Specifications Grading in Undergraduate Fluid Mechanics

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Introduction

Alternative grading practices are being used increasingly in science, technology, engineering, and mathematics (STEM) courses in place of traditional points-based grading systems [1]–[17]. One such method is specifications grading, in which student work is scored pass/fail according to whether the assignment submission met the provided requirements. The final course grade is determined by students completing pre-determined "bundles" of assignments [18].

The last several years have seen an increase in the use of specifications grading in higher education courses in STEM, including examples in chemistry [19], biology [20], physics [21], mathematics [22], first-year engineering [23], [24], engineering computer applications [25], engineering mechanics [26], thermodynamics [27], fluid mechanics [28], biomedical engineering statistics [24], a chemical engineering laboratory [29], a biomedical engineering elective course [30], and capstone design [24].

This paper will describe the implementation of specifications grading in two offerings of an undergraduate fluid mechanics course, one with lecture and laboratory components and a lecture-only course the following year. Student course performance data presented here will be limited to the assessments in the lecture portion of the course.

Pedagogical Approach

Course Description

In 2018, specifications grading was implemented in a 4-credit junior-level fluid mechanics lecture and laboratory course in a mechanical engineering curriculum. The course is typically taken in the first semester of the third year in the program. The prerequisites are courses in thermodynamics, dynamics, and differential equations. The course is a prerequisite for the heat and mass transfer course.

The lecture portion of the course was organized into 8 modules based on content: fundamental concepts, fluid statics, elementary fluid dynamics, control volume analysis, dimensional analysis, flow in pipes, external flows, and compressible flow. There were 7 laboratory experiments: pressure measurement, Venturi meter, flow loss, vertical flow through an orifice, horizontal flow through an orifice, flow meters, and fluid friction. The lecture portion of the course met twice per week for 75 minutes during a 15-week semester. The laboratory sections met approximately once every two weeks for 110 minutes.

When the course was next offered in 2019, due to a program curriculum change, the course became a 3-credit lecture, and the laboratory portion was moved to a separate course. The lecture course met twice per week for 75 minutes during a 15-week semester and maintained the 8 content modules used the previous year.

Assessments and Grading

From the 8 course outcomes specified by the program (see Appendix A), the topics were refined into a list of 16 measurable topics, listed in Table 1. The topics presented here reflect those used in the 2019 course. Quiz 2C was revised from "Determine *hydrostatic* force acting on floating or submerged bodies" in 2018 to "Determine *the buoyant* force acting on floating or submerged bodies" in 2019 to more accurately describe the problems associated with this topic.

Table 1. Standard associated with each quiz.

Quiz Number	**Topic**	**Specifications: You will earn a score of "Pass" by…**
1	Describe the scope of fluid mechanics.	correctly answering the question in your own words.
2A	Determine pressures from measurements using various types of manometers.	correctly applying the manometer rule to the given scenario.
2B	Calculate the hydrostatic force acting on a plane or curved submerged surface.	completing the following: • Sketch an appropriate free-body diagram for the given situation • Correctly apply statics principles
2C	Determine the buoyant force acting on floating or submerged bodies.	completing the following: • Sketch an appropriate free-body diagram for the given situation • Correctly apply Archimedes' principle
3	Apply Bernoulli equation to simple flow situations.	completing the following: • Correctly apply the Bernoulli equation • Correctly apply the continuity equation, if necessary
4A	Apply the principles of conservation of mass and momentum to a control volume.	completing the following: • Correctly apply the continuity equation • Correctly apply the linear momentum equation
4B	Use the energy equation to solve problems involving losses due to friction and energy input by pumps or extraction by turbine.	correctly applying the energy equation.
4C	Determine flow characteristics of incompressible, steady, laminar, viscous flow between parallel plates and through circular tubes.	completing the following: • Choose the appropriate solution to the Navier-Stokes equations • Correctly set up the appropriate equation to solve for the desired quantity
5	Use dimensional analysis to establish a set of similarity requirements for a model to be used to predict the behavior of another similar system.	completing the following: • Use the Buckingham pi theorem to determine pi terms and a relationship between them • Use similarity to determine the requested quantity

Quiz Number	Topic	Specifications: You will earn a score of "Pass" by…
6A	Solve a variety of pipe flow problems.	completing the following: • Correctly apply the energy equation • Correctly account for major and minor losses, when applicable • Correctly apply the continuity equation, when applicable
6B	Determine flowrate through flowmeters.	completing the following: • Select the correct equation relating flowrate and pressure • Determine the appropriate discharge coefficient
7A	Calculate boundary layer parameters for flow past a flat plate.	correctly setting up an equation to determine the requested quantity.
7B	Explain the physical process of boundary layer separation.	correctly answering the question.
7C	Calculate lift and drag forces.	applying the principles of lift or drag to solve the problem.
8A	Calculate Mach number for a specific compressible flow.	correctly calculating the Mach number for the specified flow.
8B	Solve problems involving isentropic flow with area change.	completing the following: • If necessary, determine whether or not the flow is choked. • Set up the correct equation to solve for the requested quantity.

Each topic was assessed by a quiz problem/question. Most were calculation-based problems; a few topics were assessed by short answer responses to a prompt. To earn a score of "Pass" on a quiz, a student had to solve the problem to the specifications, which were available in the learning management system in advance of the quiz. If a score of "No Pass" was earned, the student could request to attempt a new problem on the same topic. These additional attempts could be scheduled outside of class time during the instructor's office hours or during class. Quizzes took place approximately once per week toward the end of the class period.

In the 2018 course, a written report was required for each of the 7 laboratory experiments. To earn a score of "Pass" on a laboratory report, a student had to submit a written report that met all requirements specified in the assignment description provided in the learning management system. For an example, see Appendix B. If a score of "No Pass" was earned, the student had the option to submit a revised version when they were ready, up to the final week of the course. The separate laboratory course that was first offered in 2019 is not described here.

There were two categories of smaller assignments: 14 guided practice assignments and, in the 2018 course, 7 pre-lab assignments. Guided practice assignments were meant to prepare students in a flipped classroom for the group activities [31], [32]. The pre-lab activities were short reading assignments with a few questions to prepare students for the laboratory experiments. For the guided practice and pre-lab assignments, a student earned a score of "Pass" on each assignment by attempting each problem/question and submitting the assignment prior to the lecture or laboratory period corresponding to the assignment. A score of “No Pass” was earned if there was no submission, if any question was left blank, or if any response did not reflect a good-faith effort to be correct, such as “I don’t know”. Guided practice and pre-lab assignments could not be revised or resubmitted because these assignments were meant to be completed prior to class to prepare for the in-class activities or lab experiments.

Table 2 describes how many quizzes and laboratory reports were required to earn a particular grade [33]. Since grades with “+” or “-”, such as “B+”, could be assigned, a plus was added to the base grade if a student earned “Pass” scores on at least 13 guided practice and on 7 pre-lab assignments in the 2018 course. A minus was added to the base grade if a student earned “Pass” scores on fewer than 7 guided practice or on fewer than 4 pre-lab assignments in the 2018 course. The 2019 course used the same requirements for number of quizzes and guided practice assignments passed to earn a particular grade.

Table 2. Course grade requirements from 2018 syllabus.

To earn this grade:	Accomplish the following:
A	Earn “Pass” scores on 15 quizzes AND earn “Pass” scores on 7 lab reports.
B	Earn “Pass” scores on 13 quizzes AND earn “Pass” scores on 6 lab reports.
C	Earn “Pass” scores on 11 quizzes AND earn “Pass” scores on 5 lab reports.
D	Earn “Pass” scores on 9 quizzes AND earn “Pass” scores on 4 lab reports.

Results and Discussion

Copies of all student quizzes were kept during the course. For each of the 16 quizzes, the following data was collected for each student who completed the course (15 students in 2018 and 12 students in 2019): score on the initial attempt, number of attempts, and score on the final attempt.

The percentage of students who earned a “Pass” score on each quiz topic in the 2018 course is given in Figure 1. Two sets of data are shown, students who passed the topic on the first attempt and students who passed the topic by the end of the course. Four quiz topics were passed by all students on the first attempt: scope of fluid mechanics (Quiz 1), flat plate (Quiz 7A), boundary layer separation (Quiz 7B), and Mach number (Quiz 8A). Five additional quizzes were eventually passed by all students: manometers (Quiz 2A), buoyant force (Quiz 2C), Bernoulli equation (Quiz 3), differential analysis (Quiz 4C), and lift/drag (Quiz 7C).

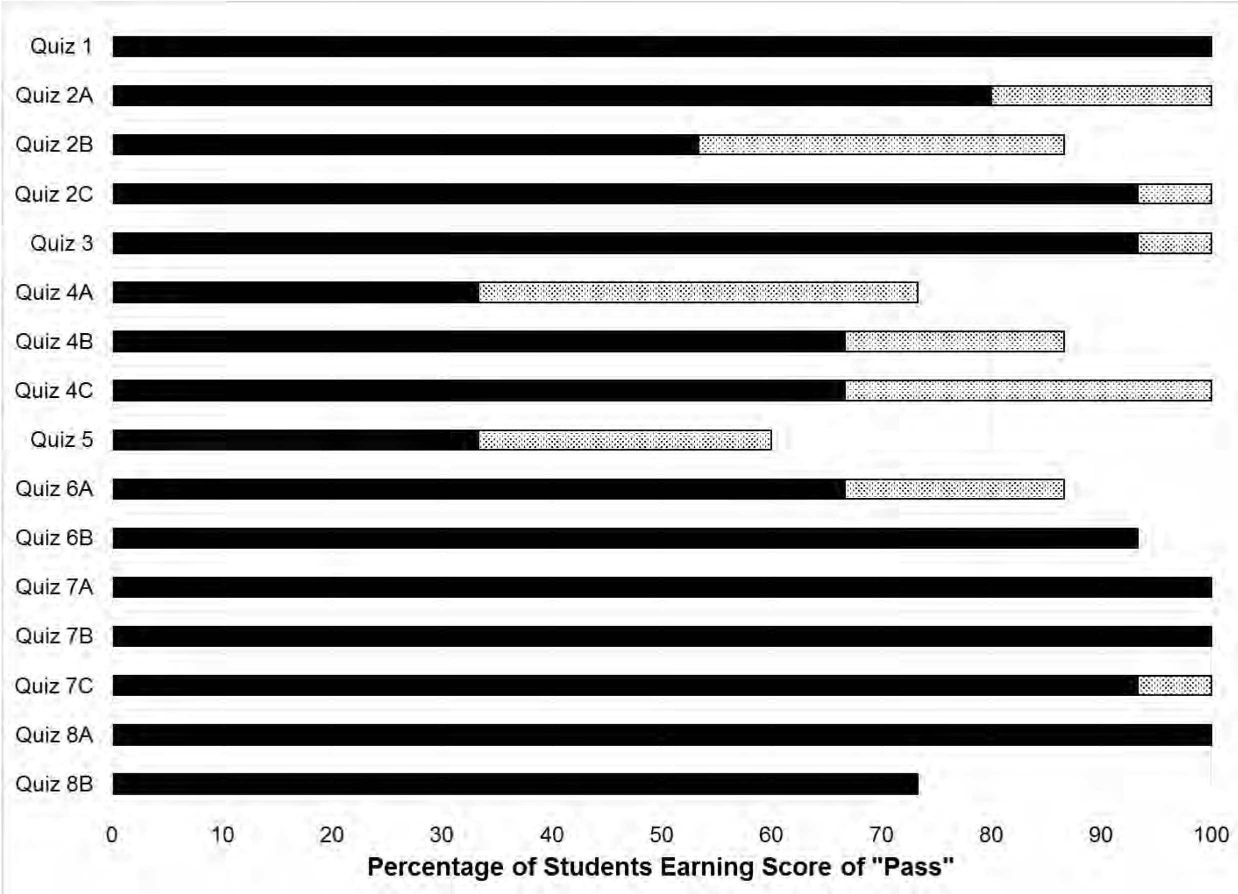

Figure 1. Percentage of students earning score of "Pass" on each quiz topic in the 2018 course. Filled bars indicate students who passed on the first attempt. Dotted bars indicated additional students who passed on a later attempt.

The percentage of students who passed each quiz topic in the 2019 course is given in Figure 2. Three quiz topics were passed by all students on the first attempt: scope of fluid mechanics (Quiz 1), buoyant force (Quiz 2C), and Mach number (Quiz 8A). Three additional quizzes were eventually passed by all students: differential analysis (Quiz 4C), flat plate (Quiz 7A), and lift/drag (Quiz 7C).

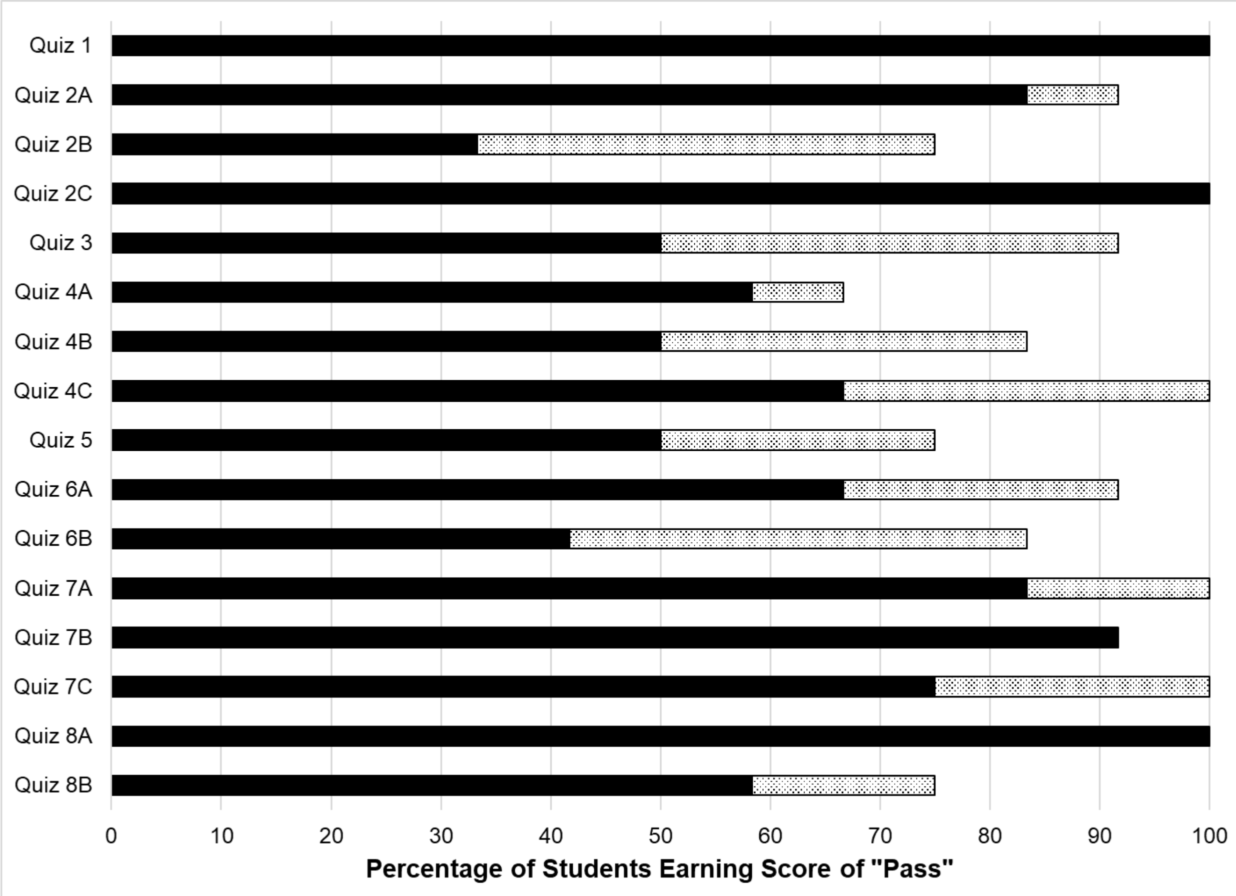

Figure 2. Percentage of students earning score of "Pass" on each quiz topic in the 2019 course. Filled bars indicate students who passed on the first attempt. Dotted bars indicated additional students who passed on a later attempt.

For the 2018 course, the average number of attempts for each quiz topic and how many students had no attempt, one attempt, two attempts, or three or more attempts are given in Table 3. The topics with the highest average number of attempts were, in descending order, mass and momentum (Quiz 4A), hydrostatic force (Quiz 2B), and dimensional analysis (Quiz 5). These are also the topics with the lowest percentage of students passing on the first attempt. Dimensional analysis (Quiz 5) had the lowest pass rate by the end of the course. Mass and momentum (Quiz 4A) had the most students taking three or more attempts.

For the 2019 course, the average number of attempts for each quiz topic and how many students took different numbers of attempts are given in Table 4. The topics with the highest average number of attempts were, in descending order, hydrostatic force (Quiz 2B), and then manometers (Quiz 2A) and flowmeters (Quiz 6B). The topics with the lowest percentage of students passing on the first attempt were hydrostatic force (Quiz 2B) and flowmeters (Quiz 6B). Mass and momentum (Quiz 4A) had the lowest pass rate by the end of the course. Manometers (Quiz 2A) and hydrostatic force (Quiz 2B) had the most students taking three or more attempts.

Table 3. Number of attempts taken for each quiz topic in the 2018 course.

	Average Number of Attempts	Number of Students			
		No Attempt	One Attempt	Two Attempts	Three or More Attempts
Quiz 1	1.0	0	15	0	0
Quiz 2A	1.3	0	12	2	1
Quiz 2B	1.7	0	8	5	2
Quiz 2C	1.1	0	14	1	0
Quiz 3	1.1	0	14	1	0
Quiz 4A	2.0	0	5	6	4
Quiz 4B	1.3	0	11	3	1
Quiz 4C	1.3	0	10	5	0
Quiz 5	1.4	1	7	7	0
Quiz 6A	1.3	0	11	3	1
Quiz 6B	1.0	0	15	0	0
Quiz 7A	1.0	0	15	0	0
Quiz 7B	1.0	0	15	0	0
Quiz 7C	1.1	0	14	1	0
Quiz 8A	1.0	0	15	0	0
Quiz 8B	1.1	0	14	1	0

Table 4. Number of attempts taken for each quiz topic in the 2019 course.

	Average Number of Attempts	Number of Students			
		No Attempt	One Attempt	Two Attempts	Three or More Attempts
Quiz 1	1.0	0	12	0	0
Quiz 2A	1.6	0	10	0	2
Quiz 2B	1.7	1	4	5	2
Quiz 2C	1.0	0	12	0	0
Quiz 3	1.4	0	7	5	0
Quiz 4A	1.3	0	9	2	1
Quiz 4B	1.4	0	7	5	0
Quiz 4C	1.4	0	8	3	1
Quiz 5	1.5	0	7	4	1
Quiz 6A	1.3	0	8	4	0
Quiz 6B	1.6	0	5	7	0
Quiz 7A	1.2	0	10	2	0
Quiz 7B	1.0	0	12	0	0
Quiz 7C	1.3	0	9	3	0
Quiz 8A	1.0	0	12	0	0
Quiz 8B	1.2	0	10	2	0

The following topics were among the lowest pass rates and/or greatest average number of attempts in both offerings of the course: hydrostatic force (Quiz 2B) and mass and momentum (Quiz 4A). In future offerings of the course, these are topics the instructor could consider changing the way the material is delivered or providing additional opportunities for students to practice.

The 2018 and 2019 courses were taught by the same instructor using a flipped classroom approach with active learning techniques including Peer Instruction [34] and group problem-solving. In addition to the removal of the lab component, another difference in the course in 2019 was the introduction of concept maps to organize course topics. Students were encouraged to create concept maps as a study tool and viewed portions of an instructor-created concept map at certain points during the course. While students found the concept maps useful for some course activities, there was not a significant difference in quiz scores compared to the previous offering of the course without concept maps [35].

The 2018 course offering was the first time this instructor had taught this course. A considerable amount of time was spent in preparation before the course began. Multiple potential quiz problems were selected or written for each topic. Compared to how this instructor prepared other courses using a traditional grading scheme with exams, much of the course preparation time was shifted from during the semester to before the course began. The student course evaluations included positive comments about the course organization, which the instructor attributes to the time invested in preparing the course.

Once implemented, specifications grading saves the instructor time [18]. While instructor time spent on this course was not tracked, the grading of quizzes could be done relatively quickly by checking if all the specifications were met and providing some feedback on what was incorrect about the solution or recommending a portion of the course materials for the student to review.

It is recommended to have some limit on how often or how many times a student may reattempt a quiz or resubmit assignments. In this course, students were able to schedule an appointment with the instructor outside of class time once per week to reattempt up to two quizzes. These appointments were available on a first-come, first-served basis and had to be scheduled 24 hours in advance. Students were also able to reattempt quizzes during a later class period by requesting the quiz two days in advance. There was no limit to how many quizzes a student could request; however, there was a limited amount of time allotted in class for quizzes, typically 20-30 minutes once per week. The final opportunity for quiz reattempts was during the two-hour period at the end of the semester that would traditionally be used for a final exam. In the course evaluations, students commented on their enjoyment of the grading system and the ability to reattempt quizzes.

Conclusions

In a course using specifications grading with quiz reattempts, students were able to revisit course material and demonstrate improved proficiency in particular topics. From the instructor perspective, more time was spent preparing the course prior to the start of the semester, but less time was spent grading compared to courses with traditional exams. The quiz score results from the two offerings of the course suggest two areas for the instructor to revise in future versions of the course: hydrostatic force and mass & momentum.

This paper described two subsequent offerings of the course in a traditional face-to-face classroom format. When the course was offered again using specifications grading in 2020, it was fully online due to the COVID-19 pandemic. Because of multiple differences between the two course formats, that work is not described here. The course returned to the traditional on-ground format in 2021 but was taught by a different instructor using a traditional grading scheme.

Future course preparation will involve revising portions of the course where quiz pass rates were low. Future work will involve surveying students on their perceptions of specifications grading.

Appendix A: Course Outcomes

Upon successful completion of the course, students should be able to:
1. Describe the scope of fluid mechanics.
2. Calculate the hydrostatic forces, pressures and moments on planar and curved submerged and floating surfaces.
3. Decide when it is appropriate to use ideal flow concepts and the Bernoulli equation.
4. Construct an appropriate control volume for a given engineering system and apply the principles of conservation of mass, momentum, and energy to this control volume in differential and integral forms.
5. Present data or governing equations in non-dimensional form and apply dimensional analysis.
6. Solve for internal flow in pipes and channels through simple solutions of the Navier-Stokes equations, the Moody chart and the head-loss equation.
7. Solve for external (laminar and turbulent boundary layer) flows, evaluate lift and drag, know when there is possibility of flow separation.
8. Describe the propagation of sound; apply the basic equations of 1D, steady compressible flow and isentropic flow with area change to solve for unknown properties using appropriate property relations.

Appendix B: Example Laboratory Report Specifications

To earn a score of "Pass", complete the following:
- Complete all sections of the cover page.
- Write an abstract that answers the five questions listed in the template.
- Correctly state the objectives of the experiment.
- Write an introduction that briefly relates the experiment to a real-world example.
- In the theory section,
  - Explain the theoretical principles behind the experiment.
  - Explain all equations used for the calculations.
  - Define all variables used in the equations.
  - Explain all assumptions used in the experiment and calculations.
- In the experimental methods section,
  - Describe in your own words how you completed the experiment.

  - Provide a sketch, diagram, and/or photo to describe the experimental set-up. The main components of the experimental set-up should be labeled in each sketch/diagram/photo.
- Summarize the results.
- Include the graphs described in "Analysis" above. You may share graphs with your group members.
- Include a discussion of the results. Your discussion may include the following:
  - Was there a difference in gage error when you increased the pressure compared to when you decreased the pressure? Why?
  - Were there any differences in the readings from the different manometer types? Why?
  - Were there differences between the pressures measured using the gage and using the manometers? Why?
- Explain possible errors in the pressure gage readings and in the manometer readings. Describe any other experimental errors.
- State your conclusions from the experiment.
- Make recommendations based on the experiment. This could be ways to improve the experiment, or suggestions for what someone should do differently next time.
- Include a caption for each table or figure (graph, diagram, photo). A table caption is placed over the table. A figure caption is placed below the figure.
- In the body of the report, refer to any books, websites, etc. that were used in writing the report and list them in the reference list.
- Consistently format the items in the reference list, stating titles, authors, publisher, date of publication, and page number, as appropriate.
- In the sample calculations, show an example of how the results were calculated. Include units. Use an equation editor.
- Include units in the data tables.
- Provide an equipment list.
- Attach a scanned copy of the raw data sheet.

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