Comparing student perspectives of intermediate classical mechanics and quantum mechanics courses

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The transition from sophomore-level classes to junior-level classes is often a significant one; the level of mathematics, abstraction, and difficulty is higher than what was encountered previously. This study examines students' perspectives of quantum mechanics and intermediate classical mechanics across two dimensions: disciplinary identity (math vs. physics course) and epistemic focus (mathematical vs. conceptual). Using a semantic differential scale methodology in semi-structured interviews with six students, we collected both quantitative (percentage estimations from the scale placements) and qualitative (student justifications of their placements) data. Here, we present our results for both types of data, which show that the 'abstractness' of quantum mechanics and 'tangibleness' of classical mechanics determine how students perceive their disciplinary identity. For the epistemic scale, instructional choices seem to be most impactful in influencing student perspectives. Mathematical preparation also appears to influence how students perceive classical and quantum mechanics on these scales.

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I. INTRODUCTION AND BACKGROUND

Upper-level courses, specifically quantum mechanics (QM), present a unique set of epistemological challenges to students. Although classical mechanics (CM) courses often build on students' prior physical intuitions, QM demands a conceptual shift toward abstract formalism, counterintuitive mechanisms, and rigorous mathematical notation [1–3].

The problems of epistemic framing in QM often involve transition errors (failing to move between conceptual and mathematical frames), displacement errors (operating in the wrong frame), or content errors (failing to activate relevant knowledge within the appropriate frame) [1, 4, 5]. Mathematical sense making in which students link formal mathematical procedures with conceptual understanding of physical systems becomes especially complex for QM, as students must reason through layered abstractions and varying notations [3]. Students also use different physical and mathematical sense-making tools to guide their problem solving and intuition about quantum phenomena [6].

Studies have shown that students often feel that physics is inductive and flexible compared to mathematics being deductive and rigid [7]. Students are frustrated when they are expected to apply unfamiliar mathematical tools in physics contexts without clear motivations or proofs, leading to a "culture shock" when high-level mathematics is *ad hoc* added to complicated physics matter. These mismatches can be particularly pronounced in QM [7, 8]. Students' perspectives on the nature and difficulty of mathematics often differ depending on the QM paradigm (spin versus wavefunction). Schermerhorn et al. [9] found that after the spin portion of a QM course, despite reporting difficulties applying the Dirac notation formalism to physical situations, the majority of students in their sample perceived physics concepts as more difficult than mathematics. This difference was due to the math feeling more familiar and simpler, while the physics concepts required a deeper understanding. Conversely, after the wave function portion of the curriculum, the majority of students reported finding the mathematics more challenging [9].

Previous work comparing QM and CM has shown that students tend to hold different conceptual frameworks for both courses, with CM often seen as intuitive, deterministic, and grounded in physical experience, while QM is viewed as abstract, probabilistic, and mathematically driven [10]. These conceptual differences are reinforced by the curriculum structures students encounter: CM emphasizes Newtonian dynamics and analytical techniques applied to real-world systems, while QM introduces entirely new mathematical formalisms, such as Dirac notation and Hilbert spaces, often without sufficient conceptual grounding [10]. A mixed-methods study by Dreyfus et al. [11] found that a significant number of students in their sample displayed different approaches to knowledge in QM and CM, particularly with regard to the connection between physics and the real world and the connection between mathematical and conceptual reasoning.

The work we present here is part of a larger study around a new QM curriculum, which builds on and combines aspects of the prior studies described above. The new QM course uses a spin-first paradigm [12], focuses on five core quantum concepts, and incorporates discussions of many quantum optical experiments. Following this course, we investigate how students perceive QM in terms of disciplinary identity (mathematics vs. physics) and epistemic focus (mathematical vs. conceptual). We employ a novel semi-structured interview methodology that evokes student perspectives on a target object (e.g., QM) by inviting participants to place the object along a physical dial representing a conceptual continuum (e.g., math course to physics course) and justify their placement through open-ended discussion. Specifically, our research questions are:

1. How do students perceive QM on a scale from a math course to a physics course?
2. How do students perceive QM on a scale from a mathematical course to a conceptual course?
3. How does students' mathematical preparation impact their perceptions of QM on these two scales?
4. How do students' perspectives of CM and QM compare on these two scales?

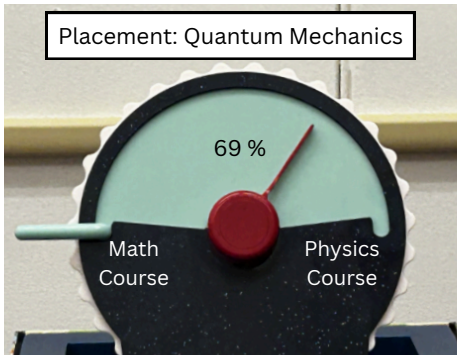

FIG. 1. A physical representation of the semantic differential dial, adapted from the board game *Wavelength*, students were presented with two labels anchoring either end of the scale and were asked to place an object within that range. In this example, the student placed "Quantum Mechanics" along the scale from "Math Course" to "Physics Course". The resulting angle was later quantified as a percentage of the dial's full range, in this case 69%.

II. METHODOLOGY

Our QM course begins with a month-long exploration of core quantum principles: superposition, entanglement, tagging, measurement, and complementarity, using spin-based formalism and optical experiments. Formal tools, including Dirac notation, the Schrödinger factorization method, and second quantization, are introduced later in the course to cover key systems such as the harmonic oscillator, angular momentum, perturbation theory, and light quantization. Formal discussions are often highlighted through experimental

TABLE I. Questions from the interview focusing on comparing Intermediate Classical Mechanics to Quantum Mechanics

Interview Questions		
Object Placed	**Left End**	**Right End**
Q1: QM	Math Course	Physics Course
Q2: CM	Math Course	Physics Course
Q3: QM	Mathematical Course	Conceptual Course
Q4: CM	Mathematical Course	Conceptual Course

descriptions and in-depth tutorial-style simulations to anchor their quantum foundations. The CM course is quite traditional. It follows Taylor's *Classical Mechanics* [13], and emphasizes Newtonian principles, the Lagrangian formulation, and applications such as central forces, oscillations, and collisions, taught in a typical lecture-style format.

All six students who completed both the QM and CM courses in Fall 2024 volunteered to participate in our study, and the interviews were conducted at the end of the semester when all coursework had been completed. Mathematics preparation varied across our six participants. While all students had completed the physics department's Mathematical Methods course and had either completed or received credit for multi-variable calculus through the mathematics department, the specific number of other mathematics courses completed varied for each student. Details of their individual mathematics preparation are provided in Table II.

The central component of the interview methodology was an interactive dial inspired by the traditional semantic differential technique, which typically consisted of antonymic adjective pairs anchored at the ends of a discrete scale (e.g., "slow" to "fast") [14–17]. Participants select a point along the continuum to place an object (e.g., "bicycling"). This format was adapted into a continuous spectrum using a physical dial instead of the traditional bins. For example, students were presented with opposing descriptors (e.g., "Math Course" vs. "Physics Course") and asked to position a given object (e.g., "Quantum Mechanics") along the given spectrum as shown in Figure 1. Students then justified their placement, explaining how they were interpreting the object and the scale ends.

While the interviews covered a range of topics, including pedagogical preferences and mathematical and experimental understanding, this paper focuses on the items related to students' perceptions of QM and CM in terms of disciplinary identity (mathematics vs. physics) and epistemic focus (mathematical vs. conceptual). These interview items are summarized in terms of their object and scale ends in Table I.

This interview method provides both quantitative and qualitative data. A quantization of the dial placement was obtained using an image-processing tool, where the dial's angular placement was recorded using a digital protractor. Each dial position was then discretized by dividing the measured angle by the total angular span of the dial, yielding a normalized percentage for analysis. Qualitative data comes from

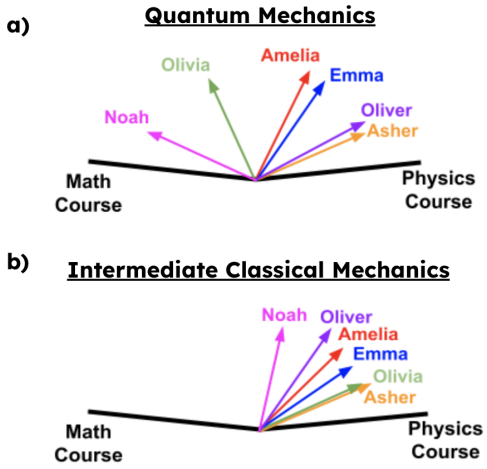

FIG. 2. A visual representation of the students' dial placement for a) QM and b) CM on a scale from "math course" to "physics course".

students' justifications for their placements. Our analysis of the justifications involved coding for emergent themes around not only students' perspectives of QM and CM, but also their interpretations of the scales math vs. physics and mathematical vs. conceptual. Throughout the results section, student pseudonyms are used in the presentation of our data.

III. RESULTS AND DISCUSSION

Table II presents students' quantized dial placement for each of the four items along with a summary of their mathematics preparation. Figure 4 shows a standard box-and-whisker plot of quantized student dial placements to all four interview items. These placements are discussed along with the qualitative justification data in the subsections that follow.

A. Math Course vs. Physics Course

Figure 2 shows a representation of each student's dial placements for QM and CM on the scale of "math course" to "physics course". 4 of the 6 students place QM on the physics side of the scale. Emma and Asher both contrast the focus of the QM course with that of their math courses. For them, the focus in QM is more on the application of tools as opposed to descriptions of tool properties in math courses.

Emma: I'm also taking math classes and how the math classes are...constructed, like they are *so different from the physics ones and also different from quantum more specifically* because like we are doing proofs in them... But like *in physics we were connecting it to real-life examples*.

Asher: Because we *barely talked anything about linear operators, in terms of its mathematical properties...* We

TABLE II. This table summarizes each student's mathematics preparation beyond multi-variable calculus and mathematical methods and presents their quantized dial placement for each item. For Q1 and Q2, a number above 50% indicates that students perceived the course as more of a physics course. For Q3 and Q4 a number above 50% indicates that students perceived the course as more conceptual.

Student	Mathematics Preparation	Q1 (%)	Q2 (%)	Q3 (%)	Q4 (%)
Oliver	Math major; 4 additional courses including linear algebra and ODE	91	74	97	62
Emma	Math major; 4 additional courses (2 concurrent) including linear algebra	74	86	42	12
Amelia	Math minor; 1 additional course (concurrent)	69	80	40	40
Asher	1 additional course (linear algebra)	93	93	97	49
Noah	No additional courses	14	60	23	70
Olivia	No additional courses	37	92	39	81

gloss those things over, so there are many important relations, like in the mathematical sense, that we didn't really cover. *We're more often just given the relations and apply that relation*.

However, for Noah and Olivia, QM is on the math side of the scale. Noah, in particular, describes the course as theoretical, focusing mostly on pen-and-paper activities, and comments on the high frequency with which new mathematical tools are introduced. While the course places an emphasis on experiment and incorporates simulations to represent real experiments, Noah notes the lack of hands-on experimentation with physical equipment as one reason for his placement.

Noah: Everything we've done is pen and paper, right? We've had simulations to see certain experiments. We've been given the historical context... if somebody needs to do some sort of beam scattering... *I'm going to use certain tools of mathematics to get it done... every chapter is some new math theorem that is supposed to be applied...* the physical connections are not readily seen unless they've already been observed... I've learned more math techniques... *we haven't been able to do any experiment, which makes sense*.

There also seems to be some correlation between students' mathematical preparation and their placements of QM on this scale, given that the students with the least number of mathematics courses completed were the only two to place QM on the math side of the scale. These students may have less practice with particular math tools and/or learning to use math tools, and as a result, had to place more of their time and focus on the mathematical foundations aspect of the QM course.

As shown in Figure 2, all 6 students place CM on the physics side of the scale. Olivia and Noah have the most notable shifts. For Olivia, familiarity with the topics is the main reason, while for Noah, it is that you can physically demonstrate and observe the phenomenon.

Olivia: I've taken mechanics like five times now... *That's like kind of the epitome of physics is mechanics*.

Noah: The math involves a lot of...physical processes that you see *before in class when we do some demos*...we have to think about why something is behaving the way it is. *They're not theoretical things.*

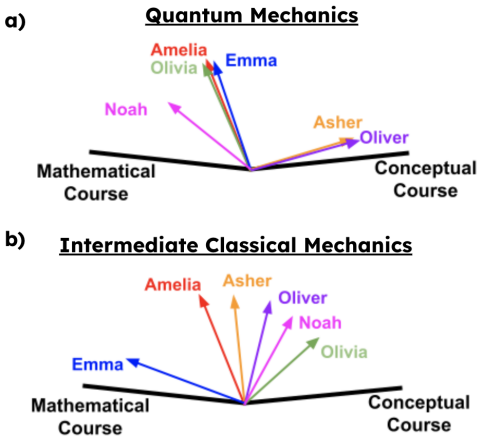

FIG. 3. A visual representation of the students' dial responses of a) QM and b) CM on a scale from "mathematical course" to "conceptual course".

B. Mathematical Course vs. Conceptual Course

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Looking at Figure 3, we see that students' dial placements vary largely across the scale for both QM and CM. However, Figure 4 shows that, in contrast to the "math course vs physics course" scale, the students were more evenly split on which course was more conceptual, with similar dial placement means for QM and CM. The medians are close to neutral for both courses, with QM only being slightly mathematical and CM only being slightly conceptual. When comparing within student responses, 2 of the 6 students placed CM as more conceptual, 3 of the 6 placed QM as more conceptual, and 1 student placed them at the same position.

Amelia is an interesting case study for this scale. Her placement of the dial slightly to the mathematical side of the scale is the same for both courses, but for different reasons. She describes the ends of the scale as a dichotomy between plug and chug versus sense-making. She believes that both courses had a mixture of both of these. In QM, she sometimes found herself doing the math without really understand-

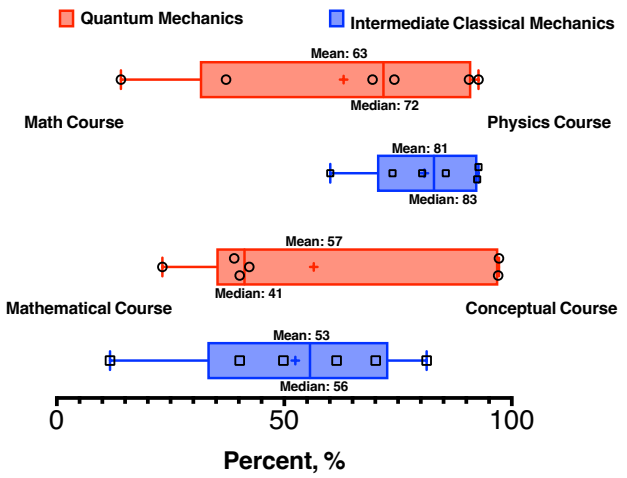

FIG. 4. Standard box-and-whisker (25-75 percent) plot of student dial responses to all four interview questions. The left of the figure at 0 percent represents the far left of the dial (math course or mathematical course), while the right of the figure at 100 percent represents the far right of the dial (physics course or conceptual course). Circles or boxes represent individual student responses; the plus represents the mean. The mean and median are numerically labeled.

ing why. However, given the QM course design, there were opportunities to practice conceptual reasoning through essay questions, which she did not get to do in CM. She reports doing more math in CM, but she felt the connection to concepts was often clearer.

Amelia (QM): I understand like what this dichotomy is getting at...*like plug and chug vibe versus like what's happening here... there was sort of like a disconnect between like what was happening and like the math that I was doing...* I think I learned like conceptual ideas in the math as well... I've given like some equation and I'm going to go manipulate it to like get a different one out that I know is like a better form, *but I'm not like connecting it to the like why and how and like all that sort of stuff.*

Amelia (CM): I think this is going to be... like around the same area...it has a different way of being sort of similar...So I think, *overall I did more math in intermediate mechanics than quantum mechanics...but like in quantum, there were lots of things that sometimes I was just like working conceptually with something where it'd be...like word answers or like I'm writing an essay about something. There's nothing like that in intermediate mechanics.* Everything always included math, *but oftentimes it was like math as like proof of concept. So I think that connection was often more clear.* But it also, sometimes that does set up a sort of feeling where you're like, okay, you just made this thing up and now we're just going to use it.

Many of these ideas came up in other students' justifications, but how they balanced them was different from Amelia's. Some students also emphasized the importance of conceptual understanding in making sense in QM, noting that mathematical proficiency alone was insufficient.

IV. CONCLUSION

This study explored students' perceptions of QM and CM along two dimensions: disciplinary identity (math vs. physics) and epistemic focus (mathematical vs. conceptual). For a QM course, designed to focus on a small number of core quantum concepts and that places an emphasis on quantum optical experiments, most students perceive it as more of a physics course. However, the abstract nature leads two students to view it still as more of a math course, and overall, CM is still viewed as more of a physics course than a math course. This indicates a potential need for careful introduction and discussion of the 'realness' of quantum experiments and phenomena in QM course design.

Students' responses to the mathematical/conceptual comparison were nuanced. They saw QM as a course that demanded high-level mathematical manipulation, but also introduced conceptual ideas that were not easily mapped onto the math. Interestingly, some students described CM as being "just math" in practice, despite its physical basis, suggesting that the "conceptualness" of a course is not just the nature of the content, but also about how it is taught and assessed.

Lastly, math preparation seems to influence student perceptions of the courses. The two students with the least mathematical preparation were the only two students who perceived QM as more of a math course than a physics course, and the only two to perceive QM as more mathematical than CM.

There are limitations to this study. First, as is common in qualitative research, the sample size is small, which limits the generalizability of our results. Second, student interpretations of the scales varied considerably. While students provided thoughtful justifications for their placements, their individual understanding of what each scale represented was not as consistent. This variability does not significantly affect within-student comparisons, such as how a single student rated different courses, but it does introduce ambiguity when making comparisons across students. This observation also points to a broader challenge inherent in the interpretation of scaled response data or Likert-type instruments. Thus, the major focus of the quantitative data for this paper is on overarching trends rather than specific student values.

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