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Unpacking Iteration: Exploring Forms of Iterative Practice in Physics Labs

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Abstract: Iteration is pervasive in current perspectives of student reasoning, but it is also often assumed, backgrounded, or minimized in favor of other empirical interests and results, despite being foundational to reasoning processes and inquiry. This paper forefronts iterative practice while examining student reasoning in a reform-based undergraduate physics lab course. We present an instrumental case study analysis of a single student group, documenting how they engaged in micro- and macro-levels of iterative practice at the nexus of experimental activity and sensemaking throughout their experimentation. These results illustrate the nuance in students' iterative practice at different levels and prompt new questions about how different forms of iterative practice may impact student learning.

Background and Theoretical Perspectives

In the Learning Sciences, there is widespread recognition of the importance of iteration. Iteration occurs as part of student reasoning within engineering design (e.g., Smith & Tjandra, 1998), scientific modeling (e.g., Windschitl et al., 2008), makerspaces (Ramey & Uttal, 2017), argumentation (e.g., Herrenkohl & Cornelius, 2013), and experimental physics (e.g., Holmes & Wieman, 2016). However, iteration is often assumed without extensive definition or backgrounded in favor of other empirical results. For example, Windschitl et al. (2008) describe an iterative framework for scientific modeling but do not empirically investigate the iterative elements of the framework in learning contexts. Thus, we have limited knowledge about the structure of iteration and its relationship to larger reasoning processes. This paper aims to shed new light on iterative practice in student reasoning by presenting an instrumental case study analysis of students' iterative practice at the nexus of experimental activity and sensemaking in a reform-based undergraduate introductory physics laboratory course. We highlight how a focus on iterative practice may serve as a conducive mechanism for analyzing complex student reasoning in scientific learning environments.

Experimental Activity and Sensemaking in Physics Labs

We define iteration as a successive process that builds and improves upon previous outcomes of theory, design, or experimentation (e.g., Elliott, 2012). While many forms of iterative practice abound, we rely upon experimental and epistemic iteration, the processes by which scientists repeat experimental steps to improve empirical results or protocols (Collins, 1992) and successively alter and refine scientific knowledge to improve accuracy or explanatory power (Chang, 2004). These constructs help conceptualize how iteration might be prevalent in students' experimental activity and sensemaking.

We conceptualize experimental activity as a hierarchical process composed of macro- and micro-level activities. At a macro-level, experimental activity involves students carrying out broad experimental actions, such as making predictions, data collection, troubleshooting, and data analysis, in the lab setting to complete experimental goals (e.g., Wieman, 2015; Zwickl et al., 2015). These macro-level actions are composed of micro-level experimental actions, such as preparing apparatus and adjusting software parameters. Each hierarchical level can evoke iteration, whereby students repeat experimental steps to increase accuracy or explanatory power. For example, at the macro-level, students can experimentally iterate between making predictions, collecting data, and comparing measurement results to predictions to produce more accurate scientific models. At the micro-level, students engaging in troubleshooting can iterate between identifying issues with apparatus, generating and testing causes, and repairing apparatus or procedures (Dounas-Frazer et al., 2016). While prior research has documented these experimental activities in physics labs (e.g., Wieman, 2015; Zwickl et al., 2015), they often minimize iteration and implicitly obscure authentic accounts of student experimental activity.

We conceptualize sensemaking as a process of iteratively constructing and critiquing explanations and procedures to resolve inconsistencies through developing a knowledge framework, recognizing an inconsistency, and enacting sensemaking moves such as mechanistic reasoning and analogy building (Odden & Russ, 2018; 2019). Students frequently engage in sensemaking processes during both macro- and micro-level experimental activity. For example, troubleshooting involves iterating between the micro-level actions to identify and resolve procedural inconsistencies. Similarly, students often iterate between conceptual and experimental elements while sensemaking at the macro-level to recognize and resolve inconsistencies between experimental evidence and hypotheses. We suspect that students' iterative practice is simultaneously experimental and epistemic, allowing improvement of experimental results and generation of new conceptual knowledge.

We ask the following research question: In what ways do undergraduate students engage in iterative practices at the nexus of their experimental activity and sensemaking in undergraduate physics lab settings? To answer this, we examined thirteen student groups' experimentation in a reform-based undergraduate physics lab course. To provide a detailed analysis, we present an instrumental case study of a student group, highlighting their iterative practice at the macro- and micro-levels of experimental activity and sensemaking.

Research Methods

This study was conducted in an Introductory Physics for Life Sciences (IPLS) laboratory course at a large, research-intensive university in the western United States. The course was recently reformed to prioritize students' autonomous engagement in authentic scientific experimentation. Enrolled students were predominantly life science majors who planned on attending medical school. The student population was majority upper-division (86%), white (67%), and male-identifying (53%). In the course, students work in groups to complete multi-week investigations by developing research questions and experimental designs to model a biological phenomenon, conducting the experiment, and developing and presenting a scientific argument to their peers and instructors.

Data from 13 groups across four labs included screen capture data of their computers and external video and audio. We first identified macro-level categories of students' experimental activity composed of micro-level actions; for instance, macro-level data collection composed of micro-level actions of adjusting experimental equipment, reviewing technical documentation, or preparing biological samples. These categories were used to code random selections of the video data, and we refined the categories until reaching saturation. Two authors then conducted interrater reliability measurements, achieving near-perfect agreement (κ=0.83) after a single round of coding changes. The first author then coded the remaining data. Next, we reviewed the coding to identify the entry (inconsistencies) and exit conditions (resolutions) in students' sensemaking. We identified sensemaking episodes related to both micro-level procedural and macro-level conceptual inconsistencies and then examined how students worked towards resolutions. We focused on both direct sequences of actions and iterative cycles across multiple actions and searched for instances where students iterated between collecting evidence, analyzing data, engaging in mechanistic reasoning, or constructing explanations (e.g., Odden & Russ, 2018).

To provide an in-depth analysis of students' iterative practice, we present an instrumental case study analysis of iterative practice from a group of four students (Lisa, Chloe, Margo, and Edmund; pseudonyms) whose iterative practice broadly represented the data corpus. This group was chosen via intensity sampling (Creswell, 2007), as it had rich, but not extreme, evidence of iterative practice. The group's experimental activity focused on investigating whether the concentration of microspheres housed within a fluid impacted their rate of Brownian motion (i.e., random motion of particles suspended in a fluid). Specifically, the group collected and analyzed video data of microsphere samples moving in fluids to determine how the concentration of microspheres impacts their rate of Brownian motion to model how medical drugs diffuse within and between human cells.

Analysis

Micro-level Iteration

Throughout their experimentation, the case study group engaged in multiple iterations of micro-level experimental activity cycles while sensemaking to resolve inconsistencies in their experiment. These micro-level iterations typically involved four steps: *proposing causes* for an inconsistency, *planning* micro-level experimental actions to work towards resolution, *carrying out* these actions, and *assessing* the action's outcomes against desired resolution. We highlight an example from early in their investigation when the group encountered a micro-level procedural inconsistency during data collection that sparked a sensemaking process.

When preparing a microsphere sample for video collection, the group recognized a procedural inconsistency: the second sample (labeled 500x) had fewer microspheres than the first (labeled 100x), contradicting their expectation that the 100x sample had a lower concentration. This inconsistency recognition initiated the group's iterative micro-level sensemaking process, where they enacted multiple iterations of micro-level experimental activity actions in direct sequence. In Step 1, the group *proposed causes* for the inconsistency, including inconsistent mixing (Chloe: "Did I shake it too much?") or microsphere settling (Chloe: "It might have just settled."). In Step 2, the group *planned* micro-level experimental actions to resolve the inconsistency. They planned to collect a new sample of their microsphere solution more carefully from the bottom of a properly mixed vial (Edmund: "Maybe closer to the bottom … not touching the bottom necessarily but just the closest you can get without touching."). In Step 3, the group *carried out* this micro-level experimental action, preparing their new sample according to their plans. In Step 4, the group *assessed* the outcome of this micro-level experimental action, identifying that the new microsphere sample looked "weird" and "squished" rather than evenly dispersed and spherical. Without resolution, the group completed additional iterations with similar experimental actions to resolve the inconsistency and move forward, reaching resolution with instructor assistance. When comparing this case to others in the data corpus, we found that most observed groups engaged in multiple iterations of micro-level experimental activity cycles while sensemaking about procedural inconsistencies, with variation in the sequence of steps, the role of instructor support, and the nature of the formal resolution.

Macro-Level Iteration

At a macro-level, we found that the group iterated between four steps that involved experimental activity and sensemaking to construct an explanation that accounted for experimental evidence. In Step 1, the group engaged in *experimental activity to collect evidence*, either through qualitative observation or through quantitative analysis. In Step 2, the group *compared their collected evidence to their initial experimental hypothesis*. In Step 3, students *recognized an inconsistency* between their collected experimental evidence and their initial experimental hypothesis, initiating a period of sensemaking. In Step 4, students *engaged in sensemaking* to attempt to resolve the inconsistency. After most iterations, the group would determine that additional evidence was needed for their explanation and then collect new evidence, initiating a new iteration.

Early in their experiment, the group engaged in the four macro-level steps while collecting videos of their microsphere samples, shifting from experimental activity to sensemaking through recognizing an inconsistency between their evidence and hypothesis. In Step 1, the group *collected experimental evidence* about speed and concentration by looking at the microsphere sample via the microscope camera and computer. In Step 2, the group *compared their observational evidence with their initial experimental hypothesis*; shortly after their initial observations, Lisa said: "Just eyeballing it, I don't think the one with more spheres was moving more." We infer that her phrasing "I don't think" suggests she had an initial expectation, from the group's hypothesis, that the sample with a higher concentration of microspheres would have faster Brownian motion, contrary to their observations. This statement leads directly to Step 3, where the group formally *recognized an inconsistency* between their observational evidence and hypothesis (Lisa: "I mean, our hypothesis could be incorrect, you never know."). Lisa recognized an inconsistency between their observational evidence and their initial hypothesis, though she was hesitant to argue outright that their hypothesis is incorrect based solely on qualitative evidence ("The data will confirm."). In Step 4, the group *enacted sensemaking moves* to resolve the inconsistency. Following Lisa's comment, Edmund and Chloe engaged in mechanistic reasoning to develop an explanation of the mechanisms that could support their initial hypothesis, even though it does not account for their preliminary evidence. Edmund incorporated his understanding of diffusive processes ("if there are more spheres in an area … they are going to want to move out.") to support the group's initial hypothesis. Chloe added description that higher microsphere concentration should result in more collisions, which she equates to more overall Brownian motion ("They're colliding with each other … so, they should be moving more."). At this stage of their experimentation, the group seemed to be confident in using their initial hypothesis for their final explanation, but they were open to revising it based on additional evidence (e.g., "The data will confirm."). After Edmund's last statement, the group shifted back to collecting additional evidence.

The group iterated through this four-step cycle several times during subsequent experimentation. For example, later, the group computed diffusion coefficients (a quantity representing the rate of Brownian motion) during several rounds of quantitative data analysis (Step 1), compared their data to their initial hypothesis (Step 2; "Just eyeballing your number, so far it doesn't look like it's bigger than eleven."), recognized the inconsistency between their evidence and hypothesis (Step 3; "I thought it was supposed to be … bigger."), and engaged in sensemaking to resolve the inconsistency through constructing new explanations (Step 4). In Step 4, the group used mechanistic reasoning to construct an explanation that reinforces their initial hypothesis. Edmund recognized that the conceptual elements of the group's hypothesis cannot support a formal explanation of their results: "Technically, similar equilibrium … they should all be distributed somewhat equally, even though there's more spheres in one or the other, how they're spaced … it's not like, in one video there's a bunch in one spot and not another, and in another video they're all …" The group recognized that developing an explanation to reinforce their hypothesis may not resolve the inconsistency since the explanation does not account for experimental evidence or align with their studied system. The group then decided to collect additional evidence.

After collecting and analyzing their final evidence, the group shifted to a final sensemaking period to explain their results and the underlying mechanisms at play. The group built multiple analogies to address elements of their system, including equating microsphere Brownian motion to "when you're in a crowded elevator" and contrasting this phenomenon with billiard ball collisions ("If you just had microspheres but got rid of the fluid, like a bunch of billiards balls that interacted with each other, that's not [your system]."). Through additional sensemaking discussion, the group eventually developed a consensus explanation (e.g., Lisa: Because when [a microsphere] bumps into a fluid particle … it's just gonna change its course versus, like, stop it from moving. When it runs into something with its same size, it's kinda gonna stop moving.”).

In summary, the group frequently shifts between four macro-level steps throughout experimentation, iterating between collecting experimental evidence, comparing their evidence to initial hypotheses, recognizing an inconsistency, and engaging in sensemaking. We found that most groups in the data corpus enacted similar macro-level iteration to construct explanations, though there was variety in the iterative sequence, flexibility of initial hypotheses, and reliance on experimental evidence during explanation construction.

Discussion

This study utilizes a theoretical lens of iterative practice to analyze student reasoning at the nexus of experimental activity and sensemaking. The results highlight two distinct forms of iteration within micro- and macro-level experimental activity. While the experimental activity observed here has been documented elsewhere, focusing on students' iterative practice begins to shed new light on the progression of student reasoning during experimental activity in ways minimized in other literature. This work sheds light on how iterative practice exists at different scales within multi-dimensional learning environments; future research can explore how iterative practice may be prevalent at different cognitive and procedural levels within student learning in other contexts. As well, while this study broadly focuses on experimental and epistemic iteration, other forms of iterative practice may be more ubiquitous in other learning environments, such as course-based undergraduate research experiences (CUREs). Beyond empirical studies, these results reinforce our knowledge that student learning in science is often nonlinear and iterative, further stressing the need for new pedagogical approaches in science education.

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