

Attending to experimental physics practices and lifelong learning skills in an introductory laboratory course

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We have designed an introductory laboratory course that engaged first-year undergraduate students in two complementary types of iteration: (1) *iterative improvement of experiments* through cycles of modeling systems, designing experiments, analyzing data, and refining models and designs; and (2) *iterative improvement of self* through cycles of reflecting on progress, soliciting feedback, and implementing changes to study habits and habits of mind. The course consisted of three major activities: a thermal expansion activity, which spanned the first half of the semester; final research projects, which spanned the second half of the semester; and guided student reflections, which took place throughout the duration of the course. We describe our curricular designs and report examples of student work that demonstrate students' iterative improvements in multiple contexts.

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I. INTRODUCTION

The design and study of undergraduate laboratory courses is an area of increasing interest in the physics education community, both at introductory^{1,2} and upper-division^{3,4} levels. Recently, the American Association of Physics Teachers released recommendations for learning outcomes of undergraduate laboratory courses, which included the ability to model systems, design experiments, and analyze data.⁵ These recommendations are in line with the cognitive tasks required for table-top atomic physics experiments⁶ as well as the scientific and engineering practices outlined in the *Next Generation Science Standards* for K–12 education.⁷ More broadly, there is growing recognition that to support student success, physics education must focus on “lifelong learning skills” such as organization,⁸ collaboration,⁹ emotional regulation,¹⁰ self-learning,¹¹ and other social and interpersonal aspects of learning.^{12,13}

We designed an introductory laboratory course that engaged first-year undergraduate students in two types of iteration: (1) *iterative improvement of experiments* through cycles of modeling systems, designing experiments, analyzing data, and refining models and designs; and (2) *iterative improvement of self* through cycles of reflecting on progress, soliciting feedback, and implementing changes to study habits and habits of mind. This course differs from typical laboratory courses in two ways. First, it is an *introductory* course that focuses on the iterative process of developing, testing, and refining models and apparatus—practices that typically feature in upper-division courses^{14,15} rather than at the introductory level⁶ (though notable exceptions exist; e.g., refinement is a major feature of introductory ISLE labs).^{16,17} Second, it incorporates a guided reflection activity⁹ that explicitly recognizes and attends to social and interpersonal aspects of learning. This explicit attention is in contrast to

most courses, introductory or otherwise, which rely on a “hidden curriculum” that students must master in order to be successful.¹⁸

In this paper, we describe our curriculum in detail using examples of student work to help clarify the nature of the course. Evaluation of the impacts of the course is beyond the scope of the present work. Our discussion is organized as follows: programmatic context for the course is provided in Sec. II; the design and implementation of activities related to our two course goals are described in Sec. III; and Sec. IV provides a summary of our work. Throughout Sec. III, we provide examples of student work to illustrate how our course *Intro to Measurement* engaged students in iterative improvement of experiment and self.

II. PROGRAMMATIC CONTEXT

We describe a course, *Intro to Measurement*, that was designed¹⁹ as part of The Compass Project at the University of California, Berkeley (hereafter, “Compass”). Established in 2006, Compass is a student-led initiative that aims to increase retention of students from underrepresented groups in the physical sciences by fostering a supportive community of graduate and undergraduate students.²⁰ Compass offers three major programs to first- and second-year undergraduate students: a residential summer program for incoming students (cf. Ref. 21); academic-year coursework that engages students in model-based reasoning and self-reflection (elaborated herein); and mentorship that starts in students' first year and may continue throughout their undergraduate experience. Students who complete the summer program are strongly encouraged to participate in subsequent coursework and mentorship.

Undergraduate students in Compass comprise a group that is more diverse than the Berkeley Physics Department as a whole. For example, of the 134 students who completed the Compass Summer Program from 2007 to 2015, 43% were women, 40% were from underrepresented minority groups, and 31% were first-generation college students. In contrast, in 2012, only 21% of Berkeley physics majors were women and 7% were underrepresented minorities, consistent with national trends.²²

We report student work from the second implementation of Intro to Measurement, during which ten students were enrolled in the course (eight students consented to use of their coursework for publication purposes²³). Enrollment was open to students who completed the Summer Program as well as first-year students from the Physics Department more generally. As a result, representation of women and underrepresented minority students in this small population was more similar to the demographics of the Physics Department than those of Compass: of 8 research participants, 2 were women, 1 was a member of an underrepresented minority group, and 2 abstained from reporting demographic information. In addition, of the 6 students who provided demographic information, 3 reported having a disability, 1 identified as a first-generation college student, and 1 identified as a gender or sexual minority.

The structure of both organizational and educational aspects of Compass is informed by four community values: student ownership, collaboration, supporting students as “whole people,” and improvement through iteration.²⁰ While each of these values features in Intro to Measurement, here we focus on the ways in which our course engaged students in iterative improvement.

III. CURRICULUM DESIGN

Intro to Measurement met for 2 h once weekly for a 14-week semester (28 h total) with ten students and two graduate student co-instructors. The course was designed for students to spend an additional 3 h per week working on assignments outside of class (42 h total). Two major objectives of the course were for students to engage in: (1) iterative improvement of experiments, through cycles of designing and refining systems and system models; and (2) iterative improvement of self, through cycles of reflection, feedback, and growth.

Our curricular design was influenced by *Complex Instruction*,²⁴ a set of strategies that promote equity in heterogeneous classrooms, and *Constructionism*,²⁵ a philosophy

that emphasizes learning through the construction of public artifacts that are shared with a community of peers. Along these lines, students worked in groups with well-defined roles on experimental tasks that were challenging and open-ended, and the course culminated in a final research project and poster session—features that can also be found in other non-traditional introductory lab courses.²⁶ Further, the course was designed to promote self-learning¹¹ and provide students with social and interpersonal support.¹² To this end, students were regularly required to submit written reflections on their growth as learners and they received individualized instructor feedback on each reflection.

In this section, we describe the curriculum in three parts (Fig. 1): a thermal expansion activity (Sec. III A), which spanned the first half of the semester; final research projects (Sec. III B), which spanned the second half of the semester; and guided student reflections (Sec. III C), which took place throughout the first 11 weeks of the course. In each subsection, we provide examples of student work, such as the particular revisions students made to the thermal expansion apparatus and samples of student reflections.

A. Thermal expansion activity

During the first half of the semester, students performed experiments with a thermal expansion apparatus that has been described in detail elsewhere.²⁷ The purpose of these experiments was to provide students with opportunities to engage in the iterative process of designing, conducting, and refining experiments, in alignment with our first course objective.

The experimental apparatus consisted of a taut horizontal wire from which a hanging weight was suspended (Fig. 2). The wire expanded when heated, causing the hanging weight to drop lower to the ground. By measuring the temperature of the wire and change in height of the mass, one could use this apparatus to determine the wire’s coefficient of thermal expansion. However, the wire’s elasticity, mass, and kinks contribute to important systematic effects that may need to be taken into account depending on the desired accuracy and precision with which the thermal expansion coefficient is to be measured.²⁷ This experimental apparatus is appropriate for an introductory lab course because the underlying principles and concepts (gravity, tension, elastic stretching, thermal expansion, and Newton’s second law) are accessible to students with an introductory physics background. The apparatus was the focus of several complementary activities in

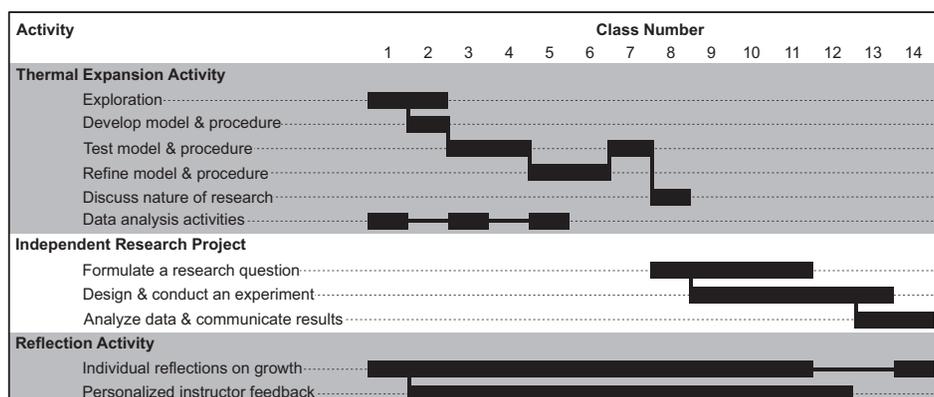


Fig. 1. Timeline of course activities.

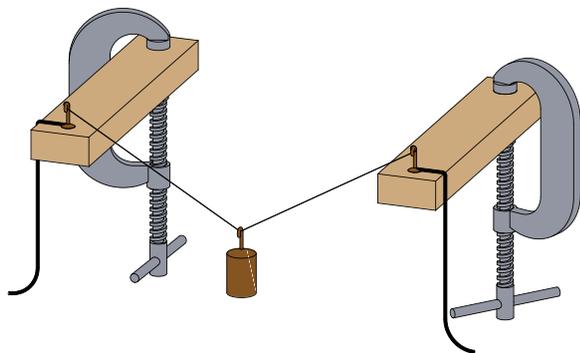


Fig. 2. Thermal expansion apparatus. The ends of a wire are attached to blocks of wood via small metal hooks. Both blocks are fastened to a level, rigid surface (not shown) via C-clamps. Insulated copper wires are attached to the hooks to facilitate electrical connections to an ac power supply. Temperature is controlled by varying the current in the wire. This apparatus has been described in greater detail elsewhere (Ref. 27).

which students engaged during this first phase of the course: exploration of the apparatus and related concepts; development, testing, and refinement of models, apparatus, and data-taking procedures; discussions about the nature of research; and inquiry-based data analysis tutorials.

During the initial exploration activity (class 1), students rotated through five hands-on research stations. At these stations, students:

- (1) used a metal ring, metal ball, liquid nitrogen, and blow torch to gain experience with the phenomenon of thermal expansion;
- (2) used a rubber band, heating lamp, and computer-aided data acquisition system to gain experience with the contraction of materials upon heating;
- (3) used thermocouples to measure resistive heating by making temperature measurements of a wire that was connected to a voltage source;
- (4) measured changes in the stretched length of a vertically hung rubber band when loads of different masses were attached to the bottom end; and
- (5) observed and documented the shapes of hanging chains, wires, and strings when loads of different masses (including zero mass, i.e., no load) were attached to the midpoint.

Each station was accompanied by a short description of the phenomenon of interest as well as instructions for relevant equipment. These investigations provided shared experiences students could draw upon to be successful later in the course, reducing disparities in prior knowledge. For example, the fifth station provided a foothold for future class discussions about whether and when the mass of the load in the thermal expansion experiment was “heavy enough” that the wire’s mass could be neglected.

In class 2, students were given the thermal expansion apparatus (Fig. 2) and tasked with designing their own experimental procedure to measure the thermal expansion coefficient of the wire. Students used their experimental procedures to collect an initial round of data the following week (class 3). In class 4, they developed an initial theoretical model to analyze their data. The model, which was algebraic in nature and neglected the mass and elasticity of the wire,²⁷ was developed through a combination of small- and large-group discussions. Throughout this process, instructors engaged students in data analysis tutorials both in and out of class. Tutorials

focused on basic statistical concepts (like averages, variances, and uncertainty propagation) as well as on the use of spreadsheet software to automate analysis of data.

Prior to class 5, students’ initial theoretical model neglected the wire’s mass and elasticity. In classes 5 and 6, students used their previously collected data to inform refinements to their models and experimental procedures. Refinements were discussed and agreed upon in small- and large-group discussions. Prior to discussions, instructors seeded ideas about which assumptions of the model to question by making anecdotal observations during data collection, such as noting that the wire hangs in a triangle even at room temperature, which cannot be explained by thermal expansion effects alone.²⁷ These comments often referred back to the exploratory activities that students completed during the first class, such as the station that involved observing and documenting the shapes of hanging chains and wires, both in loaded and unloaded conditions.

The focus of classes 5 and 6 was on characterization of effects not included in students’ original model. During class 5, students discussed potential sources of uncertainty and systematic bias in their measurements. By the end of the class, students reached consensus that they would split into three groups to perform the following tests:

- modify the apparatus in order to facilitate more precise measurements of the height of the hanging mass, and repeat the experiment with the original procedure;
- measure the elastic stretching of a room temperature wire under loads of various mass in order to determine whether elastic effects are negligible compared to thermal ones;
- measure changes in height of the hanging mass at room temperature after repeated cycles of heating and cooling the wire, all in order to determine whether plastic deformation of the wire can be neglected.

These follow-up tests—involving refinements of apparatus, model, and data-taking procedures—were conducted during class 6. Collectively, they form the second iteration of the thermal expansion experiment. The first group modified the experimental apparatus by placing a small mirror behind the hanging mass in order to minimize parallax errors when using a ruler to measure the height of the load. The second group found that they must use a load that is sufficiently heavy that the wire hangs in a triangle (i.e., the mass of the wire is negligible in comparison), but sufficiently light that thermal expansion dominates elastic stretching for temperatures achievable in the classroom. The third group determined that the effects from the stretching out of kinks in the wire over time were negligible given the measurement uncertainties.

The results from class 6 informed students’ third and final iterations of the experiment, conducted during class 7. Through a combination of small- and large-group discussions, the class decided to incorporate elastic stretching into their model for the length of the wire. In addition, they chose to repeat the experiment with a heavier mass. Thus, the third iteration of the experiment involved refinements of both the model and the apparatus.

During their final discussion of the experiment, students discussed the iterative process of using data and uncertainty to inform improvements on their model and experimental procedure. A key discussion topic was the role of iterative improvement as a general feature of scientific research.

B. Final research projects

In the second half of the course, students engaged in seven-week-long independent research projects (Fig. 1). The purpose of these projects was to provide students with additional opportunities to engage in the iterative process of experimental physics, in alignment with our first objective for the course. The details of research projects were highly idiosyncratic to the interests of the students involved, the resources available at Berkeley, and other context-dependent factors. Therefore, we only provide a brief description of the projects, focusing on aspects that could be implemented at other institutions.

During the eighth week of instruction, students were provided with a list of potential research topics. During class 8, they self-sorted into groups of 3–4 students who shared a common interest in a particular topic. After students had chosen their groups and research topics, each group was paired with a graduate student volunteer who acted as a research advisor. Once per week during classes 9–14, students met with their research advisors to discuss progress on their projects.

Under the guidance of their research advisors, students generated their own research projects related to their topic of interest. The research projects generated by students involved:

- measuring the thickness of oil on water using thin-film interference patterns;
- measuring the speed of light using a microwave and marshmallows;
- measuring the angular velocity of Earth's rotation about its axis using shadows; and,
- comparing diffusion rates in one and two dimensions using scents in tubes and ink blots on paper.

An example of the apparatus developed to measure diffusion rates in two dimensions is shown in Fig. 3.

Each group designed a unique experiment that was iteratively improved through multiple initial trials. In many cases, early results forced students to revise their initial research goals. As the project deadline approached, students analyzed the data they had collected and compiled their conclusions into a final report. In addition, students communicated their findings to the broader Compass community via a poster session at the end of the semester.

C. Guided student reflections

As part of their homework for Intro to Measurement, students were required to write weekly reflections about their college experiences. In other contexts, student reflection has been connected to students' development of problem-solving skills,²⁸ content knowledge,²⁹ conceptual understanding,³⁰ and attitudes about physics.³¹ In particular, reflection has been recognized as beneficial for learning in laboratory contexts.³² The purpose of reflection in our course was to focus students on the iterative improvement of themselves as learners, by helping them develop and improve their lifelong learning skills.

Weekly reflections were assigned only during the first 11 weeks of the course so that students could focus on their final projects during the final 3 weeks (Fig. 1). To help guide their reflections, students were given a rubric of ten lifelong learning skills such as organization, collaboration, persistence,

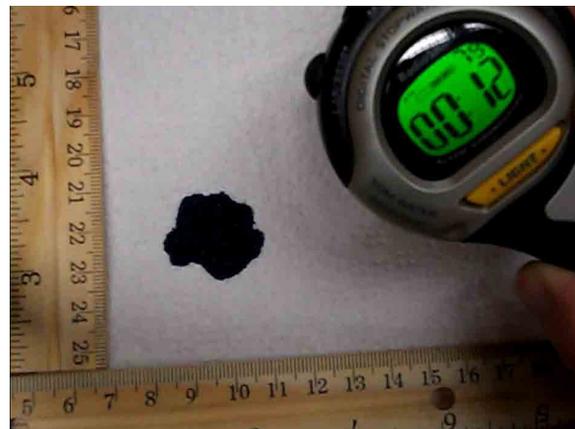


Fig. 3. Apparatus for measuring diffusion rates in two dimensions using ink blots on paper. Students placed a drop of dye on a horizontal sheet of paper towel. They recorded the diffusion of the dye through the paper towel with a video camera and used their data to measure the spot size as a function of time.

and self-compassion. The rubric was designed to encourage students to monitor their progress in developing these skills, set goals, and make plans to meet their goals—i.e., to support the types of iterative reflective practices associated with self-regulated learning.³³ To this end, the rubric defined each of the lifelong learning skills as well as what it means to be beginning, developing, or succeeding at the practice of each skill. The rubric further included prompt questions that students could use to help structure their reflections. The full rubric is included as supplementary material for this article.³⁴

In addition to weekly reflections, students were required to write a final, summative reflection at the end of the semester (class 14). The final reflection included additional prompts to the questions listed on the rubric. In their final reflection, students were asked to: (1) describe their growth as learners over the course of the semester, drawing on grades and their weekly reflections as two complementary measures of growth; and (2) discuss sources of uncertainty and/or bias in these two measures of growth. One goal of the final reflections was to encourage students to reflect on their growth on timescales longer than 1 week. A second goal was for students to use experimental physics concepts like uncertainty and bias when evaluating their grades and reflections.

Timely, supportive feedback has been shown to promote self-regulated learning.³⁵ In addition, students' perception that they are being groomed for success (rather than weeded out) has been shown to promote retention in the sciences.³⁶ Accordingly, instructors responded to students' weekly reflections with individualized feedback that provided both instructive and affective support (final reflections did not receive feedback). Instructive feedback typically involved suggesting strategies and pointing students to resources. Consider the following example of strategic feedback:

“[M]ake sure you get the most out of every problem you do. What I mean is to take a few moments after you read a problem and think generally about what concepts or techniques might be useful before you start working. After you finish the problem, reflect on what you did.”

In this example, the instructor encouraged the use of metacognitive strategies like planning and reflecting.

Affective feedback focused on supporting students through personal struggles they faced. In these instances, instructors wrote responses that were affirming, empathizing, or normalizing in nature. For example:

“Figuring out that it is okay and even beneficial to drop a class is something that is hard to deal with. I know this is something I struggled with as a student.”

Here, the instructor empathized with his/her student’s difficult decision to drop a class. Further, the instructor normalized the student’s experience by stating that the instructor, too, has had to come to terms with dropping classes. Almost all instructor responses included some aspect of affective and instructive support.

Below, we characterize the content of the weekly reflections. In addition, we highlight reflections from two students, Taylor and Micah, to illustrate how this activity facilitated iterative improvement of self.

1. Content of weekly reflections

To characterize the content of the student reflections, we analyzed 73 weekly reflections completed by eight students over 11 weeks (completion rate of 83% of 88 possible reflections). In order to characterize what skills students were reflecting on, we looked for explicit mention of rubric-related skills. When skills were not mentioned explicitly, we looked for rubric-related language from which a skill could be inferred. In 54 of 73 reflections, students explicitly stated the skills they were focused on (e.g., saying “this week I will focus on self-compassion”). In 12 of the remaining 19 reflections, students used language directly from the rubrics without explicitly stating the skill (e.g., writing about “frustration” reflects language in the persistence skill prompt). The remaining seven reflections did not follow the prompt for any particular skill. Students were not limited to one skill per reflection; in fact, almost a third of all reflections contained two or more learning skills.

The most popular skills for reflection were organization (35% of 73 total reflections), collaboration (18%), persistence (15%), self-compassion (9%), and courage (8%). The other skills were only reflected on a few times each. Thus, more than half of the reflections focused on just three skills: organization, collaboration, and persistence. These trends are consistent with other work that demonstrates that first-year college students struggle with organization generally and time management in particular.^{8,13} Indeed, reflections related to organization focused primarily on time management.

Most reflections about organization referred to time management specifically; others used phrases like, “I want to be efficient with the little time I’ve got” or “I did not have the time to keep up with my work.” Most students were not used to the workload of college, and struggled to keep up. Students made statements such as

“Due to the volume of work to be done (and the limited length of time), I sometimes find myself going through the motions ...”

and

“I stayed up all night and managed to get 2 and a half hours of sleep last night.”

Reflections about collaboration focused on working with other students, such as in a study group, or during office

hours. In contrast, reflections about persistence did not have any clear themes. Students reflected on many different areas, such as not giving up on long homework assignments, personal difficulties staying focused on schoolwork, and continuing towards a college degree despite feeling unsuccessful.

2. Taylor’s weekly reflections

Taylor engaged in iterative improvement of self over the course of a multi-week interaction with one of the instructors. Through this interaction, the student was able to shift his/her model of learning from seeing *struggle as a sign of weakness* to seeing *struggle as a sign that learning was taking place*. We provide two snapshots of Taylor’s reflections, from classes 3 and 6, to show the type of change that took place. We also provide one example of teacher feedback that seemed pivotal in supporting Taylor’s iteration on their model of learning.

During their reflection for class 3, Taylor described feeling self-doubt and uncertainty when getting stuck on a physics problem:

“Self-doubting still haunts me whenever I am trying to solve physics problems. ‘Am I thinking this right?’ this is a big question to me every time I am stuck in solving certain problems. It gives a strong sense of insecurity that my logic or intuition is wrong. I will convince myself to get help from others and get my problem resolved. But not quite, because I will end up thinking why I did not think of that or in the same way as they see the problems. Also, before I know that I answer a question correctly, uncertainty is still instilled in me. Another question hits me, ‘How can I know that I am correct?’ If during exam I have no one to refer or to compare with, how can I know that I am right?” (Taylor, Class 3)

The model of learning that seems to underlie this exposition is that success comes quickly for physicists (and capable physics students), and that one should feel certain in their answers. In the context of this model of learning, Taylor felt haunted by self-doubt when getting stuck solving a problem, which was associated with a feeling of insecurity. This self-doubt is also evident in the way Taylor spoke about seeking help from other students: rather than feeling better that the problem was resolved, Taylor questioned their own abilities (“I will end up thinking why I did not think of that”).

Taylor and the instructor discussed these feelings over a number of weeks. For example, after class 5, the instructor provided the following feedback:

“[I]t took me a while to understand when I was an undergrad was that the feeling of struggling with material is actually a good thing. Every time you struggle in a class, you learn something. It is important to struggle with problems and concepts to develop as a physicist. You also want to use your peers and instructors as resources to make the struggle as efficient and effective as possible. You don’t have to do everything alone, although struggling for a short amount of time alone can be beneficial.” (Instructor, Class 5)

In this response, the instructor *empathized* with Taylor, saying he (the instructor) had similar feelings as an undergraduate. The instructor also worked to *normalize* struggle,

saying that struggle is an important part of learning and developing as a physicist. This response resonated with Taylor and helped them iterate on their model of learning. This iteration is evident in Taylor's reflection from the following class, which Taylor wrote after taking a physics midterm:

"Last week midterm was tough, as expected. I struggled, like some of my classmates. The moment I felt upset for underperformance, your words reminded me that struggle is good; it means that you are learning something. Immediately I avoided my tendency to get frustrated and tried to study my mistakes and think of a better thinking skill to tackle problems." (Taylor, Class 6)

Taylor's response to struggling was now markedly different from before. Rather than taking struggle as a sign of inadequacy, Taylor leveraged their struggles as an opportunity to learn more.

This example is a clear instance of how reflection can help students iterate on their models of themselves as learners. Initially, Taylor viewed struggle as a sign of weakness, which was detrimental to their success. Through reflection and instructor feedback, Taylor revised their model for learning, instead viewing struggle as a tool for learning. This type of iteration allowed Taylor to improve their practices associated with learning, ultimately supporting them as a lifelong learner.

3. Micah's final reflection

While Taylor used the weekly reflections to iterate on their model of learning, Micah used the final reflection to discuss failure and iteration in learning using language and ideas from experimental physics. In their final reflection, Micah noted that tests provide a "composite score" of both knowledge and other factors:

"[T]ests, to me, are experiments where the independent variable is my knowledge and the dependent variable is my raw score. The test is a tool that I use to measure my knowledge but for me, being a disabled student, is also a source of error. There are a lot of uncertainties: the writing of the test, the amount of accommodations that I have ...and the availability of my textbooks being in an accessible format. These systematic biases lead to my tests being a composite score of how I am advocating for myself in terms of accommodations, my knowledge of the material, and the educational institutions ability to accommodate me and other disabled students."

Here, Micah drew connections between tests and experiments by identifying tests as tools for measuring knowledge. Micah further identified a mapping between accessibility issues and systematic biases, drawing on language and concepts from experimental physics in the process (e.g., independent and dependent variables, error, uncertainty, and systematic bias). According to Micah, the outcome of a test is an imperfect measurement of knowledge because Micah's ability to advocate for accommodations and the university's ability to provide accommodations also contribute to the composite score.

The idea that tests provide a composite score of both knowledge and accommodations is similar to the idea that the thermal expansion apparatus provides a "composite measurement" of both thermal and elastic effects. Using Micah's mapping, improving the thermal expansion experiment by controlling for elastic effects is similar to improving a testing experience by securing appropriate accommodations. Indeed, Micah described precisely this iterative process for improving the testing experience in Calculus I. In their final reflection, Micah noted that they failed a Calculus I midterm in the Fall semester, prior to enrolling in Intro to Measurement:

"I understood how to do calculus but I just didn't have the necessary tools to 'do the experiment', [so to] speak. ... Finally, after being recommended multiple times by the DSP [Disabled Students' Program] staff to drop the class, I did. It felt like I was giving up. The experiment had failed. ... When November came around, I knew I needed to get my accommodations ready for [the Spring] semester. I emailed the DSP staff and the California Department of Rehabilitation and coordinated the accommodations that I needed for the next semester. I would take [Calculus I] again and attempt to succeed. I would rerun my experiment correcting for error. During the remainder of the Fall semester, I focused on getting ahead for [Calculus I] and coordinating my accommodations."

After failing the midterm, Micah dropped Calculus I. However, Micah felt that their low test grades were not a pure measurement of their knowledge, but a reflection of inadequate accommodations. After dropping the course, Micah took steps to "rerun" an improved version of the "experiment" by re-enrolling in Calculus I during the Spring, after putting in place the necessary accommodations for their disability. Thus, Micah was able to use a model of grades as measurement to reinterpret the meaning of failure in their initial attempt at Calculus I.

Micah described their experience in the Spring as follows:

"When it came to the spring semester, I established my accommodation base, although it was fairly flawed in many ways, but still better than none at all. [Micah described specific accommodations.] When I took my first midterm, I got a B. ...I took the accommodation lesson (using proper tools) ...in order to get a score that was more accurate to my understanding of calculus."

Here, Micah described a cycle of iterative improvement. In preparation for the first calculus test in the Spring semester, Micah minimized accessibility-related "systematic biases" by establishing a base of accommodations. Micah referred to this improvement as "using proper tools." By using the proper tools for their experiment, Micah was able to earn a B on the test. Because Micah had minimized systematic biases contributing to their test score, they felt that this grade was a more accurate measure of their knowledge of calculus.

In Micah's final reflection, we see how the ideas of iterative improvement of experiment and self can be intertwined to form self-narratives that allow for the reinterpretation of failure. Through viewing test scores as an approximation of

their knowledge rather than a true representation, Micah constructed counter-narratives about their own ability to succeed as a physics student.

IV. SUMMARY

We have described the design and implementation of Intro to Measurement, an introductory laboratory course in which first-year undergraduate students engage in two types of iterative improvement: on experiments and on oneself. First, the course provided students multiple opportunities to engage in the type of iterative, model-based experimental physics tasks that are more typically found in upper-division lab courses^{3,4} than in introductory ones.⁶

Second, Intro to Measurement provided students with opportunities to engage in iterative cycles of reflection, feedback, and growth—a process that is connected to self-regulated learning^{33,35} and retention in the sciences.³⁶ During weekly reflections, students wrote about their development of one or more lifelong learning skills, with a major focus on organization, collaboration, and persistence. We demonstrated how individualized feedback from instructors supported one student, Taylor, in making changes to their understanding of the relationship between struggling and learning.

Finally, we showed how a second student, Micah, synthesized the ideas of iterative improvement of experiment and self to construct a narrative about an experience of failure in an educational context. In this narrative, Micah interpreted test scores as composite measurements of both knowledge and issues related to accommodation of their disability; for this student, iterative improvement of self-involved minimizing systematic bias in test scores by addressing their accommodation needs.

Thus, Intro to Measurement is an example of an introductory laboratory course that engaged students in authentic physics practices while simultaneously attending to the social and personal aspects of learning that are important for first-year undergraduate students. Nevertheless, several open questions remain. To what extent does this course format support all students in drawing connections between experimental physics and learning, as Micah has done? And how might such connections benefit students, especially those from marginalized groups, in reinterpreting experiences of failure, advocating for institutional support, and persisting in the physics major? While these questions are beyond the scope of the present work, they may inform longitudinal studies of Intro to Measurement in the future.

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Differential Thermophile

This is one of many pieces of late nineteenth apparatus that are preserved at St. Mary's College in Notre Dame, Indiana. Alternating bars of bismuth and antimony are clamped side by side, and adjoining bars of dissimilar metals are soldered together at their ends, thus giving a set of thermo-junctions connected in series. In use, each end is pointed toward a different thermal source, and the output signal is dependent on the difference of their two temperatures. This example is by Ducretet of Paris. (Notes and picture by Thomas B. Greenslade, Jr., Kenyon College)