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Work in Progress: Using Experiment-centric Learning Pedagogy to Increase Student Understanding of Chemical Principles and Concepts

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Abstract

The hands-on approach in teaching and learning is an important resource to be explored because it offers a meaningful platform for student-instructor interaction that fosters sound scientific reasoning and improves the understanding of abstract chemistry concepts. Experiment-centric pedagogy (ECP) is a contemporary teaching approach that integrates active student participation in problem-based activities through hands-on mobile devices. This paper describes how experiment-centric pedagogy (ECP) has been used to teach key chemistry concepts to undergraduate students in the chemistry discipline at an Historically Black University (HBCU). To assess whether ECP achieves a lasting increase in undergraduate student curiosity and engagement in the chemistry discipline, ECP was implemented from Fall 2021 to Fall 2022 using an inexpensive, safe, and portable electronic instrumentation system usable in both classrooms and laboratories. The Motivated Strategies for Learning Questionnaire developed by Pintrich, Smith, García, and McKeachie in 1991 was used to measure the key constructs associated with students' curiosity and engagement. The classroom observation protocol (COPUS) was used to assess instructors' effectiveness, and signature assignments were used to evaluate knowledge gains.

Keywords –experimental-centric learning, hands-on, curiosity, engagement.

Introduction

Laboratory experiments help students understand basic chemistry ideas. Simple experiments work best, but complicated experiments can cause confusion and boredom. Over time, students may forget what they learned and cannot use the information in other areas [1], [2]. There is often a disconnect between the teaching methods used by educators and the learning styles of individual students, leading to a lack of engagement and understanding. There have been numerous studies conducted on this topic, and several factors have been identified as contributing to the gap between teaching and learning, including teaching methods that are not aligned with students' learning styles, lack of hands-on or interactive activities in the classroom, insufficient scaffolding or support for students to build a deep understanding of complex concepts, and overreliance on rote memorization rather than critical thinking and problem solving [3], [4], [5]. This is where experiment-centric pedagogy can come in to bridge the obvious gap between teaching and learning because it encourages the use of hands-on technology where students can perform experiments, visualize, analyze, and come to conclusions themselves using portable inexpensive devices in their experiments.

Generally, there are many reasons for which experiments are performed in chemistry, and one of the most important reasons is to promote spot-on observation and explanation of the results observed. Kolb addressed through his learning cycle model the need for students to interact with course materials in other ways that are relevant to the students' everyday challenges [6]. This encourages students to have their own viewpoints, thereby improving critical thinking.

Hands-on pedagogy has been found to have a positive impact on chemistry learning, retention, and lasting gains. Research has shown that students who engage in hands-on activities in the classroom have improved learning outcomes and increased motivation for learning[7], [8]. This paper describes how experiment-centric pedagogy (ECP) has been used to teach key chemistry concepts to undergraduate students in the chemistry discipline at Historically Black University (HBCU).

Literature Review

Educational research has shown that the motivation of learners is determined by the choice of the instructor's pedagogical and behavioral approach in teaching concepts [9], [10]. Different types of situations in the classroom may produce different types of learner motivation, and these specific types of motivation help to shape students' persistence, curiosity, critical thinking, engagement, and achievement [11], [12], [13].
It has been well documented that among all teaching approaches, laboratory experiments have proven to be the most efficient in battling many issues in facilitating student learning from engineering and science laboratories compared to other traditional teaching methods because they give room for students to learn on their own through hands-on experience [14], [15].

The hands-on approach in the laboratory is increasingly becoming popular in chemical engineering education because it offers a unique learning experience for students. It is an effective method of teaching concepts, as it allows students to apply theoretical knowledge to practical situations. This approach makes learning more engaging and memorable, as students are able to connect what they learn in class to real-world experiences [16].

Theoretical Framework

The process of learning is different between individuals. It is important for instructors/educators to know how different strategies of pedagogy are developed, how new knowledge is learned and how new motivation strategies can be developed. In recent years, educational theorists have conducted research to ascertain how people acquire, retain and recall knowledge, which has resulted in the existence of multiple learning theories. The two major learning theories are (1) Behavioral learning theory, which stresses that learning occurs when a student responds favorably to some form of external stimuli [17]. Behaviorist learning is nothing more than the acquisition of new behaviors; they do not stress that thinking or any other form of mental activity as such variables are not observable behaviors. (2) Constructivist learning theory, through which students build their own knowledge as they participate in activities such as hands-on experiments, discussions or group projects. This learning theory emphasizes how students can be agents of their own learning [18], [19]. Constructivism states that knowledge is acquired through four assumptions.

- Learning involves active cognitive processing.
- Learning is adaptive.
- Learning is subjective and not objective and
- Learning involves both social and individual processes.

In this project, constructivist learning theory was used.

Constructivist Learning Theory Using the 5E Model.

The 5E model is built around a structured sequence, and it is designed as a functional way for teachers to implement constructivist theory. The 5Es serve as an aid for instructors to structure a new learning experience in a systematic way that is consistent with a constructivist view [20]. The 5E model focuses on allowing students to understand a concept over time by going through a series of established steps or phases. These series of established phases include Explain, Explore, Explain, Elaborate and Evaluate [21]. Figure 1 shows the pathway the phases of the 5E model take during a learning process. The first phase is the Engage phase, where you enable the student to be involved in the learning task. The activities of this phase should have a connection with past and future experiments/teaching, which helps the student connect previous experiences to the one at hand. The phase that follows is the Explore phase, which is aimed at establishing experiences that an instructor can use later to introduce a concept. During this process, the students are given time to explore the equipment or objects given to them, and as a result of this mental and physical involvement, the students begin to establish connections and form their own ideas. The next phase is the Explain phase. In this phase, the students and instructor give their various explanations to what they have observed in the two previous phases. First, the students will be asked to explain what they have observed; then, the instructor gives an explanation in a formal manner. Then, comes the stage whose aim is to elaborate on what students have learned thus far by extending or clarifying the concepts or processes learned in the classroom or laboratory. This phase may help instructors to attend to misconceptions the students might have about what they learned in the previous phases. This then leads to the final phase, which is the Evaluate stage, where students receive feedback or assessments. This stage helps students to use the skills they have learned and then they can evaluate themselves thereafter.

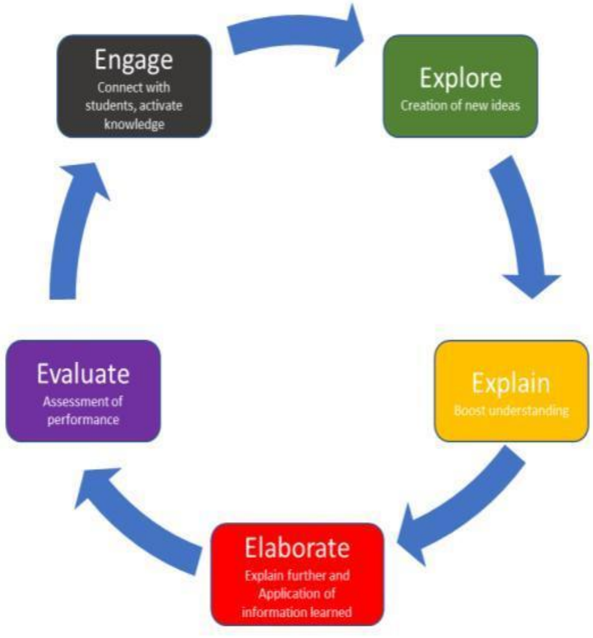

Figure 1 The 5E Model of Constructivist Learning Theory [21]

Methodology

This study was conducted to assess undergraduate students' curiosity and engagement using experiment-centric pedagogy (ECP). To do that, some courses in the chemistry department adopted the experiment-centric pedagogy to conduct the pH and turbidity test from fall 2021 to spring 2022 semesters. The Motivated Learning Strategy Questionnaire (MLSQ) and the Litman and Spielberger curiosity assessment instruments [22] were used to assess the key structures associated with the student's motivation, curiosity, self-efficacy and success. Signature assignments were also administered to measure the increase in students' understanding of the concepts taught. In each of the courses, a well-structured course module where ECP could be utilized was implemented (Figure 2).

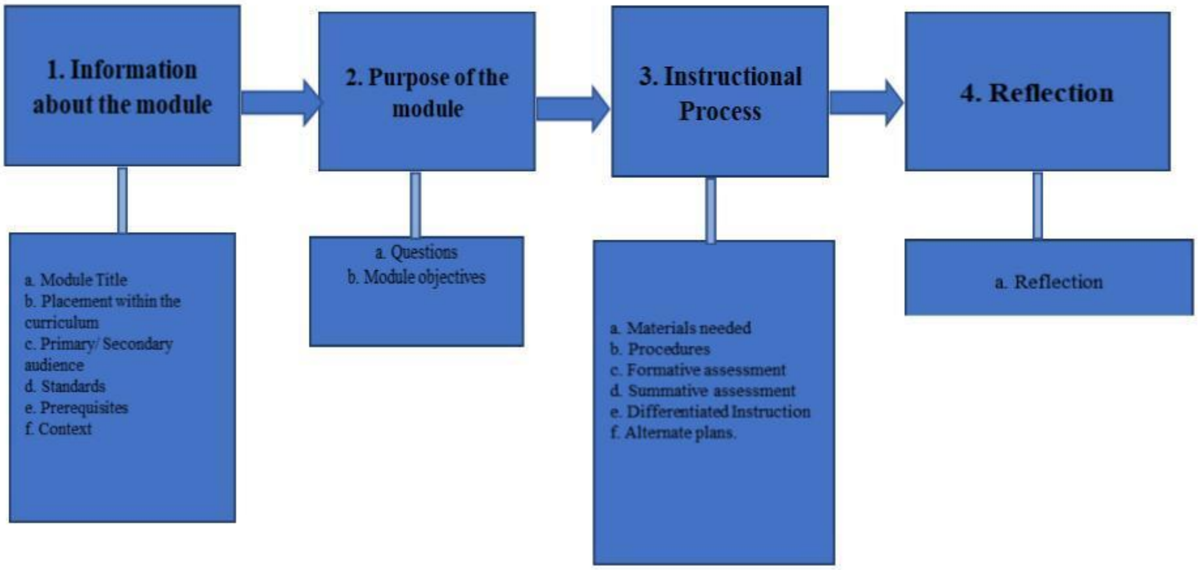

Figure 2 The ECP Module Instructional Design [23]

Module Instructional Design

Qualitative and quantitative data were collected before and after each module. Using the theoretical framework in Figure 2, the MLSQ was used to measure students' motivation and self-regulated learning as they relate to chemistry. The MLSQ is a 44-item instrument that uses a 7-point and 4-point Likert scale with statements related to each construct. The MLSQ measures two different scales, motivation and learning strategy. The motivation scale measures intrinsic and extrinsic goals together with the task value, which assesses students' goals, their belief in their ability to succeed in chemistry and their anxiety about achieving their desired test scores in chemistry. The learning strategy assesses students' management of different resources. The Litman and Spielberger curiosity assessment instruments were used to measure students' level of curiosity, self-efficacy, task value, learning strategies and test anxiety (Table 1).

Table 1: MLSQ Table

Item/Scale	Sample Question	Code
Intrinsic Goal Orientation (3 items)	In a class like this, I prefer course material that truly challenges me so I can learn new things	IGO
Extrinsic Goal Orientation (3 items)	Getting a good grade in this class is the most satisfying thing for me right now	EGO
Task Value (3 items)	I am very interested in the content area of this course	TV
Expectancy Component (3 items)	I believe I will receive an excellent grade in this class	EC
Test Anxiety (2 items)	I have an uneasy, upset feeling when I take an exam	TA
Critical Thinking (3 items)	I often find myself questioning things I hear or read in this course to decide if I find them convincing	CT
Metacognition (4 items)	If course materials are difficult to understand, I change the way I read the material	MC
Peer Learning (3 items)	When studying for this course, I often try to explain the material to a classmate or a friend	PL
Interest Epistemic Curiosity (5 items)	I enjoy exploring new ideas	IEC
Deprivation Epistemic Curiosity (5 items)	Difficult conceptual problems can keep me awake all night thinking about solutions	DEC

The Classroom Observation Protocol for Undergraduates (COPUS), which was developed for undergraduate students in STEM by Smith et al. [24], was used to measure students' engagement. COPUS is generally used to determine how instructors and students spend their time in the classroom, and this helps to provide feedback to instructors about how much impact they have in the classroom.

COPUS is composed of 25 codes in two categories that describe what the instructor is doing and what the student is doing. To analyze the results of the observations, a bar chart should be used, as it will show the proportion of results calculated as percentages of two-minute intervals during which the instructor and students' behaviors are recorded using the appropriate codes [25].
Signature assignment was administered before the module and after the module, and it was used to determine the level of knowledge gained for each module. An outcome assessment was also conducted by giving students projects to work on.

Brief Description of the Experiments

Below, a brief description of the experiments is presented.

The pH Experiment.

The pH experiment was conducted in the organic chemistry class to determine the relationship between the pH value and voltage. The experiment involved the use of an ADALM2000 computer interface, pH scale, analog pH meter, ADALP analog part kit, stirring rod, transparent plastic cup, and indicator, a funnel, a sieve and a personal computer. The experimental components are shown in Figures 3 and 4.

Figure 3 ADALM2000 [26]

Figure 4 Experimental Setup

Water Turbidity Experiment

A water turbidity experiment was also conducted in the chemistry department to determine the amount of cloudiness in the water. It is a measurement of the amount of light that is scattered by the material in the water sample when light is shined through the water sample. The devices utilized for this experiment were an ADALM1000 computer interface, wash bottle with distilled water, sediments such as silt and clay, logger pro and a computer.

Figure 5 ADALM1000

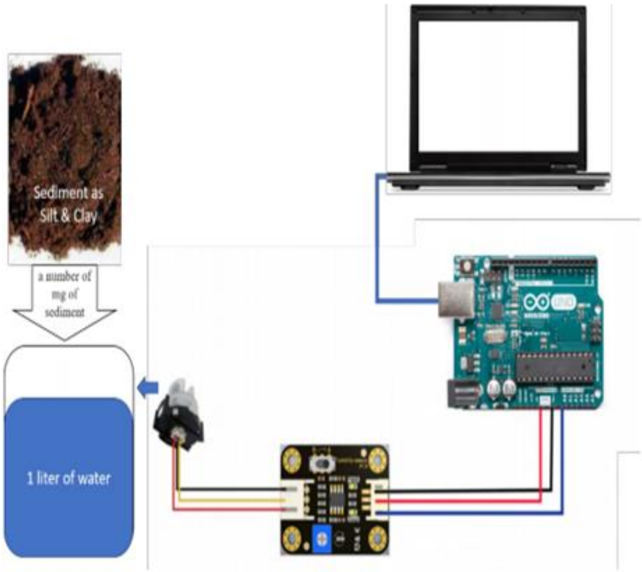

Figure 6 Experimental setup

A pretest was administered before each laboratory experiment, and a posttest was also administered after every laboratory experiment and data was collected only on one section for each semester.

Results and Discussion

The results in Table 2, Table 3 and Table 4 show the statistics summary and the p values of paired t tests for pre- and posttest scores of students for each construct. Descriptive statistics results for the pre- and posttest scores of the MSLQ subscales are shown in the last column of Tables 2 to 4. There is no clear significant difference in the constructs for fall 2021, as shown in Table 2.

Table 2 MLSQ Data Analysis (Fall 2021)

MLSQ SCALE	Pretest	Post-test	Difference in Mean	p value
	Mean±SD N=12	Mean±SD N=12		
Intrinsic Goal Orientation (EGO)[a]	2.25±0.87	2.27±0.85	-0.02778	0.339
Task Value (TV)[a]	1.97±1.12	1.80±0.99	0.16667	0.082
Peer Learning Collaboration (PLC)[a]	2.94±1.75	2.97±1.72	-0.02778	0.339
Deprivation Epistemic Curiosity (DEC)[b]	2.45±0.66	2.46±0.66	-0.01667	0.339

[a] 1-7 Likert Scale (Note: 1 =not at all true of me, 7 = very true of me)
[b] 1-4 Likert Scale (Note: 1 =never., 2= sometimes, 3 =often, 4 = always)

However, in spring 2022, a clear improvement in the intrinsic goal orientation and task value was observed with a p value < 0.05.

Table 3 MLSQ Data Analysis (Spring 2022)

MLSQ SCALE	Pretest	Post-test	Difference in Mean	p value
	Mean±SD N=8	Mean±SD N=8		
Intrinsic Goal Orientation (EGO)[a]	5.37±1.11	2.70±1.45	2.66667	0.004*
Task Value (TV)[a]	6.20±0.64	2.37±1.48	3.83333	0.000*
Peer Learning Collaboration (PLC)[a]	4.37±2.10	3.29±1.91	1.08333	0.246
Deprivation Epistemic[b] Curiosity	2.60±0.88	2.57±0.75	0.02500	0.908

[a] 1-7 Likert Scale (Note: 1 =not at all true of me, 7 = very true of me)
[b] 1-4 Likert Scale (Note: 1 =never., 2= sometimes, 3 =often, 4 = always)

In Fall 2022, the descriptive results revealed a significant difference in the extrinsic goal orientation, as shown in Table 4. Clearly, from these results, it can be seen that ECP has increased students' understanding of chemistry concepts.

Table 4 MLSQ Fall 2022

MLSQ SCALE	Pretest	Post-test	Difference in Mean	p value
	Mean±SD N=9	Mean±SD N=9		
Intrinsic Goal Orientation (EGO)[a]	1.70±0.59	2.00±0.93	-0.2963	0.396
Extrinsic Goal Orientation (EGO)[a]	1.56±0.47	3.04±1.67	-1.48148	0.038*
Task Value (TV)[a]	2.11±1.31	2.11±1.21	0.00000	1.000
Peer Learning Collaboration (PLC)[a]	2.59±1.00	2.44±1.09	0.14815	0.377
Deprivation Epistemic Curiosity (DEC)[b]	2.04±0.76	2.27±0.58	-0.22222	0.42

[a] 1-7 Likert Scale (Note: 1 =not at all true of me, 7 = very true of me)
[b] 1-4 Likert Scale (Note: 1 =never., 2= sometimes, 3 =often, 4 = always)

When comparing the class observation of student and instructor behaviors across the three semesters when ECP was implemented, the classes reveal good engagement with ECP. In Fall 2021 as shown in figures 7 and 8, students participated in groups during the experiment despite the technical issues in the process.

Fall 2021

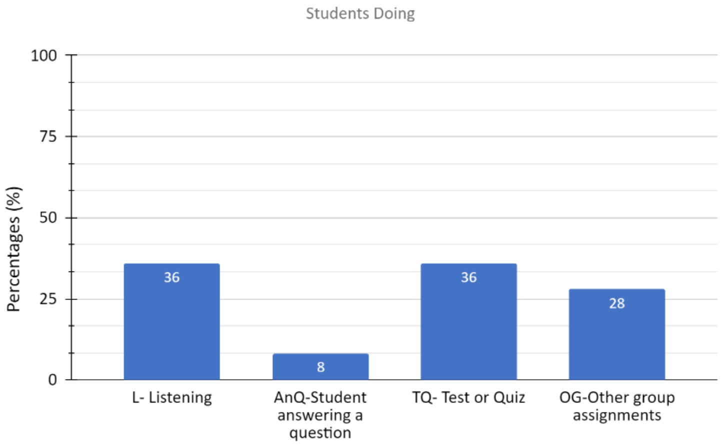

Figure 7 Class Observation (Students)

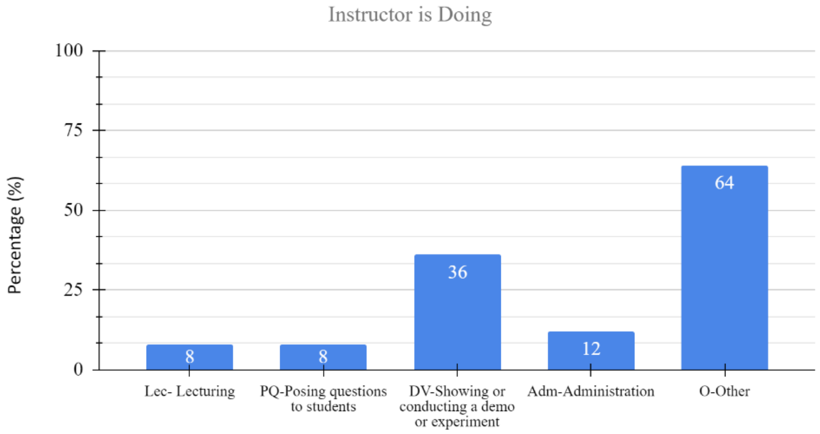

Figure 8 Class Observation (Instructor)

However, in Spring 2022, as shown in figure 9, there was great improvement in the student and instructor's behavior. A total of 57.1% of the students were curious by posing questions to the instructor about concepts, while 85.7% were critically thinking through the chemical principles. A total of 35.7% of the students were involved in class discussions on the subject matter, while 42.9% were making predictions of the result.

Spring 2022

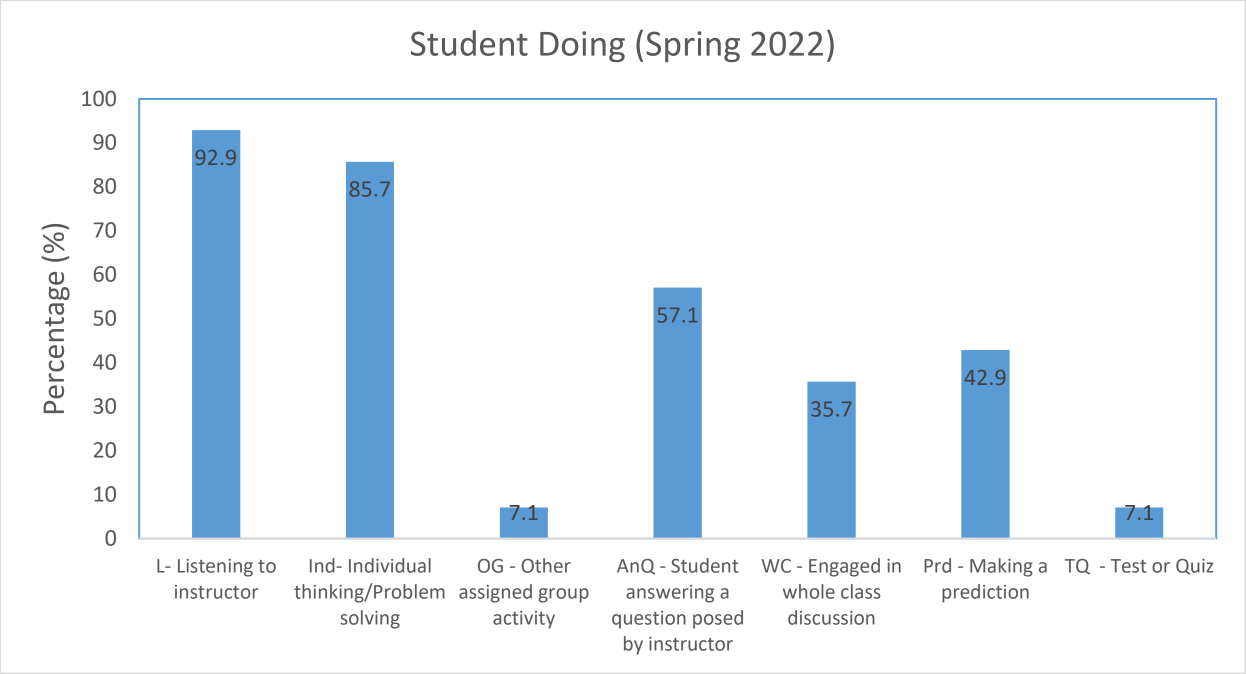

Figure 9 Class Observation (Students)

The instructor, on the other hand, as shown in figure 10, ensured that the students participated and followed up on the student's curiosity about the concept.

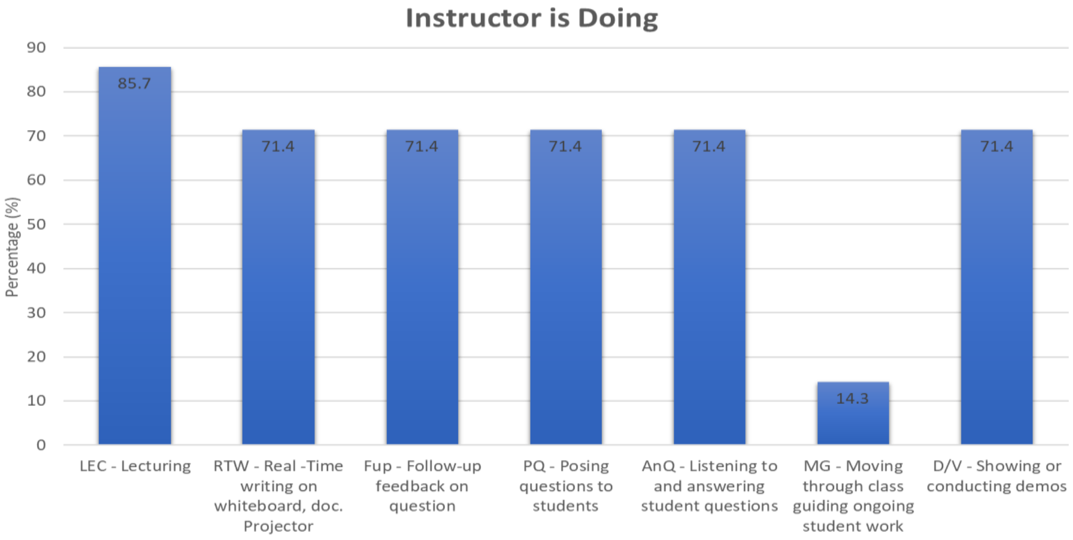

Figure 10 Class Observation (Instructor)

Based on the data obtained in Fall 2022, as displayed in figures 11 and 12, students participated and engaged the instructor by asking questions as it relates to the experiment, thus revealing their curiosity.

Fall 2022

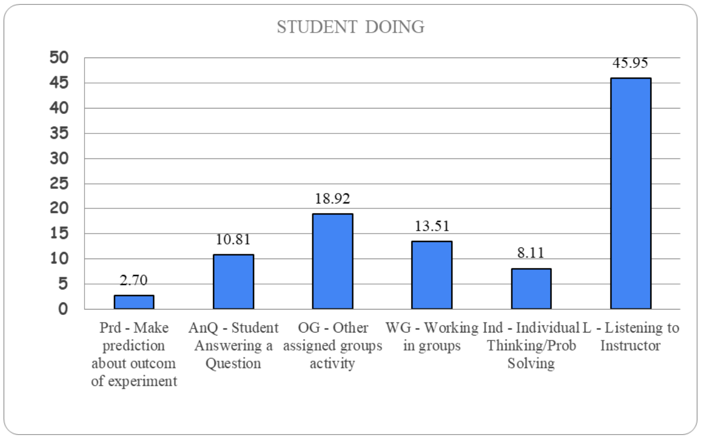

Figure 11 Class Observation (Students)

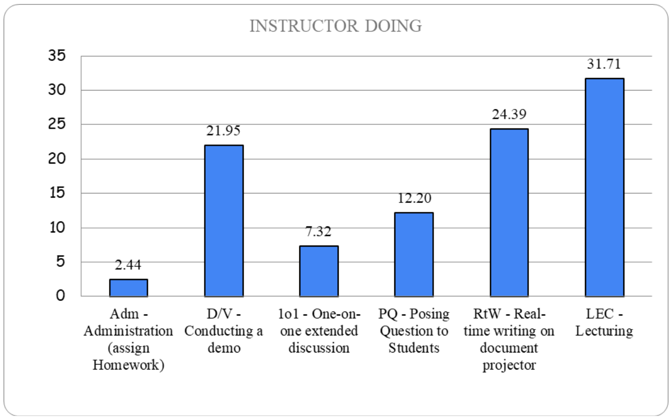

Figure 12 Class Observation (Instructor)

During the implementation of the ECP, signature assignments were administered to the students before and after implementation in Fall 2021, Spring 2022 and Fall 2022 as shown in figures 13, 14 and 15. An improvement was seen across the three semesters, which indicates students' understanding of the concepts that were taught.

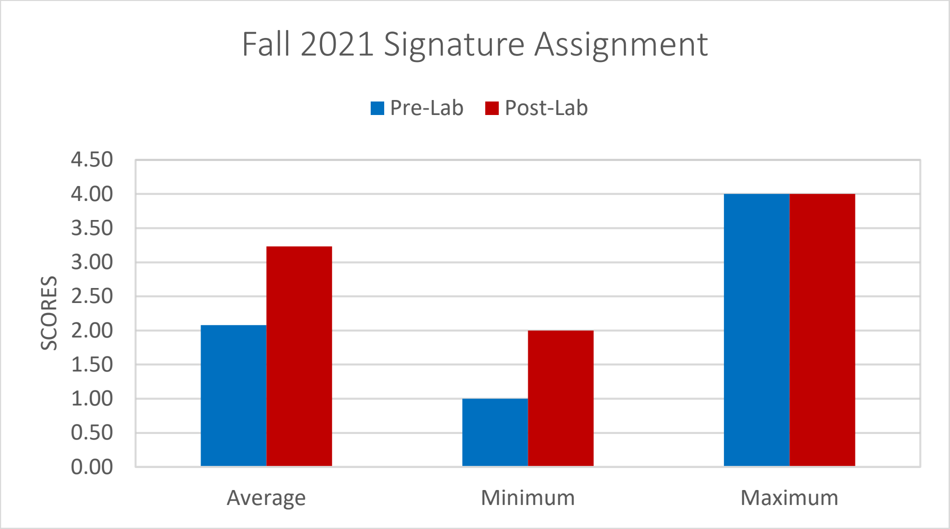

Figure 13 Signature Assignment (Fall 2021)

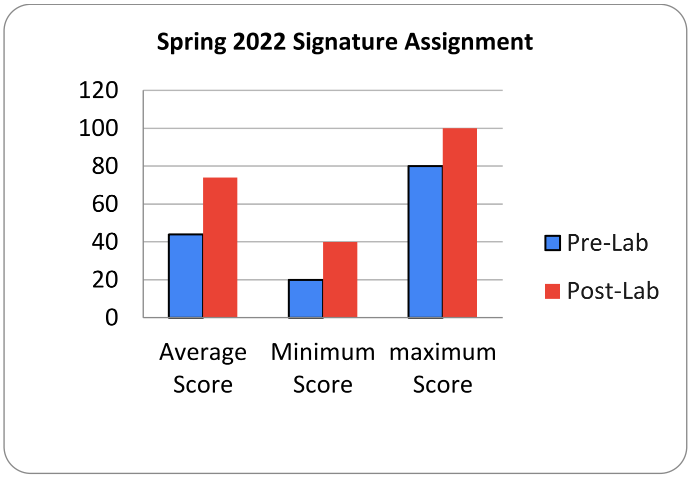

Figure 14 Signature Assignment (Spring 2022)

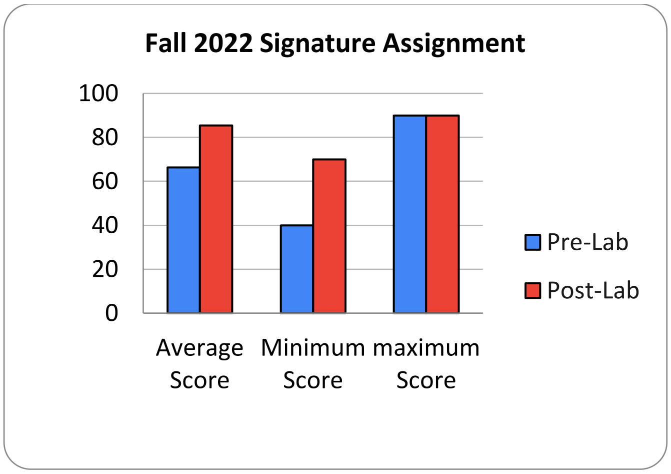

Figure 15 Signature Assignment (Fall 2022)

To assess the students' understanding of these chemistry concepts, a validated instrument that assesses the ability to conduct, analyze and interpret, develop experiments, and draw conclusions was administered. The outcome assessments were conducted in Fall 2021 (Figure 16), Spring 2022 (Figure 17) and Fall 2022 (Figure 18). A 75% target performance was set for each criterion. This means that at least 75% of the students must either be at the satisfactory or exemplary level, and 25% of them must be at the developing and unsatisfactory level. Over 75% of the students met the targeted performance criteria across the three semesters for “describe the hypothesis being tested”, formulate adequate simulation or experiment and hypothesis”, “acceptance of reasonable variance between numerical or experimental results and predictions of hypothesis”, understand the functions and limitations of the computer or laboratory tool/equipment used” and “uses laboratory tool/equipment or computer simulation correctly”, “recognizes the relation in precision between input and input data”, “determines sources of error” and “organizes experimental or simulation data”.

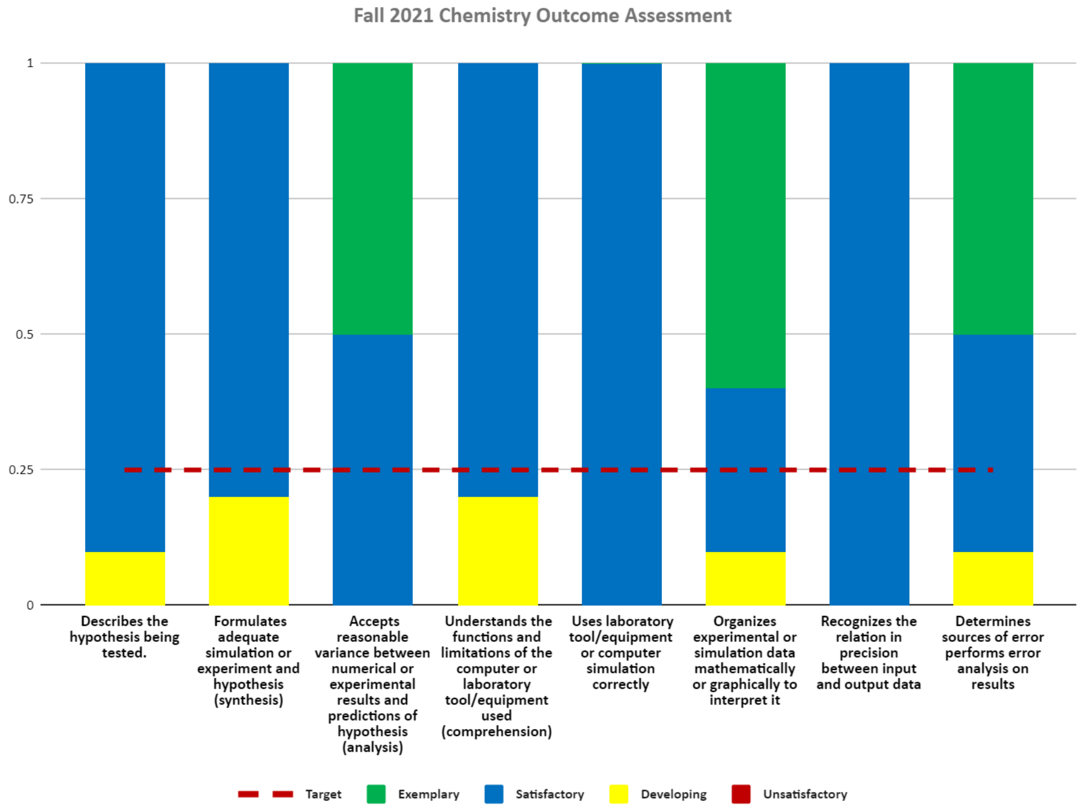

Figure 16 Outcome Assessment Fall 2021

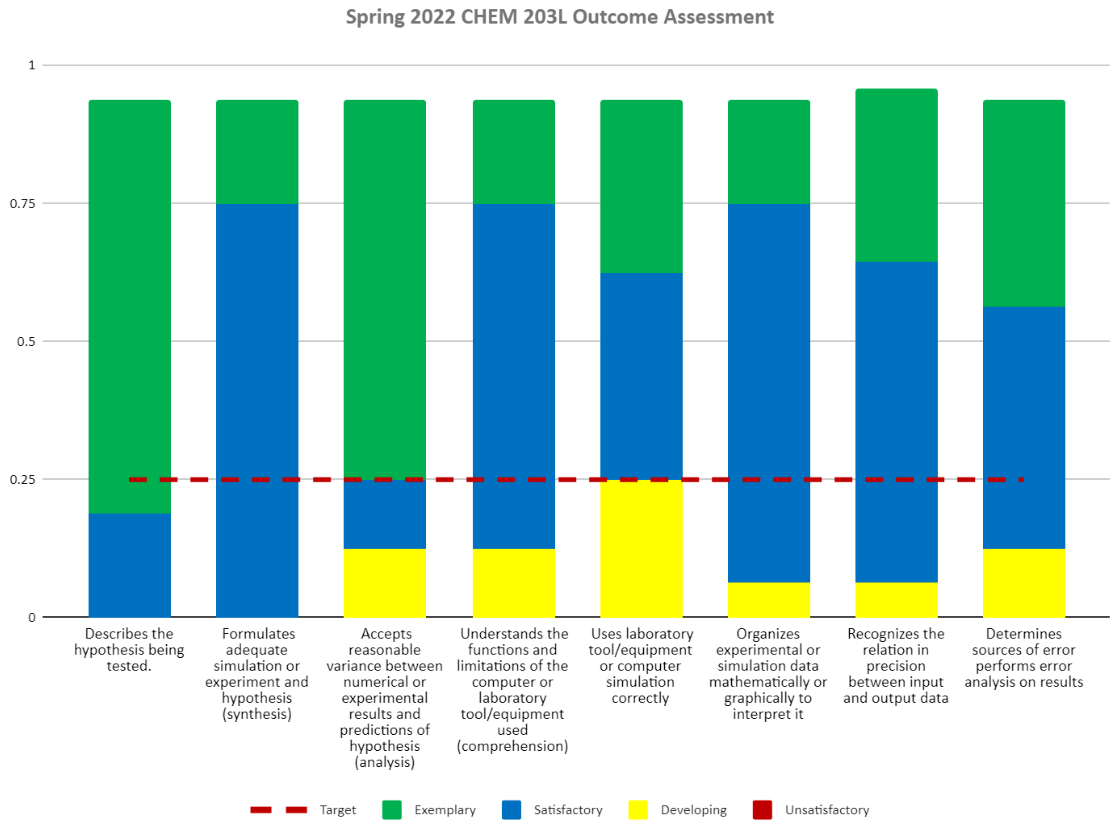

Figure 17 Outcome Assessment Spring 2022

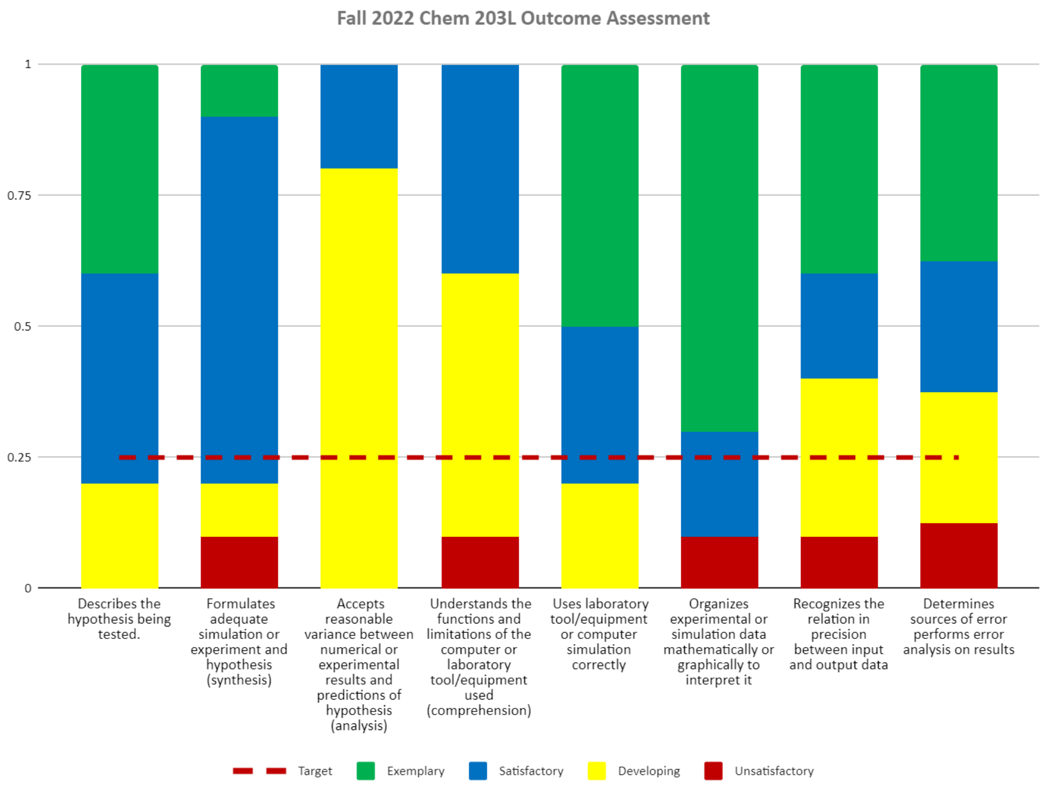

Figure 18 Outcome Assessment Fall 2022

Conclusion

Overall, the study looked at how a teaching method called ECP affected students' motivation and understanding of chemistry concepts in three different semesters. The study found that in Fall 2021, there was no significant difference in the students' motivation levels, but in Spring 2022, there was a significant improvement in intrinsic goal orientation and task value. In Fall 2022, there was a significant difference in extrinsic goal orientation, and ECP increased students' understanding of chemistry concepts. The class observations also showed good engagement with ECP, with improvements in student and instructor behavior over time. Overall, the study suggests that ECP can be a useful teaching method for improving students' motivation and understanding of chemistry concepts.

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