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Complex Dynamics of Epistemic Agency in a College Physics Lab Course

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Abstract: We study students in a college physics lab course encountering a designed-for discrepancy between their data and the relevant physical model. We examine the moment-by-moment dynamics of the groups' efforts at problematizing and sensemaking, with a specific focus on *epistemic agency*. Drawing from prior studies of agency – as it relates to learning (Damşa et al., 2010), inquiry (Keifert et al., 2018), and scientific practice (Pickering 1995) – we study the complex ways in which epistemic agency manifests (and doesn't) in the students' work. Our analysis suggests several influences on the students' agency, including features of the social and material context as well as how the students frame what it is they are doing (Hammer et al., 2005), in the lab as a whole and in moments within it. The findings suggest implications and questions with respect to designing labs to support disciplinary practices.

Introduction

There are several efforts at reform in introductory physics labs to position students with greater epistemic agency, in line with many years of calls for reform in physics instruction (Otero & Meltzer 2017; Miller et. al. 2018). Rather than guide students toward "discovering" canonical results, curriculum developers have been designing activities to generate uncertainty (e.g., Phillips et al. 2021), often guiding students to experience particular empirical discrepancies. These labs aim to promote students' problematizing (Phillips et al., 2017) and sensemaking (Odden & Russ, 2019). Evidence to date shows that sometimes students take up these opportunities (Sundstrom et al., 2020), and sometimes they do not (Phillips et al. 2021) – more study is clearly needed.

We build on this previous work and draw as well on research in other contexts, including elementary school science (Manz, 2015; Louca et al. 2004) and college biology (Hayes & Gouvea, 2020), to study why, how, and when students in reformed undergraduate physics labs take up opportunities to act as epistemic agents. We adopt Miller et al. (2018)'s definition of epistemic agency as "students being positioned with, perceiving, and acting on opportunities to shape knowledge building" (p. 1058). In our case, lab is designed to provide students with opportunities to shape knowledge building. We attend to students' perception of these opportunities, which we see as part of their framing what is taking place.

Framing in the sense we adopt here refers to how an individual or a group understand what is taking place (Tannen, 1993). To frame a situation is to tacitly answer the question "what is it that's going on here" (Goffman, 1974) and how an individual or group frames a situation shapes their understanding of what could happen, what features of the event require attention, and what qualifies as appropriate action (Hammer et al., 2005). For example, Phillips et al. (2021) found that students who framed the learning activity as confirming a known result or as a series of hoops to jump through to complete the assignment did not problematize upon encountering a discrepancy between their data and the models they were testing. Hayes and Gouvea (2020) similarly found that students framing lab as "about demonstrating a target idea" and that destabilizing this framing helped students better see opportunities to construct knowledge.

Like Hayes & Gouvea (2020), we examine how students perceive and take up opportunities to engage in knowledge building. Through an analysis of the moment-to-moment evolution of these students' framing as they work in the lab we explore questions of why, how, and when they take up opportunities to act as epistemic agents.

Theoretical framework

We draw from Damşa et al. (2010) and Keifert et al. (2018) to identify evidence of epistemic agency. Damşa et al. (2010) outline *shared epistemic agency* as a descriptive construct to understand collaborative efforts to create knowledge objects. Damşa et al. (2010) focus on actions and outline two main dimensions of shared epistemic agency: actions that lead to the creation of a knowledge object (epistemic); actions that organize the process of knowledge creation (regulative). While Damşa et al. (2010) provide a way to identify when collaboration in learning environment involves epistemic agency, Keifert et al. (2018) develop a conceptualization of epistemic agency centered on the experience of participants engaged in inquiry; their lens "focuses our attention on what participants do that signals productive work *to them*" (p. 2). Specifically, Keifert et al (2018) examine the interactions in which participants negotiate the context of inquiry.

Additionally, we use Pickering's (1995) account of experimental science as a dance of agencies to connect the students' enactment of epistemic agency to disciplinary practices. In this view, scientists set up an experimental apparatus and then position it with a kind of agency: they see what it has to say, what it contributes to knowledge, in the data it produces. The dance is between scientists' agency and the materials' – "a dialectic of resistance and accommodation" (p. 22) – a complex and cyclic interaction that, hopefully, progresses toward alignment. This formulation provides a detailed account of meaningful activity in experimental science.

Course context and data collection

The data analyzed here comes from an introductory physics lab in a large, four-year research university in the northeastern United States. The data were produced as part of a project to study students' thinking in labs designed to promote student autonomy in devising experimental methods and drawing their own conclusions (Descamps et al., 2022; Philips et al., 2021). Graduate or undergraduate teaching assistants taught sections of up to 14 students. Instruction occurred in the Spring of 2021 when the course was operating in a hybrid format due to the COVID-19 pandemic. Students worked in groups of two or three, with some students in-person and others virtual. Students recorded their video calls, and we had a camera and audio recorder in the room.

The first author watched the videos, taking notes and logging activity in 5-minute intervals (Derry et al., 2010). He then selected candidate episodes for workshopping (Hammer et al., 2018), focusing on episodes of (potential) sensemaking and scientific inquiry (Odden & Russ, 2019; Watkins et al., 2018). He prepared analytic memos (Bailey, 2007) to present to the research team, constructing and revising based on discussion and feedback. Like in Hammer et al., (2018), the team considered a range of theoretical scales, from individuals' thinking (diSessa, 1993; Tannen, 1993) to social interactions and activities (e.g., Jordan & Henderson, 1995)

In this episode, two of the students, Peter and Holly, are in-person at the same lab table; their other lab partner, Judy, is virtual (all pseudonyms). The students are in the second week of the first lab activity of the semester: investigating Galileo's claims that the period of a pendulum does not depend on either the mass of the bob or on amplitude. In fact, the period does depend on amplitude, which careful measurement can show; the lab is designed for student to encounter and grapple with that discrepancy. The instructions for the lab ask students to provide an "unambiguous statement" of whether their data do or do not deviate from Galileo's claims. We turn now to our data and analysis of the students at work, as they work to analyze their data.

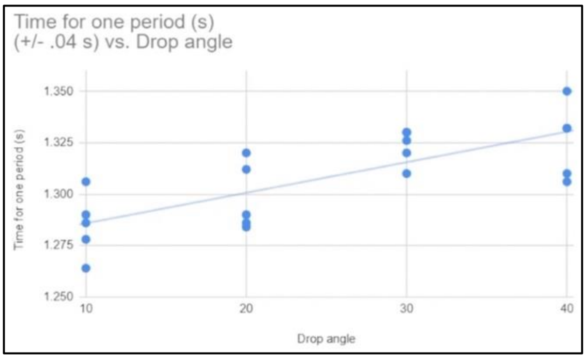
Data and analysis

We present the data and analysis in four sections, beginning with the students first noticing the discrepancy, continuing with their taking two different approaches to addressing it, and finally their arriving at their conclusion. Line numbers refer to the full transcript, which we excerpt here.

The students encounter a discrepancy

Holly, Judy, and Peter produced data for amplitudes of 10, 20, 30, and 40 by timing five swings of their pendulum and dividing by five to find the average period; they did five trials at each amplitude. They estimate their uncertainty in timing to be ±0.2 seconds, which makes the uncertainty in their period measurements ±0.04 seconds. To show their data, we provide as Fig. 1 a graph the students produce toward the end of the lab period.

Figure 1
Students' data



This episode begins immediately after they finish collecting data, a little over an hour into their lab period.

01 Peter:	I mean so we are clearly seeing like very slight changes. I know, I think we had the same thing last time that the amplitude seemed to change it just a tiny bit. I wonder what about like how we're doing it is making it change it consistently?
02 Holly:	Is it not supposed to change?
03 Peter:	Uh, it should be the same regardless of amplitude. But I guess there must be something else that we're doing that's making it change just a little bit. Although it's very insignificant.
04 Holly:	I wonder if it's, um, friction. Like, is it— does this move back and forth [reaches up to examine pendulum string]— No

Peter immediately sees the data as "clearly" showing "slight changes" in the period with amplitude, which he remembers their seeing in the first lab session as well. He locates the problem in their doing of the experiment: something they did made the data change in this way. With Holly's question about what is supposed to happen and her suggestions in line 4, we infer that both Peter and Holly are framing their lab activity as confirming a known, correct result. Judy, on the other hand, suggests a different interpretation of the data:

08 Judy:	But I feel like the correlation is too strong to ignore, like it— like it makes sense, like it's decreasing very slightly as you decrease the amplitude
09 Peter:	Yeah, I mean, I think looking at our data, it would seem that it is related, but just at a really small like ratio I guess, so like the amplitude has a really small effect. But like, I know, theoretically we shouldn't be seeing any effect. So I'm wondering what about what we're doing is making it look like that.
10 Holly:	I don't know. Like, yeah, like where is our error coming from?
11 Peter:	Uh… also, what parts could have error? The drop, the starting and ending of the timer

In line 8, Judy begins to argue that the amplitude does have an effect on the period. Her saying "but" suggests she distinguishes her interpretation from Peter's and Holly's; that the effect they see in their data could be a feature of the phenomenon. She does not seem to frame the goal of their work as confirming Galileo.

In line 9, Peter acknowledges the logic of this reasoning, that "it would seem" the period changes, based on their data. Still, he continues in line 9 to defend his articulation of the problem. He clearly vests epistemic authority in Galileo (or perhaps the instructor). At the same time, he readily admits that their data is saying something different; he and Holly frame the problem they need to solve as finding the source of their "error."

The problematizing evident in these first 11 lines is a clear demonstration of epistemic agency: the students identify a discrepancy between their data and the theoretical model and then, in dialogue with each other, they refine their understanding of what is the problem to solve. For both Damşa et al. (2010) and Keifert et al. (2018), students developing ideas that help regulate the direction of their intellectual work is fundamentally epistemically agentive (inter)actions. In addition to the social negotiation occurring here, the apparatus and phenomenon are central to the emergence of epistemic agency.

Peter and Holly troubleshoot their apparatus

Following Holly's comment in line 10, she and Peter begin to brainstorm ideas for where their error could come from. Judy does not participate. Instead, after Peter remarks "Although it's very consistent for some reason" (line 13) Judy suggests they graph their data and starts working on that. In other words, she decides to produce a new knowledge object. Meanwhile, Peter and Holly try to figure out their problem.

19 Holly:	I wonder if error could also be in the drop itself. Like if you don't just like [random noises] take your hand directly away, like if it's like cushioning it at all. But like, I don't know how that would
20 Peter:	Yeah and, I mean, would that have a larger effect at higher drop height? That's the question.

21 Holly:	I don't know. I mean actually it might
22 Peter:	It might. Cause I think, like I'm doing my best to release the ball at once and obviously I'm not
23 Holly:	Right. I see and there's nothing you can do to make that better, unless you have like a literal like hard thing holding it up and you take that away immediately, like there's no way to remedy that.
24 Peter:	Yeah, so I mean, that could be it. Do we think, can we think of a reason why it would be a larger effect at a higher drop. I mean, say it's staying exactly where it is for a little bit before it starts to fall.
25 Holly:	Um, well I don't know. Cause like if you only bring it out to here it has more velocity in the x direction than the y direction whereas up here [pendulum stand almost falls over] […] If you bring it up here, like it has like, past— well it's not like we're going passed 45 degrees, but like there's more velocity in the y direction up, up at a higher point… maybe

Holly suggests a possible physical effect that might affect the pendulum's motion, perhaps in releasing the bob; Peter asks if that effect would vary with amplitude. In this way both students are focused on possible physical mechanisms that might explain the trend in their data. It is possible Judy's critique had an influence – Judy told them not to ignore the correlation. Their first ideas, that the error might come from timing or from the drop, are not sufficient explanations to them. Rather, they are the beginning of a search for a mechanism that would consistently increase the period length as they increase amplitude. We see this troubleshooting work as an aspect of disciplinary practice as they are holding possible explanations accountable to the data.

Indeed, the troubleshooting seen above embodies Pickering (1995)'s description of scientific practice as a dance of agencies: the students have constructed a combination of instruments and machinelike human practices (e.g., stopping the timer) to capture the phenomenon of pendulum motion. Their experiment produced data contrary to their intentions and now the students are actively and intentionally working to accommodate this "resistance" (Pickering 1995) on the part of the materials. Holly's and Peter's work here involves grappling with and deconstructing the production of their data, a sophisticated epistemological framing (e.g., Hardy et al., 2020) that is nested within, and we suggest supported by, their confirmation framing of the lab as a whole. That is, they expect to confirm the authoritative claim, but the apparatus resists with discrepant data, and this prompts them to troubleshoot. The clear material resistance drives Peter and Holly to enact epistemic agency.

New ideas for data interpretation

A few turns of talk after line 25, Judy returns to the conversation to share with them the spreadsheet she has made, and Peter works to plot this data.

40 Judy:	Cause, yeah um, it looks like it's really linear.
41 Holly:	Yeah.
42 Judy:	Do you see this? [laughs]
43 Peter:	Yeah. Wha— uh…
44 Holly:	Guys we just disproved Galileo's theory
45 Judy:	It's a literal straight line!
46 Peter:	No no no, it's it, this is not a straight line for the reason you think this is a straight line, look at the axes flipped [laugh]
47 Judy:	But like it's so straight, like the line is like
48 Peter:	I mean the reason it's straight is because we're, this isn't an actual x-axis on the bottom, like look at what the units are on the bottom
49 Judy:	Oh, I'm so silly [laughs]

Judy's sharing her spreadsheet prompts Peter and Holly to shift their attention back to the data. Looking at the clear, "straight line" of the graph, Holly and Judy conclude that they have disproved Galileo, that amplitude affects period. Holly, who was previously invested in figuring out how their experimental procedure caused error, now exclaims "we just disproved Galileo" (line 45). From her tone, it is not clear how much she believes this statement; perhaps she was less than fully serious. Judy, on the other hand, is clearly happy about this development.

Peter, however, notices a mistake in the graph that is the reason for the straight line. We do not have direct evidence of the mistake, but we reproduced what we suspect it was: they included the word "seconds" in the cells with their raw data, and the period values are to the left of the amplitudes. This would have Excel ignore the period values and plot (1, 10), (2, 20), (3, 30), and (4, 40) – a straight line that does not reflect their data.

Judy recognizes the mistake Peter identifies – "I'm so silly" – and in the work that follows she steps aside, asking, "Can somebody else attempt this, I'm, maybe I'm just terrible at Excel but it's literally just not letting me" (line 59). For the rest of the lab session, Judy's participation is notably diminished.

We return to the students' work as they examine a new graph of their data. Holly leans towards her computer and says,

64 Holly:	It almost looks like it dips down at 30
65 Judy:	Yeah, it could just be from like error. But they're all like 1.3 something, {like they're very close—}
66 Peter:	{Oh. That's, that's that's} the issue, it's cause this was, uh, was 1.28 here and 1.33 and [Unclear] uh cause we had it 30 20 10 40

Peter and Judy briefly discuss some spreadsheet logistics and Peter narrates some data reformatting for about a minute before Holly makes another observation about their data.

69 Holly:	It's interesting how much closer the 40-degree and 30-degree values are compared to the 10-degree and 20-degree ones
70 Peter:	Yeah
71 Holly:	So I wonder if using a bigger amplitude would have us— or, a larger amplitude would allow us to have more accurate results in accordance with the theory
72 Peter:	It's possible. Yeah I think it would probably be easier to measure for larger amplitude because we are, you know, it's a more extreme peak.
73 Holly:	So then maybe it is a timing error for the smaller ones.
74 Peter	It might be.

In addition to her comments in lines 64 and 68, Holly's body language – leaning in towards her computer – is evidence she is focused on interpreting the data. Her observation and conjecture in lines 69 and 71 reflect and support a return to sensemaking, as she considers another possibility for explaining the discrepancy. Peter joins this work, articulating this explanation in his own words and elaborating on the mechanism.

Judy, too, seems to shift in her approach to the data and to the activity. Even though her comment in line 65 is an evidence-backed explanation, she now seems to view the data as relatively consistent. That said, Peter's comment in line 66 suggests that, perhaps, the current plot has the amplitude data incorrectly ordered. As figure 1 makes clear, reordering the amplitude data would undercut the evidence for a linear relationship, perhaps informing Judy's new explanation. Recall the dispiriting exchange in line 40-50, which could also have contributed to her shift. Additionally, that she says "just" seems to indicate that the abstract notion of "error" is a now sufficient explanation for the data, which is certainly a shift in her thinking.

In between lines 66 and 69 Peter generates a new and (likely) accurate graphical representation of their data. In contrast with their first sensemaking conversation in which Holly and Peter deconstructed their experimental set up to think through the possibilities for error, here, their sensemaking is grounded in their plot and data interpretation. In lines 69-74 Holly and Peter position their data as a legitimate source of information that needs to be explained and/or reconciled with the theoretical model.

Furthermore, the central idea of their discussion – perhaps there are larger timing errors for the smaller amplitudes because those are harder to measure – exemplifies the complex, entangled relationship between human and material agency that Pickering (1995) envisioned: "disciplined human agency and captured material agency are, as I say, constitutively intertwined; they are *interactively stabilized*" (p. 17). Holly and Peter claim here that certain configurations of their apparatus – which involves both instruments and machinelike human actions – enables them to capture the phenomenon and produce data more accurately.

Starting in line 74, Peter returns to tweaking the formatting of their plots. First, he seeks to plot "exact" averages of their trials, then tries to include the extrema of trend lines. That is, he wants to plot the trend line from the shortest period of the smallest amplitude to the longest period of the largest amplitude and vice versa in order to compare them (this is a technique the TA mentioned at the beginning of the lab when talking about how uncertainty measurements influence the conclusions you can draw from data). Before she joins Peter in figuring out how to plot such trendlines, Holly continues to make observations about the data.

Although we do not include the transcript (mostly discussion of Excel), it is important to point that this discussion, too, treats their data as a legitimate source of information. To use the language of knowledge-creation, Peter and Holly are invested in generating knowledge-objects to concretize their ideas; this Excel reformatting is a demonstration of shared epistemic agency. Notably, they engage in this behavior while still framing the activity as confirming a known result. Their (epistemic) agency is disciplined by their (epistemic) framing of the activity.

The students reach a conclusion

The students have excel put in a generic trendline for their data, which spurs the following exchange

92 Holly:	Unfortunately, it's not super horizontal
93 Peter:	Yeah, I mean it, I think actually it is close enough to horizontal because of how small our axis is. Like if I zoom this out, uh, if I go from like 0 to 2, like it's extremely horizontal
94 Holly:	Do we want to like make another copy of this graph, show a zoomed in version versus a zoomed out version?
95 Peter:	We could do something like that.
96 Holly:	And be like, despite what it looks like this line is actually fairly horizontal.

Line 92 is a representative description of how Holly and Peter have been interpreting their data: "Unfortunately, it's not super horizontal." Holly is honest about what their graphical analysis demonstrates and understands it to be a problem. While Peter had previously shared in this interpretation of their data (see line 1), his response in line 93 seems to be a departure: it's close enough to horizontal, it's *actually* not a problem. On its face, Peter's explanation is not based in physical or mechanistic reasoning – that the graph looks horizontal is the evidence.

Still, rescaling plots to gauge the relative size of an effect is a reasonable, if novice, analytic technique. It does not seem to us that Peter means to manipulate their data to hide this problem. In fact, following the exchange above (line 97), he asks Judy directly about her thoughts on this new zoomed out graph, clearly a bid for her participation, and perhaps a bid for consensus. In line 94, Holly signals her agreement by suggesting that they show both graphs. Holly has her own conditions for being satisfied with this explanation and conclusion to their inquiry: intellectual honesty and epistemic accountability.

Part of what makes Peter's invitation for Judy to participate notable is that Judy is largely absent from the later discussions. Judy responds to Peter's question by letting him know that she can't even see the graph that they are referring to. They work it out for her to see the graph, but it is clear (and unsurprising) that Judy not being in the room with Holly and Peter generates different experiences. For example, in line 75, Holly makes another observation about the data Judy starts to respond, but Peter talks at the same time and neither he nor Holly seem to recognize that Judy was cut off. Furthermore, the general tone and pace of conversation between Holly and Peter is notably different than when Judy participates. By the end, despite Peter's invitation to participate, she mostly remains quiet. In essence, we both see how intersubjectivity drives their enactment of (shared) epistemic agency and we see how constraints on that sharedness distort or inhibit epistemic agency.

After Peter shows Judy the zoomed-out graph it appears that Judy agrees with Peter's explanation. Less than a minute later, the TA enters their video call, which changes the activity and ends the episode.

Discussion

Trends in education research and contemporary national curricular standards have shifted toward objectives of students' *doing science*, seeking to "engage students in knowledge construction—to position them as doers of science, rather than receivers of facts" (Miller et. al. 2018, p. 1056). Yet, designing for doing science and effectively supporting students enacting epistemic agency is not simple (e.g., Manz, 2015, Sundstrom et al., 2020 Phillips et al., 2021). As more undergraduate science labs seek to promote disciplinary practices and epistemic agency, it is crucial to examine the dynamics underpinning the emergence of productive behavior.

Holly, Judy, and Peter's encounter with anomalous data – more specifically, the inconsistency between their results and their expectations – leads them to problematize, troubleshoot their apparatus, and produce various plots to analyze their data. They primarily work to build an explanation for their discrepant data and ultimately conclude that the effect they are seeing is insignificant. In this episode, Holly, Judy, and Peter are epistemically agentive: they take their data seriously as a meaningful reflection of the phenomenon they have constructed and, upon encountering unexpected results, enact various (epistemic) actions.

That they position themselves as epistemic agents while simultaneously framing the activity as confirming a known result is surprising. In previous studies examining student framing in instructional labs designed to support student agency (Smith et al., 2018; Smith et al., 2020; Phillips et al., 2021), researchers observed that students framing the activity as confirming known result did not take up epistemic agency. These students focused on producing or aligning their data with what they presumed to be the "correct" answer. As Philips et al. (2021) point out: "if a group of student expects to reproduce known results in the lab, they regard knowledge as something that will be given to them by the instructor or written resources rather than constructed by them" (p. 2). Indeed, as we see in line 9, Peter admits that just looking at their data would indicate amplitude has an effect, but the authoritative claim they have been given by the instructor paints a different picture; much of their intellectual work is driven by their commitment to an external epistemic authority.

Consider also the perspective of Reiser, Novak, and McGill (2017) who state that if students do not have a hand in articulating the overarching question driving their experimental work, then they cannot be "truly engaging in scientific and engineering practices" (p. 4). Once again, Holly, Judy, and Peter's commitment to an external epistemic authority drives their work – they frame the activity as confirming Galileo. Still, their framing shifts in subtle and complex ways throughout this episode. Nested within an overarching confirmation framing, the students engage in troubleshooting and data interpretation. They are not simply going through the motions of science, but agentively engaging in disciplinary practices.

Holly, Judy, and Peter view their data as a genuine problem and work to resolve it. In the beginning, all three participants signal, negotiate, and experience their efforts as productive inquiry. The material resistances they encounter motivate their intentional, disciplinary accommodations (Pickering, 1995). That they frame the activity as confirming a known result is a key reason that they seek out such accommodations. They attend to the production of their data and create, refine, and make sense of concretized conceptual artifacts; throughout, they wrestle with the entanglement of human and material agencies that facilitated the capture of this phenomenon. Through both conceptual and procedural actions, the students show epistemic agency.

We have identified several aspects of this learning environment that affected this agency: supportive social interactions and access to them, values of intellectual honesty and epistemic accountability, material resistances that are clear to the students, the freedom to create knowledge-objects, as well as their framing the activity as confirming a known result. The last may be surprising, as confirmation framing is generally associated with limited epistemic agency (Philips et al., 2021; Smith et al., 2020). Here, as in other cases (e.g., Jeon et al., 2023; Sundstrom et al., in prep), much seems to depend on the particular dynamics of the group. Idiosyncrasy is a general feature of complex dynamics, and it suggests limits on what curriculum and course designs can accomplish in themselves to support students' epistemic agency.

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