Competency Based Learning In ”Aerospace Structures I” In an Online Environment – Work in Progress

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Competency based learning in “Aerospace Structural Analysis I” in an online environment

Abstract

In Fall 2020, we converted the engineering upper division class “Aerospace Structural Analysis I” from a traditional format to a competency-based learning model. “Aerospace Structural Analysis I” is a combination of topics from statics and strength of materials applied to aerospace systems. A total of about 100 students were enrolled in the class. Due to the coronavirus pandemic in 2020, this class was conducted in an online environment for the first time in Fall 2020. Competency based learning assesses students on how many topics/skills they are proficient, and allows students to engage with more complex topics only after mastering prerequisite skills. To pass the class in the competency-based learning model, students must be proficient on seven fundamental skills related to aerospace structures. Students are required to be proficient on further skills to obtain a higher grade. Students demonstrate proficiency on a skill by completing a quiz without major errors. The class was offered in Fall 2020 as fully online, with synchronous, recorded lectures. Although the online format poses new challenges for students, we think that it was easier for students to progress at their own pace in an online environment. The effectiveness and limitations of the competency-based pedagogy are assessed in the paper comparing students’ progress and grade between Fall 2020 and the previous class offering (Fall 2019). In addition, students’ experience and perception about the new format are assessed with an end-of-semester survey. Students generally had a positive experience with competency-based learning format, but they identified the necessity to provide more timely feedback.

Introduction

“Aerospace Structural Analysis I” is a required junior class in Aerospace Engineering that introduces students to concepts in statics and strength of material. The class consists of several topics that result in a fast-paced course, leaving some students behind. Over the years, this class has been characterized by high failing percentage rates (20% in 2019) and equity gaps (0.22 in 2018). Equity gaps are defined by the difference in mean grade between students belonging to underrepresented groups and the rest of the class. In order to improve the learning outcomes of the course, the authors introduced a competency-based learning approach (CBL) in Fall 2020. The approach seemed suitable to support students to master the class learning outcomes, by moving from a breadth to a depth learning priority. The available research indicates that competency-based learning is ideal to support weaker students while maintaining rigor. It allows them to move at their own pace and be more successful and confident as they gain a higher level of understanding in the required topics [1], [2].

This paper utilizes quantitative and qualitative methods to show whether competency-based learning generates positive results in achievements and learning, and to understand whether students positively reacted to mastery learning. The authors will answer the following research questions

1. What is the impact of CBL on student learning outcomes for students enrolled in "Aerospace Structural Analysis I"?
2. What are students' perceptions of CBL in "Aerospace Structural Analysis I"?

Background literature

Competency-based learning – CBL - (also called "mastery learning", "self-paced", "student-centered", "performance-based") is an instructional method that uses time flexibility to improve students' learning [3] and focuses of mastery of measurable student outcomes [4]. Students' progress is based on whether students demonstrate mastery of clearly communicated and measurable outcomes. Students cannot progress to a new competency until they master the prerequisite outcomes. According to the Department of Education, CBL improves student outcomes, and at the same time improves student engagement [5]. In the last two decades, CBL has received higher attention in engineering education [4].

Traditionally, students are graded on how well they learn each topic. Obviously, some students may still pass the class but not have a strong grasp on some fundamental topics. CBL suggests, instead, that students should be graded on how many topics they learn well, and that they should engage with more complex topics only when they have mastered prerequisite topics. Studies have shown that CBL benefits a diverse student body, and makes sure that all students have mastered fundamental skills [1], [2], [4], [6]. Specifically, CBL has been shown effective on courses such as "Aerospace Structural Analysis I" for which each topic builds on the previous ones.

The use of CBL teaching techniques has also been shown to improve students' retention, as students are required to master prerequite material before they were able to progress to more complex content. It has also been shown to improve students' study habits, as students learn to constantly review material before progressing to the next content [4]. The CBL approach has also been shown to better support a diverse students' population, especially when remote learning is integrated in the curriculum, as it promotes individualized learning [7]. Students have also been shown to respond positively to CBL resulting in improved students' outcomes and attitudes [3], [8], [9].

Description of implementation

The following instructional elements are included in competency-based learning [3]: curriculum alignment between teaching and testing, formative evaluations (usually in the form of short quizzes), corrective feedback, retesting and criterion specification grading (students' performance are not compared to other students' in the grade determination). The authors re-designed the class in order to include these elements into the instructional approach. First of all, curriculum alignment between teaching and testing has been prioritized using frequent quizzes that test students on the clearly presented learning objectives, formative and summative assessment has been included in the form of ten short quizzes. Students could retake a quiz on the same topic multiple times, until they passed. Different questions on the same topic were assigned to the students when a quiz was retaken.

"Aerospace Structural Analysis I" is a 4-unit class taught at a large, public university. The class meets twice a week for 100 minutes per session. In Fall 2020, the class was conducted remotely due to the COVID-19 pandemic, and no in-person instruction was provided. Two sessions of 100 minutes each were taught synchronously, with additional office hours. The class was conducted using Zoom and Twitch, and students interacted both with the instructor and their peers by asking questions and solving problems in groups by virtually raising their hand or using the chat. The class meeting was recorded and provided to the students. Two sections were taught with a total enrollment of 109 students, divided in two sections of 51 and 58 students. Both sections were taught by the same instructor. In addition, students were offered the possibility to take an extra 1-unit workshop class to gain additional practice on each topic, to which they had to be formally enrolled. A total of 16 students attended the optional workshop. The workshop met for once a week for a synchronous 60 minutes session through Zoom. During each workshop session, students were assigned 2-4 problems, that they solved collaboratively in groups through breakout rooms. Each group consisted of 3-4 students. The instructor joined each breakout room to provide feedback and guidance when appropriate. Toward the end of the session, the students joined the main zoom session as a class and discussed the assigned problems with the instructor.

Following the approach suggested by Okamoto [1], the class topics were divided into three categories, “Preliminary”, “Required” and “Supplementary”, for a total of 10 topics (Table 1). Each topic is aligned with the class learning outcomes. Students had to take a quiz on each topic, and they had to pass it before they were able to take the following quiz. The first quiz was offered during week 2, and students could take make-up quizzes for the rest of the semester. The alignment between each topic and the course learning outcomes (CLOs) is listed in Table 1. Each quiz consisted of one or two questions on the topic, and students had 15 minutes to complete it. If a quiz was not passed, students could retake the quiz, and they were assigned a different question on the same topic.

The grade in each quiz was determined based on the number of major mistakes in the problem’s solution: each major mistake accounted for a 10% reduction in quiz grade. Minor mistakes were not considered as part of the grading system. A quiz was considered as passed if the grade was higher than 75%. The quizzes were manually graded by the teaching assistants, with instructor supervision. During the last week of the semester, students who had passed at least 7 topics were offered the opportunity to attempt the quizzes for topic 8, 9 and 10. This action was considered as a necessary tool given some of the challenges that this first CBL implementation presented.

Table 1. List of topics and their classification for mastery learning progression

Topic #	***Classification***	***Course Learning Outcomes***
P1	Preliminary	Estimate forces on particles in equilibrium in 2D and 3D
P2	Preliminary	Estimate moments and couples on bodies in 2D and 3D
R3	Required	Create free-body diagrams and solve with vector algebra in 2D and 3D
R4	Required	Compute the resultant of constant and triangular distributed loads acting on a wing, and its point of application

R5	Required	Apply equilibrium principles to compute internal and external forces on truss and frame structures.
R6	Required	Compute area properties of two-dimensional wing and fuselage cross sections: centroid and moments/products of inertia.
R7	Required	Calculate stresses and strain
S8	Supplementary	Construct shear force and bending moment diagrams for a cantilevered wing under constant and triangular distributed loads.
S9	Supplementary	Calculate axial stressed and strain along a wing-type structure in bending.
S10	Supplementary	Calculate shear stress and angle of twist along a shaft-type structure in torsion.

In addition to the CLOs assessed by the quizzes, an additional course learning objective focusing on engaging the students with real-world practices was separately assessed with a research paper that students submitted at the end of the semester. Students were asked to find five recent peer-reviewed publications and explain how the papers are tied to the concepts presented during the semester.

The final grade of the students was determined based on four items: the topic quizzes, a research paper, a final exam and ten homework. Each homework was aligned with one specific topic. The final grade was determined according to the following grading scheme:

Quizzes: 50%
Homework: 10%
Final exam: 20%
Research paper: 20%

Results

The students' progress in passing each quiz topic is depicted in Table 2, that represents the cumulative percentage of students that passed each quiz for each week of the semester. As described previously, no quiz was administered during week 1 of the semester (W1), and students were able to take some extra quizzes during the last week of the semester (W17). The percentage of students who successfully passed and completed each topic at the end of the semester is also depicted in Figure 1. For example, students were able to complete the quiz to topic R7 on week 12, and only 3% of the class passed the topic during this week. By the end of week 17 (W17), however, 81% of the class passed the R7 quiz. Students could retake the assessment for each topic multiple times, and each time they were assigned a different question on the topic picked from a question bank.

Table 2. Students' progression during the semester. For each topic, the table shows the cumulative percentage of students that passed each topic week by week. W17 is the final week of the semester

Topic	Week																
	W1	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**	**W13**	**W14**	**W15**	**W16**	**W17**
P1		81	92	99	99	99	99	99	99	99	99	99	99	99	99	99	99
P2				87	94	94	96	97	97	98	99	99	100	100	100	100	100
R3					69	75	85	86	87	87	88	89	89	89	89	89	92
R4							67	75	82	83	85	85	85	85	89	89	93
R5								9	55	70	71	76	77	79	80	82	87
R6										50	51	55	63	66	67	72	81
R7												3	43	44	50	59	81
S8															2	10	32
S9															1	5	42
S10																12	72

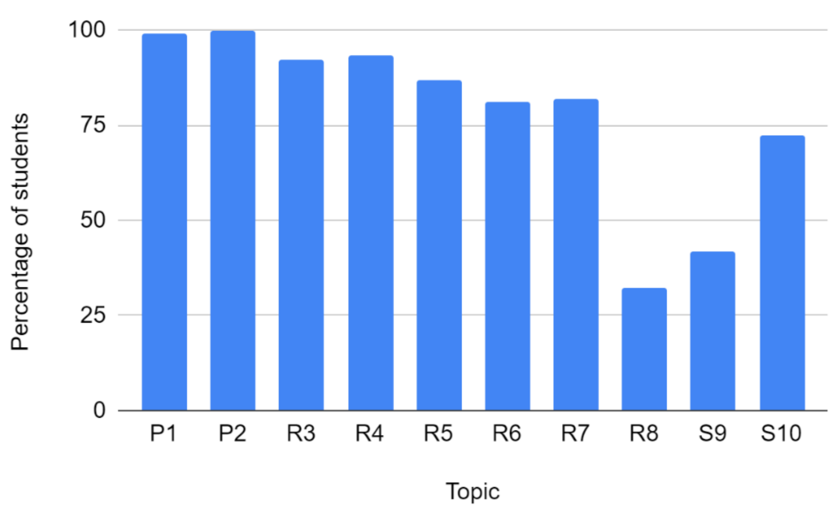

Figure 1. Percentage of students of passed each topic quiz by the end of the semester

By the end of the semester, the majority of students (81%) passed the 7 required topics, and more than a third of the students passed at least an extra topic quiz. These results are very encouraging, as they show that students were able to master more simple concepts and then successfully pass more advanced topics.

Students’ scores on each final exam question are compared to the previous class offering (Fall 2019). The two class offerings had two different instructors, but they worked closely to make sure that the topics and the material presented was consistent in the different semesters. Both instructors are authors of this paper. The class material used by the instructors in Fall 2019 and Fall 2020 was the same, and the authors believe that this comparison provides an initial understanding of the effect of CBL on students’ learning with respect to traditional teaching approaches. The students’ scores for the mastery learning approach is provided in Table 3 and the students’ scores in the final exam for the traditional offering is described in Table 4. The average students’ score in the final exam in Fall 2020 was 74%, compared to a 69% in Fall 2019. This improvement in students’ grade is encouraging. To understand how students’ learning has been affected, a breakdown of final exams’ questions and the respective topic is presented in Table 3 and Table 4 as well. Students exposed to CBL in Fall 2020 showed acceptable understanding of all the topics, with average scores above 70% for all questions except question 5 which included assessment of multiple advanced topics (S9). In the previous class offering in Fall 2019 students lacked understanding on multiple topics, even less advanced topics (Table 4).

Table 3. Mapping of final exam questions to topics' progression with competency-based learning, Fall 2020.

Question #	**Points**	**Avg score**	**Topic #**
Q1	10	72%	R5
Q2	10	75%	R5
Q3	10	72%	S10
Q4	10	87%	R4
Q5 (follow up of Q6, Q8)	10	67%	P2; R3; R4; R6; R7; S8; S9
Q6 (follow up of Q8)	10	71%	P2; R3; R4; S8
Q7	10	74%	R6
Q8	10	71%	P2; R3; R4;
Q9	10	71%	R5
Q10	10	79%	S10
Global	**100**	**74%**	

Table 4. Mapping of final exam questions to topics' progression in traditional teaching format, Fall 2019.

Question #	**Points**	**Avg score**	**Topic #**
Q1	15	91%	R5
Q2	5	75%	P2; R3; R4;
Q3	10	74%	P2
Q4	20	63%	P2; R3; R4; R6; R7; S8; S9
Q5	15	53%	R3; R5
Q6	5	78%	R3; R5
Q7	20	61%	P2; R3; R6; S9

Q8	10	73.2%	R6
Global	**100**	**69%**	

A part of the differences in the students' scores may be due to multiple factors, in addition to CBL. The latest offering of the class which implemented CBL has been offered in an online modality due to the COVID-19 pandemic, while the Fall 2019 offering was offered fully in person. In addition, different instructors taught the two offerings, although the class material was kept as uniform as possible. Both instructors are authors to this paper, and they have worked together to ensure consistency of the material presented and difficulty of assessment with lengthy discussion before, during and at the end of the semester.

The final course grades are also compared between the CBL offering in Fall 2020 and the previous Fall 2019 offering (traditional approaches). Figure 2 shows the percentage in grade distribution between the two offerings. The chart shows that the percentage of "A" and "B" grades was similar, but fewer students failed the course (corresponding to a grade of "D", "F" or "W" – students are allowed to withdraw from the class at any point during the semester) in Fall 2020 when CBL was implemented with respect to the previous offering. Our experience of CBL pedagogy particularly supports the weaker students, by focusing on their learning of the fundamental class topics.

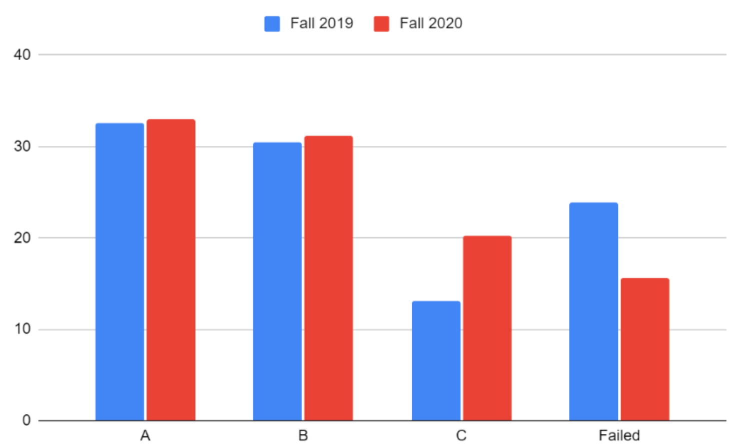

Figure 2. Course grade distribution (in percentage) for AE112 using CBL (Fall 2020) and traditional approaches (Fall 2019)

The grade distribution in Fall 2020 and Fall 2019 has been compared to determine whether CBL results in statistically different grade distributions among students, as well as among different students groups. The comparison has been conducted by converting letter-grades to a 4-points scale according to university policies. There is a statistically significant difference between the total Fall 2019 and Fall 2020 grade distribution as determined by one-way ANOVA, $p = 0.015$ (Table 5). An in-depth comparison of the grades divided by gender (Table 6) as well as by race (Table 7) did not reveal statistically significant differences between the grades that different groups of students earned in the two offerings. We can therefore conclude that the improvement in grade mean with CBL is statistically significant for all the students, but that no student group was particularly affected by the change in pedagogy.

Table 5. Results of one-way ANOVA in comparing students' grades between Fall 2020 (CBL implementation) and Fall 2019 (traditional). Significance level $\alpha = 0.05$.

	All students
Fall 2019 - student means	2.526
Fall 2020 - student means	3.069
one-way ANOVA p-value	0.015

Table 6. Results of one-way ANOVA in comparing students' grades between Fall 2020 (CBL implementation) and Fall 2019 (traditional) separated by gender. Significance level $\alpha = 0.05$.

	Gender	
	Female	Male
Fall 2019 - student means	2.117	2.588
Fall 2020 - student means	3.385	3.019
one-way ANOVA p-value	0.091	0.066

Table 7. Results of one-way ANOVA in comparing students' grades between Fall 2020 (CBL implementation) and Fall 2019 (traditional) separated by race. Significance level $\alpha = 0.05$.

	Race			
	Asian	Hispanic	Other	White
Fall 2019 - student means	2.548	2.083	3.433	2.740
Fall 2020 - student means	3.139	3.071	3.105	2.946
one-way ANOVA p-value	0.056	0.063	0.673	0.670

Students' experience

The authors are also interested in understanding how students reacted to being taught with mastery learning. Student experience toward mastery learning was explored with an anonymous end-of-semester survey that contained four questions that allowed to gather both qualitative and quantitative data: two open-ended questions, one fixed-response question and one five-point Likert scale question. The survey was administered using GoogleForm; a total of 27 students answered the survey, which represent 25% of the students enrolled in the class. The two open-ended questions asked students to: (1) "List one positive aspect of the modular quiz approach used in the class" and (2) "List one negative aspect of the modular quiz approach used in the class". The fixed-response questions asked students (3) "Do you feel like you have gained the skills being taught in class?" (I learnt "Everything at a high level", "Everything on a surface level", "Most things" and "Very little"). A final summative question asked students (4) "How would you rate the modular quiz approach used in this class with respect to a traditional teaching approach?" with possible responses: “I like it very much”, “I like it”, “It’s OK”, “Do not like it much”, “Do not like it at all”.

Quantitative results show that more than half of the students rated mastery learning positively, (36% rated it as “I like it very much” and 21% as “I like it”). Only 14% of the students rated CBL negatively, see Figure 3.

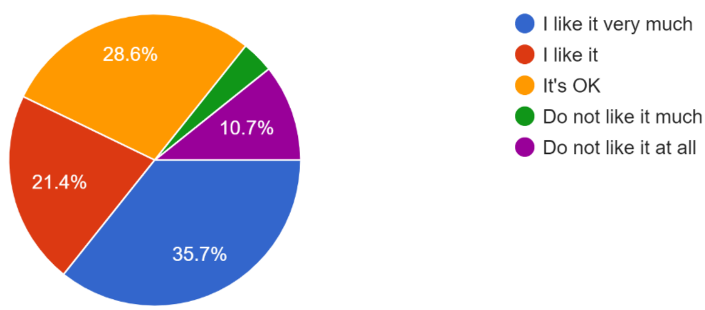

Figure 3. Students’ response to question "How would you rate the modular quiz approach used in this class with respect to a traditional teaching approach?”.

Students’ are divided on the level at which they feel they have learnt the class material, as seen in Figure 4.

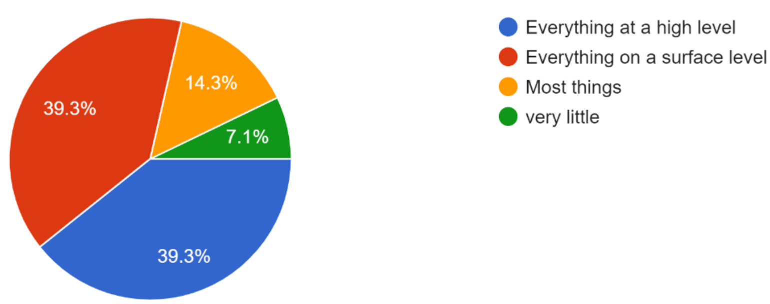

Figure 4. Students' response to question “Do you feel like you have gained the skills being taught in class?”

The responses to the two open ended questions have been hand-coded and then a coding scheme has been employed in order to look for emergent themes or domains of meanings or meaningful patterns across the responses [10]. An analysis of the two open ended questions on the modular approach yielded three major themes related to the students' perceptions of CBL and the impact on their learning, defined as “Room for Errors”, “Stress-free learning” and “Timely feedback” as explained in the following.

Room for Errors

Mastery of content was most frequently and commonly cited by the students as a positive aspect of the modular quiz approach used in the class. The quizzes are also perceived not just as an assessment but as a way of learning the material as well as reinforcing learning (Students 14, 24 and 26).

Most students attributed their mastery of topics and better engagement with the content to the ability to retake a quiz. As one student clearly stated, "*Knowing that I have a chance to go over my mistakes with the professor and get another chance to take the quiz makes me able to focus more on the material and overall allows me to perform better*" (Student 9). Students also recognize that repeated opportunity to learn from their mistakes without the fear of failure allows them to fix their mistakes and learn the content better: "*It allows for students to learn the material even if they did not know it at the time of the test*" (Student 16). Students 4 and 26 emphasized that the retakes allowed them to focus, learn and understand the course material in depth instead of failing in a quiz and moving onto the next topic without really understanding the topic in which they failed. The approach also encourages students to "*have a deep understanding for the basic concepts since they have to pass the quiz in order to take the next one*" (Student 27).

Many students also believe that the retakes encourage learning.

> *It helps us learn where we went wrong. We are more capable of fixing our mistakes. We are more capable of fixing our mistakes instead of guessing where we went wrong*. (Student 2)

Another student adds that "*it feels more rewarding to pass*" (Student 3).

A student even recommends the approach to be used in other classes, "*It allows for students to learn the material even if they did not know it at the time of the test. Personally, I think this approach should be used in every class. I probably would have passed some of my other classes with higher grades or understanding if this method was used*" (Student 16).

A few students had a slightly differing perception regarding mastering the course material. They attributed the modular approach to less retention of the content. Student 7 shares, "*hard to recall information that isn't used throughout the entirety of the course*" Another student attributes the approach to being less motivated to be proficient:

> *Learned all the material for the quiz -- took and passed the quiz -- promptly forgot the info because I already passed the quiz. Less motivation to maintain proficiency on topics after quiz was taken*. (Student 5).

Stress-free Learning

In addition to acknowledging that the modular approach allowed them to learn better and be engaged with the content, the students also shared that the approach was less intimidating. Many of the students indicated that the approach used in the class was less stressful, encouraged learning and increased their confidence as well. The students felt more prepared attempting the assessments. As Student 6 said, "*I felt confident taking the quizzes because I knew I had the knowledge to answer the question being asked*" Another student expresses that, "*The modular quizzes were not as* *stressful as exams would be and allowed for focus on the learning objective of each chapter*" (Student 11).

Multiple students alluded to the lack of stress and pressure to get it right the first time and felt that it helped them focus and learn the course content better.

> *The modular Quiz allows me to maintain my composure. Every time I take it, I don't feel like I was under pressure because I know I'm allowed to take it again to master the topic* (Student 12).

> *It overall allows me to perform better because I don't have so much pressure to get it right the first time* (Student 9).

The flexibility offered through the modular approach was also cited by students as a positive aspect of the class that helped them enjoy their learning and master the content. "*I enjoyed the freedom of time to take each quiz whenever I was ready*" (Student 4).

The students felt that the self-driven pace of learning was useful in learning the concepts as well as made the learning more enjoyable. "*I enjoyed the topics we learned, and the pace of the objectives*" (Student 11). "*It's useful in helping the students pace themselves in the class*." (Student 15). Another student believes that quizzes following soon after each topic was taught helped them perform better as well since "*we always had the info fresh in our minds*." (Student 5)

There were some students who shared that though the class was stress free in the beginning, toward the end of the semester it became stressful predominantly due to the lag in grading and receiving feedback: "*towards the end of the course, things started to get messy, the last minute quizzes*" (Student 20).

Students also shared that for those who fell behind, it was stressful as the quizzes accumulated toward the end of the semester and they had to complete all modules in the final week. "*Took too long to grade, so I got behind easily and had to take a majority of the quizzes towards the last week and in finals which was hectic*" (Student 25). Another student expressed: "*It became hard and stressful when falling behind*" (Student 13). The student also shared that falling behind on the quizzes made them less motivated to continue learning: "*Sometimes I fell behind in the quizzes and it made me lose motivation and lead to more stress because I didn't know what the next quiz was on or if I'd finish in time*."

Timely Feedback

While many of the students found the modular quiz approach beneficial to their learning, in response to the negative aspect of the approach, there was a common theme that emerged: timely feedback. Students shared that the success of the approach relied heavily on timely feedback from the instructor and any delay resulted in students falling behind in their learning goals. A student points to the lack of feedback and shares, "*entire quiz system is buggy/heavily relies on communication with the professor*" (Student 4). Another student emphasizes on the need for a faster feedback response to the quizzes and to have lecture available for a longer period of time. Students articulate how the downside of not having timely feedback and not following the set timeline is detrimental to the modular approach:

> *There was no direct feedback from the professor to indicate certain mistakes and reasons for failing each quiz. It is very easy, almost guaranteed, to fall behind in the class, should one fail a quiz. Being unable to receive direct feedback on problem solving was extremely detrimental to student learning, causing a feeling of frustration as there is no way to tell what concept was mistaken or misunderstood.* (Student 19)

> *Direct feedback on mistakes is crucial to the learning feedback. I feel that this modular quiz approach needs to be reevaluated as this semester felt more frustrating than insightful.* (Student 19).

Most students strongly emphasized on the need for prompt grading and feedback to ensure that they progress well and achieve the learning goals set for the course.

Discussion and conclusion

The results presented in the paper show that competency-based learning is beneficial to students' success and supports the students who struggle the most. The CBL teaching method resulted in higher students' achievement but gender and race had no significant influence on students' achievement. Students report about having a positive experience with the new pedagogy, and they highlight that the possibility of re-taking their assessments creates a less stressful and more enjoyable learning environment, boosting their confidence as well. Some of the drawbacks of the approach consists in the necessity to provide timely feedback to the students, so that they have sufficient time to practice on the material as well as to avoid the piling up of multiple assessments toward the end of the semester. The authors have been happy with the initial results of the implementation of competency-based learning plan to continue using the approach in future offerings. Providing timely feedback using automatic grading or more structured grading approaches will be implemented as well. In addition, the next offering of the class will have both an in-person section and an online section, and the authors expect to be able to differentiate the effect of competency based learning in different learning settings.

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