Successfully implementing Inquiry-Based Labs: A case study for a college Waves and Modern Physics course

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ABSTRACT

Inquiry-based instruction is a form of active learning that scaffolds investigation of authentic problems. It relies on collaborative activities that engage students in discipline-specific practices that promote the use of high-level cognitive skills – analysis, decision-making, and evaluation. Inquiry-Based Laboratories extends this approach to lab experimentation. Compared to traditional labs, inquiry-based labs require students to make decisions that are critical to the process – what methods to use, what data to collect, etc. We report on a case study conducted in Fall 2021, featuring a design focus IBL implementation in a college Waves and Modern Physics course. The case study spanned the 15-week semester with students' scientific reasoning assessed at three points: pre-test, immediate post-test, and delayed post-test. Students showed improvements in their scientific reasoning with positive changes to their epistemic beliefs – i.e., thinking more like scientists.

Keywords: inquiry-based labs, inquiry-based instruction, active learning, design-based instruction, scaffolds

1. INTRODUCTION

Inquiry-Based (IB) instruction is a form of active learning [1, 2], situated within the context of investigating authentic problems [3-5]. Guidance, or scaffolding, is provided by the teacher and is used strategically as part of the lesson design [6]. Grounded in socio-cognitive theories of learning, IB leans heavily on collaborative activities that engage students in discipline-specific practices that promote the use of high-level cognitive skills – analysis, decision-making, and evaluation. We have reported on IB instruction and the use of scaffolds for a college Waves and Modern Physics course [7], and now extend this approach to lab experimentation, i.e., Inquiry-Based Labs (IBL).

Compared to traditional labs, IBL requires students to make decisions that are critical to the process – what methods to use, what data to collect, etc. [8, 9]. Furthermore, shifting away from traditional labs is desirable; a study by Holmes and al. [10] showed that, "… we found universally and precisely no added value to learning course content from taking the labs as measured by course exam performance. This work should motivate institutions and departments to reexamine the goals and conduct of their lab courses, given their resource-intensive nature." IBL at the post-secondary levels could help address the issue stated by Holmes et al., however, successful implementations within the context of curriculum demands can be a challenge.

We report on a case study conducted in Fall 2021, featuring a design focus IBL implementation that has met the challenge successfully. The case study spanned the 15-week semester with students' scientific reasoning assessed at three points: pre-test, immediate post-test, and delayed post-test. Two specialized instruments were used: (1) George's Ice Cream (GIC)

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tests [11, 12], adapted by our research team; and (2) the Topic Specific Epistemic Beliefs (TSEB) questionnaire [13], designed and validated by other studies. Students showed improvements in their scientific reasoning about experimental design decisions. In addition, results of the TSEB questionnaire show students also increased their awareness of how scientific knowledge is generated, i.e., thinking more like scientists.

Section 2 shows how the IBLs were mapped during the semester. It provides an overview of the activities that students engaged with during the semester and includes examples of some of the provided scaffolds and hand-outs. A comparison between the GIC pre-test and delayed post-test, as well as the TSEB questionnaire, both done during weeks 1 and 15 is provided in section 3. A discussion is provided in section 4.

2. MAPPING THE INQUIRY-BASED LABS OVER A SEMESTER OF A WAVES AND MODERN PHYSICS COURSE

The IBL case study was set in a Québec (Canada) college level Waves and Modern Physics course taken by all students pursuing studies in the Natural Sciences (including Health Science and Pure & Applied Science) [7, 14]. This course follows one on Mechanics and is equivalent to a freshman year physics course elsewhere in North America. It was a fully synchronous in-person semester with 5 hours of class time per week - 3 hours for lecturing and active learning activities, and 2 hours of lab time. There were 36 students registered in the class with two lab sections of 18 students each. Students in each lab section are then put into teams of 3-4 students which were kept constant for the entire semester.

Our model for IBL is based on that presented by Blanchard et al. [8] and is shown in Figure 1. We modified this model slightly and have identified four lab inquiry competencies: a) **asking** a research question (RQ), b) **designing** a methods (or procedure), c) **collecting** and **analyzing** data, and **interpreting** results, d) **writing** a lab report. As such, we developed 4 IBL modules based on the harmonic motion and mechanical waves sections of the course. Each module includes competencies b and c. Competency d is included in modules two and four. Only the last module includes competency a. This is summarized in Figure 2.

Each module has a series of scaffolds to help students become more competent for the four lab inquiry competencies. Some scaffolds are labelled “student activities” where students are actively designing methods, performing experiments, etc. Other scaffolds are labelled “teacher activities” where the teacher provides reflective questions to the students, initiates a class discussion, provides feedback, etc.

Each activity leads to students completing a task(s) and submitting work to the teacher, these are labelled “student artifacts.” These artifacts can be submitted individually, in pairs or in full teams. They are used for formative and summative assessments by the teacher, and analyzed by our research team.

The “assessments” row in Figure 2 refer to the two specialized instruments used, i.e., GIC and TSEB, and other student tasks such as learning reflections and self/peer assessments on the quality of their work.

Modules 1 to 3 have dedicated lab time incorporated into our lab schedule. The IBL student activities replace the previous traditional labs that were part of our past lab schedule. Most of module 4 is done out-of-class. This allows for some non-IBL experiments covering geometric optics, wave optics and modern physics to remain in our lab schedule.

2.1. Module 1 – Simple Harmonic Motion (block-spring system)

The first task for students begins on week 2 of the semester, after some class time spent on simple harmonic motion. They are to design two methods for two research questions provided by the teacher. During the lab period, the students have access to all equipment needed to perform block-spring based simple harmonic motion experiments. They are encouraged to use the equipment and “mess-about” with it, such that they discover with the equipment can do and test their methods before submitting it by the end of the lab period.

Inquiry Activities

Level of Inquiry

	Source of the Question	Data Collection Methods	Interpretation of Results
Level 0: Verification	Given by teacher	Given by teacher	Given by teacher
Level 1: Structured	Given by teacher	Given by teacher	**Open to student**
Level 2: Guided	Given by teacher	**Open to student**	**Open to student**
Level 3: Open	**Open to student**	**Open to student**	**Open to student**

Figure 1: IBL model based on that presented by Blanchard et al. [8].

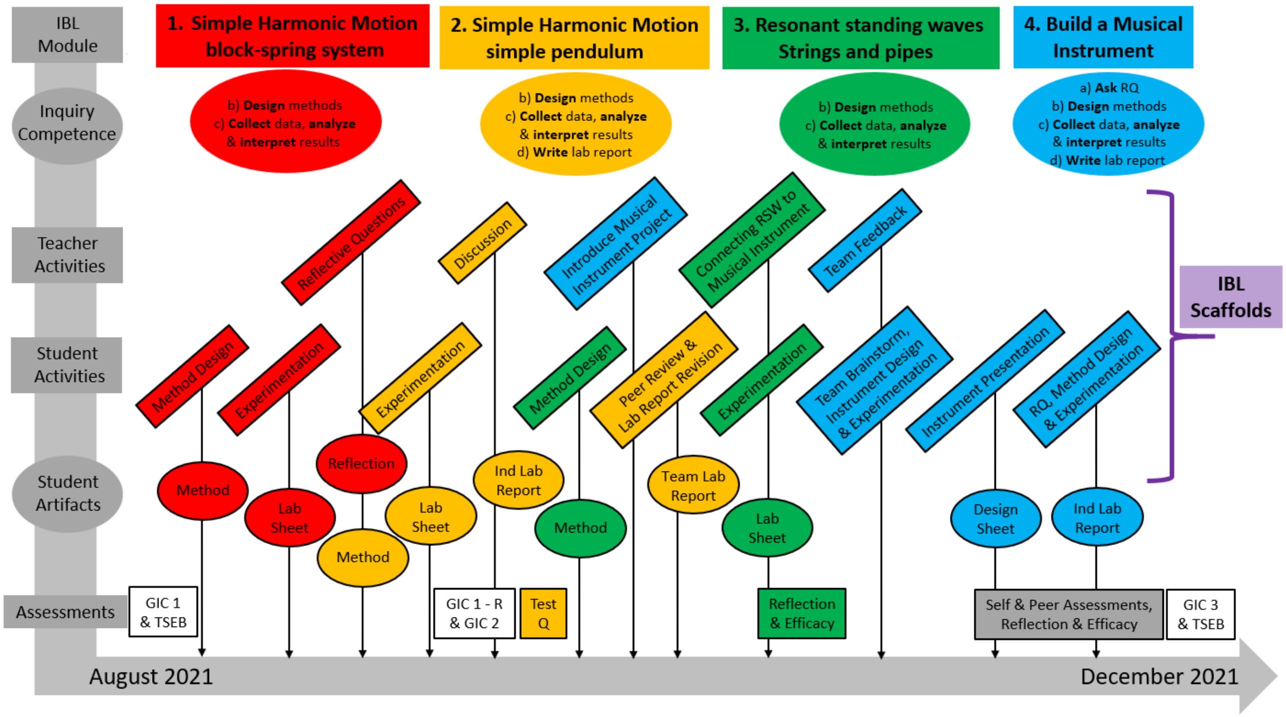


Figure 2: Mapping IBLs over a semester of a Waves and Modern Physics course.

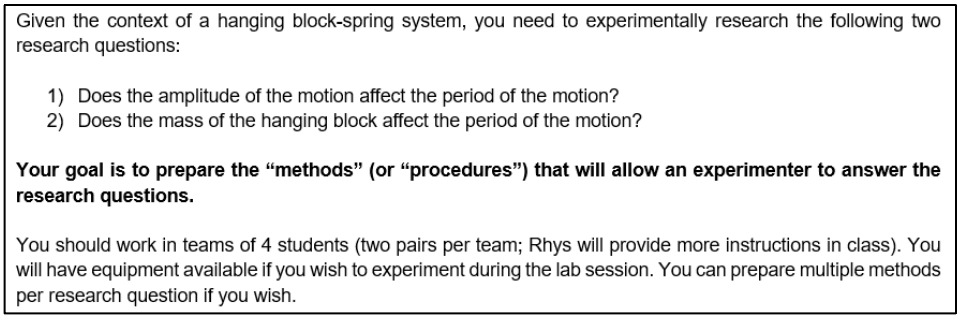
The following week, the students perform the experiments they proposed. The collect and analyze data, and interpret the results. The students need to present their data in tables and graphs, but they are free to choose how many data points, trials, etc. they wish to collect. By the end of the second lab period, the students are to submit the data, analysis and answer the two research questions. The scaffolds provided by the teacher for both weeks 2 and 3 are presented in Figure 3.

Next is an individual student reflective assignment done as homework using myDALITE [15]. The teacher provides an "expert" data collection and analysis for the block-spring based simple harmonic motion experiments. The students first need to describe the methods that led to this expert data collection. They then reflect (compare/contrast) between these new methods and the ones they used for the experiment. Next, following this reflection, the students are given two simple pendulum based simple harmonic motion research questions (similar to the block-spring based ones) and must prepare methods for each. Figure 4 shows examples of what the teacher provides to students and of a reflective question.

2.2. Module 2 – Simple Harmonic Motion (simple pendulum)

During the lab period after the reflective assignment, the students perform the simple pendulum experiment they proposed. They work in their teams and must first decide whose methods to use (they are allowed to modify it). Given that the experimental setup is straightforward, the students are not given any “mess-about” time. Their tasks are to collect and analyze data, and interpret the results. The scaffolds provided by the teacher are like those presented in Figure 3 (b).

The next task is to prepare a lab report, and this is divided into three parts. First, students need to complete an individual lab report. The students are given the lab report writing guidelines and assessment rubric. They are also provided with a full data collection set, periods of oscillation, for many simple pendulum lengths and angles (including both small and large angles). Even though many groups did collect more data for the simple pendulum than for the block-spring system, the idea here is give all students more data than they need and to have them choose which data to analyze for their reports. Part two is done during class time. The students work in their teams and peer review each other’s lab reports, using both the guidelines and assessment rubric during the process. Once the peer review process is completed, the students are given another opportunity to submit a revised lab report, but this time, it is one submission on behalf of the team. The students need to agree on what and how to present. They can choose to work off an existing individual lab report and improve it or start anew.



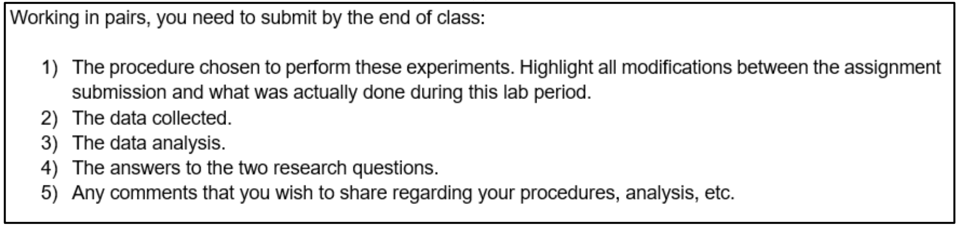
Given the context of a hanging block-spring system, you need to experimentally research the following two research questions:

1) Does the amplitude of the motion affect the period of the motion?
2) Does the mass of the hanging block affect the period of the motion?

Your goal is to prepare the “methods” (or “procedures”) that will allow an experimenter to answer the research questions.

You should work in teams of 4 students (two pairs per team; Rhys will provide more instructions in class). You will have equipment available if you wish to experiment during the lab session. You can prepare multiple methods per research question if you wish.

(a)



Working in pairs, you need to submit by the end of class:

1) The procedure chosen to perform these experiments. Highlight all modifications between the assignment submission and what was actually done during this lab period.
2) The data collected.
3) The data analysis.
4) The answers to the two research questions.
5) Any comments that you wish to share regarding your procedures, analysis, etc.

(b)

Figure 3: Module 1 scaffolds provided by the teacher for (a) week 2 and (b) week 3.

2.3. Module 3 – Resonant Standing Waves (strings and pipes)

Module 3 begins on week 6 of the semester and follows class time on mechanical waves (which includes transverse and longitudinal travelling waves, standing waves, etc.). Comparable to the first part of module 1, the students are to design methods for research questions provided by the teacher. The research questions focus on the harmonic series for the resonant standing waves on strings and in pipes, and on how to experimentally find wave speeds. During the lab period, the students have access to equipment and are encouraged to “mess-about” with it. This step is crucial for module 3 because few students have experience with specialized equipment such as signal generators, mechanical oscillators, etc. The teacher must provide some extra guidance (i.e., verbal scaffolds) to help students with their ideas. They are to submit their methods by the end of the lab period.

Before the following lab period, the teacher introduces Musical Instrument Project (discussed in section 2.4) during class. As such, the students are to make connections between the project and their experiments on resonant standing waves. In addition to getting more experience with collecting and analyzing data, the students gain experience with equipment that will later be useful for their project experiments to be done at home. The scaffolds provided by the teacher are similar to those presented in Figure 3.

Module 3 ends with a reflective activity and questionnaire targeting students' engagement, efficacy, and confidence with respect to the different lab related skills. This helps inform the teacher and is later used during a teacher-team feedback session.

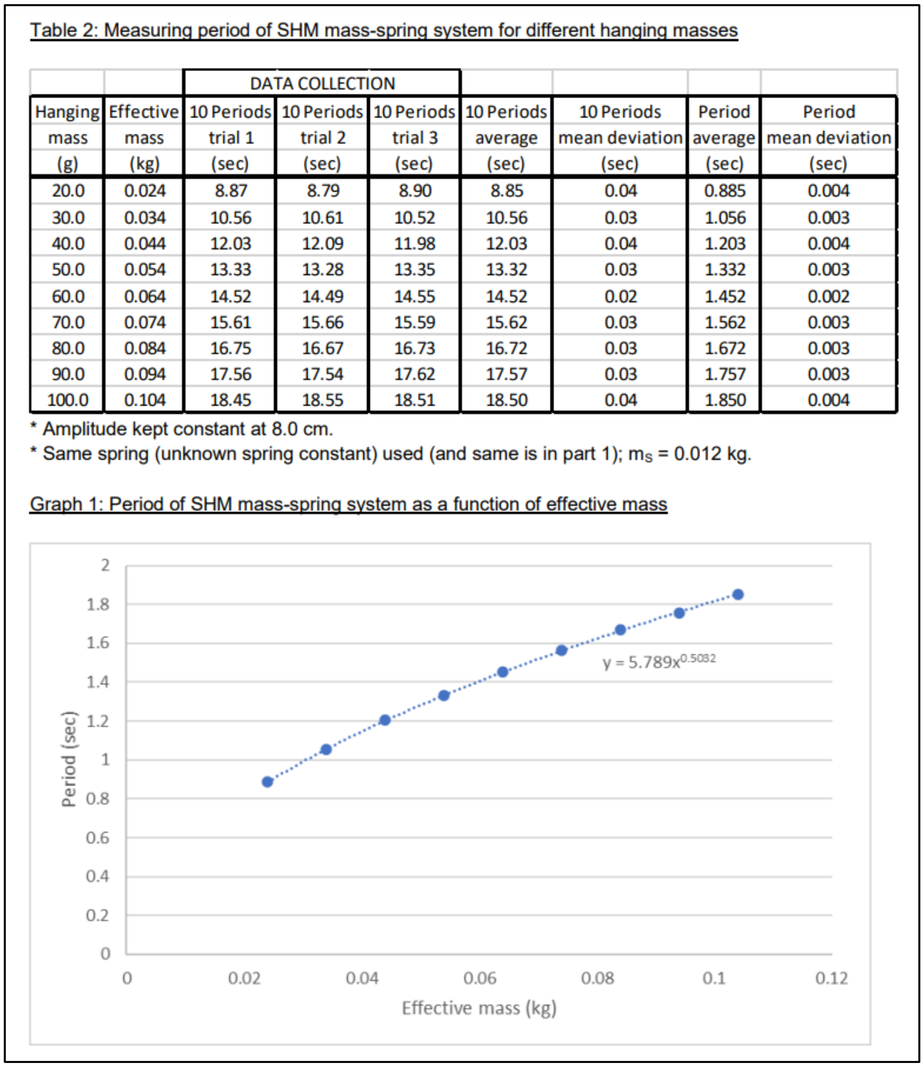


Table 2: Measuring period of SHM mass-spring system for different hanging masses

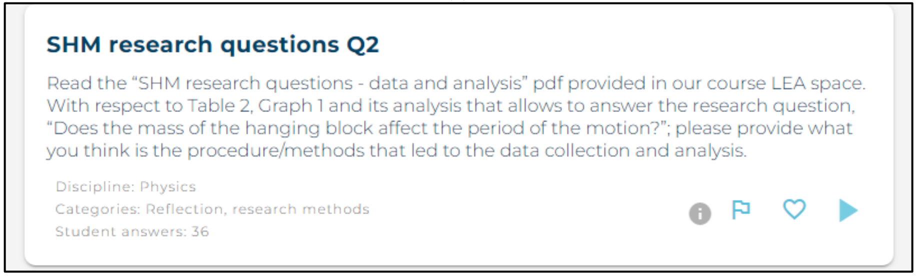
		DATA COLLECTION						
Hanging mass (g)	Effective mass (kg)	10 Periods trial 1 (sec)	10 Periods trial 2 (sec)	10 Periods trial 3 (sec)	10 Periods average (sec)	10 Periods mean deviation (sec)	Period average (sec)	Period mean deviation (sec)
20.0	0.024	8.87	8.79	8.90	8.85	0.04	0.885	0.004
30.0	0.034	10.56	10.61	10.52	10.56	0.03	1.056	0.003
40.0	0.044	12.03	12.09	11.98	12.03	0.04	1.203	0.004
50.0	0.054	13.33	13.28	13.35	13.32	0.03	1.332	0.003
60.0	0.064	14.52	14.49	14.55	14.52	0.02	1.452	0.002
70.0	0.074	15.61	15.66	15.59	15.62	0.03	1.562	0.003
80.0	0.084	16.75	16.67	16.73	16.72	0.03	1.672	0.003
90.0	0.094	17.56	17.54	17.62	17.57	0.03	1.757	0.003
100.0	0.104	18.45	18.55	18.51	18.50	0.04	1.850	0.004

* Amplitude kept constant at 8.0 cm.

* Same spring (unknown spring constant) used (and same is in part 1); $m_S = 0.012$ kg.

Graph 1: Period of SHM mass-spring system as a function of effective mass

(a)



SHM research questions Q2

Read the "SHM research questions - data and analysis" pdf provided in our course LEA space. With respect to Table 2, Graph 1 and its analysis that allows to answer the research question, "Does the mass of the hanging block affect the period of the motion?"; please provide what you think is the procedure/methods that led to the data collection and analysis.

Discipline: Physics
Categories: Reflection, research methods
Student answers: 36

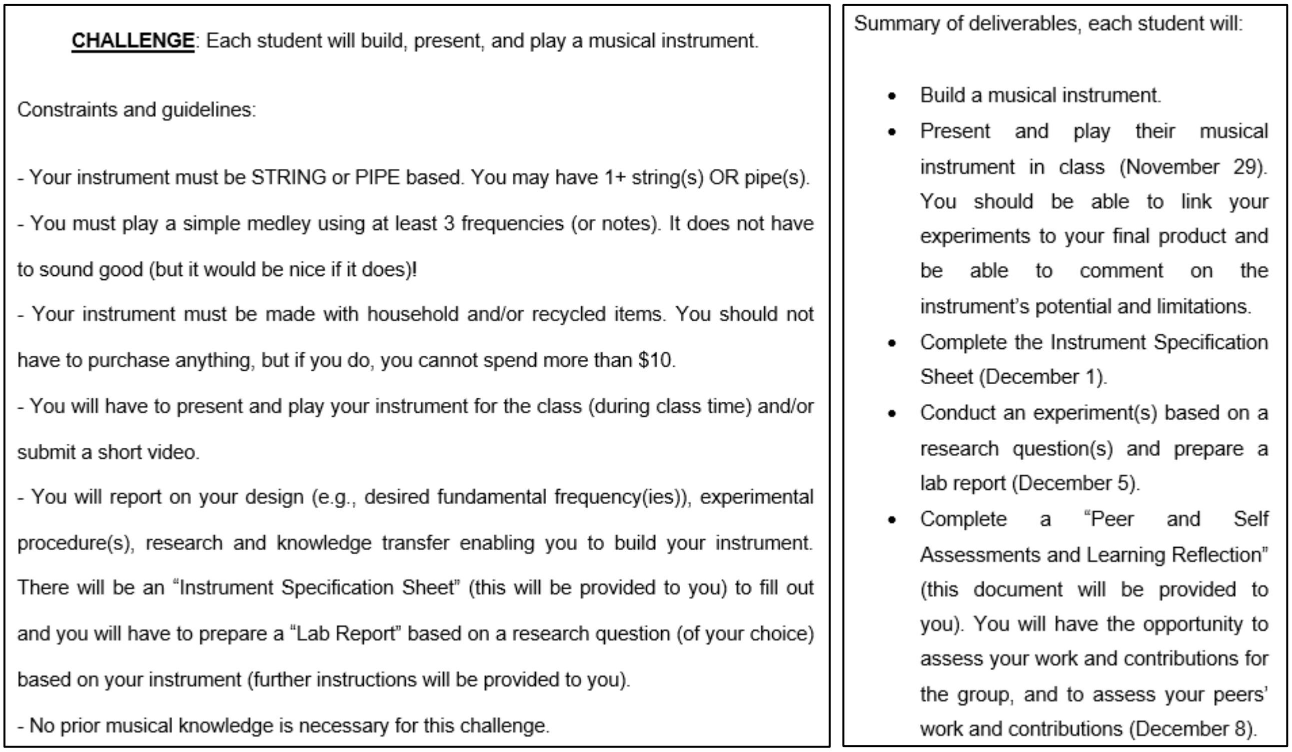
(b)

Figure 4. (a) Example of an "expert" data collection and analysis for the block-spring based simple harmonic motion experiments. (b) Example of a reflective question.

2.4. Module 4 – Building a Musical Instrument Project

The second half of the semester is dedicated to module 4. The project description is presented in class during week 6 (see Figure 5) and there is one dedicated lab period after module 3 where students can brainstorm as a team, explore lab equipment available to them, run some experiments and have a team feedback session with the teacher. During the feedback session, the teacher goes over the module 2 team lab report, highlighting the strengths and weaknesses. The teacher then addresses the reflective activity and questionnaire that concluded module 3. Last, each student is share ideas about their research question(s) that they wish to explore for module 4. Even though the students have seen examples of research questions for modules 1-3 (these act as scaffolds for module 4), this is their first attempt of proposing their own research question. Some students have difficulties formulating their ideas into an appropriate research question and the teacher's role here is to guide them (for example, many students have research questions that link the fundamental frequency of a string to its length, tension or string type). The overall goal of the feedback session is to have each student be confident that he/she can complete all tasks that relate to the project and the four lab inquiry competencies.

As mentioned before, much of the work that follows is done individually at home. The students do have access to the college lab equipment if they request it and the teacher is available to answer questions and address concerns. The deliverables of the project are listed in Figure 5 (b). The students need to build a string- or pipe-based instrument, and then present it and play it for the class. Accompanying the instrument is a "specification sheet" that includes questions about their design, their process of creation, the frequencies the instrument can play (including some calculations based on course content). In parallel, the students perform an experiment at home based on strings or pipes. The students propose their own research question, design the methods, collect and analyze data, interpret results and write a lab report. The last item to complete is a peer- and self-assessment of their and their team's work, including a learning reflection and questionnaire about IBL and the project.



CHALLENGE: Each student will build, present, and play a musical instrument.

Constraints and guidelines:

- Your instrument must be STRING or PIPE based. You may have 1+ string(s) OR pipe(s).
- You must play a simple medley using at least 3 frequencies (or notes). It does not have to sound good (but it would be nice if it does)!
- Your instrument must be made with household and/or recycled items. You should not have to purchase anything, but if you do, you cannot spend more than $10.
- You will have to present and play your instrument for the class (during class time) and/or submit a short video.
- You will report on your design (e.g., desired fundamental frequency(ies)), experimental procedure(s), research and knowledge transfer enabling you to build your instrument. There will be an "Instrument Specification Sheet" (this will be provided to you) to fill out and you will have to prepare a "Lab Report" based on a research question (of your choice) based on your instrument (further instructions will be provided to you).
- No prior musical knowledge is necessary for this challenge.

Summary of deliverables, each student will:

- Build a musical instrument.
- Present and play their musical instrument in class (November 29). You should be able to link your experiments to your final product and be able to comment on the instrument's potential and limitations.
- Complete the Instrument Specification Sheet (December 1).
- Conduct an experiment(s) based on a research question(s) and prepare a lab report (December 5).
- Complete a "Peer and Self Assessments and Learning Reflection" (this document will be provided to you). You will have the opportunity to assess your work and contributions for the group, and to assess your peers' work and contributions (December 8).

(a) (b)

Figure 5. Musical Instrument Project (a) description and (b) summary of deliverables.

3. MEASURING STUDENT SCIENTIFIC REASONING AND EPISTEMIC BELIEFS

The GIC tests were used to measure student scientific reasoning about experimental design decisions. The pre-test was conducted during the first day of class and the delayed post-test was conducted during the last week of class (see Figure 6). The comparison between the two is as follows:

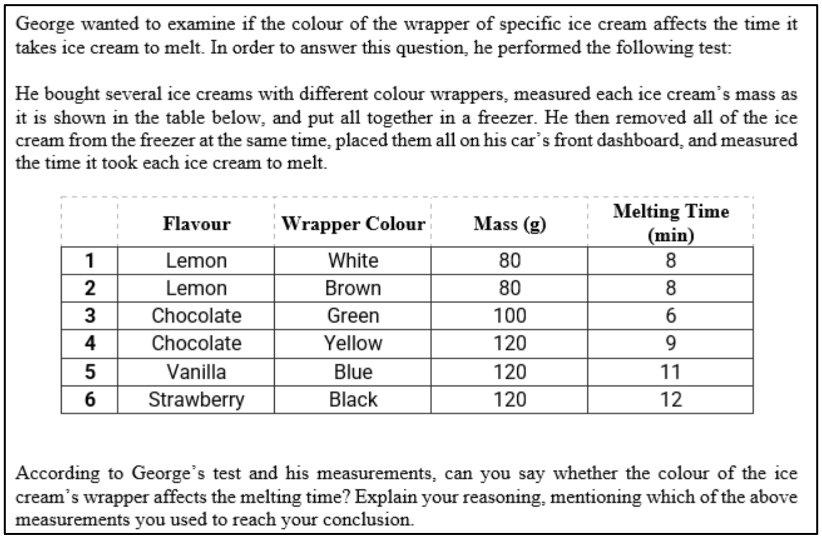
PRE-TEST:

- Majority of students could recognize that the variables were not controlled.
- Most inferred there was a dependent variable (DV), but none used the term DV.
- Most recognized that mass was a confounding variable, but none used the term.
- Half tried to explain why the results are muddled BUT did not clearly explain not being able to draw any conclusions from the data.
- Some students talked about the data that have patterns and tried to draw some conclusions even when there are so many confounding variables.
- Less than 10% explicitly said that there was insufficient data and that the experiment was flawed.

DELAYED POST-TEST:

- ALL students were able to explain the need to control variables and were able to distinguish DV and IVs (though only a few named them as such).
- All students suggested there is confounding but less than 25% stated it clearly enough to be able to code it as such (these students stated it as the need to make separate experiments).
- Main improvement – the need for more trials and suggesting a reason why.
- Half the students were explicit about needing more data to make better conclusions.

To summarize, there is a modest improvement in their explanation of the problem with George's experiment, but there appears to be more confidence in making their claim.



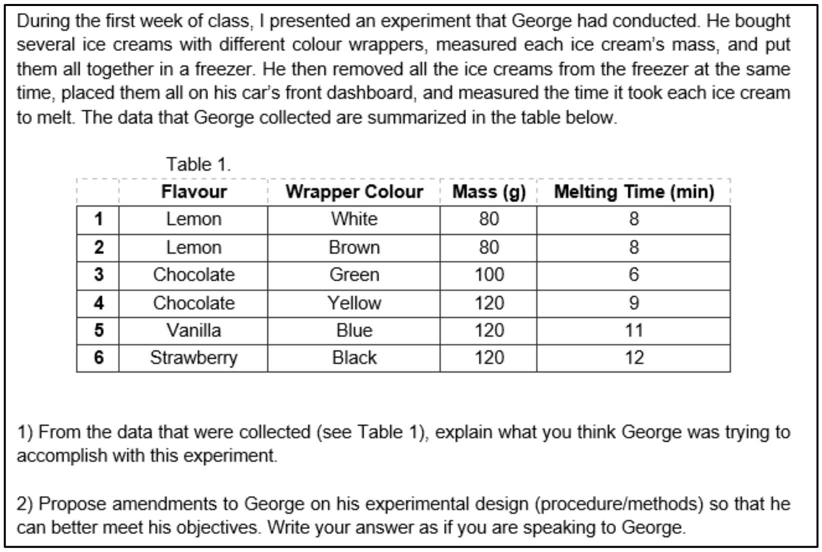
George wanted to examine if the colour of the wrapper of specific ice cream affects the time it takes ice cream to melt. In order to answer this question, he performed the following test:

He bought several ice creams with different colour wrappers, measured each ice cream's mass as it is shown in the table below, and put all together in a freezer. He then removed all of the ice cream from the freezer at the same time, placed them all on his car's front dashboard, and measured the time it took each ice cream to melt.

	Flavour	Wrapper Colour	Mass (g)	Melting Time (min)
1	Lemon	White	80	8
2	Lemon	Brown	80	8
3	Chocolate	Green	100	6
4	Chocolate	Yellow	120	9
5	Vanilla	Blue	120	11
6	Strawberry	Black	120	12

According to George's test and his measurements, can you say whether the colour of the ice cream's wrapper affects the melting time? Explain your reasoning, mentioning which of the above measurements you used to reach your conclusion.

(a)



During the first week of class, I presented an experiment that George had conducted. He bought several ice creams with different colour wrappers, measured each ice cream's mass, and put them all together in a freezer. He then removed all the ice creams from the freezer at the same time, placed them all on his car's front dashboard, and measured the time it took each ice cream to melt. The data that George collected are summarized in the table below.

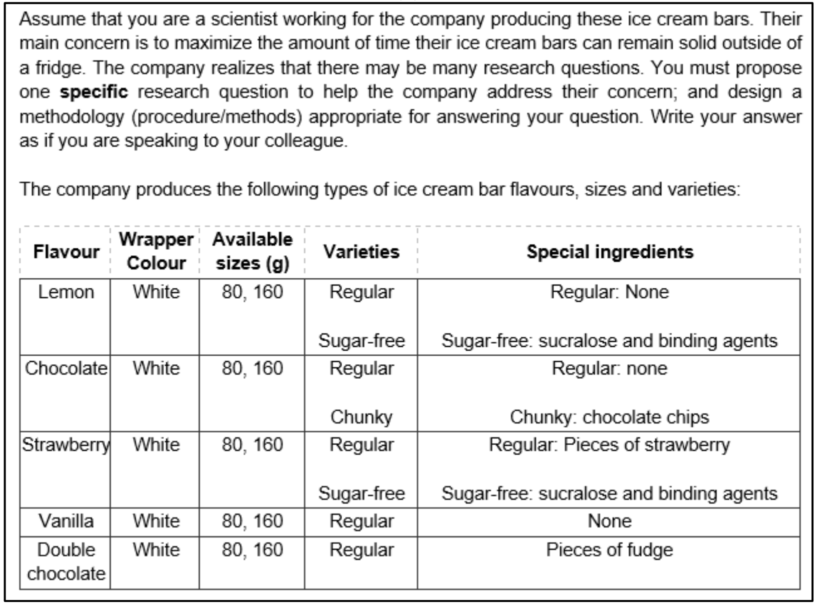
Table 1.

	Flavour	**Wrapper Colour**	**Mass (g)**	**Melting Time (min)**
1	Lemon	White	80	8
2	Lemon	Brown	80	8
3	Chocolate	Green	100	6
4	Chocolate	Yellow	120	9
5	Vanilla	Blue	120	11
6	Strawberry	Black	120	12

1) From the data that were collected (see Table 1), explain what you think George was trying to accomplish with this experiment.

2) Propose amendments to George on his experimental design (procedure/methods) so that he can better meet his objectives. Write your answer as if you are speaking to George.

(b)



Assume that you are a scientist working for the company producing these ice cream bars. Their main concern is to maximize the amount of time their ice cream bars can remain solid outside of a fridge. The company realizes that there may be many research questions. You must propose one **specific** research question to help the company address their concern; and design a methodology (procedure/methods) appropriate for answering your question. Write your answer as if you are speaking to your colleague.

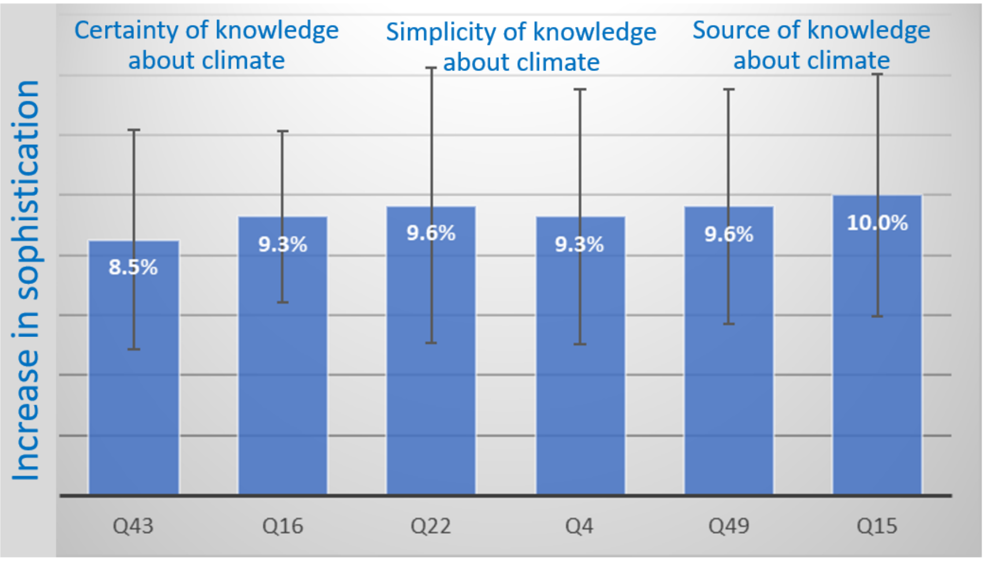
The company produces the following types of ice cream bar flavours, sizes and varieties:

Flavour	**Wrapper Colour**	**Available sizes (g)**	**Varieties**	**Special ingredients**
Lemon	White	80, 160	Regular Sugar-free	Regular: None Sugar-free: sucralose and binding agents
Chocolate	White	80, 160	Regular Chunky	Regular: none Chunky: chocolate chips
Strawberry	White	80, 160	Regular Sugar-free	Regular: Pieces of strawberry Sugar-free: sucralose and binding agents
Vanilla	White	80, 160	Regular	None
Double chocolate	White	80, 160	Regular	Pieces of fudge

(c)

Figure 6. GIC tests measuring student scientific reasoning. (a) Pre-test, (b) and (c) delayed post-test.

The same TSEB questionnaire was also conducted during the first day of class and the last week of class. The questionnaire is supposed to measure four different dimensions of epistemological beliefs about the topic of climate: certainty of knowledge about climate, simplicity of knowledge about climate, source of knowledge about climate, and justification for knowing about climate. Of the 49 questions, 6 showed an improvement when comparing the average class score between weeks 1 and 15, as shown in Figure 7. The other questions showed no statistical difference.



Q43: “The only thing we know for certain about climate problems, is that nothing is certain”

Q16: “Within climate research, truth is unchanging” (Reversed scale; improvement shown)

Q22: “Knowledge about climate consists of highly interrelated concepts rather than an accumulation of facts”

Q04: “Within climate research, facts are more important than theories” (Reversed scale; improvement shown)

Q49: “When I read about issues related to climate, I try to form my own understanding of the content”

Q15: “Ordinary people have no basis for speaking about issues concerning climate” (Reversed scale; improvement shown)

Figure 7. TSEB questionnaire, 6 questions showing an improvement when comparing the average class score between weeks 1 and 15.

4. DISCUSSION

Implementing IBL in a semester long college physics course is feasible. However, it does take careful planning and scaffolding such that the goals are attainable for students without introducing too much frustration (i.e., zone of proximal development [16]). This applies to the micro level (e.g., implementing module 1 by itself as one IBL for the semester) and to the macro level (e.g., module by module, leading to a final project). During the final week of class, students answered a questionnaire about IBL and the project. When asked, “Were the tools / equipment / online platforms / resources [i.e., scaffolds] provided as part of the labs difficult to use?,” 65% of students who completed the questionnaire said that they were easy to use. 31% said that they were sometimes difficult to use and only 4% said that they were very difficult to use.

Subjectively, the teacher of the class did feel that students were more engaged during IBLs. This was true when comparing the fall 2021 cohort when the did IBLs and non-IBLs (i.e., traditional labs), and is also true when comparing to past cohorts that did only non-IBLs. This observation may be supported by data taken from the student questionnaire. When asked, “Is this a way you would like to do labs in the future?,” 28% of the students replied, “Maybe for a few labs.” 31% replied, “Yes, absolutely for all labs in this discipline.” 35% replied, “Yes, absolutely for all labs for all science disciplines,” and 6% replied, “other.” No one replied, “no.”

Regarding grades, there was no statistical difference when comparing the overall lab grade between this IBL cohort and previous non-IBL cohorts. However, the student perception about learning physics via IBLs was positive. When asked, “Did engaging in this series of labs and tasks [IBL] help you learn Physics?,” on a 5-point likert scale, with 1 being “no, not at all,” and 5 being “yes, a lot,” 41% of the students chose 4 and 59% chose 5.

With respect to measuring student scientific reasoning about experimental design decisions and their epistemic beliefs, it is encouraging to see that there was an improvement in both. Our next steps are, 1) to analyze all the student artifacts, including the delayed post-test to observe individual student trajectories throughout the semester, and 2) to carefully measure the impact of the IBL implementation by comparing future IBL cohorts to control groups that continue with non-IBLs.

5. CONCLUSIONS

We have reported on case study featuring a design focus IBL implementation in a college Waves and Modern Physics course. Four modules span the 15-week semester and engage students in a series of scaffolded activities helping them to develop four lab inquiry competencies: a) asking a RQ, b) designing a methods, c) collecting and analyzing data, and interpreting results, and d) writing a lab report. Based on two specialized instruments, GIC tests and the TSEB questionnaire, the students showed improvements in their scientific reasoning about experimental design decisions and increased their awareness of how scientific knowledge is generated.

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