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Instructional Module Design Based on Student Readiness: Leveraging Differentiated Instruction Principles in the Engineering Classroom

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ABSTRACT

Differentiated instruction (DI) is a teaching approach in which learning experiences are designed and adapted to meet students' diverse needs to facilitate student success. Advocates of this approach have implemented it in primarily K-12 learning environments with limited investigations into implementing it in college/engineering course environments despite the existence of variance in student readiness (their proximity to a learning objective) at this level of education. In this study, a novel module design that incorporates adaptations based on student readiness using DI principles is devised for an electrical engineering course, and its impact on student mastery and attitude is assessed using test scores and survey responses. The results of these analyses validate that this module design aids in improving student learning and has a positive impact on student attitudes towards learning with this approach. This evidence motivated the creation of a framework for module design for future implementations beyond an electrical engineering course context. In addition to this framework, a list of requirements for effective implementation and key implementation challenges that must be addressed for ease of scalability and instructor adoption are presented.

INTRODUCTION

If we were to examine an engineering classroom, we would observe differences among individual learners. We would no doubt observe differences in the pre-requisite knowledge each student possesses as well as differences in their levels of motivation to learn. Engineering instructors are intuitively aware of these differences, but we traditionally use a one-size-fits-all approach to instruction that does not adapt to learner differences. Various articles have advocated for a transition from this traditional model to one more responsive to student diversity both in K-12 and college environments (Sizer 1999; Tomlinson 2004; Felder and Brent 2005; Pearl Subban 2006). This study investigates an approach that leverages data on student learner differences to improve their mastery of and enhance their interest in the content of an engineering course module.

What is Differentiated Instruction?

Differentiated instruction (DI) is a teaching approach in which learning experiences are designed and adapted to meet students' diverse needs to facilitate student success. This approach is different from a "one-size-fits-all" instructional approach, where learning experiences are designed with little thought of adaptation to student differences. As referenced in Tomlinson (2014), an instructor can differentiate instruction in four areas: content (the information used to reach learning goals), process (the mechanism by which students interact with content), product (the article a student uses to demonstrate mastery of a topic), and environment (the climate or tone of a classroom). In DI, adaptation of a student's learning experience is based on student data concerning three characteristics: student readiness (their proximity to a learning goal), student interest (their passions, affinities, kinships that motivate learning), and learner profile (their preferred learning style).

There is currently no conclusive empirical evidence that student achievement is improved by adapting instruction based on learner styles (Cuevas 2015; Pashler et al. 2008). Furthermore, Landrum and McDuffie (2010) conclude that there is insufficient evidence to support learning styles as an instructionally useful concept when planning and delivering individualized and differentiated instruction. As a result, the current study does not use learner styles as a theoretical framework. However, there is theoretical and empirical support for the effectiveness of adapting learning experience based on readiness and interest.

The theory that supports adaptation based on readiness is Vygotsky's theory describing a zone of proximal development (ZPD) for students (Vygotsky 1978). The ZPD describes the difference between what a student can perform independently and what a student can accomplish with the assistance of a "knowledgeable other", which can be an instructor or peer. The relevance of ZPD to instructional design is that instructors should design learning experiences that are not too far beyond a student's current level of readiness, which may result in missteps and frustration, and not at or below their level of readiness, which may result in minimal effort and disinterest, that is, within their ZPD. A common way to perform this adaptation is by instructional scaffolding where support mechanisms are included in instructional sessions. Empirical evidence supporting the effectiveness of scaffolding can be found in the articles authored by Palincsar and Brown (1984) as well as Belland (2017).

The theory for differentiating instruction based on interest contends that interest affects motivation, which in turn influences each student's desire to put effort into learning (Ernst and Ernst 2005; Tomlinson et al. 2003). Interest, in this context, is a motivational variable that refers to the psychological state of engaging or the predisposition to reengage with content (Hidi and Ann Renninger 2006). Studies support the positive influence of interest on learning (Ainley, Hidi, and Berndorff 2002), specifically, attention (McDaniel et al. 2000; Renninger and Wozniak 1985), achievement goals (Harackiewicz et al. 2000; Senko and Harackiewicz 2002) and levels of learning (Alexander and Murphy 1998; Köller, Baumert, and Schnabel 2001; Krapp, Hidi, and Renninger 1992; Ann Renninger and Hidi 2002; Schiefele 1999). Therefore, modifying instruction to stimulate student interest should be viewed as an effective instructional approach.

By incorporating information about student readiness and interest into the design of differentiated learning experiences, DI acknowledges the diverse characteristics of the individual learner with the intent of realizing learning gains that exceed the one-size-fits-all paradigm.

Why use DI in College Environments?

Advocates of DI have focused primarily on implementing this approach in K-12 learning environments (Tomlinson 2014; Tomlinson et al. 2003; Santamaria 2009; Schleicher 2016). While a K-12 classroom environment will likely possess higher levels of student variance in the areas of readiness and interest, student variances still exist in the college classroom. An example of this variance is observed in the prerequisite letter grades of the students that participated in this study (Fig. 1).

Fig. 1 shows significant percentages of students in each letter category, which points to considerable variance in student readiness and makes a strong case for implementing DI in this college classroom.

Instructional and Research Design Methods Employed by Empirical Studies of DI in College Environments

To clearly identify the contributions of this study to the current body of knowledge it is instructive to review empirical studies that investigate the impact of DI on student learning as well as student and/or instructor opinion of DI in college environments. There were 17 studies that meet this criteria. These included four education courses (Griess and Keat 2014; Joseph et al. 2013; Santangelo and Tomlinson 2009; Tulbure 2013), three mathematics courses (Chamberlin and Powers 2010; Chen and Chen 2018; Leonardo, Nivera, and Reyes 2015), three engineering courses (Chin, Worthy, and Colebeck 2019; Nathan 2007; Sohoni et al. 2019), one chemistry course (Wu, Wong, and Li 2019), an education psychology course (Dosch and Zidon 2014), a computer science course (Mok 2012) and a political science course (Ernst and Ernst 2005). The three remaining studies extended beyond course environments to the STEM programs in a university (Balgan, Renchin, and Ojgoosh 2022), multiple departments and schools in an academic college (Turner, Solis, and Kincade 2017) and a College of Education and Behavioral Sciences (Melese and Tinoca 2019).

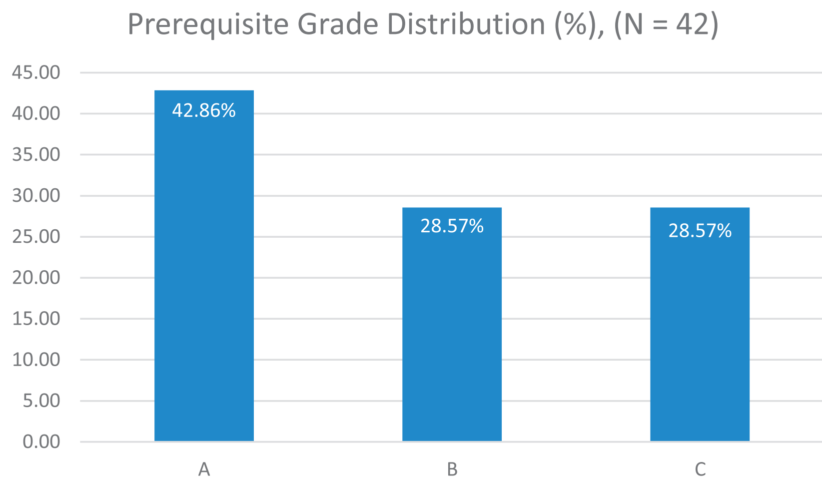

Figure 1. Prerequisite Grade Distribution in (%) for Student Participants in Study.

The approach to incorporating DI into instructional design varied per study. Five studies (Chamberlin and Powers 2010; Ernst and Ernst 2005; Joseph et al. 2013; Leonardo, Nivera, and Reyes 2015; Santangelo and Tomlinson 2009) made broad use of DI, where information of student readiness, interest and learner profile was used to differentiate content, process and product, while 10 other studies utilized DI in a more limited capacity either by gathering data on a subset of the three student characteristics and/or by using this data to differentiate only a subset of the four differentiation areas (Balgan, Renchin, and Ojgoosh 2022; Chen and Chen 2018; Chin, Worthy, and Colebeck 2019; Dosch and Zidon 2014; Griess and Keat 2014; Mok 2012; Nathan 2007; Sohoni et al. 2019; Tulbure 2013; Wu, Wong, and Li 2019).

Student readiness data were typically obtained using pre-assessments at the beginning of the course/module/exercise (Chamberlin and Powers 2010; Chin, Worthy, and Colebeck 2019; Mok 2012; Nathan 2007) and/or formative assessments embedded in the course/module (Chamberlin and Powers 2010; Chin, Worthy, and Colebeck 2019; Ernst and Ernst 2005; Sohoni et al. 2019). Interest inventories were often used to obtain interest data while learning style inventories were used to collect learner profile data (Balgan, Renchin, and Ojgoosh 2022; Dosch and Zidon 2014; Leonardo, Nivera, and Reyes 2015; Tulbure 2013). Santangelo and Tomlinson (2009) collected student demographic information that encompassed readiness, interest and learner profile.

Data collected was used to guide differentiation in different ways for each study. A common method for differentiating process was flexible groupings, which involved dividing the class into heterogenous or homogenous groups according to readiness or interest (Chamberlin and Powers 2010; Ernst and Ernst 2005; Griess and Keat 2014; Joseph et al. 2013; Leonardo, Nivera, and Reyes

2015; Sohoni et al. 2019). Other common practices included using tiered assignments to differentiate process based on readiness (Chin, Worthy, and Colebeck 2019; Ernst and Ernst 2005; Joseph et al. 2013; Leonardo, Nivera, and Reyes 2015; Mok 2012; Nathan 2007; Santangelo and Tomlinson 2009), providing differentiated reading materials based on readiness or interest (Griess and Keat 2014; Joseph et al. 2013; Santangelo and Tomlinson 2009) and learning centers based on interest (Griess and Keat 2014; Santangelo and Tomlinson 2009). Product was typically differentiated by allowing students to choose assignments or projects based on interest (Chamberlin and Powers 2010; Dosch and Zidon 2014; Ernst and Ernst 2005; Griess and Keat 2014; Joseph et al. 2013; Santangelo and Tomlinson 2009) or learner profile (Ernst and Ernst 2005).

Two of the studies implemented DI instructional design in non-standard ways. Wu et al. (2019) sought to enhance titration capabilities of chemistry students by applying DI to a virtual reality titration experiment, where user hand gestures are used to perform operations on virtual objects within the titration experiment. DI was used to create different learning intensities (easy, normal, hard) for titration. Chen and Chen (2018) used an approach where students were split into groups randomly and exposed to a calculus curriculum via a group competition, with each group seeking to solve different calculus problems.

Different research designs were used by each study to assess the impact of DI on student academic performance as well as assess student and/or instructor attitude towards DI. All designs surveyed were quasi-experimental. Eight studies utilized a mixed methods approach employing both quantitative and qualitative designs (Balgan, Renchin, and Ojgoosh 2022; Chamberlin and Powers 2010; Chen and Chen 2018; Chin, Worthy, and Colebeck 2019; Dosch and Zidon 2014; Joseph et al. 2013; Leonardo, Nivera, and Reyes 2015; Santangelo and Tomlinson 2009), while eight studies used qualitative-only designs (Ernst and Ernst 2005; Griess and Keat 2014; Melese and Tinoca 2019; Mok 2012; Nathan 2007; Sohoni et al. 2019; Turner, Solis, and Kincade 2017; Wu, Wong, and Li 2019) and the remaining study used a quantitative-only design (Tulbure 2013).

The quantitative designs used in these studies mostly incorporated two-groups (experimental versus control) and used either a pre- and post-test (Chamberlin and Powers 2010; Leonardo, Nivera, and Reyes 2015; Tulbure 2013) or post-test only to assess change in student learning (Chen and Chen 2018; Chin, Worthy, and Colebeck 2019; Dosch and Zidon 2014; Joseph et al. 2013; Santangelo and Tomlinson 2009). The items used for analysis were typically assessments of student learning, that is, final exams, tests, quizzes, or assignments.

The intent of most qualitative studies was to assess student attitude towards learning in an instructional environment structured to facilitate DI (Balgan, Renchin, and Ojgoosh 2022; Chamberlin and Powers 2010; Chen and Chen 2018; Chin, Worthy, and Colebeck 2019; Dosch and Zidon 2014; Ernst and Ernst 2005; Joseph et al. 2013; Leonardo, Nivera, and Reyes 2015; Mok 2012; Nathan 2007;

Santangelo and Tomlinson 2009; Wu, Wong, and Li 2019). Some qualitative studies also assessed instructor opinion of the impact of DI on student learning and/or instructor perspective on the factors involved in implementing DI in college environments (Griess and Keat 2014; Melese and Tinoca 2019; Turner, Solis, and Kincade 2017). The most common qualitative method used was participant surveys/evaluations that typically incorporated a mixture of structured and free-response questions (Chin, Worthy, and Colebeck 2019; Dosch and Zidon 2014; Ernst and Ernst 2005; Joseph et al. 2013; Leonardo, Nivera, and Reyes 2015; Mok 2012; Santangelo and Tomlinson 2009; Turner, Solis, and Kincade 2017; Wu, Wong, and Li 2019), but could also be completely free response (Chen and Chen 2018). Interviews were another common qualitative method used in these studies (Chamberlin and Powers 2010; Joseph et al. 2013; Melese and Tinoca 2019; Nathan 2007; Sohoni et al. 2019). In addition to surveys and interviews, some researchers employed other qualitative methods. For example, Balgan et al. (2022) used the VAK behavior test to monitor change in student engagement. Chamberlin and Powers (2010) performed analyses of students' work to qualitatively assess the impact of DI on the students' mathematical understandings. Joseph et al. (2013) employed a range of qualitative methods that included focus group discussions, classroom observations and instructor reflections. Griess and Keat (2014) and Ernst and Ernst (2005) used instructor reflections as method of analysis.

The quantitative analysis results for most studies indicated improvement in achievement of students because of DI. Four of the six studies that performed statistical analysis of scores from DI (treatment) and non-DI (control) groups observed statistically significant improvement in grades (Chamberlin and Powers 2010; Chen and Chen 2018; Dosch and Zidon 2014; Leonardo, Nivera, and Reyes 2015), while the other two found no significant improvement (Chin, Worthy, and Colebeck 2019; Tulbure 2013). Three other studies observed an improvement in grades/scores for DI students compared to non-DI students, but statistical analysis was not performed (Balgan, Renchin, and Ojgoosh 2022; Joseph et al. 2013; Santangelo and Tomlinson 2009).

The qualitative analysis results of 11 of 12 studies that examined student attitude reveal that students have a positive assessment of DI as a teaching approach (Balgan, Renchin, and Ojgoosh 2022; Chamberlin and Powers 2010; Chen and Chen 2018; Chin, Worthy, and Colebeck 2019; Dosch and Zidon 2014; Ernst and Ernst 2005; Joseph et al. 2013; Mok 2012; Nathan 2007; Santangelo and Tomlinson 2009; Wu, Wong, and Li 2019). More specifically, students perceived that the DI approach was beneficial to their learning (Dosch and Zidon 2014; Ernst and Ernst 2005; Santangelo and Tomlinson 2009), that it enhanced engagement (Balgan, Renchin, and Ojgoosh 2022; Ernst and Ernst 2005; Joseph et al. 2013) and that it is a more democratic teaching approach because it allows student choice in selecting materials, activities, and assessments (Joseph et al. 2013). The only study that did not observe a change (positive or negative) in student attitude towards the subject as a consequence of DI was the one conducted by Leonardo et al. (2015).

The qualitative analysis results of instructor attitude reveal a positive attitude towards DI, with concerns related implementation (Ernst and Ernst 2005; Griess and Keat 2014; Melese and Tinoca 2019; Turner, Solis, and Kincade 2017). See the next subsection.

Impediments to Applying DI in College Environments

DI does not appear to have found widespread adoption as a teaching approach in college environments, despite the encouraging results described in the previous section. Therefore, it is instructive that we also examine the impediments to applying DI that studies have cited. A review of various studies (Ernst and Ernst 2005; Griess and Keat 2014; Melese and Tinoca 2019; Turner, Solis, and Kincade 2017) that examined this topic reveal some common themes:

i. Instructors had a positive attitude towards DI, with 76% of instructors in one study expressing that DI was a somewhat important or extremely important teaching strategy (Turner, Solis, and Kincade 2017).
ii. Instructors find DI hard to define due to limited specific knowledge of the theories, models, and principles of using DI (Melese and Tinoca 2019).
iii. Instructors find DI difficult to implement due to large class sizes, limited instructional time, lack of resources, and lack of training (Ernst and Ernst 2005; Griess and Keat 2014; Melese and Tinoca 2019; Turner, Solis, and Kincade 2017).
iv. There is a concern about the fairness of the approach because it may lead to students being assessed differently (Ernst and Ernst 2005).

Prior Investigation into DI

The generally encouraging results of applying DI to college environments motivated investigating the impact of applying DI to a module of a circuit analysis course in an undergraduate electrical engineering program. Specifically, content and process are differentiated based on data that assess student readiness throughout the module. A prior investigation into using this approach indicated a positive student perception of the use of DI strategies, but there was no statistically significant improvement in student performance based on test scores (Chin, Worthy, and Colebeck 2019). The current investigation involved a substantial redesign of the module with the addition of automated feedback features to the pre-module quiz and formative assessment, the creation of heterogenous groups based on formative assessment results and the creation of a tiered homework assignment that includes scaffolding features. The current work also involved redesigning the experiment with a pre-post design replacing a post-test only design for quantitative analysis and a completely rewritten survey, with questions that directly target student opinion of DI strategies used in the module.

Overview of Instructional Design and Research Questions

The primary purpose of this investigation is to assess the impact of implementing DI strategies on student mastery/performance and student attitudes. The research questions are:

1. Will utilizing differentiated instruction methods in a circuit analysis course module improve student mastery of the topics taught in that module?
2. Do engineering students have a favorable attitude towards learning using a differentiated instruction approach for a single module of a circuit analysis course?

A secondary purpose of this investigation is to assess the challenges associated with implementing DI in electrical engineering course environments.

There are three main contributions of this paper. Firstly, it provides rigorous mixed-method analysis of applying DI-based instructional methods to an undergraduate engineering classroom environment. The literature review has not found a study that duplicates this. Secondly, one of the study outcomes is a recommended framework for instructors who may be interested in applying this approach to their engineering courses. Finally, there is a discussion of the challenges to implementing DI in engineering course modules and recommendations for how these might be overcome.

In the following sections, I first describe the instructional design of the course module based on DI principles and the design of the experiments used to assess the two research questions. Secondly, I present the results of the quantitative and qualitative analyses of the experiments, and thirdly, I discuss inferences that can be made from these results and present the framework for future implementations of this module design.

METHODS

Instructional Design

The module selected for implementation of DI strategies based on student readiness examines the topic of complex DC circuit analysis using nodal and mesh analysis techniques. This topic was selected for two reasons:

i. The topic requires prerequisite knowledge of content taught earlier in the course as well as knowledge of content taught earlier in the program.
ii. Student assessment data associated with this module, collected over several semesters, indicate that students have trouble in mastering this topic.

The module is designed to follow the sequence of activities detailed in Figure 2. These activities are completed within 300 minutes of instructional time broken into six, 50-minute sessions held over

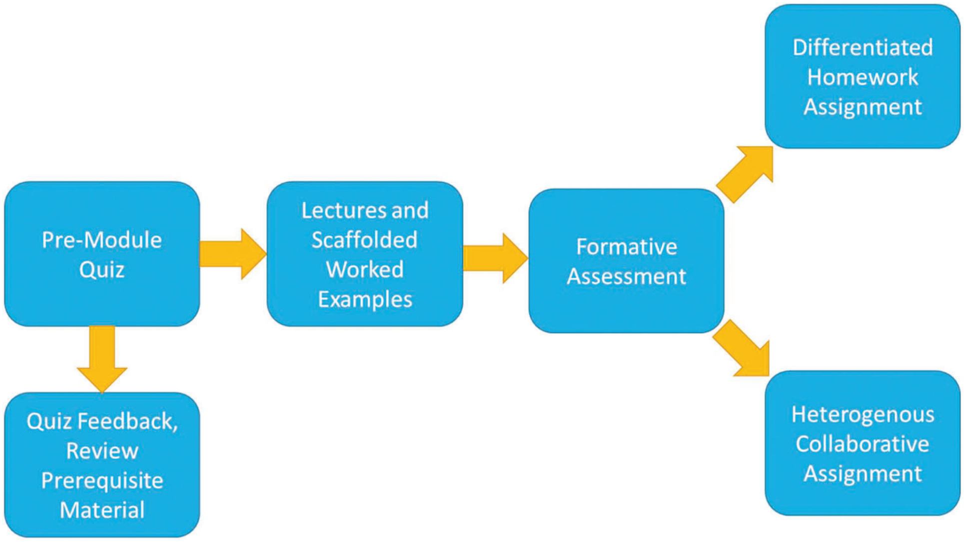

Figure 2. Sequence of Module Activities.

a two-week period. Two assessment activities within the module (Pre-module Quiz and Formative Assessment Quiz) are used to guide differentiation of content (Pre-module Quiz Feedback and Pre-requisite Material Review) and process (Heterogenous Collaborative Assignment and Differentiated Homework Assignment) within the module.

Pre-module Quiz, Feedback and Review of Prerequisite Material

The pre-module quiz is designed to assess each student's mastery of prerequisite knowledge needed to successfully master the analysis techniques being taught in the module. The prerequisite knowledge assessed includes fundamental circuit analysis laws (Ohm's law, Kirchhoff's current law and Kirchhoff's voltage law) as well as mathematical methods for solving a system of linear equations. This multiple-choice quiz is administered online within a learning management system (LMS) prior to the 1st class session of the module. It provides automated feedback for each question, after quiz submission, based on the answer choice selected. If an answer is correct, the feedback confirms the correctness of the choice with a check mark. If the answer is incorrect, the feedback not only shows what the correct choice is but also provides supplementary remedial material (video and text) that review the prerequisite knowledge the question assesses (Figure 3 and Figure 4). In this way, the content presented to each student is differentiated based on their mastery (readiness in DI jargon) of prerequisite knowledge/skills.

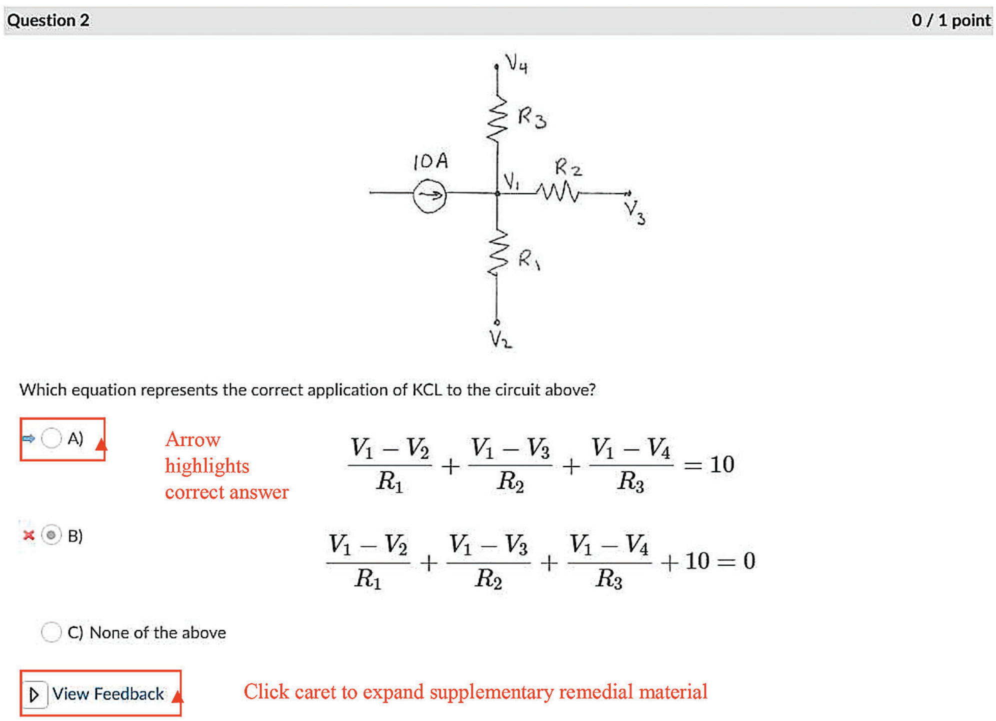

Figure 3. Sample Pre-module Quiz Question with Correct Answer Feedback.

Lectures and Instructor-Led Worked Examples

After the pre-module quiz is administered, lecture sessions are used to examine the nodal and mesh analysis techniques used to analyze complex DC circuits. The lecture sessions consist of instructor-led descriptions of the concepts, instructor-led solutions of representative examples and time reserved for students to attempt solving examples independently. The emphasis during instructor-led solutions is on highlighting how prerequisite knowledge/skills can be integrated into a structured step-by-step approach to analyze a circuit using either technique. When students attempt to solve a problem independently, the instructor is available to answer impromptu questions, and the solution is reviewed by the instructor prior to moving on. The first five out of six sessions followed this format. The sixth session is reserved for the heterogenous collaborative activity.

Formative Assessment Quiz

After the fifth session a formative assessment is given to each student via the LMS. This assessment consists of four multiple-choice questions: two nodal analysis and two mesh analysis, and it is designed to assess student mastery of these analysis techniques after the lecture sessions. The results of this quiz are used to guide the differentiation of subsequent activities for each student.

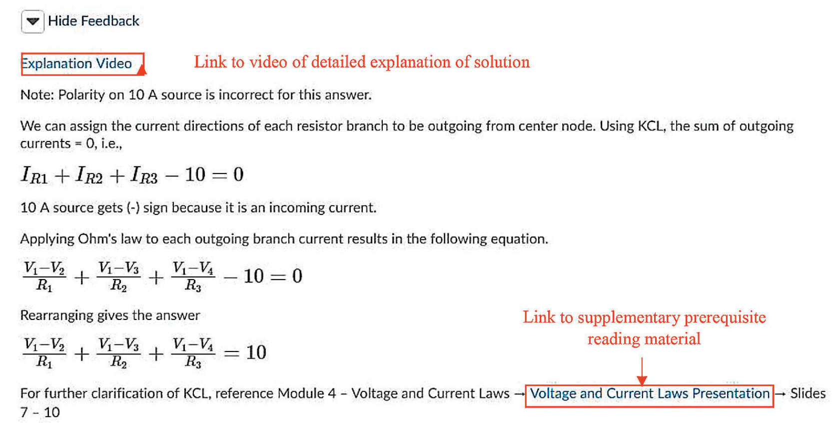

Figure 4. Sample Pre-module Quiz Question with Supplementary Material Feedback.

Heterogenous Collaborative Assignment

A collaborative learning activity involves students working together in groups of two or more to learn new concepts, solve problems and/or create products. Collaborative learning has been shown to increase student involvement in the learning process, enhance retention of knowledge, promote higher order thinking skills as well as develop social interaction skills (Laal and Ghodsi 2012; Panitz 1999; Zambrano et al. 2019). The final class session of the module involves a collaborative learning activity where the class is divided into groups of three, and they are required to complete an assignment that consists of the two problems (one nodal, one mesh). The difficulty level of both problems is consistent with problems that students would be expected to solve for summative assessments (tests or exams). It should be noted that this activity was implemented using an online video conferencing/collaboration tool due to in-person occupancy restrictions associated with the COVID-19 pandemic. Individual grades from the formative assessment are used to guide instructor selection of group members so that groups are heterogenous with respect to readiness. Empirical studies have shown that heterogenous groups are beneficial for student achievement and student satisfaction compared to homogenous groups, especially for students with lower achievement levels (Marzano, Pickering, and Pollock 2001; Wang 2013; Zamani 2016). These findings influenced the choice for heterogenous groups.

Differentiated Homework Assignment

The final activity of the module is a differentiated (tiered) homework assignment that is completed one week after the final class session of the module. The homework assignment contains ten questions that are tiered according to difficulty level as follows:

- *Needs Help* – 4 questions (2 nodal, 2 mesh) that have step-by-step hints to aid in completing the question.

- *On-Level* – 4 questions (2 nodal, 2 mesh) with no hints included.
- *Challenge* – 2 questions (1 nodal, 1 mesh) that extend the solution beyond finding node voltages and mesh currents to finding branch voltages, currents and power.

Students are required to complete any six questions of their choice and are instructed to use their formative assessment results to guide their selection of questions.

Experimental Design

A quasi-experimental, mixed methods approach was used to collect data to assess the two research questions. In Fall 2020, the module was taught to a treatment group of students using the DI-inspired approach previously described, while the control group of students was taught using a more traditional approach in Spring 2021. The traditional approach involved a sequence of activities that included sessions consisting of lectures and instructor-led worked examples, a collaborative assignment with groupings mixed by last name, and a homework assignment that contained no tiers. The no-tier homework assignment consisted of eight questions that corresponded to the four *Needs Help* questions and the four *On-level* questions of the differentiated homework assignment, but no hints were included for the *Needs Help* questions.

The demographics of the treatment and control groups are presented in Table 1, which shows similarities in the mixture of gender and age groups between treatment and control groups.

Quantitative Data

The purpose of quantitative data is to assess whether the DI-inspired instructional design improved student mastery of the topics taught in the module (Research Question 1). Quantitative data

Table 1. Demographics of Experiment Participants.

		Treatment		Control	
		Count	%	Count	%
Gender	Male	19	79.17	22	95.65
	Female	5	20.83	1	4.35
Age	15–19	6	25.00	2	8.70
	20–24	15	62.50	19	82.61
	25–29	1	4.17	2	8.70
	30–34	0	0.00	0	0.00
	35–39	0	0.00	0	0.00
	40–45	1	4.17	0	0.00
	46–49	1	4.17	0	0.00
	Total	24	100.00	23	100.00

Table 2. Pre-Test/Post-Test Question Rubric (Task 1).

Task 1: Generate system of equations	
Student correctly derives system of equations based on KCL/KVL	10 points
Student has minor derivation errors in generating system of equations (e.g. +/- signs are confused, enters incorrect I, V, R values)	7.5 points
Student has major derivation errors in generating system of equations (e.g. incorrect application of KVL, KCL, Ohm's law, mesh/supermesh approach, node/supernode approach are confused, enters incorrect I, V, R values)	4 points
Student does not generate system of equations	0 points

Table 3. Pre-Test/Post Test Question Rubric (Task 2).

Task 2: Solve system of equations	
Student correctly solves system of equations to obtain node voltages/mesh currents	5 points
Student has computational errors in solving systems of equations	3.5 points
Student has algebraic errors in solving systems of equations	2 points
Student does not solve system of equations	0 points

were collected from a pre-test conducted prior to the module and a post-test conducted within one week of the completion of module activities. Both pre-test and post-test consisted of the same two questions (one nodal analysis and one mesh analysis). The process for solving either of these questions can be divided into two tasks: generating a system of equations and solving the system of equations. The rubric used to grade each question is based on this decomposition of the solution process (Table 2 and Table 3). In addition to pre-test and post-test data, the Formative Assessment Quiz scores from the treatment group were collected. These scores are compared to the treatment group post-test scores to obtain a more specific assessment of the impact on student mastery of the two activities (Heterogeneous Collaborative Assignment and Differentiated Homework Assignment) that were differentiated based on formative assessment scores.

Qualitative Data

A survey was conducted after the module activities were completed with the intent of measuring student attitude towards learning using the DI approach (Research Question 2) as well as their subjective assessment of which DI-based activities worked well, and which did not. The survey consisted of a mixture of Likert scale questions and open-ended response questions. The Likert scale questions gave students an opportunity to assess the impact of each DI strategy on their learning. The questions are listed in Figure 5, and the scale consisted of five values ranging from highly positive impact to highly negative impact. The three open-ended response questions included in the survey asked students to

Please assess the impact of the following differentiated instruction strategies on your learning.

	Rating System					
	Highly Positive Impact	Mildly Positive Impact	No Impact	Mildly Negative Impact	Highly Negative Impact	N/A
1. Pre-module quiz with its automated feedback and solutions.	○	○	○	○	○	○
2. Differentiated learning material. For example, prerequisite review material and solutions to pre-module quiz and formative assessment.	○	○	○	○	○	○
3. Formative assessment with its automated feedback and solutions.	○	○	○	○	○	○
4. Group assignment activity.	○	○	○	○	○	○
5. Differentiated homework assignment based on my understanding of the material.	○	○	○	○	○	○

Figure 5. Likert Scale Questions from Student Survey.

give their opinions on the most-helpful and least-helpful activities conducted within the module as well as to provide suggestions for improving the module. The answers to the open-ended response questions are evaluated using the thematic analysis approach described in a paper authored by Braun and Clarke (2006). This approach is used to identify, analyze, and report themes within data. More specifically, it involves a semantic approach where themes are identified based on what participants have written.

RESULTS

Quantitative Data

The mean and standard deviation of the post-test scores for treatment and control groups are shown in Figure 6. They show a small increase in mean post-test score for the DI group compared to the control group. The post-test scores are analyzed using an analysis of covariance (ANCOVA)

Descriptive Statistics

Dependent Variable: Posttest Score

Group	Mean	Std. Deviation	N
Control	86.01	20.742	23
Treatment	87.28	14.328	19
Total	86.59	17.928	42

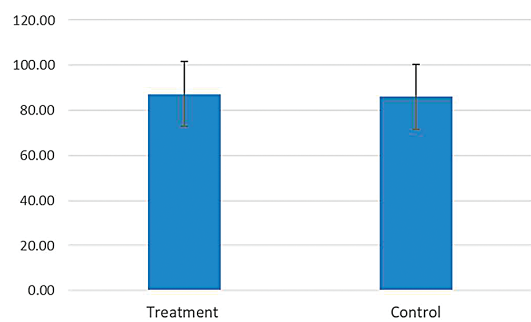

Figure 6. Descriptive Statistics of Post-Test Scores.

Mean Formative Assessment Score (FAS)	Mean Post-Test Score (PTS)	Mean FAS to PTS Score Change
65.8	87.3	21.5

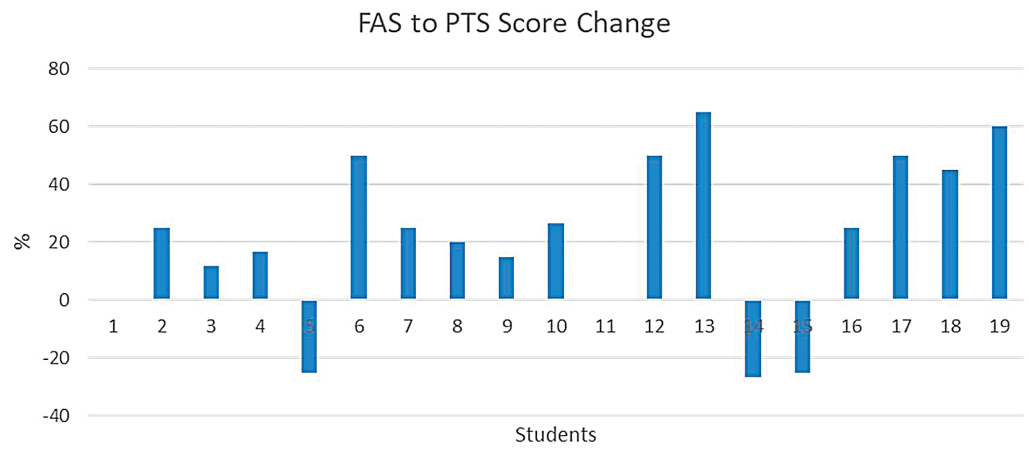

Figure 7. Formative Assessment to Post-Test Score Change.

with pre-test scores being the confounding factor. The results show no significant effect of group on post-test score after controlling for pre-test, $F(1, 42) = .143$, $p = .707$.

While the ANCOVA results do not point to an improvement in student mastery as evidenced by post-test scores, an examination of the change in scores from Formative Assessment Quiz to post-test reveals that 14 out of 19 students experienced an improvement in score with the average improvement being 21.5% (Figure 7). This points to the positive impact of the Heterogeneous Collaborative Assignment and Differentiated Homework Assignment on student mastery.

Qualitative Data

Likert Scale

The responses to the Likert scale questions are summarized in Figure 8. The bar graphs indicate that the students perceived the Differentiated Homework (59% highly positive, 32% mildly positive) and the Collaborative Assignment (63% highly positive, 17% mildly positive) to be learning activities that had a strong positive impact on their learning. The students perceived the Differentiated Learning Material (46% highly positive, 50% mildly positive, 4% no impact) to have a positive impact on their learning though not as strong as the previously mentioned activities, and they also perceived the Pre-Module Quiz (21% highly positive, 46% mildly positive, 21% no impact) and the Formative Assessment (33% highly positive, 33% mildly positive, 29% no impact) to have mild to no impact on their learning.

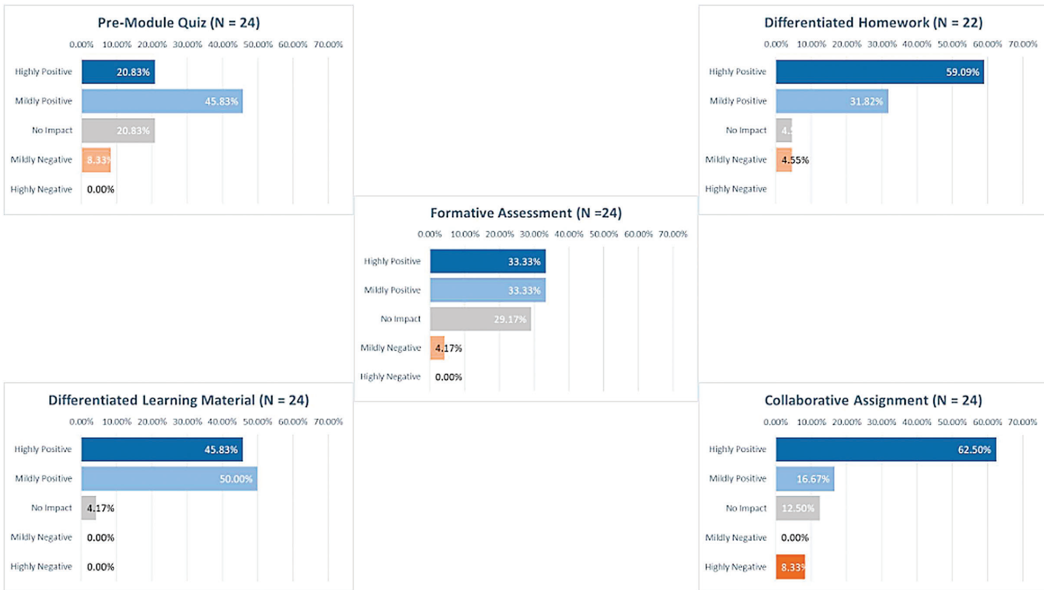

Figure 8. Summary of Likert Scale Responses to Question.

Open-ended Responses

The responses to the question "What part of class activities (in class and out), in this module, has been MOST HELPFUL to your learning and why?" were coded and grouped using thematic analysis, and the results are summarized in Figure 9. The bar chart indicates that students found Differentiated

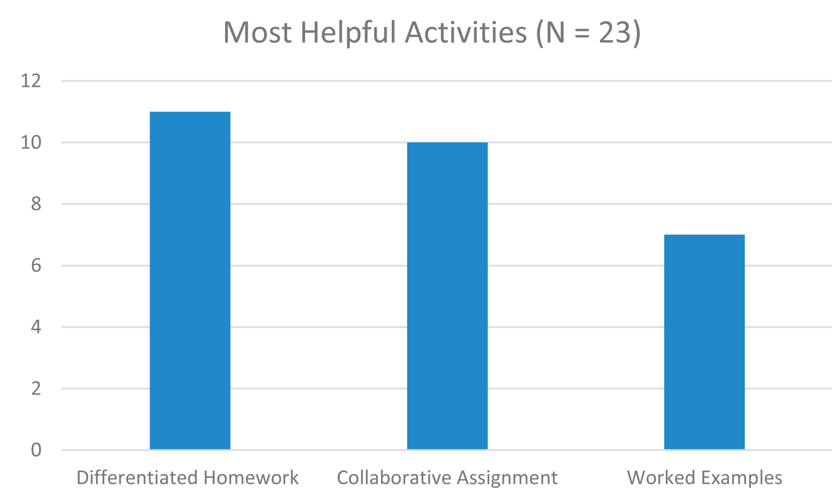

Figure 9. Bar Chart of Open-ended Responses for Most Helpful Activities.

Homework (11 respondents), Collaborative Assignment (10 respondents) and Instructor-led Worked Examples (7 respondents) to be the most helpful for their learning.

Students who selected Differentiated Homework had responses that indicated an appreciation of the different levels of question difficulty provided in the assignment, because this enabled a matching to their level of understanding and gave them the ability to choose questions based on their understanding. For example, *"Getting to pick which problems of the homework to do based on our own individual understanding of the content."* Students also appreciated the fact that the different tiers of difficulty within this assignment helped them to assess their personal level of proficiency versus the level of proficiency expected for the summative assessment. For example, *"The differentiated homework. Allowed me to gauge how well I understood the different levels of difficulty."* The responses of students who selected Collaborative Assignment identified the benefits of collaborating with peers to clarify and reinforce understanding of module concepts as the main reason for selecting this activity. For example, *"I would say the group assignment was definitely really helpful in learning the material from this module since it allowed me to work with others, which lets us help each other out in understanding all of the concepts of the module,"* and "*The group assignment was helpful in cementing the ideas a bit earlier in the unit. The worked examples and homework have also been very helpful for external studying - once I understood the group assignment and the examples, I felt ready for the test.*" Students who selected Worked Examples cited being able to view the step-by-step application of module theory in the context of a problem as the underlying reason for selecting this activity. For example, *"The worked examples really help, because you can actually see step by step the process."*

Figure 10 summarizes the responses to the question "What part of class activities (in class and out), in this module, has been LEAST HELPFUL to your learning and why?" The bar chart reveals that

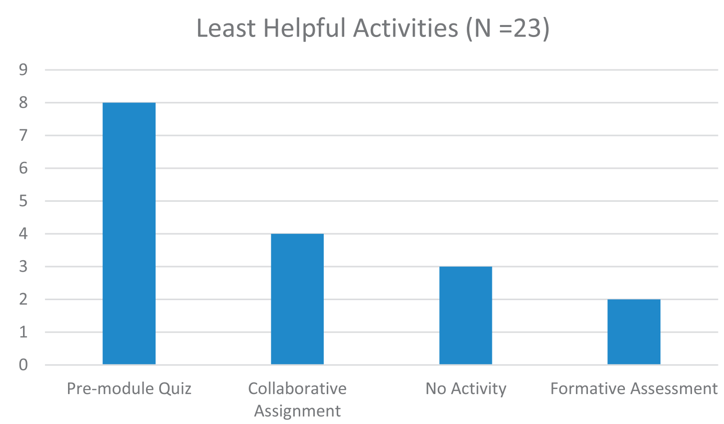

Figure 10. Bar Chart of Open-ended Responses for Least Helpful Activities.

students found the Pre-module Quiz (8 respondents), Collaborative Assignment (4 respondents), No Activity (3 respondents) and the Formative Assessment (2 respondents) to be the least helpful activities for their learning.

Students who selected Pre-module Quiz in their responses expressed that this activity required that they use knowledge of material that they either did not know or were not prepared to use. For example, *“The Pre-module quizzes because I know I’m not going to do very good due to not knowing the material.”* Also, *“The pre-module quiz was too sudden.”* Students who selected Collaborative Assignment cited the lack of participation of some group members that may be associated with performing this activity virtually as the reason for assessing the activity to be least helpful to their learning. For example, *“Group Assignments because due to the pandemic there isn’t a lot of working together that can be done virtually.”* Also, *“group activities. Sadly, just one person doing the work and turning it in.”* Students who selected Formative Assessment specified that they did not use the formative assessment as a mechanism to assess their learning and they did not find the activity helpful to their learning. For example, *“Formative Assessment. I didn’t use it as intended; I used the homework as my gauge.”* Also, *“Formative assessment, because I didn’t learn anything new from it.”* The three respondents that selected No Activity indicate that these students found every learning activity helpful for their learning. For example, *“All of it has been helpful. I cannot think of something as of the moment that was least helpful.”*

The final open-ended question states “Please give at least one suggestion for improving your learning experience with differentiated instruction.” The only theme derived from student responses to this question is that students desired more group activities for the module (four responses, ~17%). A representative response is *“I think another group assignment in this chapter would be helpful to have.”*

DISCUSSION

The analysis of pre-test and post-test scores shows that there was no statistically significant impact of the DI-based module activities on post-test scores. Despite this, analysis of the score change from the Formative Assessment Quiz to the post-test shows that most students (14 out of 19) in the treatment group experienced an improvement (21.5% mean score improvement) in their mastery of module topics, and this may be attributed to the differentiated activities that were conducted after the Formative Assessment Quiz and prior to the post-test.

Analysis of student responses to the Likert scale questions indicate that students found different aspects of this DI-based module design to have a positive impact on their learning. Specifically, students found the Differentiated Homework and Collaborative Assignment to have strong positive impacts on their learning, the Differentiated Learning Material to have a moderately positive impact on their learning, and the Pre-Module Quiz and Formative Assessment had mildly positive to no impact on their learning. To obtain deeper insight into why students made these assessments of the DI-based module activities with the intent of creating an improved framework for future implementations, I refer to the student responses to the open-ended questions of the survey.

A review of the open-ended responses related to the Differentiated Homework activity reveals that students often mentioned the benefit of having problems of different levels of difficulty that matched their individual understanding. This suggests that an underlying reason for students' positive perception of this activity as a learning tool is that it provided a scaffolded framework for students to identify their ZPD and select problems that are best suited to their ZPD. This means that this activity leverages the learning benefits of instructional scaffolding (Belland 2017; Palincsar and Brown 1984) as a mechanism for optimizing effectiveness. Students also mentioned that the tiered difficulty levels enabled them to evaluate the strengths and weaknesses of their learning in the context of how they would be assessed. Therefore, another reason for positive student perception is that the Differentiated Homework activity encouraged students to engage in metacognitive assessment of their learning.

Student responses related to the Collaborative Assignment show that many students (~43%) found this activity to be most helpful to their learning while some students found it to be least helpful (~17%). Those who found it most helpful cite the enhanced learning they experienced through peer collaboration, while those who assessed it to be least helpful communicated the lack of collaboration that occurred because the activity was implemented using an online video conferencing/collaboration tool. From the instructor's perspective, managing the Collaborative Assignment via the online video conferencing/collaboration tool required monitoring/guiding 13 breakout groups, and this made it more difficult to encourage student participation compared to an in-class scenario. Also, ~17% of respondents suggested that additional collaborative assignments be included in the module to improve it. Overall, student responses point to the heterogenous grouping of students for the collaborative assignment being an effective approach for enhancing student learning, which agrees with findings in prior studies (Marzano, Pickering, and Pollock 2001; Wang 2013; Zamani 2016). However, adequate support for student collaboration must be provided to ensure positive learning experiences, especially in virtual implementations.

~30% of student respondents selected Worked Examples as being most helpful. These students specified the benefits of observing the explicit step-by-step integration of component skills used in a variety of problem scenarios. The integration of component skills is a key part of the process of developing student mastery (Ambrose et al. 2010) and being able to observe this integration in multiple contexts effectively supported the development of student mastery in the opinion of these students. It should be noted that this activity was common to both treatment and control groups along with its associated learning benefits.

~35% of respondents selected the Pre-Module Quiz as being least helpful. An examination of open-ended responses shows that this activity only served to reveal insufficient pre-requisite knowledge for some students without activating any potential pre-requisite knowledge that may have been useful for completing the quiz. A potential modification for this Pre-Module Quiz would be to embed hints/scaffolds within quiz questions to activate pre-requisite knowledge at the point of need. This should not only help in explicitly activating pre-requisite knowledge, but also should help with linking this prior knowledge to the new material that will be taught in the module. The recommendation for activating student prior knowledge for the purpose of improving student learning is presented in the book authored by Ambrose et al. (Ambrose et al. 2010) and empirical support of this practice can found in two journal articles (Gick and Holyoak 1980; Peeck, Van den Bosch, and Kreupeling 1982).

The Formative Assessment was designed to provide readiness data at the end of the lecture sessions to inform the instructor on how to create heterogenous groups for the Collaborative Assignment and to inform each student of their personal progress towards mastery of the topics taught. Ideally students should have used this assessment as a prompt to engage in metacognition of their learning, specifically evaluating their knowledge proficiencies and deficiencies. However, ~13% of respondents selected this activity as being least helpful and ~29% of Likert scale respondents stated that this activity had no impact on their learning. This implies that many students did not interact with the Formative Assessment as intended. A potential remedy would be to create automated feedback to incorrect responses to Formative Assessment questions that includes three components geared toward stimulating the cycle of metacognitive processes discussed in Ambrose et al. (Ambrose et al. 2010) for each student: an explicit prompt to have students evaluate their learning, common errors made for each question and suggestions for questions to attempt in the Differentiated Homework based on errors made. Another improvement would be to include the formative assessment as a graded component with the Differentiated Homework grade. This might reduce student apathy and provide extrinsic motivation.

In summary, the survey responses indicate that the module design based on readiness has a strong positive impact on student learning. It is anticipated that this impact will be more significant with the proposed design improvements to the Pre-module Quiz and Formative Assessment as suggested by the student responses.

Requirements and Framework for Instructional Module Design Based on Student Readiness

The analysis results suggest that a module design based on student readiness can positively impact student learning. These results led to the formulation of a novel framework for module design that leverages DI principles and can be implemented in engineering course environments. Prior to engaging in module design, three key requirements must be established.

i Module Learning Outcomes: Clear learning outcomes are necessary to define what readiness means for a module and to guide the creation of formative and summative assessments.

ii List of Prerequisite knowledge/skills: A list of prerequisite knowledge/skills will inform the design of the Pre-module quiz and differentiated remedial material in response to Pre-module Quiz answers.

iii Teach-Assess-Differentiate Cycle: To leverage DI based on readiness there needs to be at least one iteration of teaching content, conducting a formative assessment and differentiating instruction based on formative assessment data prior to conducting any summative assessment.

The framework for module design based on readiness includes the following components:

i. Pre-module Quiz: Assesses student mastery of prerequisite knowledge/skills, activates these knowledge/skills if present or leads to differentiated remedial material if not present.

ii. Instructor-led, in-class sessions: These sessions can take any format deemed by the instructor to be effective in helping students learn the new content taught within the module.

iii. Formative Assessment: Assesses student mastery after instructor-led sessions and provides data for differentiating subsequent module activities based on readiness.

iv. Differentiated Activities: Activities that use readiness data to create a differentiated learning process for each student. Examples are tiered homework assignments and heterogenous collaborative work groups.

Implementation Challenges

This novel approach to module design in an engineering course context has the potential to improve student learning, but this is not without challenges to implementing this design within a typical engineering course environment. The most prominent challenge to implementing this design are the data acquisition and process differentiation tasks (e.g. heterogenous group selection) associated with grading formative assessments. These tasks will become prohibitively burdensome for large class sizes and/or few contact hours typically associated with a course module if these tasks are done manually by an instructor. Automation of grading and differentiating decisions based on grades, possibly using machine learning (Zervoudakis, Mastrothanasis, and Tsafarakis 2020), will mitigate the burden of these tasks and is key to implementation in a college course context. Also, conducting the heterogenous collaborative assignment virtually presented challenges associated with getting group members into their assigned breakout groups and then monitoring each group to encourage participation. This can be remedied by providing instructions that describe how to navigate the environment as well as establish expectations related to participation for each student prior to the group session. Note that these logistics will not be encountered if the collaborative assignment is conducted in-person.

CONCLUSION AND FUTURE WORK

Qualitative analyses of the novel module design based on student readiness reveal that this approach has a perceived positive impact on student learning. Quantitative analysis of pre-test/post-test scores did not show a statistically significant difference between treatment and control groups, but analysis of changes in scores from formative assessment to post-test within the treatment group clearly shows an improvement in scores. Overall, the results of these analyses establish that this novel approach to module design improves student learning and has a positive impact on student attitudes towards learning. Results also point to design modifications that have the potential to enhance student learning even further. Given evidence of improved student learning, a framework for future implementations beyond a circuit analysis course context was created along with a list of requirements for effective implementation and key implementation challenges that must be addressed for ease of scalability and instructor adoption. The next step in this research process is to apply this framework to different modules within this course and expand the number of participants in the study to attain more insightful statistical results. Differentiation based on interest will also be considered further into the future.

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