Editors' Suggestion

Intuition in quantum mechanics: Student perspectives and expectations

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(Received 23 August 2022; accepted 12 January 2023; published 21 February 2023)

Broadly speaking, many physicists value intuition in their work, and many instructors hope their students develop intuition (while possibly being wary of their initial, unrefined intuitions). These considerations are especially relevant in quantum mechanics, a subject many see as counterintuitive because it is removed from classical everyday experience. Do students consider quantum mechanics intuitive, how does this affect their approach to the subject, and what does "intuitive" mean to them? We investigate these questions through a mixed-methods approach within the context of one upper-division quantum mechanics class at an R1 university. We find that most students in this population expect to have little intuition for quantum mechanics, so many consider it more unintuitive than counterintuitive. We also find that students use the word intuitive to refer to a number of distinct ideas. Overall, students have a diverse set of perspectives on intuition and its role in studying quantum mechanics. This study lays groundwork for additional research into students' views on intuition in physics and informs how we can address intuition as educators. Quantum instructors should be aware of their students' perspectives on intuition, and can integrate the different ways students perceive intuition into their lessons.

DOI: 10.1103/PhysRevPhysEducRes.19.010109

I. INTRODUCTION

As a concept, intuition is elusive and defies definition. Nonetheless, if it plays any role in learning and doing physics, we are compelled both to communicate our intuitions when teaching and to communicate about intuition when conducting education research. This work aims to lend clarity—and the perspective of students—to this communication, with a focus on quantum physics.

Quantum theory deviates from classical physics in profound ways. For example, observation affects subsequent outcomes, incompatible observables are unknowable simultaneously, and entanglement leads to nonlocal effects. Does this make quantum mechanics nonintuitive? These ideas are far removed from our macroscopic lived experiences. Does this make them counterintuitive?

A common claim in education research about quantum mechanics is that the subject matter is not intuitive. References [1–11] refer to quantum mechanics or certain subtopics as *counter*intuitive (meaning contrary to one's intuition). Others refer to the subject as *un*intuitive (meaning one lacks intuition) or simply *non*intuitive (meaning either *counter* or *un*) [12–14]. Often, these statements are made in passing, and authors may not intentionally use one term over another. Still, as a whole, the literature seems to agree: quantum mechanics topics are often counterintuitive (or at least unintuitive), and this is a relevant consideration when teaching.

This raises multiple questions, and this paper focuses on the following three:

1. Do students consider quantum mechanics as counterintuitive as the literature suggests they might?
2. What does "intuitive" mean to students?
3. How do students' views on intuition affect their approach to learning quantum mechanics?

Investigating these questions will illuminate students' perspectives on intuition in quantum mechanics with possible implications for future research and for instruction.

To address these research questions, we interviewed and surveyed students drawn from two semesters of undergraduate quantum mechanics. We will present quantitative survey results, but focus more on qualitative analysis. We adopt a phenomenographic approach for our qualitative analysis [15,16]: we set out to characterize the different ways that students perceive and experience intuition when learning quantum mechanics. We do so without an *a priori* categorization scheme in mind, meaning we can address our research questions without establishing a definition of intuition. We employ this strategy because our objective is to forefront student perspectives.

In line with this goal, we avoid value judgments of student statements about intuition. For example, we consider the view that quantum mechanics is intuitive to be neither inherently expertlike nor inherently novicelike. Instruction often aims to help students develop intuition, and we share this goal. We also recognize that some physicists perceive the differences between classical and quantum physics as nonintuitive even when—or perhaps because—they understand those differences well. In this work, we investigate distinctions beyond an intuitive or nonintuitive binary.

We begin by grounding this study in the existing literature (Sec. II) and describing our methodology (Sec. III). We then present our findings (Sec. IV) in order of our research questions. We conclude with discussion of possible instructional implications as well as potential future research directions (Secs. V, VI, and VII).

II. INTUITION IN PER LITERATURE

There is a large body of work discussing intuition both within physics education research (PER) and more broadly: "Philosophers, writers, mystics, psychologists, biologists, and educators have all contributed to the great conversation" [17]. A comprehensive review is beyond the scope of this paper, but a brief survey of PER literature will contextualize the present study. Discussions of intuition in PER literature vary in content, context, and purpose; we organize our summary of these discussions using four categories. The categories are not mutually exclusive, and this paper fits best in the fourth category. The discussions in the first two categories do not probe the nature of intuition directly but do investigate its presence in student thinking and use in the classroom.

Intuitions as barriers to understanding or problem solving.—In some cases, students' initial, intuitive reactions to a given physics problem may cause errors in their solution strategy. This can possibly be explained in terms of dual-process theories, which posit that reasoning consists of two modes: a "fast," intuitive process, and a "slow," deliberate, or rational process [18–21]. If students fail to activate a slow process when solving problems, they can be misled by their initial intuitions, which may be incorrect or incomplete.

The *elicit, confront, resolve* paradigm for instructional activities is one strategy for addressing this problem. Used most notably in the *Tutorials* produced by the University of Washington [22], the strategy aims to helps students "overcome deeply rooted ideas" that are incorrect, which may arise from students' intuitions [23]. The broad body of research into student "misconceptions" overlaps with this perspective on intuition.

Intuition as an instructional goal.—Some instructional strategies or materials are designed with the explicit goal of helping students develop intuition. For example, Elby discusses guiding students through the process of "refining raw intuitions" when teaching introductory mechanics [24], and Whittmann and Morgan describe the design of an "Intuitive Quantum Physics" course for nonscience majors that foregrounds "everyday" thinking [25]. Bao and Redish discuss the "difficulty in building intuition" in quantum physics, but name helping students in doing so as an explicit instructional goal [26].

Ontology: Intuition as a specific category of knowledge or type of thought process.—Research in this category attempts to characterize or define *intuitive thinking* or *intuitive knowledge*. The dual-process theories mentioned above undertake this effort [18–21], as does diSessa's work on "phenomenological primitives," which are fundamental, intuitive ideas or thought patterns from which more systematic knowledge may be constructed [27]. Other examples include work from Chi and Slotta, who argue that intuitive knowledge has more structure than suggested by diSessa [28], from Brock, who presents intuition as a form of "tacit knowledge" [29], and from Sherin, who studies the role of intuition in physics problem solving [30]. In contrast, Singh examines physicists' thought processes explicitly when they have minimal intuition about a given problem [31].

Epistemology: Practitioners' perspectives on intuition.—Regardless of the exact definition of the term, if intuition is a part of knowing physics, then physicists' views on intuition constitute part of their epistemologies (beliefs about the nature of knowledge). Research in this category treats intuition as a part of knowledge or type of thought process, but focuses on people's perspectives on knowledge instead of attempting to classify or define it directly.

Intuition is a consideration in work studying students' epistemologies in quantum physics [32–34], but little work in PER has focused primarily on students' views on intuition. Outside of PER, Marton *et al.* have investigated the views on scientific intuition expressed—not by students—but by Nobel prize-winners in yearly panel discussions [35]. Their findings include that the discussion participants: (a) did, for the most part, consider scientific intuition to exist as a process distinct from analytic thinking; (b) used the word "intuition" to describe a person's capability (e.g., someone with a knack for intuitive understanding), something that happens (e.g., being struck by intuition), or an outcome (e.g., having an intuition); (c) believed that intuition can be developed through experience, but that it comes more naturally for some; and (d) considered intuition to be something that one can feel or experience.

Similar in both spirit and methodology to the work of Marton *et al.*, this paper investigates the views on intuition expressed by students in a quantum mechanics course. Students' epistemologies affect their learning in physics generally [36,37] and in quantum mechanics specifically [32,33,38]. Moreover, as discussed in the introduction, intuition is perhaps especially pertinent in quantum mechanics. Hence, learning what students have to say about intuition can illuminate this element of students' epistemologies to complement theoretical work, inform further research, and guide instruction that seeks to help students develop or refine their intuition.

III. METHODOLOGY

We employed a mixed-methods approach to investigate students' perspectives on intuition in quantum mechanics, including surveys and interviews. In this section, we describe the courses from which interviewees and survey respondents were drawn, detail the survey questions and interview protocol, and summarize our analysis strategy. Table I provides a summary of data collection.

A. Quantum mechanics course

Surveys were administered in two semesters of the junior-level quantum mechanics course at a large, R1 university. Interviewees were drawn from the first semester only. The first semester (Fall 2020) had 63 enrolled students, and the second semester (Spring 2021) had 99 enrolled students. During both semesters, the class was taught by the same PER faculty (author SP). Both times, the class was taught fully remotely due to the COVID-19 pandemic, meaning the lectures were held synchronously over Zoom and were also recorded and made available to students asynchronously. Lectures included interactive elements such as frequent clicker questions.

The vast majority of students in the class were physics majors, with some astrophysics majors as well. The class reflects the demographic breakdown of the upper-division physics and astrophysics majors, which the university reports as follows. Approximately 20% of majors are reported to be female [39]. The major is split evenly between in-state and out-of-state students, and 14% are first-generation college students. 58% of majors are identified as White, an additional 22% as international, 9% as Hispanic/Latino, 7% as Asian, and below 5% as any other race/ethnicity.

TABLE I. Summary of data collection. Other than interviews, all data were collected from weekly prelecture surveys ("preflights") administered during two semesters of an upper-division quantum mechanics course. The surveys and interviews are described in the text.

Instrument	Administration and timing
Question about incoming expectations for intuition in quantum	Once per semester, on the first prelecture survey, due on the first day of class
Intuition characterization question (Fig. 1)	Every other week on prelecture surveys
Questions about struggle	Every other week on prelecture surveys
Interviews (Fig. 2)	Week 9 of the fall semester
Question about the role of intuition in quantum	Once, on the prelecture survey for week 6 of the spring semester
Question about developing intuition in quantum	Once, on the prelecture survey for week 10 of the spring semester

The class, which is the first half of a two-semester quantum mechanics sequence for physics majors, was taught using a "spins-first" instructional paradigm following McIntyre's *Quantum Mechanics* text [40]. The postulates of quantum mechanics were first presented in the context of a two-state, spin-½ system, and only later applied to position-space wave functions. Prerequisites included a linear algebra course, and the department's modern physics course, which includes a unit on quantum mechanics. This means students had some prior classroom exposure to quantum topics.

Three lectures were held each week. Additionally, one optional weekly recitation section was held (also over Zoom) in which students worked on conceptual worksheets (tutorials) in small groups under the guidance of the professor and assistant instructors. Approximately 30% of students attended the optional tutorials. The tutorials, as well as homework assignments and clicker questions, are available at [41]. In both semesters, the course included two midterm exams and a final exam.

B. Surveys

In both semesters, the course included online prelecture surveys assigned once per week, which we call "preflights" [42]. The preflights, which were graded for participation only, typically consisted of brief conceptual questions about recently covered material. They additionally included survey questions for this research study, which were always asked first, before any physics content questions.

On the first preflight of each semester, which was due on the first day of class, we asked the following question to gauge students' expectations for intuition in quantum mechanics:

> *Think back on your previous physics courses: did you consider what you learned in those courses to be "intuitive" or "unintuitive" (or even "counterintuitive")? Why? (Maybe you felt differently about different courses.) How do you expect Quantum Mechanics to compare to your previous courses, in terms of how intuitive (or not) you will find the material?*

Students were able to respond in a single open-ended text box.

To probe whether students considered quantum topics intuitive, the question in Fig. 1 was included on preflights biweekly during both semesters. Students were asked to characterize their intuition about the topics they had learned that week, and could check boxes corresponding with *intuitive, unintuitive, counterintuitive,* or *unconcerned*. Students were allowed to check multiple boxes, because in any given week some new ideas may feel intuitive while others do not.

How would you characterize your intuition about the ideas/concepts you learned this week?

Check ALL that apply.

- ☐ The ideas seem **intuitive**
- ☐ Some of the ideas seem **COUNTER**intuitive (they disagreed with my intuition about the world)
- ☐ Some of the ideas seem **UN**intuitive (I don't have any intuition about them one way or another)
- ☐ I'm not worried about/interested in how intuitive the ideas were

FIG. 1. This question was administered on online prelecture surveys (preflights) approximately every other week during each of two semesters of undergraduate quantum mechanics. The preflights were mandatory and students received participation credit for completing them. Preflights typically also included physics content questions.

During the first semester, every time the intuition characterization question was asked it was followed by:

> *Optional: Explain your response to the previous question about intuition.*

After a few weeks, few students (roughly 20%) provided explanations. During the second semester, we only included the explanation option the first time we asked the intuition characterization question. On two later preflights that semester, we asked each of the following once:

> *FOR YOU PERSONALLY, how important is intuition to your learning in physics? What role does it play?*

and

> *Do you feel like you're developing intuition about quantum mechanics in this class? If so, what has helped you develop it? If not, why not?*

Both were asked directly following the intuition characterization question for the given week.

In addition to questions about intuition, we also asked students about their "struggle" with different aspects of the material on preflights. Approximately biweekly, students were asked on preflights to rank their struggle with: the physics; the math; connecting the math and the physics; notation; language; and quantum "weirdness." For each category, students chose from an ordinal scale of: no struggle (0); mild struggle (1); moderate struggle (2); severe struggle (3). The struggle questions were asked as a follow-up to our work characterizing student discomfort with the material in quantum mechanics [44], but also allowed us to investigate the potential relationship between students' sense of intuition and their self-reported sense of struggle with the content. In the first semester, the struggle questions were asked on the same preflights as the intuition questions; they were asked on alternating weeks in the second semester so the preflight length would be more consistent every week.

C. Interviews

To study student thinking on intuition more deeply, we conducted 11 interviews with students from the Fall 2020 semester's quantum mechanics class. Student volunteers each received a $20 gift card, and all students in the class were invited to participate in interviews. Interviews, which lasted 30 minutes and were held over Zoom, were conducted about halfway through the semester (around week 9 of a 15-week semester). The protocol consisted of 12 guiding questions as shown in Fig. 2. Interviews were recorded and later transcribed.

The interviewees were representative of the class in terms of their course performance: of the 11 interviewees, 5 averaged between 90–100% on exams, 2 between 80–90%, and 3 between 60–70%. The 11th interviewee withdrew from the class some time after the interview. The overall

Interview Protocol

1. Do you think physics is "intuitive?" Why? What are the things that make it "intuitive" or not?
2. What does "intuitive" mean?
3. How important do you think "intuition" is in your understanding in physics classes generally? What about in your problem solving (e.g., doing homework or taking exams)?
4. How about in Quantum Mechanics this semester specifically?
5. Do you think Quantum Mechanics is "intuitive?" Why? What are the things that make it "intuitive" or not?
6. What does "intuitive" mean for you in your QM course specifically?
7. Do you feel like you are developing/have developed a sense of intuition in QM this semester? Can you describe what that process is like for you? What helps you develop a sense of intuition?
8. In previous interviews, some students distinguished "counterintuitive" (something that is different from what you would intuitively expect) from "unintuitive" (something that you don't have an intuition for one way or another). What do you think about this distinction?
9. Do you feel like you've had to "unlearn" things when developing intuition in QM? (In other words, did you find things "counterintuitive?")
10. Can something simultaneously "make sense" but be "unintuitive?"
11. Can something simultaneously "make sense" but be "counterintuitive?"

FIG. 2. Protocol used for interviews. Interviews were semi-structured and conversational: the interviewer occasionally asked follow-up questions or skipped questions in the protocol that the interviewee had already addressed.

class exam average was 75%. We report exam averages and not overall course grades because the course grade distribution was unusual compared with previous semesters due to considerations for difficulties caused by emergency remote teaching and the COVID-19 pandemic.

D. Analysis

The multiple-choice preflight question asking students to characterize their intuition lent itself to a quantitative analysis; we report various counts and correlation coefficients in Sec. IV A. Additionally, students' struggle rankings allowed us to investigate possible correlations between students' self-reported struggle and sense of intuition, as discussed in Sec. IV C. Our remaining data required qualitative analysis.

We employed a phenomenographic approach for our qualitative analysis. Phenomenography is a methodology for drawing out and characterizing different perceptions of the same phenomena [15,16]. In this study, the phenomenon in question is intuition (or specifically intuition in quantum mechanics), and the themes or categories that arise describe different ways students perceive or experience it. Notably, the categories are of student statements, not of students themselves.

Phenomenography sometimes produces a set of themes or categories that are arranged hierarchically (see [45] for an example from PER); however, this is not required. We do not consider any perspective on intuition to be inherently expert- or novice-like, meaning there is no obvious hierarchy to apply to these perspectives. Our application of phenomenography is informed by Marton *et al.*, who implemented this methodology to (nonhierarchically) categorize the ways Nobel laureates perceive "scientific intuition" [35].

We applied emergent coding to the interview transcripts and identified themes relevant to each of our three research questions: whether students consider quantum mechanics intuitive; what students appear to mean by intuitive; and the role and importance that students attribute to intuition in quantum. We then applied the same codes to all open-ended preflight responses. We found evidence for all codes in the broader sample of student responses, and did not find that any new codes emerged from the broader sample.

The coding was primarily conducted by author GC, but all codes were refined in discussion with all three authors examining student quotations until consensus was reached. Coding was conducted for one research question at a time, and codes were applied to entire sentences (or fragments), but not all sentences received codes. Several complex student statements received multiple codes, but most received only one. The same process was applied to preflight responses.

We also identified themes related to a fourth question: do students initially expect quantum mechanics to be intuitive? Some discussion of this question arose in interviews, but it was also asked explicitly on the first preflight of both semesters. A broader range of more direct responses to the question arose on the preflights, hence our codes in related to this question were emergent from the preflight data rather than from the interviews.

The purpose of this thematic analysis was to draw out the range of ideas that are relevant for students when considering intuition in quantum mechanics. We do not focus on the relative frequencies of various themes because they may be sensitive to the student population, the instructor, and the specific survey and interview questions we asked. Nonetheless, all themes we report were observed in multiple student statements in both interviews and preflight responses. The identification and organization of themes presented below can guide other instructors and researchers who aim to discuss or investigate intuition.

IV. FINDINGS

We present our findings beginning with survey data about whether students consider quantum mechanics intuitive, and discuss these results in light of student statements from the interviews (Sec. IV A). Next, we consider what intuitive appears to mean to students. We describe *facets* of the word intuitive arising from a thematic analysis of interviews and free-response survey questions (Sec. IV B) and we also report on the relationship between students' sense of intuition and their self-reported sense of struggle with the material (Sec. IV C). Finally, we discuss what students describe as the role of intuition in their learning, and the expectations they have for intuition in quantum mechanics (Sec. IV D). Overall, we set out to characterize the variety of ways students perceive and experience intuition in quantum mechanics, and we avoid making value judgments of student statements.

A. Is quantum mechanics intuitive for students?

This section addresses the first research question from the introduction: do students consider quantum mechanics as counterintuitive as the literature suggests they might? Our findings suggest that our students do not.

Approximately every other week during two semesters of undergraduate quantum mechanics, we asked students to characterize what they were learning as *intuitive, unintuitive,* or *counterintuitive* (Fig. 1). Students were allowed to select multiple options, and could also indicate that they were *unconcerned* with their sense of intuition. Figure 3 shows the overall breakdown of responses between these four categories, aggregated over both semesters.

Nearly half of the responses indicated that "the ideas seem intuitive." About 6% of responses included the *unconcerned* option, while the remaining 45% indicated that the material was somehow nonintuitive. Notably, *unintuitive* accounted for over a quarter of responses, whereas *counterintuitive* accounted for slightly less than a fifth. Although the counterintuitive nature of quantum mechanics was relevant for these students, they more often reported simply having no intuition for quantum

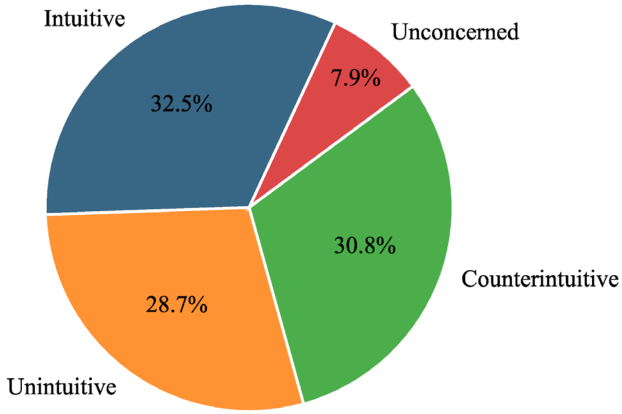

FIG. 3. Overall breakdown of students' responses to a prelecture survey question about intuition (Fig. 1), aggregated over both semesters of data collection. Includes 894 total responses from 163 students. Because students could select multiple options, the percentages are out of the total number of boxes checked.

mechanical topics one way or another (i.e., *unintuitive*). Students also expressed this sentiment in interviews, as discussed in depth below (Sec. IV D).

Before discussing interviews, we must clarify three things about Fig. 3: the effect of allowing students to select multiple options; week-by-week shifts in the breakdown of responses; and how responses varied by student. On the preflight given during the first week of both semesters, students selected 1.5 options on average, meaning approximately half selected two options (e.g., *intuitive* and *unintuitive*), whereas the rest selected only one. However, across the entire semester, only about one-fifth of students selected two options in a given week (i.e., an average of 1.2 options). Only 2% of all responses included three or four options, which corresponds with about one student doing so each week.

Table II shows the breakdown of student responses aggregated over both semesters and accounting for the possibility that students selected two options. The students who selected multiple options chose *intuitive/unintuitive* and *intuitive/counterintuitive* at similar rates, and fairly few students selected *unintuitive/counterintuitive*. It was also rare for students to select *unconcerned* and another option in the same week.

There was minimal temporal variation in student responses, although some patterns did emerge. The *intuitive* option was less common on the first preflight of each semester—accounting for about 33% of boxes checked as opposed to 49% for the whole term (averaged over both semesters). In addition, *counterintuitive* and *unintuitive* were approximately equally common on the first preflight. After the first preflight, however, things roughly and rapidly leveled off to reflect the quantities reported in Fig. 3 and Table II.

We did observe an uptick in *counterintuitive* during the unit on entanglement and the Einstein-Podolsky-Rosen paradox, which may be unsurprising to readers familiar with those topics. Conversely, we saw a decrease in *counterintuitive* in the week when the class transitioned from spin-½ systems to position-space wave functions. This could be related to the fact that students are more familiar with position than with spin, but overall we hesitate to overinterpret these weak temporal signals.

TABLE II. Breakdown of students' responses to a prelecture survey question about intuition (Fig. 1), aggregated over two semesters. The cells along the diagonal represent responses where students selected only one option. Off-diagonal cells represent responses where students selected two options (e.g., "The ideas seem intuitive" *and* "Some of the ideas seem UNintuitive"). Unlike in Fig. 3, the percentages given in this table are out of the total number of responses (894) as opposed to the total number of boxes checked. Omitted from the table are the 2% of responses where students checked three or more boxes.

	Intuitive	Un-	Counter-	Unconcerned
Intuitive	43.0%	⋯	⋯	⋯
Unintuitive	7.8%	18.9%	⋯	⋯
Counterintuitive	5.9%	3.6%	12.5%	⋯
Unconcerned	1.6%	0.5%	0.2%	4.2%

Whereas we did not observe strong temporal dependence in students' responses, we did see significant variation between students, as shown in Fig. 4. Almost every student selected a unique combination of options during the span of their quantum mechanics class. Some students considered almost everything intuitive and others found almost everything nonintuitive, but most students were somewhere in the middle. Taken together with the lack of significant temporal variation, Fig. 4 indicates that different students considered different weekly topics more or less intuitive.

Figure 4 strongly suggests that students are far from monolithic when it comes to their perceptions of intuition in quantum mechanics. It may be the case that this is true in physics more broadly as well. When asked if they thought physics was intuitive, three interviewees said the following three things:

> *Definitely very, very intuitive…that's what I love about it.*
> *Sometimes I feel that way. And then I'm proven wrong.*
> *I personally don't.*

The other interviewees offered a similar range of responses. As shown in Fig. 4, interviewees' weekly preflight responses were equally varied.

One might expect that students' sense of intuition would correlate with their course performance, but we observed weak correlations. As shown in Fig. 4, high-performing students varied significantly in how they responded to the preflight questions. The Spearman's rank correlation coefficient (ρ, which ranges in magnitude from 0, meaning no

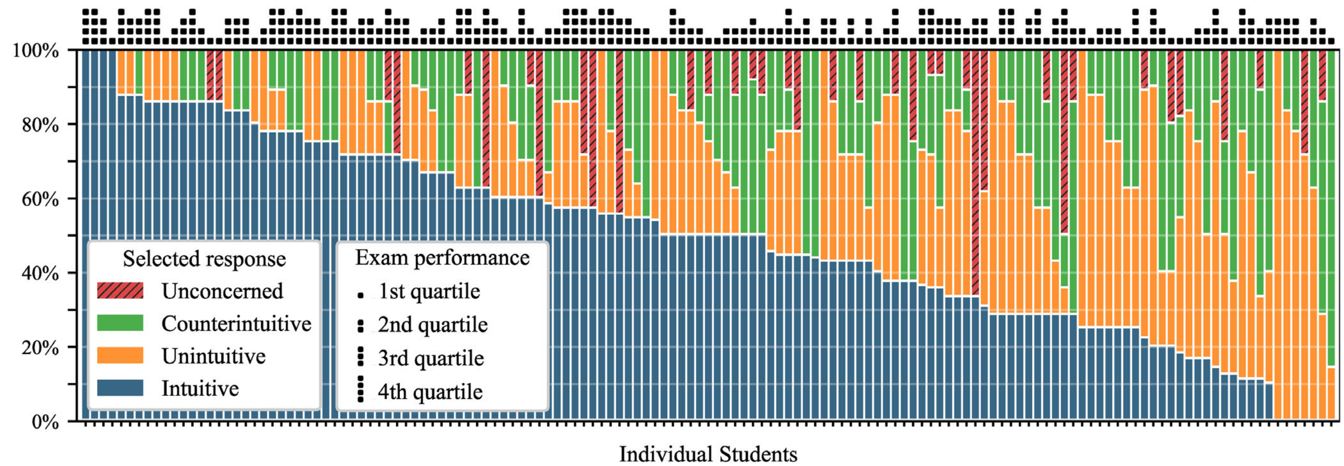

FIG. 4. Student responses to a prelecture survey question about intuition (Fig. 1), which was repeated approximately biweekly. The figure includes students' responses from two semesters. Each bar corresponds with a single student who answered the question on 4 or more prelecture surveys. 139 students are represented in the figure—24 students (15% of the 163 total) who only responded 3 or fewer times are omitted. Students could check multiple boxes. The percentages indicate how many times the student selected a given choice (e.g., "the ideas seem intuitive") out of the total number of boxes they checked aggregated over all the student's responses for the semester. The 10 columns marked "*" represent students who were also interviewed (the 11th interviewee is omitted because they dropped the class and did not respond to 4 or more surveys). Students are sorted horizontally based on the rate at which they chose the *intuitive* option. The vertically stacked squares above each bar represent the given student's overall exam average in their quantum mechanics course: one square indicates that the student's exam average fell in the first (lowest-performing) quartile, two squares indicates the second quartile, etc. As discussed in the text, there is little correlation between students' responses to the survey questions about intuition and their exam performance.

correlation, to 1, meaning perfect correlation) between students' exam averages and the rate at which they chose *intuitive* (i.e., the height of the *intuitive* bars in the figure) was 0.18 ($p < 0.05$). The correlation coefficient between students' exam averages and the rate at which they chose *counterintuitive* was -0.20 ($p < 0.05$; note that this correlation is negative). These both constitute weak correlations. There was also no correlation between students' exam scores and the rate at which they chose *unintuitive* ($\rho = -0.03$, $p = 0.7$). We share speculations on these correlations (or lack thereof) in the discussion.

B. Facets of intuition

This section addresses the second research question from the introduction: what does intuitive mean to students? Our findings indicate that the word has a range of meanings for different students, as summarized in Table III.

Students in quantum mechanics may consider the subject at least as unintuitive as they consider it counterintuitive, or possibly more so. Students also often reported that they found the ideas they were learning to be intuitive. But what does intuitive mean to students? Although we asked interviewees this question directly, we cannot paint a comprehensive picture of how any specific individual perceives the concept of intuition. We can, however, characterize the ways students used and describe the word, which we call *facets* of intuition.

We use the word facet because we consider intuition a multifaceted construct [46]. The "side" of intuition that surfaces in student statements likely depends on the context and content of the questions we ask them, but by collecting responses from many students we can begin to piece together the entire shape. Although each facet is distinct, some facets may overlap. Each facet generalizes ideas expressed by multiple students.

This section reports results of a thematic analysis of interviews and open-ended preflight responses, from which six facets of intuition emerged. The six facets, which we describe with examples below, are summarized in Table III. Every facet arose in both interviews and preflight responses from multiple students. Each facet refers to a use of the word intuitive that we were able to distinguish from all other facets; however, the definitions of the facets are not intended to be mutually exclusive.

1. *Matching one's expectations*

A physical problem may be intuitive if its behavior matches your expectations, counterintuitive if it does not, or unintuitive if you have few expectations for how it should behave. Two interviewees said,

> *For me, like intuitive is, you know, does it behave in the way I would expect it to?*
> *I would say to me, it would mean having a natural feeling as to what will happen.*

Whereas a third remarked that their quantum course,

TABLE III. Facets of intuition: the ways students use the word intuitive or discuss intuition in interviews and open-ended preflight questions. All codes arose at least a dozen times (possibly including multiple times in the same interview) and in statements from multiple students. Something is unintuitive when none of these facets apply (e.g., you have no expectations for how a system should behave, or you have no directly related intellectual experience). Something is counterintuitive when a facet applies, but it leads to an incorrect conclusion (e.g., your expectation is inaccurate, or the connection you make to prior intellectual experience leads you astray). The facets are described in depth in the text.

Facet of intuition	Something is intuitive when…	Example student quote
Matching one's expectations	You can predict how a system will behave, or you can anticipate what the solution to a problem will be.	*I think intuition is, like, something you can predict.*
"Physical" or "real-world" observable	You encounter it in everyday life, or you can see it with your own eyes. For example, the behavior of a bouncing ball.	*My physics classes have been pretty intuitive. This is because usually, we have dealt with situations that I am familiar with and could encounter and observe.*
Related to prior intellectual experience	It is connected to concepts or techniques you have learned or practiced before, possibly in other classes. For example, the eigenfunctions of a "particle in a box" are related to standing sound waves in pipes.	*The Coulomb force being the same as, like, gravity…I think that automatically makes it way more intuitive because…I can connect those immediately.*
Something one experiences	It "just naturally makes sense to you" (interviewee quote), you can make leaps of logic or understanding, or you feel that the concepts you are learning build or fit together in a comprehensive way.	*If you have intuition, then you have an instinctive feel as to what is right and what is wrong [when solving a physics problem].*
Mathematical intuition	You can make sense of it using mathematical tools you feel you understand.	*Those points that were not intuitive became intuitive after I understood the math governing the laws.*
Visualization	You can visualize it in a helpful but abstract way (e.g., a graph).	*It has been…intuitive in the sense that I was able to utilize a lot of visualization to help me learn the material.*

> *…didn't seem counterintuitive, but rather unintuitive, where I didn't know what to expect.*

Facets of intuition can arise in negative statements. For example, this student indicates that unintuitive means *not* knowing "what to expect," implying that intuitive means the opposite (knowing what to expect).

In interviews and, commonly, in preflight responses, students said they rely on their intuition to check their answers. For example, one preflight response said, "I'll use my intuition to sanity check." This use of intuition aligns closely with this facet: checking the "sanity" of one's answers against one's intuition relies on having an intuitive expectation for what the answer ought to be.

2. "Physical" or observable in the "real-world"

To quote one interviewee, "A lot of intuition comes from the physical world." Students said they gained intuition about physical systems by observing them, with their own senses, in everyday life. Commonly, this facet arose when students argued that classical mechanics is intuitive while quantum mechanics is not. One interviewee said

> *Classical mechanics, I think that's very intuitive because it's basically dealing with things that you can witness happening.*

On the other hand, a preflight response read

> *So many of the processes in quantum have little to no reference in our day-to-day lives; there's not much we can do to intuit it in [our] minds without a reference and so it becomes hard to conceptualize.*

This student argues that quantum mechanics is not intuitive for them because the systems under study do not relate to their everyday experiences.

3. Related to prior intellectual experience

In addition to relying on real-world experience, students can also gain intuition by relating new concepts to their academic experiences—that is, to things they learned previously, possibly in another class. For example, one interviewee said

If there's something that I don't really understand, I often try to connect it to other things that I've learned in the past

Others related the ability to make such a connection to the sense that something was intuitive. Along these lines, another interviewee said

[if] I understand something as being intuitive, it's, can I look it at an equation or a sentence or something, a graph and can I feel like it's related to something else I know very well?

Another interviewee said that, to them, intuitive "mostly means relatable. Like I have something to draw off of." Similarly, one preflight response described the week's quantum topics as "sort of intuitive because there are a lot of parallels here to classical mechanics." Connecting what they were learning to something they already knew granted this student some intuition for the new topics.

4. Something one experiences

This facet amalgamates three separate codes, each of which referred to a nebulous, elusive *sense* of intuition. The first code was for the idea that something is intuitive when "it just makes sense," as one interviewee described it. The second related to the ability to make leaps of logic or understanding: "something that you kind of subconsciously put together," as another interviewee said. The third was the feeling that concepts you are learning build or fit together in a satisfactory way. One interviewee, who considered quantum mechanics intuitive, said

Everything aligns up and builds off of itself in a clear and intuitive way. That's sort of how physics works. And it's part of why I love it so much.

Each of these codes describe intuition in an abstract fashion that is difficult to pin down. The idea that intuition can be felt or experienced is also described by Marton *et al.* in their work studying how Nobel laureates discuss scientific intuition [35].

An experience of intuition is potentially explained by other facets. For example, perhaps something "just makes sense" to you because it matches your expectation, or perhaps you can "subconsciously" put something together because of your prior intellectual experience. However, student statements assigned to this facet described a sense or experience of intuition without elaboration. One such statement read

[Intuitive] would mean having a natural feeling as to what will happen or how things work, like, without being told the rules without being told the math and everything and you just know, based on a gut feeling.

This student described intuition as a "gut feeling," which is consistent with the idea that intuition can be experienced.

5. Mathematical intuition

Students often discussed mathematics as playing a role in their intuitive understanding of physics, usually as an aid, but also as a hindrance. One interviewee said

Intuition, for me is more in a mathematical sense. And physics is a fun way to apply that mathematical intuition, but it doesn't have to necessarily make, like real world sense for intuition for me to apply.

This student's sense of intuition for math allowed them to feel that the physics they were learning was intuitive as well—even when that physics fails to make "real world sense." Similarly, a preflight response read

As long as the math makes sense to me then it's intuitive to my standards.

For these students, their mathematical intuition was separable from—but played a key role in—their physical intuition.

Conversely, although less frequently, other students described the math as a barrier to their intuitive understanding. On one early preflight, one student justified their *counterintuitive* selection by saying

The only thing that's really messing me up is the math and connecting it to the physics …I'm very intimidated by eigen stuff.

This student also separated their mathematical understanding from their physical understanding (the math was the "only thing" messing them up), but they said their difficulty with the math caused them to select *counterintuitive*.

Many students said they considered math especially relevant when making sense of or developing intuition in quantum mechanics, in part because the theory is not directly observable in everyday life. On a preflight, one student chose the *counterintuitive* option but, in their explanation, said

…because we are learning the math behind the strangeness, it is easier to comprehend

This student felt that learning the underlying math was helping them overcome what they saw as the counterintuitive nature of quantum strangeness.

For another student, though, mathematical intuition was not enough to consider quantum mechanics intuitive. On a preflight, they said

The math all feels intuitive but once you start thinking about what the math is saying happens it feels somewhat counterintuitive.

This student considered the physical interpretation of the math to be counterintuitive, despite considering the math itself intuitive.

Finally, one student explicitly distinguished mathematical calculations from intuition, saying on a preflight

> *The concepts in quantum are easier to understand because it relies more on calculations than intuitions.*

This student saw the need for intuitive understanding as a barrier to success, and found quantum mechanics easier because, to them, it relied more on mathematics that did not require intuition. Although this student presents calculation as an alternative to intuition, most students appeared to consider math as relevant to their sense of intuition.

6. Visualization

The final facet that arose was the idea that intuition is related to one's ability to visualize a problem in one's head. Here we discuss abstract visualization as opposed to literally observing a physical scenario. Other research has pointed to the utility of abstract visualization in understanding quantum mechanics [49]. Abstract visualization might refer to a graph or other specific mathematical tool, but it includes any sense in which someone claims to "see" a physical concept or scenario in their head. The relation between visualization and intuition is bidirectional: visualization can help one gain intuition, and intuition can help one visualize a problem.

One preflight response read

> *For me, the most intuitive learning was…if graphs were involved that I could use to visualize what is physically going on.*

For this student, graphs (an abstract visualization) were a key feature of "intuitive learning." Meanwhile, another response read

> *Intuition is somewhat important, as I have to fit ideas and concepts into my cognition as something I can visualize or otherwise manipulate in order to fully understand them.*

It is unclear whether this student sees intuition as an aid to visualization, visualization as an aid to intuition, or the two as intertwined. Regardless, abstract, "in one's own head" visualization arose as a distinct facet of intuition.

C. How does students' sense of intuition relate to their sense of struggle?

This section also addresses the second question from the introduction: what does intuitive mean to students? We consider the possibility that students' sense of intuition is entangled with their perception of how difficult the material is, and find some evidence in favor of this idea.

We have identified several meanings of intuitive in the form of facets that describe the varied ways students use the word. Zooming out from these nuances, interviewees seemed to agree that physics was *easier* when it felt intuitive. One interviewee said,

> *I just think it will be harder for you to learn the material if you're not having some sense of intuition for it.*

This idea also arose in multiple preflight responses, one of which read "I think that learning new things is easier with intuition." To what extent does students' sense of intuition relate to their sense of difficulty, or struggle, with the material?

Approximately every other week on preflights, we asked students to rank their struggle with six different categories of the material on a scale of 0–3 (*no struggle* to *severe struggle*). For each student, we calculated an overall struggle score by summing their rankings for all six categories over all preflights they responded to. We normalized the overall score by dividing by the maximum struggle the student could have reported: the number of preflights they responded to multiplied by 6 (categories) multiplied by 3 (maximum per-category ranking). To address our question, we computed the correlation between students' overall struggle score and their self-reported sense of intuition.

Spearman's rank correlation coefficient between students' overall sense of struggle and the frequency with which they selected *intuitive* was -0.54 ($p < 0.001$). We expected a negative coefficient because we expect these quantities to be inversely related: a student who reports more struggle will presumably report less intuition. Each of the six struggle categories independently exhibited a statistically significant correlation with intuition, with *math* having the weakest correlation, and *physics* and *weirdness* having the strongest. The correlation between overall struggle and intuition was stronger in the fall semester (-0.63, $p < 0.001$) than in the spring semester (-0.49, $p < 0.001$), possibly because the struggle and intuition questions were asked on the same weekly preflights in the fall, but on alternating weeks in the spring.

Overall, we did observe an anti-correlation between students' self-reported sense of struggle and their sense of intuition as characterized on preflights. However, we do not know if this correlation is due to a causal relationship and, if so, which is the causal direction: do students report more struggle because they find the material nonintuitive, do they report less intuition because they find themselves struggling, or were these two survey questions simply measuring similar things because students consider intuitive and "lack of struggle" to mean similar things? Independent of these questions, we see that when we discuss intuition with students, we also get a sense of how much they consider themselves to be struggling with the material.

D. Student reflections on intuition in quantum

This section addresses the third research question from the introduction: how do students' views on intuition affect their approach to quantum courses? Our findings indicate that students expected quantum mechanics to be nonintuitive, prompting some to intentionally drop or ignore their incoming intuitions.

On surveys and in interviews, students were asked to reflect on intuition in quantum mechanics beyond simply indicating whether they considered the subject matter intuitive. In this section, we report on students' expectations about intuition in quantum, and also briefly discuss the role that students consider intuition to play in their learning.

1. Expectations: Cleaning the intuitive slate

On the first preflight each semester, which was due on the first day of class, we asked students whether they expected the material in quantum mechanics to be intuitive, and how they expected it to compare to previous classes. Over both semesters, 163 students responded. Of these responses, 127 gave a clear answer to the question and included some explanation. We coded students' responses as presented in Table IV.

A significant majority of students (78%) expected quantum mechanics to be either nonintuitive or less intuitive than other courses (or possibly both). Nine percent of students expected quantum to be comparably intuitive to their other physics courses, but did not indicate whether they considered other courses intuitive. Only 6% of students expected quantum to be intuitive or more intuitive than other courses, and the remaining 6% were unsure what to expect.

TABLE IV. Students' expectations for intuition in quantum mechanics, as described in responses to a prelecture survey question that was due on the first day of class. The percentages in the table are out of 127 student responses.

Students expect quantum mechanics to be…	%
Nonintuitive (exclusively)	41%
Less intuitive than other courses (exclusively)	25%
Both nonintuitive *and* less intuitive	9%
Comparably intuitive to other courses (exclusively)	9%
Both nonintuitive *and* comparably intuitive	3%
Intuitive or more intuitive than other courses	6%
Unsure or a mix of intuitive and nonintuitive	6%

Why do students expect quantum mechanics to be nonintuitive, and what effect does this expectation have on their approach to the course? We do not have a definitive answer to the first question, but we do present some speculation in the discussion. The interviews did, however, provide insight into the second question.

Most interviewees claimed to have intentionally let go of—or even ignored—their incoming intuitions at the start of their quantum mechanics class. One interviewee summarized as follows:

> *Coming into this class, like, like, I knew, like, things are gonna be weird and things are gonna be counterintuitive. So I automatically dropped my assumptions before I started.*

Because this student expected quantum to be counterintuitive, they tried to approach the subject without making intuitive assumptions. Similar statements were made in most interviews, such as,

> *I came into the class, with this idea of, it's not going to behave in the way I think it's going to behave…I kind of just wiped my slate clean.*

For this student as well, the expectation that quantum mechanics would behave differently than expected prompted them to wipe their "intuitive slate" clean. Some interviewees also suggested that the need to drop one's intuitions at the start of a new physics course was not unique to quantum mechanics.

We can interpret students cleaning their intuitive slates in both positive and negative lights. The awareness that one's intuitions must be adjusted in light of new evidence could be considered evidence of intellectual maturity. A third interviewee considered this to be one of their strengths:

> *One of the things that makes me good at physics is I'm pretty good at shifting my thinking, to, to match the observations.*

A fourth interviewee felt strongly that, as a student, "the only thing we can do is to learn," saying it was their job to reconcile their intuitions with the new ideas and facts they learned in class.

Although the willingness to adjust one's intuitions is important, it is potentially concerning that students have so little faith in their existing physical intuitions when it comes to learning quantum mechanics. One student called this out on a preflight:

> *There is some notion of a quantum intuition forming in my head, though at the moment it mostly just consists of "don't listen to classical intuition." This is not great…*

The student was concerned that knowing to ignore their classical intuition, "only eliminates one wrong idea rather than pointing me toward the correct thought process." Although naively applied classical intuition may fail for quantum systems, quantum mechanics is not so hopelessly "weird" and disconnected from other subjects that classical intuition is never useful.

On a positive note, although most students expected quantum mechanics to be nonintuitive, and many may have dropped their incoming intuitions as a consequence, a number of students expressed faith that, with time, they would develop a new, "quantum" intuition.

2. The role of intuition in learning quantum

On surveys and in interviews, we asked students how important intuition was to them personally when learning physics. For some students, intuition is essential; for others, it barely matters (although they may still consider it nice to have). One preflight response said intuition plays a "very very very very large role" in doing physics; meanwhile, another student said in an interview

> *At some point intuition doesn't really matter and you have to trust the theory.*

A second preflight response said intuition is "not very important. I just need to see the math," while a third considered intuition

> *The main part of physics to me. Without intuition, I'm just doing math.*

Preflights and interviews both contained a range of ideas about the importance of intuition in physics, although more students considered intuition important than unimportant.

Intuition can be useful to students in a variety of ways. Many students suggested that intuition could be used to check or make sense of their solutions to problems, which is related to the *matching one's expectations* facet of intuition. Some students made the point that their lack of intuition in quantum mechanics meant they could not tell if their solutions were reasonable. Intuition can also be relevant at the start of problems: some students suggested that intuitive insight was often required to identify a solution path. A handful of students said that intuition was not so important in the classroom, but that it was important when doing physics research.

As discussed above, when considering the relationship between intuition and struggle, one common idea expressed by most students was that physics becomes easier when you have intuition. This could be localized to specific content (e.g., analyzing spin-½ systems is easier once you develop an intuition for them), but a small number of students expressed that physics was difficult for them in general because they tended to lack intuition for it. One interviewee who had previously made this point said

> *I would obviously say I don't think [intuition] is that important…because without intuition, I can still usually try to understand what's happening anyway. I guess, like, it isn't a requirement…I think it really helps.*

This person and another interviewee both indicated that their success in physics to this point was *despite* their perceived lack of intuition, implying that their continued participation in physics required a degree of resiliency. These remarks suggest that students' sense of intuition may play a role in their self-efficacy or possibly in their sense of physics identity.

V. DISCUSSION

In this section, we reflect on key findings and also discuss limitations of this work. Over two semesters of undergraduate quantum mechanics, we regularly asked students to characterize what they were learning as intuitive, unintuitive, or counterintuitive. We found that, half the time, students considered things intuitive, and, when they did not, they were more likely to say things were unintuitive than counterintuitive. This may be surprising given quantum mechanics' popular reputation and given that quantum topics are often called counterintuitive in PER literature.

Before the study, we naively expected a strong correlation between sense of intuition and course performance. Further reflection led to some counterarguments; for example, we might expect strong students to recognize counterintuitive elements of quantum mechanics. It turned out that students' self-reported sense of intuition was, at most, weakly correlated with their exam scores. We can think of at least three possible explanations for this lack of correlation. First, students may be imperfect judges of whether or not they find material intuitive. Second, different students value intuition differently: where some may consider it crucial to their success, others may not. Third, students have different ideas about what intuition is and how it relates to answering questions correctly.

We asked students to describe their expectations for intuition in quantum mechanics, and conducted 11 interviews about this topic. We learned that a significant majority of students initially expect quantum mechanics to be somehow nonintuitive or less intuitive than other physics courses. Interviews provided evidence that, as a consequence of this expectation, many students may consciously drop their incoming intuitions at the start of their quantum class. This helps explain why *unintuitive* was more common than *counterintuitive* in preflight responses: something cannot disagree with your intuition—it cannot be counterintuitive—if you intentionally disregard your intuitions.

One possible reason why the surveyed students expected quantum mechanics to be nonintuitive is that they had all seen some quantum topics in their sophomore-level modern physics course. Some students mentioned this in their preflight response, saying they considered the subject nonintuitive then and expected it to be similar now. A second possible reason is that quantum mechanics is often described as “weird” both in popular culture and within the physics community. A third possible reason is that upper-division students may be noticing a trend of increasingly difficult and nonintuitive subject matter covered in their physics courses. Many preflight responses mentioned that upper-division electricity and magnetism had been mathematically intensive and, as a result, nonintuitive, and some said the same of middle-division classical mechanics. More study is required to discern the reasons behind students’ expectations for intuition in quantum mechanics.

We identified six facets of intuition. The facets arose empirically from the data, but also relate to prior research in the field. For example, real-world observability and visualization were both previously found to be relevant for students’ epistemologies in quantum mechanics [50]. The idea that intuition is something one experiences is similar to a theme identified in [35]. The idea that students find quantum mechanics less intuitive than classical mechanics, and as a consequence rely on mathematical understanding over conceptual understanding, has been reported elsewhere [34].

This study has several limitations, including the fact that students’ perspectives on quantum mechanics were likely biased due to their prior exposure to the material. Although the study includes 163 students from two semesters, all students were in the same quantum mechanics class with the same professor. The professor considered helping students develop intuition to be an instructional goal, which may have biased students’ perspectives on intuition. Moreover, interviewed students had been answering a preflight question about intuition on a biweekly basis leading up to their interviews, meaning they may have been thinking about intuition in quantum mechanics more than they otherwise would have been. Finally, the study was conducted during a period of emergency remote teaching prompted by the COVID-19 pandemic, which presented extraordinary and difficult circumstances for many students. Thus, although we have reported statistically meaningful results, their generalizability to other student populations remains open to investigation. We believe many of these limitations are mitigated by the qualitative focus of this study. For example, the six facets of intuition we identified may be useful to instructors and other researchers even if additional unidentified facets were to be relevant in other contexts.

VI. IMPLICATIONS FOR INSTRUCTION

We did not observe a strong correlation between students’ self-reported sense of intuition and their grades. This suggests that, at least in our course, the instructional goal of helping students develop a sense of intuition is independent from the instructional goal of helping students achieve good grades. The professor of the course included in this study valued both goals, but the correlation was weak nonetheless. If instructors value intuition as an instructional goal, they likely need to address it explicitly.

It may be useful for instructors to know that students might expect quantum mechanics to be nonintuitive and furthermore that students may attempt to disregard their incoming intuitions. Distinguishing quantum and classical physics is a reasonable instructional goal. In our case, though, students already appeared to recognize this distinction, at least when it came to their sense of intuition. We have not investigated reasons for this, but it may have been due to our students’ prior exposure to quantum topics in their academic career. We believe this leaves room for instruction to encourage students to refine their incoming intuitions instead of leaving them at the door. For example, instruction could point out cases where classical intuitions can be carefully and productively applied to quantum systems.

Instructors should first confirm that their students have similar incoming expectations. Instructors should also realize that students may have significantly varied perspectives on whether quantum topics are intuitive. Students may also have varied working definitions of intuitive, and may or may not consider intuition important. Some considered intuition paramount, while others thought it was unnecessary. Nonetheless, most students seemed to agree that intuition (however defined) makes learning physics easier.

We emphasize that, despite initial expectations, students classified what they were learning as intuitive approximately half the time. Evidently, there is significant opportunity for students to develop intuition in quantum mechanics. We believe that the facets of intuition we identified point to ideas instructors can focus on when discussing intuition.

Although real world, everyday life observability is more difficult in quantum physics as opposed to classical physics, instructors can recognize this difficulty explicitly and draw students’ attention to other facets. For example, abstract visualization can provide a useful alternative to direct observability. Students can also be encouraged to practice making qualitative predictions about quantum systems, which both emphasizes that one can have intuitive expectations for quantum mechanics and allows students to sharpen these intuitions. Familiar mathematics can also be used to guide students’ intuition, as can connections to physical examples or other knowledge that students have prior experience with. These elements probably already exist in most quantum courses, but it may be worth occasionally presenting them with the explicit, announced purpose of helping students form intuitions.

We have mentioned five facets of intuition, but the sixth—intuition as something one experiences—is harder to integrate directly into instruction: we do not have a prescription to make physics "just make sense."

VII. CONCLUSION

We used a mixed-methods approach to investigate students' perceptions of intuition in two semesters of an upper-division undergraduate quantum mechanics course. We found that there is room for intuition in quantum mechanics, but that the majority of our students enter the class expecting the subject to be nonintuitive or less intuitive than other courses. Some students claim to intentionally disregard their incoming intuitions and, consistently, view quantum as more unintuitive than counterintuitive.

The present study could be extended in several ways. The study could be repeated in other quantum courses, ideally at other institutions, to determine whether the quantitative patterns hold true for other student populations taught by other instructors. For example, it could be interesting to compare the results between this class, which uses a "spins-first" instructional paradigm, and a "position-first" class. Future studies could also disentangle struggle and intuition: we observed a correlation between students' self-reported senses of struggle and of intuition, but discussion of struggle or ease did not arise in the facets of intuition, suggesting that the correlation may be nontrivial.

The facets of intuition presented in this paper can support future work. The mathematical intuition category was especially rich, and a future study could potentially identify subcategories. A study of a broader population of quantum students could reveal how common each facet is relative to the others. Extended studies could also be conducted in nonquantum physics courses—or even in nonphysics courses—which would allow for comparisons between these contexts, both in terms of the relative frequency of each facet, as well as to see if wholly new definitions of intuitive arise in other contexts. One might hypothesize, for example, that students would approach intuition differently in classical mechanics than they do in quantum mechanics (or in, say, a computer science class), or that their beliefs about intuition might evolve over their tenure in a physics major. A longitudinal study could track the evolution of students' perspectives on intuition throughout their academic career. A future investigation could also examine the ways that and extent to which students use each facet of intuition when solving problems related to various topics.

Overall, student statements about intuition were rich, and they often touched on other PER topics, such as math-physics connections or student self-efficacy. We consider intuition a powerful lens for investigations into practitioners' perspectives on learning, knowing, and doing physics.

ACKNOWLEDGMENTS

We are grateful for the illuminating and unique perspectives of all the students included in our study. We also thank Bethany Wilcox for her support and Jessica Hoehn for her extensive feedback. This material is based upon work supported by the National Science Foundation under Grants No. PHY-2012147 and No. 2011958, as well as No. DUE 1626280, No. 1626594, and No. 1626482.

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