Amplifying Physics Students' Voices: How Learners Approach Wonky and Unknowable Quantum Mechanics

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Scholarship on Quantum Mechanics (QM) in physics education research (PER) tends to persist in examining learners' reasoning from a deficit perspective by emphasizing learners' incorrect approaches. Although there is a common understanding that QM is challenging, with students describing it as "wonky," "bizarre," or "weird," much of the deficit literature examines learners' difficulties by documenting students' incorrect strategies. Alternatively, some research literature and instruction seek to elevate students' approaches to QM. Drawing on resource theory and epistemological approaches, the current study aims to amplify students' voices, not through judgment or a deficit lens, but rather by foregrounding how they articulate QM and what strategies they find meaningful. Data were collected through ethnographic-style solo and pair open-ended interviews with undergraduate quantum physics learners. Coding their verbal responses identified three approaches students take to navigating wonky QM: reasoning across scale boundaries, relying on mathematics, and drawing on classical knowledge. Although prior deficit literature has identified two of the three approaches as barriers to quantum learning, we document cases where students view these approaches as their learning strategies. Furthermore, in the relevant literature, reasoning across scale boundaries has been overlooked as an approach to QM, thereby highlighting a new quantum learning opportunity. The results described throughout are situated in a broader literature emphasizing students' voices in PER, offering instructional implications, and prioritizing students' perspectives over researcher-imposed judgments.

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I. INTRODUCTION AND BACKGROUND

Across a body of scholarship on Quantum Mechanics (QM) in physics education research (PER), there has been a tendency to emphasize unproductive reasoning and learning deficits [1]. The literature commonly recognizes that learning QM is challenging (e.g., [2–4]), describing it as non-trivial, counterintuitive, and conflicting with classical understandings [5, 6]. Challenges tend to be attributed to the advanced mathematics [7], language [8], and overall abstractness of QM [9]. The deficit perspective research focuses on documenting learners' difficulties by identifying misconceptions brought into the physics classroom and then exploring the extent to which they persist after instruction [1, 5].

The literature views misconceptions as interfering with the instructional target (scientific understanding) and resisting change (e.g., [5, 10, 11]). Within the focus of learners' difficulties, an extensive collection of articles has explored epistemic framing, such as viewing students' difficulties in QM as the result of an unproductive framing [12], including transitions between frames [13], or being stuck in physics or math mode [14]. Much of this QM PER literature rests on researcher-imposed judgments about the correctness or appropriateness of students' reasoning and overlooks opportunities to build on students' ideas and interpretations.

Some recent research has looked towards elevating students' interpretations by examining their diverse perspectives and exploring the moments learners describe QM as nonintuitive [15]. Other research emphasizes students' interpretations, rather than solely those of scientists, regarding quantum theory's interpretations and physical meaning [16]. Given the focus on students' interpretations, studies have examined how learners adopt realistic interpretations of quantum phenomena that contrast with the Copenhagen interpretation [17, 18]. These studies amplify students' voices on the physical interpretation of QM by prioritizing their perspectives. While their reasoning may not align with the Copenhagen interpretation, this research showcases the depth of the interpretive frameworks students bring. As the field advances toward designing and implementing new QM curricula, it is vital to center students' existing interpretations and ideas. Recognizing and building on students' prior understandings is more than a thoughtful consideration; it is foundational to effective instruction, as demonstrated by decades of research supporting constructivist approaches to learning (e.g., [19, 20]).

II. THEORETICAL FRAMEWORK

The current study is situated in a resource theory perspective that assumes learners have a complex knowledge system for building new ideas about the physical world [21]. Knowledge resources can include ideas from prior mathematics and classical physics to everyday life experiences brought to any academic learning environment. While instructors may sometimes assume that students lack the necessary knowledge resources for understanding QM, they should not be considered empty vessels when approaching their learning journey [22]. Rooted in diSessa's [23] theoretical framework of Knowledge in Pieces, empirical analyses have since demonstrated the benefits of using resource theory to unravel students' reasoning, offering advantages in guiding curriculum development [24] and modeling learners' cognition about challenging topics [25]. While the current study does not examine precise knowledge resources, this constructivist perspective of learning and cognition shapes the research design.

Within resource theory, a sub-collection of studies has examined students' beliefs about knowledge and learning in classical mechanics [26–28], mathematical sense-making in QM [29], and epistemological stances shaped through group interaction [30]. The current study goes beyond broad epistemological beliefs – the notion that QM is fundamentally different – to examine students' epistemological approaches: how they act on such beliefs in the learning context. For example, a student who views QM this way might respond by avoiding conceptual understanding, relying on mathematical procedures, or disengaging altogether. Recognizing students' underlying epistemological approaches helps elevate their voices, aligning with a growing body of research showing that epistemology shapes QM learning [31].

Some studies have bridged resource theory with epistemological framing to understand students' transitions to QM [32]. Bing and Redish [25] examined how implicit or unconscious epistemological frames influence disagreement and progress. Other work identified framing clusters that support sensemaking [33], including valuing messy student reasoning [34]. Both resource theory and deficit-based framing studies share an understanding that various frames are used when learning QM that are connected with mathematics and classical physics. However, the epistemological approaches identified in the current study intentionally center students' views by shifting focus away from researcher-imposed judgment and prioritizing learners' interpretations.

Consistent with this perspective, a growing trend in educational research emphasizes equity by amplifying or elevating voices traditionally marginalized in academia. In PER, this includes efforts to broaden participation in physics [35], elevate the experiences of underrepresented students in engineering [36], and co-design curricula around student voices [37]. The current study adds to this vein of the PER scholarship genre by addressing overlooked and neglected students' voices regarding their epistemological approaches to making sense of wonky QM. Drawing from the Odden & Russ definition of sensemaking [38], we use the broader term, making sense, to emphasize learners' ongoing efforts to construct an evolving understanding of unknowable quantum phenomena. Alongside a resource theory perspective, we prioritize amplifying students' voices by highlighting in their own words how they conceptualize QM and which epistemological approaches they find helpful. Thus, our research question is: *How do students' epistemological approaches shape their strategies towards making sense of QM?*

III. RESEARCH METHODS

The study data come from interviews with undergraduate learners in the Department of Physics and Astronomy at a large research university in the United States. Students were recruited through email and in-person class announcements advertising the option to participate in a solo or pair interview (with a peer of their choosing), each lasting approximately one hour. During the interviews, we collected video, audio, and written data. Ten students were interviewed, four solo interviews and three pair interviews, totaling seven interviews, during which saturation was achieved (e.g., across the interviews, codes were observed multiple times [39]). Of the ten participants, five self-identify as women (four cisgender, one transgender), and five as cisgender men. This gender parity is atypical in physics courses, which are traditionally weighted toward cisgender men [40].

To capture a range of perspectives, we recruited students at different points in their quantum learning journey. Four students were currently enrolled in a sophomore-level modern physics class that introduces topics such as wave-particle duality, potential wells, and the basics of the Schrödingers equation, often using classical and early quantum notation. Two students had completed that course, but were not enrolled in further quantum-related courses. One student was enrolled in the junior/senior-level advanced undergraduate QM course that provides a rigorous and formal exploration, including Dirac notation, harmonic oscillators, and sophisticated mathematical formalism using the spins first, McIntyre textbook [41]. Three students had completed the junior/senior-level advanced undergraduate quantum course.

Our interview protocol was designed to create a comfortable environment for students to discuss their views, beliefs, and experiences with QM. We used an ethnographic approach [42] to design the interview protocol. The interviewer presented as someone genuinely interested in learning alongside and began engaging in discussion and study sessions with participants. Furthermore, given the ethnographic approach and prior role as an undergraduate physics student, the interviewer knew about half of the students. Interview sessions began with the interviewer giving anecdotes about recent undergraduate physics learning challenges. Following the introduction, questions were asked about the students' experiences in QM, their views on the role of math in physics, the potential well, and the Heisenberg uncertainty principle. Throughout the interviews, the goal was not to evaluate the correctness of their ideas; instead, we were interested in students' genuine articulations and responses that deviated from our expectations. For instance, when asking students to describe a potential well, we probed for explanations that transcend textbook definitions, reflecting students' unique understanding. The flexibility of an open-ended interview creates opportunities to capture individual reflections and explore students' thoughts, feelings, and ideas. An online demographic survey was completed at the end of the interview, which included an opportunity to choose their pseudonym.

After every interview, transcripts were prepared using *AssemblyAI* [43] and converted to a Microsoft Excel document. Following guidelines from the observe, schematize, and systematize cycle (OSS; Refs. [44–46]), multiple passes of the videos were made to examine verbal communication for nuanced layers of understanding, strengths, weaknesses, or generalized confusion. Our team engaged in the process of iterative coding as three researchers examined data together through collaborative viewing sessions and analytic conversations [47, 48]. We refined and built a code book that captures epistemological approaches as students discussed wonky QM. Following the completion of the code book, the first and third authors conducted interrater reliability that yielded a Cohen's kappa value of $\kappa = (.84)$, indicating near-perfect agreement [49]. After schematizing observed occurrences [46], we generated excerpts using *invivo* strategies and developed code names grounded in their dialogue [50]. Informed by resource theory and attentive to the natural flow and language used by participants [23], this study amplifies students' voices. The data presented reflect representative ideas within each code. The following three codebook categories, named using student phrasing, describe three distinct epistemological approaches:

At tinier scales, things aren't always what they seem: While discussing QM, the learner articulates a scale-based implication (big or small). For example, talking about the range or scope of the scale (small-scale objects to larger classical objects), discussing when the quantum scale is or is not applicable, or attempting to visualize the quantum scale. **The bread and butter of quantum is math:** The interviewee is talking about math's implications or connections with QM. For example, asserting that math is unconditionally integral to quantum knowledge. **I'm thinking of it classically:** Students articulate classical experiences, knowledge, analogies, terminology, or visualization strategies and offer an implication about QM.

IV. ANALYSIS OF THREE EPISTEMOLOGICAL APPROACHES

We demonstrate three epistemological approaches to shaping students' strategies for making sense of QM. The first example captures students' epistemology broadly across the interviews, that something about QM is fundamentally different. The moment occurs with Antares, a senior undergraduate in the junior/senior-level advanced undergraduate quantum course. She is conceptualizing the square well, prompted by being asked, "What would be the most basic version of the well?" Antares discusses why the potential would be zero at some point inside the well and infinity outside when she articulates her epistemological belief that there is something about QM that "we don't know."

> **Antares:** *And that's like the basics of quantum mechanics, right?* ***Like why does it do that? We don't know it just does it.*** *Um, but like, time evolution's pretty weird*

too. I don't know really, you know. Just things that I don't really, [whispers] understand.

As seen above, when describing the basics of QM, Antares focuses on the unknowns about why it does what it does, saying: "Like why does it do that? We don't know it just does it." This statement reveals an epistemology distinct from a lack of knowledge or a misconception; she questions why QM works a certain way and concludes that "we don't know." We interpret this statement to mean that she believes a fundamentally unknowable aspect of QM exists. Epistemological beliefs about QM influence students' epistemological approaches by shaping how students engage with quantum content and the knowledge they activate (e.g., [33, 34]). Antares says, "time evolution is pretty weird too," suggesting that she is extending her epistemology to specific features of QM, signaling an emerging awareness of scale-dependent processes. By drawing on a quantum analogy, treating time evolution as similarly unknowable, she engages in a learning strategy that reflects a broader epistemology in which "evolution" is associated with complex and difficult-to-understand processes. Conversation with Antares reveals that the barrier to quantum understanding lies not in students' capacity, as the deficit model suggests, but due to QM inherently defying complete explanation.

Next, we see how two students - Donna and Amelia, enrolled in a sophomore-level modern physics class - approach QM's wonky behavior. First, Donna reasons across scale boundaries, followed by Amelia's reliance on mathematics. The moment occurs halfway into the interview session when they are asked, "What is quantum mechanics?" A brief, lighthearted conversation began as Amelia responded "I don't even know how you would explain that." After a few moments of laughter, Donna provides an insightful discussion about QM through the lens of what "physicists actually do and need to know" by contextualizing that different reasoning is needed when classical physics breaks down.

Donna: *What we just barely referred to as classical which is like physics one and two, things moving and things going in circuits and, the stuff that engineers need to know and then there's what physicists actually do and need to know, uh which is where physics starts to break down* ***when things are too big or too small or theoretical,*** *and then things just kinda get wonky from there.*

For Donna, *At tinier scales, things aren't always what they seem* means that this boundary emerges "when things are too big or too small or theoretical." She describes the boundary of classical physics as being defined by scale, a threshold beyond which predictability fails and familiar reasoning becomes unreliable. The statement reflects an epistemological approach in which classical knowledge is viewed as appropriate only within certain bounds, and scale serves as a cue that signals the need for a different approach. Similarly, Bing and Redish described epistemology in terms of frames as "a student's perception or judgment of the kind of knowledge that is appropriate to bring to bear in a particular situation [25]." Donna starts with a familiar classical approach, "things moving and things going in circuits," reflecting a strategy in which limited classical reasoning still applies. The scale then triggers a shift in epistemological approach ("things just kinda get wonky from there"), signaling the breakdown of classical assumptions and the perceived need for new rules or strategies suited towards QM.

Similar to Antares, we interpret Donna's statement "wonky from there" to mean that she views quantum phenomena as fundamentally distinct and accessible only through nonclassical reasoning. As the interview continues, Donna expands her understanding of what it means to think like a physicist while reasoning about scales. She defines a boundary between the everyday "normal stuff" that engineers focus on and the more theoretical, scale-extreme phenomena that physicists study, such as "black holes colliding" and "things that are so crazy tiny." Her epistemological approaches are a resource for her, highlighting how physicists and engineers approach and interpret the same phenomenon differently depending on their goals.

Next, Amelia approaches QM's wonky behavior by relying on mathematics. She emphasizes that understanding certain phenomena requires using math as the primary approach. She describes her epistemology that QM is behaviors that "shouldn't be but are," similar to views expressed by Antares and Donna. Amelia emphasizes the tension between theoretical expectations and mathematical formalism. She provides an example of electron spin to position mathematics as an essential epistemological approach for understanding otherwise conceptually inaccessible phenomena.

Amelia: *I would say maybe like, the unexplained or the hard to explain behavior and properties of the universe, that we can't really infer from intuition because either like the theory doesn't line up with the math or the math doesn't line up with the theory and it's just a bunch of things that shouldn't be but are [laughs, Donna quietly agrees].* ***And so it just kind of breaks your brain and you're like that should not work but it does.*** *Kind of thing, so, like we were talking about the other day, like um, an electron, like, isn't spinning, but it has [enunciates] spin, to it, kind of thing that like, you wouldn't think it's not, like, intuitive, but like,* ***the math shows that that's the way it is kind of thing.*** *So, like, I guess it's the hard to explain or unexplainable, things that, just shouldn't be but are.*

For Amelia, *The bread and butter of quantum is math* means "the math shows that that's the way it is." Her epistemology reflects a belief that quantum phenomena cannot be fully grasped through physical reasoning alone. When confronted with concepts that defy classical understanding (electron spin that "isn't spinning"), Amelia considers mathematics as a tool and the epistemological approach for making sense of unexplainable and wonky behavior.

Our last example is during a conversation with Lily at the beginning of the interview session, where she describes approaching QM's wonky behavior by reflecting on classical understanding. At the time of the interview session,

Lily had completed the junior/senior-level advanced undergraduate quantum course. She describes an alternative epistemological approach that positions QM as the foundation and classical behavior as a resulting emergent phenomenon. Her orientation reveals a unique epistemological approach by reinterpreting classical behavior as the exception, not the rule.

> **Lily:** *I don't remember who said the quote but, they said,* ***it's not remarkable, that the universe behaves the way quantum mechanics says it does, what's remarkable is that, on, our scale of existence, um things behave classically.*** *Like the fact that you get classical mechanics out of quantum mechanics compounded upon quantum mechanics, you know, thousands, millions, trillions of times. That, you know is sort of the remarkable thing, but, of course, it's not our lived experience, which is why it's, I think difficult conceptually.*

For Lily *I'm thinking of it classically*" means classical mechanics is not the fundamental rule of the universe, but rather an emergent phenomenon that becomes visible, "compounded upon quantum mechanics, you know, thousands, millions, trillions of times." She approaches classical behavior as the exceptional case, not the norm. By saying, "what's remarkable is that, on, our scale of existence, um things behave classically," she flips conventional approaches and assumes QM as the foundational framework, the default reality, from which classical behavior arises. While many students draw on classical knowledge resources to make sense of quantum phenomena, Lily demonstrates a distinct and refined epistemological approach to QM by providing context for when and how reasoning can explain why the classical world behaves as it does. She further remarks, "but, of course, it's not our lived experience, which is why it's, I think difficult conceptually," reaffirming that our experiences condition the boundary to comprehending QM.

The study data from interviews with undergraduate learners demonstrate how they recognize that QM defies complete explanation and that they actively attempt to make sense of it anyway through their unique epistemological approaches. Donna reasons about scales to approach the limits of classical reasoning and predictability. Amelia relies on mathematics to navigate unexplainable behavior. Lily provides context for describing the classical world from quantum phenomena. These students' epistemological approaches shape their strategies for making sense of wonky QM and highlight the need to amplify students' voices in curriculum design that builds on their interpretations, ideas, and prior knowledge.

V. DISCUSSION

This paper contributes to the PER literature by shifting the focus from student deficits to students' epistemological approaches when navigating wonky QM: reasoning across scale boundaries, relying on mathematics, and drawing on classical knowledge. Students' epistemological approaches are guiding tools, similar to results found elsewhere (e.g., [10–14]); however, this study deepens that insight as we amplify students' voices, not through judgment or a deficit lens. Students demonstrate self-awareness of their learning as they decipher when and how their prior knowledge applies. We shift the focus away from misconceptions and recognize that students do not position themselves as lacking ability; instead, they are actively working to make sense of QM.

While this study offers insight into students' epistemological approach, it does not explore its connection to frames [32] or epistemology in adjacent fields such as chemistry, nuclear engineering, or quantum computing. Additionally, while participants discussed their knowledge openly, few explicitly connected their ideas to problem-solving contexts, focusing instead on broader implications. These limitations allow future investigations to examine how epistemological approaches, frames, and knowledge resources manifest across disciplinary contexts and problem-solving situations.

Rich articulations are, however, observed while participants reasoned across scale boundaries, where quantum phenomena become increasingly salient at smaller scales. Using metaphors and analogies to express quantum's resistance to familiar ways of knowing, learners describe a broad sentiment: classical reasoning breaks down at a scale boundary, beyond which mathematical representations become essential. The insights presented throughout point to an overarching structural issue in the curriculum. The barrier to quantum understanding lies not in students' capacity but in the mathematical emphasis and instructional direction through which it is taught. While math can be a powerful quantum learning tool, students recognized that over-reliance reduces conceptual understanding.

Future work would benefit from continually avoiding researcher-imposed judgments and providing counter-narratives to the deficit perspective by moving the field toward centering student voices and perspectives during curriculum redesign, as explored elsewhere in PER (e.g.,[37]). For example, consider a learning sequence that forefronts QM first, an idea born out of discussions with Lily, where she views QM as the foundation to classical mechanics. Research on reordering the physics curriculum to foreground quantum reasoning remains underexplored, especially when considering the meaning of scale boundaries and resulting implications. Another intriguing inquiry is whether students self-internalize a deficit perspective about their ability to understand QM. Exploring the intersection between students' self-efficacy and epistemology could provide an alternative to a deficit model by flipping the investigation's focus.

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