for instance conservation of momentum vs. conservation of energy) to specific applications. |
| 7. Structuredness – Interdisciplinary | To what degree is knowledge required from multiple disciplines? | **HIGH/MEDIUM** | The course requires a fusion of physics principles, applied mathematics, and (to a lesser extent) chemistry and material science principles. It is one of the first courses in which students necessarily have to apply calculus to describe physical systems, hence this is significant jump from the straightforward calculations often presented in introductory mathematics courses. Fluid mechanics is critically important across and connecting a broad range of disciplines, but again the introductory course design constrains this aspect. |
| 8. Structuredness – Dynamicity | To what degree are the variables or operators dynamic or emergent in the analysis? | **LOW/MEDIUM** | The course design constrains the dynamicity of the problems by creating problems with modest scope that address a specific topic or principle. |
| 9. Structuredness – Legitimacy of competing alternatives | What are the number of conceivable options for executing operators in various solution paths? | **LOW/MEDIUM** | The course design constrains the alternatives by organizing the content in focused modules. However, an important part of the learning outcomes is to be able to identify what principles are effective for various types of problems. |

To answer these questions, we designed a new educational model for learning fluid mechanics based on the hypothesis that an interactive learning environment would show greater learning outcomes than the traditional modeling-and-mimicry approach. Further, the current study begins to address the observation by O'Flaherty and Phillips [16] that there has been an under-utlization of conceptual frameworks to evaluate the effectiveness of blended classrooms, a sentiment repeated by McNally et al. [17] and Lundin et al. [18].

## 2. Description of the Intervention

In the Civil Engineering (CE) and Environmental Engineering (EnvE) undergraduate degree programs at Georgia Institute of Technology (hereafter Georgia Tech), fluid mechanics content is delivered in an introductory course. The semester-long, three-credit-hour course is intended for the first semester of 3rd-year in both degree programs. The course meets for 50 minutes of class time three days each week for a 15-week semester. Summer offerings of the class are on an 11-week semester schedule with 70-minute sessions three times per week although course content remains consistent with fall and spring semesters. As noted above, specific topics covered in the course include fluid properties, shear stress in fluids, hydrostatic pressure variation, describing fluids in motion, integral control volume analysis, conservation of mass, pressure variation in moving fluids, conservation of momentum, conservation of angular momentum, conservation of energy, dimensional analysis, boundary layers, and differential control volume analysis. By the end of the term, the goal is for students to have mastered techniques for conducting flow analysis on fluid systems, thereby demonstrating their understanding of the basic concepts of fluid mechanics. This introductory course does not include a laboratory component; however, it should be noted that a subsequent more-applied course called Hydraulic Engineering includes laboratory activities that align well with the content in the introductory course.

### *2.1 Traditional Class Format*

Prior to 2012, the instructor taught the Fluid Mechanics course via a traditional model-and-mimicry format. Lecture content was delivered predominately via hand-written content on the whiteboard. The lecture content included descriptions of the fundamental principles and extensive problem solving examples. Still images and videos were displayed and discussed to provide example applications of the particular topic. Students were asked to participate via a dialog with the instructor and classmates, particularly during problem solving examples. Therefore, students had the opportunity to be active in class via writing notes and generating questions. Attendance was not required. Students were given hand-written homework assignments weekly, resulting in 11 or 12 assignments consisting of 66 to 72 total problem-solving exercises over the course of the semester. Starting in 2010, the hand-written assignments were replaced with on-line homework assignments via the WileyPlus system (described further below) with a similar number of total assignments and problems as previous. Examinations were the primary assessment tool and consisted of three mid-semester examinations and a final examination. The exception was during the Summer semester offerings of the course, in which only two mid-semester examinations were administered due to the abbreviated calendar (and the examinations were longer, i.e., 70 minutes vs. 50 minutes). The examinations consisted of problem-solving exercises. The number of problem-solving exercises was similar between academic year classes (3 exams times 3 problems = 9 total exercises) and summer semester classes (2 exams times 4 problems = 8 total problems). The instructor manually graded the examinations to assess the student's ability to: (1) identify an effective approach to the problem solving exercises, (2) set up the problem solving technique including a sketch, if needed, (3) accurately apply the correct principle(s) for the analysis, and (4) perform the calculations to produce the solution.

### *2.2 Blended Classroom*

First implemented in Spring 2013 semester, the instructor developed a blended classroom approach for the Fluid Mechanics course with the intent to shift the majority of the in-class activities to be constructive and interactive engagement. The course format is described as "blended" following the taxonomy defined by Margulieux et al. [19] and is consistent with what many educators refer to as a "flipped classroom". The course format is described in detail in Webster et al. [20] and is briefly summarized here. Fig. 1 shows a flowchart of the sequence of activities in the course.

Prior to each class session, the students watch a small number of lecture videos and review the relevant section(s) in the textbook [21]. The lecture videos were recorded in the instructor's campus office, without an audience, using the Tegrity recording software (McGraw-Hill Higher Education, Burr Ridge, Illinois). The lecture content was a mix of theoretical presentation/derivation of the principles and example problem solving exercises. Seventy-four lecture videos were recorded with an average length of 11.6 minutes. The instructor

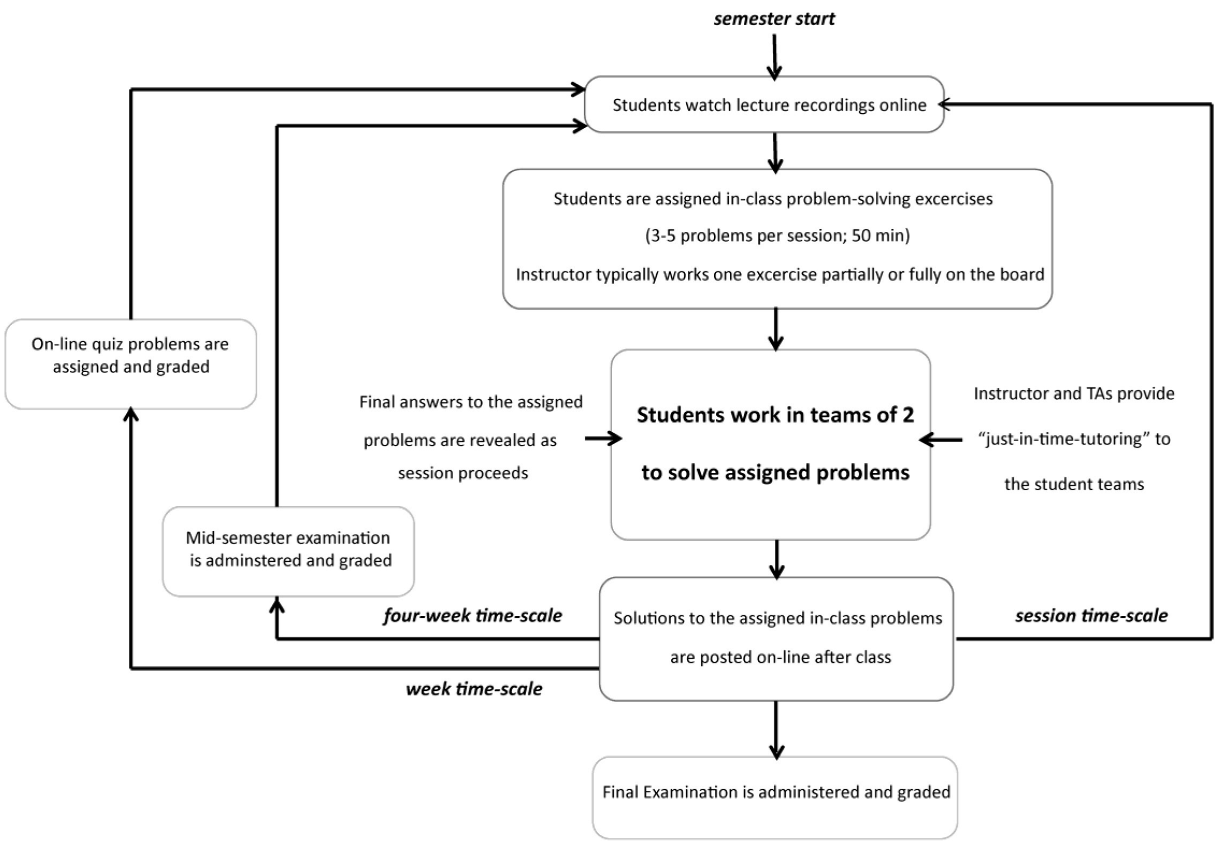


**Fig. 1.** Description and sequence of the blended classroom format for the Fluid Mechanics course.

predominately hand-wrote the lecture content using a stylus on a tablet PC running the Open Sankoré software (http://open-sankore.org/), which served as a digital whiteboard. The handwritten content delivery created a pace that facilitated verbal description by the instructor and allowed students to actively write notes. Simultaneous with the lecture content, the instructor's voice and image were recorded via a webcam for playback in a separate window. Students have substantial control during viewing including setting the window sizes. Students also can play the recording at up to twice regular speed and can pause, rewind, and fast-forward the recording. Students further can annotate the recordings with bookmarks and notes for future reference. The presentation was brisk and highly focused due to a lack of an audience during recording and because of the student's control during viewing.

In contrast to the modeling-and-mimicry approach, class time was devoted to student teams of two analyzing 3 to 5 problem-solving exercises. The exercises were similar in style to exam questions or textbook homework problems, generally requiring the students to read and interpret the problem statement, draw a sketch (for instance to define a control volume for analysis), apply fundamental principles, and calculate the solution. In total, over 110 problem-solving exercises were assigned for the in-class sessions during the semester. The instructor often worked one exercise on the white board either partially or fully at the start of the session. During the remainder of the session, students interactively worked with their partner to construct solutions to the exercises. A team size of two was selected to facilitate an interactive learning environment in which the students verbally and visually communicated with constructive dialog. Webster et al. [20] provide details on the partner selection process. The instructor and two assistants were available in the classroom to answer student questions and act as "just-in-time-tutors". Students used laptops, tablets, or other mobile devices during the class session to reference the online textbook and other sources for equations, tabulated data, and example exercises. Attendance was recorded for each session via a sign-in sheet and 10% of the student final grade depended on attending and participating in the sessions [20]. Due to this enticement to attend the sessions, attendance was very good with a small number of absences for any individual session. Otherwise, the students did not receive credit for working on the in-class exercises, and student work was not formally assessed by the instructor for correctness. Final answers to the exercises were written on the board during the session. After the session, the instructor posted his hand-written solutions for the session's exercises so the students could compare to their own (team) work.

Online quizzes were assigned each week with input parameters uniquely specified for each student using the WileyPlus system. Eleven quizzes (or nine quizzes during the abbreviated summer semester) were assigned for the total of 55 graded problems. The quiz content followed in-class exercises on the same topic, hence students generally had experience and confidence to be able to address and solve the quiz problems. Students were given three attempts to submit the correct answer for credit (within $\pm 2\%$ for numeric answers). The problem statements included links to the relevant textbook section and other instructional content. In the event that the student did not submit the correct answer by the third attempt, he or she gained access to the problem solution in PDF-file-format.

Student assessment primarily consisted of three semester examinations (or two during the abbreviated Summer semester) and a final examination. The format of the examinations was hand-written problem solving exercises. Student examinations were manually graded by the instructor in a manner identical to the traditional format described above.

With the purpose of managing the extraneous and germane cognitive load placed on the students, all course materials were provided in a course website that was organized around the class sessions. The links to the relevant video lectures and a PDF file of the exercises were posted in advance in a folder for each class session, which was titled by session number and date. Further, a link to the WileyPlus system was provided in the folder matching the due date for the quiz. The structure of the website allowed the students to chronologically progress through the semester with minimal ambiguity about the timing and content of the assigned activities and student responsibilities. Note that the first offering of the blended classroom format (in Spring 2013) did not employ the website design described here and that it was first implemented in the Summer 2013 semester.

## 3. Study Design and Assessment

The objective is to assess the impact of the shift to constructive and interactive in-class activities in the blended classroom approach on student performance in and perceptions of the course. The instructor taught the Fluid Mechanics course on eleven occasions using the traditional modeling-and-mimicry format in the period 2002–2012. Starting in 2013, the same instructor offered the Fluid Mechanics course in the blended classroom format on four occasions. The instructor, learning outcomes, course content, and physical environment were essentially identical among these course offerings. Thus, a primary difference across this comparison is the course format, particularly the interactive nature of class time, as described above. Another difference is student control of the lecture material. At home, the student can slow down the delivery, repeatedly view the recordings, stop and reflect, or make other choices about how they want to experience the lecture content.

Data for the comparison include demographic information of the student populations as well as the experience-level and previous academic performance. Course totals are calculated in a consistent manner across all sections to yield a score on a 100-point scale. The formula for calculating course total is 60% for the sum of the mid-semester examinations, 30% for the final examination, and 10% for the aggregate of the homework or quiz scores. The examinations were consistent in format and level of difficulty. Note that for consistency across sections, the course totals for the blended classroom students were re-calculated using this formula rather than the formula used to assign grades during the semester, which included an attendance component as described above. All examinations were graded using a consistent rubric by the same instructor across all sections. Further, data are compared regarding students who failed to achieve a C (i.e., "satisfactory") or better final grade. Student perceptions were collected via a digital Course-Instructor-Opinion-Survey (CIOS) that was administered online at the end of each semester by the Institute on a volunteer and anonymous basis. Several of the questions in the CIOS changed in 2011, hence some of the comparisons are limited to the period since that date.

Statistical comparisons were performed to test hypotheses about the similarity of results from different population groups by employing Student's *t*-tests. Significant differences were noted for $p$ values of 0.05 and less, which indicates a less than 5% chance of being similar. The lower the significance, the more confidence the researcher can have in the result. The effect size, $d$, is a measurement of the difference between two group averages accounting for different standard deviations, or statistical spreading of the data, between the two groups. Cohen [22] established effect sizes as 0.2 = small, 0.5 = moderate, and 0.8 = large.

The researchers in this study also employed multivariate regression to measure the effects of a group of independent variables (predictors) on a dependent variable (the measured outcome, in this case, final course total). By examining relationships between the independent variables – taken as a whole – and the dependent variable, the researcher can determine the relative impact of each independent variable on the dependent variable. Regression results include a regression coefficient (*B*) for each independent variable. This coefficient shows the relationship between the independent variable and the dependent variable. For example, if the independent variable is the student's GPA and has a *B* of 18, this would indicate that for every increase of one point in GPA, we would predict the dependent variable (in this study, final course total) would increase 18 points. "Dummy variables" are binary (one or zero) and are used to measure the effect of an independent variable when present. For example, if gender is coded in the data as 1 = Male and 0 = Female, and the *B* for gender is 0.3, then males are predicted to score 0.3 points higher on final course total than females. The *t*-test is used to establish the statistical significance of each independent variable on the dependent variable and provides a probability value of how confident the researcher can be in the results. For example, if a *t* statistic has a significance value of 0.05, one would conclude that there is a 95% chance that the measured relationship is "real" and not due to chance. (There is a five percent chance that there is no relationship between the two variables.) The lower the significance, the more confidence the researcher can have in the result for each independent variable. Similarly, the *F* test is used to measure the significance of the regression model when taken as a whole. Regression results also include the $R^2$ statistic, which measures the percent of variation in the dependent variable that is explained by the independent variables. For example, an $R^2$ of 0.45 would indicate that 45% of the variation in the dependent variable is explained by that particular grouping of independent variables. The $R^2$ is almost never equal to one (i.e., 100%) because there are factors that contribute to the variation in the dependent variable that the researcher simply cannot or has not measured.

## 4. Results

Six-hundred-ninety students were enrolled across fifteen sections of Fluid Mechanics from the Summer of 2002 through the Spring of 2017. Table 2 shows demographic information for the student populations in these sections, including enrollments by gender crosstabluated with the type of section (traditional vs. blended classroom). There is a higher percentage of female students in the blended classroom sections (35.8%) than in the traditional sections (24.2%). This is a statistically significant difference, with a chi-square of 8.413, significant at $p \leq 0.01$. The explanation is that the overall percentage of female students in the CE and EnvE programs increased over time during this period, and the blended classroom sections were taught most recently. Table 2 shows a crosstabluation of class-year (2nd, 3rd, and 4th-years) by type of section. Second-year students are defined as a student entering the course with between 31 and 60 semester credit hours completed, 3rd-year as between 61 and 90 credit hours, and 4th-year as 91-or-more credit hours. While 2nd-year enrollments are generally small, the course has been roughly evenly split between 3rd-years and 4th-years, with a few exceptions (e.g., Spring 2013, when 4th-years outnumbered 3rd-years 75% to 25%). While 3rd-years outpaced 4th-years in enrollments in the traditional sections of the course (56.8% to 38.3%, respectively), the two groups are about evenly distributed in the blended classroom

**Table 2.** Student demographic information by course format.

| | | | **Format** | | |
|---|---|---|---|---|---|
| | | | **Traditional** | **Blended Classroom** | **Total** |
| **Gender** | **Female** | N | 128 | 37 | 186 |
| | | % within format | 24.2% | 35.8% | 27.0% |
| | **Male** | N | 400 | 104 | 504 |
| | | % within format | 75.8% | 64.2% | 73.0% |
| **Year** | **2nd-year** | N | 21 | 2 | 23 |
| | | % within format | 4.0% | 1.2% | 3.4% |
| | **3rd-year** | N | 300 | 79 | 379 |
| | | % within format | 57.7% | 48.8% | 55.6% |
| | **4th-year** | N | 199 | 81 | 280 |
| | | % within format | 38.3% | 50.0% | 41.1% |
| **Total** | | N | 528 | 162 | 690 |

Table 3. Prior academic achievement for two student groups

| | Format | N | Mean | Std. Deviation | Std. Err. Mean | *t* (*p*-value) |
|---|---|---|---|---|---|---|
| **Incoming GPA** | Traditional | 528 | 2.97 | 0.61 | 0.027 | 1.708 (0.088) |
| | Blended Classroom | 162 | 3.06 | 0.56 | 0.044 | |
| **Total number of semester credit hours completed prior to course** | Traditional | 528 | 85.1 | 21.6 | 0.94 | 3.669 (<0.001) |
| | Blended Classroom | 162 | 92.0 | 18.1 | 1.4 | |
| **Number of semester credit hours completed at Georgia Tech prior to course** | Traditional | 528 | 53.0 | 29.9 | 1.3 | 0.722 (0.47) |
| | Blended Classroom | 162 | 54.9 | 26.8 | 2.1 | |

Table 4. Means analysis of final course total between blended classroom and traditional sections

| | Format | N | Mean | Std. Deviation | Std. Err. Mean | *t* (*p*-value) |
|---|---|---|---|---|---|---|
| **Course total (on a 100-point scale)** | Traditional | 505 | 71.4 | 14.8 | 0.66 | 4.738 (<0.001) |
| | Blended Classroom | 160 | 77.4 | 13.8 | 1.094 | |

sections of the course (48.8% to 50.0%, respectively). These differences by year are also statistically significant, with a chi-square of 11.345, significant at $p \leq 0.05$.

We also compared the student populations in the traditional and blended classroom sections by looking at students' average incoming GPA, number of credit hours when entering Fluid Mechanics, and number of credit hours earned specifically at Georgia Tech when entering Fluid Mechanics, as shown in Table 3. Average incoming GPAs for the traditional and blended classroom sections are similar, and the difference is not statistically significant. The average number of credit hours of incoming students was significantly different (greater for the student population in the blended classroom sections). However, there is no statistically significant difference in the average number of credit hours obtained specifically at Georgia Tech. This indicates that students entered the Fluid Mechanics course with a similar level of experience in Georgia Tech courses, but students in the (more recent) blended classroom sections brought in more credit hours from AP or IB or transfer credit.

As shown in Table 4, the average final course total (on a 100-point scale) in the blended classroom sections was 77.4, whereas the average final course total in the traditional sections was 71.4. This difference is statistically significant ($p \leq 0.001$) and has an effect size (Cohen's *d*) of 0.42, a moderate effect. The improved learning gains reported here are consistent with many, but not all, studies of the effectiveness of the blended classroom approach. Recent studies that reported improved learning gains in blended classrooms include [16, 23–27], whereas inconclusive results were found by McClelland [28], specifically in fluid mechanics, and others.

We regressed students' final course total on a 100-point scale on a dummy variable for the blended classroom, as well as with controls for student gender, student major, and prior achievement measured as incoming GPA. The results in Table 5 show this model for all students, as well as for female students only and for male students only.[1] The blended classroom variable is significant at $p \leq 0.001$ for all three models. The control for prior achievement (GPA) is statistically significant across all models, and the constant is statistically significant across the all models. The models also explain a strong amount of variation in final course total with adjusted-$R^2$s exceeding 0.5 in each model (Table 5). Regression coefficients (*B*) in these models suggest that the blended classroom format adds approximately four to five points to final course total, with coefficients of 4.44 for the model with all students, 5.40 in the model with female students only, and 3.96 for the model with male students only.[2]

[1] The authors explored whether the blended classroom might have an effect specifically for low-achieving students by running the model only for those students with GPAs below 2.8. That model showed no significance except for the GPA control variable. A question for future research would be to look in more detail at the data on such students use of the lecture videos (i.e., if they were less likely to have watched the videos before class).

[2] The authors also ran the regression analyses on only the summer sections to determine if the results differed owing to differences in the course format between the 11-week summer sections and the 15-week fall and spring sections. The summer results were nearly identical, showing very similar adjusted $R^2$s, *F*s, and *t*-test results as the aggregate models.

**Table 5.** Results of models regressing final course total (on a 100-point scale) on blended classroom and control variables

| | Model | B | Std. Err. | Beta | *t* (*p*-value) | Adj. $R^2$ | *F* (*p*-value) |
|---|---|---|---|---|---|---|---|
| **All students** | (Constant) | 18.23 | 2.22 | | 8.19 (< 0.001)*** | 0.56 | 215.17 (< 0.001) |
| | Blended† | 4.44 | 0.91 | 0.13 | 4.86 (< 0.001)*** | | |
| | Gender† | 0.28 | 0.87 | 0.01 | 0.32 (0.75) | | |
| | CE Major† | –1.38 | 1.08 | –0.03 | –1.28 (0.20) | | |
| | GPA | 18.16 | 0.64 | 0.73 | 28.50 (< 0.001)*** | | |
| | **Model** | **B** | **Std. Err.** | **Beta** | ***t* (*p*-value)** | **Adj. $R^2$** | ***F* (*p*-value)** |
| **Female students** | (Constant) | 14.63 | 3.42 | | 4.28 (< 0.001)*** | 0.67 | 123.54 (< 0.001) |
| | Blended† | 5.40 | 1.40 | 0.17 | 3.85 (< 0.001)*** | | |
| | CE Major† | –1.89 | 1.47 | –0.06 | –1.28 (0.20) | | |
| | GPA | 19.38 | 1.05 | 0.79 | 18.54 (< 0.001)*** | | |
| | **Model** | **B** | **Std. Err.** | **Beta** | ***t* (*p*-value)** | **Adj. $R^2$** | ***F* (*p*-value)** |
| **Male students** | (Constant) | 19.45 | 2.76 | | 7.05 (< 0.001)*** | 0.53 | 179.92 (< 0.001) |
| | Blended† | 3.96 | 1.16 | 0.11 | 3.42 (< 0.001)*** | | |
| | CE Major† | –0.89 | 1.47 | –0.02 | –0.60 (0.55) | | |
| | GPA | 17.74 | 0.78 | 0.71 | 22.66 (< 0.001)*** | | |

† Denotes a dummy variable:
Blended: Blended classroom section = 1, Traditional section = 0.
Gender: Male = 1, Female = 0.
CE Major: Civil Engineering = 1, all other majors (mostly Environmental Engineering) = 0.
*** Denotes significance at $p \leq 0.001$.

**Table 6.** WFD data for student populations in the Fluid Mechanics course. W corresponds to student "withdrawal" from course prior to the drop deadline, F corresponds to "failing", and D corresponds to "passing". For comparison and to fully describe the grade scheme, A corresponds to "excellent", B corresponds to "good", and C corresponds to "satisfactory"

| Semester | Format | N | W | F | D | WFD rate |
|---|---|---|---|---|---|---|
| 2002 Summer | Traditional | 34 | 2 | 2 | 4 | 23.5% |
| 2002 Fall | Traditional | 68 | 4 | 2 | 4 | 14.7% |
| 2006 Spring | Traditional | 76 | 0 | 5 | 7 | 15.8% |
| 2006 Summer | Traditional | 26 | 1 | 1 | 4 | 23.1% |
| 2007 Fall | Traditional | 65 | 1 | 1 | 7 | 13.8% |
| 2007 Summer | Traditional | 37 | 1 | 1 | 6 | 21.6% |
| 2008 Fall | Traditional | 64 | 4 | 4 | 3 | 17.2% |
| 2009 Fall | Traditional | 42 | 3 | 3 | 3 | 21.4% |
| 2010 Fall | Traditional | 68 | 1 | 3 | 0 | 5.9% |
| 2012 Spring | Traditional | 23 | 1 | 3 | 0 | 17.4% |
| 2012 Fall | Traditional | 30 | 2 | 3 | 1 | 20.0% |
| **WFD rate for Traditional sections** | | | | | | **16.3%** |
| 2013 Spring | Blended | 40 | 2 | 2 | 2 | 15.0% |
| 2013 Summer | Blended | 24 | 0 | 0 | 2 | 8.3% |
| 2014 Spring | Blended | 40 | 1 | 0 | 1 | 5.0% |
| 2017 Spring | Blended | 58 | 0 | 2 | 2 | 6.9% |
| **WFD rate for Blended Classroom sections** | | | | | | **8.6%** |

Table 6 shows the results of an analysis of the rates of withdrawal and course grades of F or D in the Fluid Mechanics course (i.e., the "WFD rate"). The WFD rate for traditional sections was 16.3%, while the WFD rate for blended classroom sections was 8.6%. This is a significant

**Table 7.** Summary of results for the Course-Instructor-Opinion-Survey (CIOS). Mean scores are for a 1 to 5 scale, as defined for each question

| | Traditional | Blended Classroom | *t* (*p*-value) | Cohen's *d* |
|---|---|---|---|---|
| Instructor's clarity in discussing or presenting course material. 5: exceptional; 1: very poor | 4.71 (N = 48) | 4.75 (N = 122) | 0.500 (0.618) | 0.075 |
| Instructor's level of enthusiasm about teaching the course. 5: extremely enthusiastic; 1: detached | 4.31 (N = 48) | 4.74 (N = 121) | 3.671 (0.001) | 0.738 (large) |
| Instructor's ability to stimulate my interest in the subject matter. 5: made me eager to learn more; 1: ruined my interest | 4.24 (N = 46) | 4.57 (N = 122) | 2.269 (0.026) | 0.432 (moderate) |
| Helpfulness of feedback on assignments. 5: extremely helpful; 1: not helpful | 4.47 (N = 44) | 4.58 (N = 115) | 1.396 (0.165) | 0.237 |
| Considering everything, the instructor was an effective teacher. 5: strongly agree; 1: strongly disagree | 4.66 (N = 255) | 4.80 (N = 122) | 2.339 (0.020) | 0.256 (small) |
| Rate how prepared you were to take this subject. 5: extremely well prepared; 1: completely unprepared | 3.90 (N = 48) | 3.84 (N = 122) | 0.370 (0.712) | 0.283 |
| How much would you say you learned in this course? 5: an exceptional amount; 1: almost nothing | 4.33 (N = 48) | 4.60 (N = 122) | 2.313 (0.022) | 0.404 (moderate) |
| Degree to which activities and assignments facilitated learning: 5: exceptional; 1: very poor | 4.27 (N = 48) | 4.65 (N = 122) | 2.665 (0.010) | 0.521 (moderate) |
| Degree to which exams, quizzes, homework (or other evaluated assignments) measured your knowledge and understanding. 5: exceptional; 1: very poor | 4.32 (N = 47) | 4.46 (N = 122) | 1.051 (0.295) | 0.180 |
| Considering everything, this was an effective course. 5: strongly agree; 1: strongly disagree | 4.42 (N = 48) | 4.72 (N = 121) | 2.030 (0.046) | 0.400 (moderate) |

difference with a chi-square of 4.961, which is significant at $p \leq 0.05$.

Table 7 compares student ratings on the CIOS administered in the traditional and blended classroom sections of Fluid Mechanics. All responses were on a scale from 1 to 5, defined for each question in Table 7. The overall effectiveness of the instructor was rated higher in the blended classroom with a small effect size. The student's perception of the instructor's ability to stimulate interest, the amount learned, the degree that activities facilitated learning, and the overall course effectiveness were all significantly higher in the blended classroom with a moderate effect size. And finally, the student perception of the instructor's enthusiasm about teaching the course was higher in the blended classroom with a large effect size.

For the courses after 2011, students were also asked to report the number of hours per week spent on the course. Fig. 2 shows the responses in each strata of hours per week (0–3 hours, 3–6 hours, etc.). There is little difference in terms of the amount of work students put into the class at the lower end of the scale, with the greatest number of responses being between 3 and 9 hours per week, tapering off with fewer students reporting a higher amount of hours per week. However, the fraction of students reporting beyond nine hours per week spent on the course is larger in the blended classroom format than in the traditional classes. This stands to reason, as the blended classroom requires time spent watching the lecture videos outside of class as well as time spent in-class on problem-solving. There is less opportunity in a blended classroom format for students to "coast" by attending lectures only and putting in little time and effort outside of class. Further, the course format and materials provide a framework for students who need additional engagement in the content in order to achieve a "satisfactory" final grade or better. This investment of time pays off in both increased student engagement with the material and higher final course total. The CIOS results indicate that students in the blended classroom sections found that the activities and assignments in the course facilitated learning more than did students in the traditional classes.

## 5. Discussion

Our findings, covering sixteen years and encompassing eleven traditional modeling-and-mimicry classes and four blended classroom implementations, demonstrate changes in both student performance and student perceptions between these two

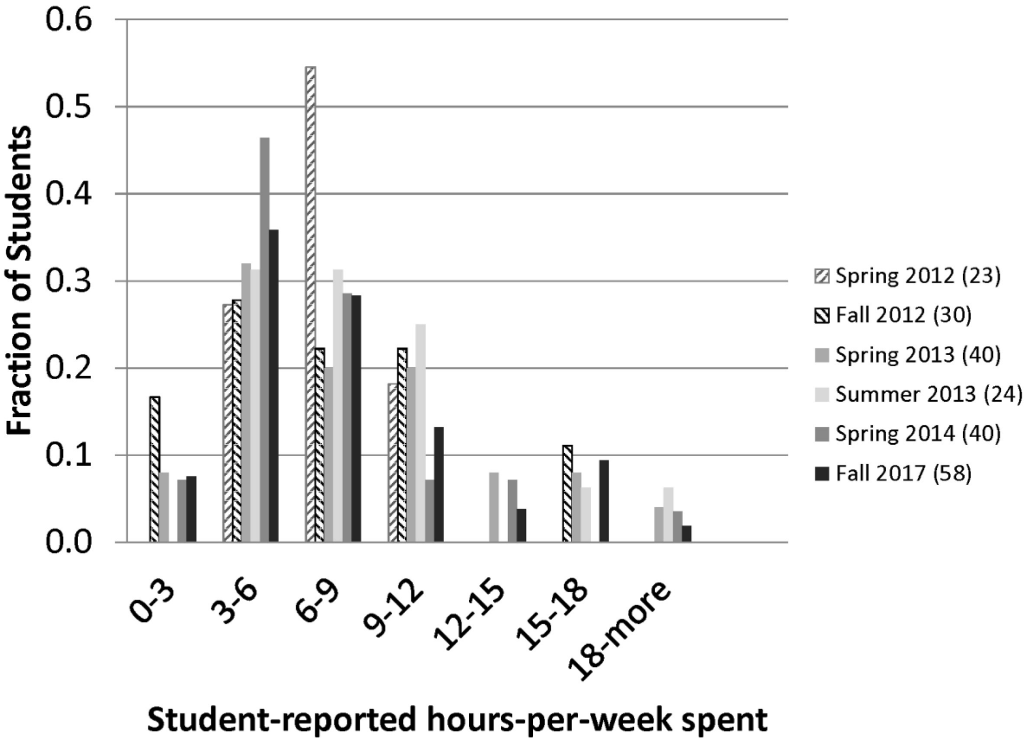


**Fig. 2.** Student-reported hours-per-week spent on the course reported as the fraction of students in the class reporting for each range. Data are from the Course-Instructor-Opinion-Survey (CIOS). Four classes were in the blended classroom format (solid bars), and two classes were in a traditional lecture-based format (hashed bars).

course designs. While we see an overall increase of six points in the average final course total aggregated from weekly assignments and exams in the blended classroom (Table 4), it is the reduction of the WDF rate from 16.3% to 8.6% that is most compelling (Table 6). This is a reduction by nearly half for the percentage of student who can be described as "not successful in the course". These improvements in student performance are remarkable since the intrinsic cognitive load of the class content and problems remained constant or arguably increased. While the actual exam items changed from-semester-to-semester to prevent cross-semester student-sharing of specific questions, the style and challenge-level was constant. What significantly changed, however, was the course design, the addition of the videos for out of class viewing, and the classroom experience. The blended classroom supports participant structures that value constructive peer-to-peer interaction as best suited to engaging the specific cognitive processes that leads to learning in the context of significant cognitive load. One explanation for improved student outcomes is the control the student has over the lecture content when viewed at home. In this content delivery mode, he or she can control the speed of delivery, the timing and number of viewings, and even stop the video to anticipate the instruction to see if he or she can replicate in advance what the instructor does. Such control means the delivery can be tailored to the current needs of the specific student.

Abeysekera and Dawson [29] proposed that blended learning may provide opportunities to manage cognitive load and thereby improve learning, and there is evidence, although limited, that this may be case (e.g., [30, 31]). Our conjecture is that this blended classroom model positively alters the extraneous cognitive load, at a time when it is most critically needed, by providing more effective and timely scaffolding in the form of peer, teaching assistant, and instructor interactions in the midst of problem solving. As a result, the germane load is reduced, thus freeing up more cognitive capacity for learning. However, we have no direct measures of reduced cognitive load or germane load. A future study could use the Pass Cognitive Load Scale to measure perceived cognitive load in the two types of classrooms to further substantiate our conclusion [32]. Complementing this study would be one in which we query students directly on what aspects of the classroom format most impacted their fluid mechanics learning. Studies like these that attempt to directly measure the cognitive and germane loads associated with engineering topical areas are sorely needed in engineering education research.

The findings for female students from regression modeling are also compelling. On average, we see a regression coefficient for the female-only student group of nearly five-and-a-half points in the final course total due to being in the blended classroom, which is roughly one-and-a-half points greater than the gain for the male-only group (Table 5). We suggest that the collaborative, rather than the competitive, classroom mode is better suited to the learning predispositions of the female students (e.g., [33]). In the interactive classroom, he or she can work together with another student, get situated feedback when he or she is stuck, and generally communicate more intimately with a teaching assistant or the instructor than is typically possible in the traditional mode, in which the whole class is queried: "Are there any questions?" Targeted efforts to recruit and select the teaching assistants may also be a significant explanation. Female graduate students, not much older than the undergraduate students, are aggressively recruited to serve as teaching assistants for the blended classroom. A future study could use more qualitative methods to illuminate how students experienced the learning environment – its affordances for collaborating, learning, and mastering the content.

Previously reported student perceptions of blended classrooms have been mixed with some reporting a stereotypical resistance by students (e.g., [34–36]) and other studies reporting improved student satisfaction in a blended classroom (e.g., [16, 23, 37, 38]). While the CIOS scores in the current study for the traditional offering by the same instructor were typically high compared to the normative data for the Institute, the scores in the blended classroom treatment were higher in all categories. A category of particular interest was "instructor's level of enthusiasm about teaching the course." What is happening in a blended classroom environment such that students perceive that the instructor to be more enthusiastic? One explanation might be the "micro-messaging" that occurs when the instructor makes an effort to reach a learning pair, i.e., come to the students rather than requiring them to come to the instructor. Do these physical actions of trying to get to students in need, sometimes requiring navigating through furniture and other teams, signal enthusiasm? Or is it what happens when he reaches the pair? Or is it the intimate interaction when all of the instructor's attention is focused on getting a team through a difficult patch? A word that repeatedly comes up in the qualitative section of the CIOS results is "care". We suspect that caring is connected to perceived instructor engagement and enthusiasm. So, in short, the revised participant structures of the classroom that values and, is driven by, interaction among the students and instructor create the perception among the students that the instructor is effective, stimulating, enthusiastic, and clear in his explanations.

Further, the added investment of time reported in the CIOS (Fig. 2) paid off in both increased student engagement with the material and higher final course totals. Students in the blended classroom sections report that the activities and assignments in the course facilitated learning more than did students in the traditional classes. The change in participant structures, specifically the combined use of the lecture videos, the online quizzes, and the interactive exercises in class, provided more opportunity to understand, apply, and evaluate solutions to engineering problems. Likewise, the CIOS results show that students in the blended classroom format believed they learned more than students in the traditional sections. Student perceptions are corroborated by the analysis of final course total (Tables 4 and 5), showing a significant increase in the blended classroom sections.

A few thoughts to take away about implications for practice: First, the blended classroom pedagogy is effective in medium-sized classes and is not solely effective for small classes. The blended classrooms in this study had an average of 40 students. We have also applied the course design to fundamental engineering mechanics courses in excess of 80 students [39]. Second, the selection of teaching assistants is important, particularly as class size increases, since it becomes increasingly difficult for the instructor to personally connect with every student as the class size grows. The assistants were mentored to tutor the student teams in order to help them through challenges rather than directly reveal the solution. Assistants in the implementations described here were often graduate students and, as described above, a mixture of genders among the assistants was aggressively sought. Undergraduate students have also been successfully employed as assistants, typically selected from the student population who had completed the blended classroom course and had performed at an excellent level. Therefore, such a course design could be successfully implemented at universities lacking significant graduate student populations. Third, the classroom environment and layout also may not be optimal for a blended classroom, but this can be overcome by the design of the in-class interactions. In the implementations described here, the course met in general purpose classrooms as well as moderate-sized (up to 90 seats) lecture halls with fixed seating and tables. The important factor is that the desk and chair arrangements are able to effectively support interactive communication between the student partners as well as with the instructor and assistants. Movable tables and chairs are not necessary, but can make the in-class interactions easier in some cases. On occasion, the instructor rejected room assignments in which tables were designed for three students, due to the belief that the best way to achieve interactive learning was to have groups of two students. Fourth, the instructor must be willing to cede control of the classroom during the in-class sessions. The learning in the classroom is typically "messy" in the sense that students make numerous mistakes and get off track and the instructor should watch for the key moment to provide assistance. With patience and gentle tutoring, the instructor and assistants can steer the students to not only complete the exercise, but to actually understand what they are doing and why. The tutoring provided by the instructor and assistants often comes at the moment when students are most receptive to it since they are at an impasse in the exercise. Finally, clearly publishing and maintaining the course schedule and creating an easy-to-navigate website are important to reduce the cognitive load for the students. By presenting an easy-to-follow sequence of course events with easy-to-find materials allows the student to focus on learning the material rather than expending cognitive load on deciphering what is required, when to do it, or where to locate the key course materials. The course content is typically challenging enough, therefore our advice is to make the learning environment accessible and easy to follow.

While our findings have begun to fill some gaps in our understanding of the efficacy of a blended learning environment, we still have much to understand based on our findings. First, we have questions regarding how weaker performing students respond to the blended classroom and how this relates to the improved WFD rate observed in Table 6. Another gap not filled by this research is how differently identified, or more commonly labelled under-represented minorities, experience the blended classroom environment. The data suggest that women appear to fare better, but what about students of color, differently-abled, and LGBTQ students? Do they experience this blended classroom environment as inclusive, welcoming, and valuing their individuality? Or do the interactions among peers, teaching assistants, and the instructor send ambiguous or negative micro-messages? Our intent is to continue to view the blended classroom as a laboratory to understand how to better support all students, for in this new age of awareness of inclusive and exclusive pedagogies, we need studies that provide missing answers to these important questions.

To conclude this discussion, we bring our findings back to the engineering classroom and to the larger engineering education community. In this work, we have brought together three independent research threads: cognitive load, problem complexity, and the cognitive implications of classroom practices. We have argued that unless we understand problem complexity, as defined by Jonassen [6], attendant on mastering course material, we may very well be engaging in classroom practices that fail to reduce both extraneous and germane loads. In fact, by not attending to such complexity, we may very well be inadvertently increasing both, which bodes poorly for mastery and transfer of the material to new contexts. As a first step, we propose that faculty members, and the engineering education community collectively, take on the task of analyzing complexity in all courses addressing engineering fundamentals to better understand the cognitive burden we can expect our students to experience. With this shared understanding, the community as a whole has the opportunity to develop more effective pedagogies that address the learning challenges associated with significant intrinsic load. Developing such an analysis would be tantamount to pulling away the curtain and revealing in concrete terms where the difficulty of a certain class of problems comes from, while cuing what they, as learners, need to do cognitively to be successful. A question for future research would be whether such knowledge is helpful to learners in their ability to master challenging course material.

## 6. Conclusions

Our hypothesis that the traditional education style of modeling-and-mimicry is insufficient for deep learning and mastery is supported by the data. The core objective of the blended classroom course design, namely to create a constructive and interactive in-class environment for learning a complex and ill-structured subject, is successful in reducing the extraneous and germane cognitive load. This conclusion is supported by significant gains observed in student performance in the blended classroom format while holding as many factors constant as possible (i.e., instructor, course content, physical environment, and assessment practices). We further ground this claim in illuminating the cognitive processes that are called to action when the participant structures are intentionally altered in the classroom to promote student-to-student generation and negotiation. The results further show greater performance gains among female students, thus indicating an added benefit of providing a learning environment that supports individuals from populations that are traditionally under-represented in engineering education. Finally, student reported opinions of the course support our conclusions and specifically reveal significant improvement in the course's ability to stimulate interest in the subject, the perceived amount learned, the student appreciation of the degree that activities facilitated learning, and the student's perception of the instructor's enthusiasm for the course.

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**Donald R. Webster** is the Karen and John Huff School Chair and Professor in the School of Civil & Environmental Engineering at Georgia Tech where he has been a faculty member for over two decades. He earned his PhD in Mechanical Engineering from the University of California at Berkeley and held post-doc appointments at Stanford University and University of Minnesota. His research expertise lies in environmental fluid mechanics with an emphasis on the influence of fluid mechanics and turbulence on biological systems. Dr. Webster's educational activities include an NSF-supported Integrative Graduate Education and Research Training (IGERT) program that trains graduate students in the physics, chemistry, and ecology of chemical and hydrodynamic signaling in aquatic communities. He also has been a faculty mentor for an NSF-supported Research Experience for Undergraduates (REU) program addressing the interdisciplinary area of aquatic chemical ecology.

**Robert S. Kadel** is former Assistant Director for Research in Education Innovation with Georgia Tech's Center for 21st Century Universities. His research emphases include measuring the effectiveness of online and blended learning strategies, building communities of inquiry in MOOCs, leveraging learning analytics for student success, and implementing tools/strategies to help close the digital divide for economically disadvantaged students. He spent seven years as an independent educational technology research consultant, with clients across the US, and six years with Pearson Education, where he regularly extolled the virtues of quality research design with clients worldwide. Dr. Kadel continues to teach online courses in the sociology of education, criminology, and juvenile delinquency for the University of Colorado, Denver. Dr. Kadel earned his PhD in Sociology from Emory University.

**Wendy C. Newstetter** is the Assistant Dean of Educational Research and Innovation in the College of Engineering at Georgia Tech. Dr. Newstetter's research focuses on understanding cognition and learning in interdisciplines with an eye towards designing educational environments that support the development of integrative thinking and problem solving. Towards that end, she uses ethnographic methods to study in-vivo learning and problem solving in research laboratories – tissue engineering, neuroengineering and biorobotics – where the nature of the problems demands multidisciplinary teams with complementary skills and knowledge. Dr. Newstetter uses this research to then inform the design of problem-based learning (PBL) classrooms to support the development of integrative knowledge building and reasoning strategies. Dr. Newstetter earned her PhD from Lancaster University.