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Do students think that objects have a true definite position?

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Previous research on student thinking about experimental measurement and uncertainty has primarily focused on students' procedural reasoning: Given some data, what should students calculate or do next? This approach, however, cannot tell us what beliefs or conceptual understanding leads to students' procedural decisions. To explore this relationship, we first need to understand the range of students' beliefs and conceptual understanding of measurement. In this work, we explored students' philosophical beliefs about the existence of a true value in experimental measurement. We distributed a survey to students from 12 universities in which we presented two viewpoints on the existence of a true definite position resulting from an experiment, asking participants to indicate which view they agreed with more and asking them to explain their choice. We found that participants, both students and experts, varied in their beliefs about the existence of a true definite position and discussed a range of concepts related to quantum mechanics and the experimental process to explain their answers, regardless of whether or not they agreed with the existence of a true value. From these results, we postulate that students who exhibit similar procedural reasoning may hold widely varying philosophical views about measurement. We recommend that future work investigates this potential relationship and whether and how instruction should attend to these philosophical views in addition to students' procedural decisions.

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I. INTRODUCTION

Scientists learn about the world by making observations, performing experiments, and collecting and analyzing data. Determining what types of conclusions can be drawn from these observations and data is an important goal of undergraduate science education. The physics education research community has explored how students think about experimental data and how to report uncertainty (see, for example, the brief review in Ref. [1]).

One key aspect of this research literature is students' ideas about the nature of a physical phenomenon and what an experiment can tell us about that phenomenon. Hull *et al.* [2] proposed a framework to organize these ideas with respect to probability. This framework includes two ontologies: a deterministic ontology, which includes events that lead to predictable outcomes (e.g., projectile motion as described by kinematic equations), and a random ontology, which includes events that have unpredictable outcomes (e.g., radioactive decay lifetimes). They argue that many students believe these two ontologies cannot simultaneously describe a single phenomenon: that "random is incompatible with predictable" [2] (p. 70). They further argue that this incompatibility contributes to naive student ideas (also known as misconceptions) about physical phenomena and measurement.

This ontological framework can particularly help explain student reasoning about physical measurement in two ways: ideas about the physical phenomenon being measured and, separately, ideas about the experimental process itself. These two are not mutually exclusive, as students' ontology of the physical phenomenon under study may influence their thinking about the experimental process. For example, in a quantum-mechanical system, students may believe that all uncertainty in an experimental measurement is due to randomness caused by the Heisenberg uncertainty principle, so all variability in an experimental measurement is inherent to the phenomenon of interest rather than due to the experimental process itself [3,4]. To describe the motion of a projectile, in contrast, students may believe that all uncertainty in an experimental measurement is due to the limitations of the experiment [3,4].

Additionally, students' ontology of the experimental process can influence their ideas about experimental measurement uncertainty. For example, students who believe that measurement should be deterministic may

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argue that any individual data point can be the single correct value of a measurement and that variability is the result of mistakes made by the experimenter [5]. On the other hand, students who believe that measurement should be random may argue that multiple measurements are needed in an experiment and that experimenters should report an uncertainty interval [6].

The most influential model for understanding student thinking about the experimental measurement process focuses on students' procedural reasoning [7]. This model was developed to describe introductory-level students' reasoning about uncertainty in a simple projectile motion experiment in which a ball rolls down a ramp on a table and students measure how far from the table the ball hits the floor. In this model, students' procedural ideas or choices are separated into either pointlike or setlike paradigms based on how students draw conclusions about the result of an experiment, focusing especially on the importance they place on either single measurements or a collection of measurements. Pointlike thinking places importance on a single measurement. Students using pointlike thinking tend to report only a single measured value as the result of an experiment. They often attribute variability among measurements to mistakes made by the experimenter and they do not report a numerical uncertainty. On the other hand, setlike thinking places importance on a collection, or set, of measurements. Students using setlike thinking tend to report a probabilistic range of values for the result of an experiment based on uncertainty analysis, rather than just a single value.

Although most prior research on student reasoning about experimental measurement uncertainty has used the point and set paradigms to classify student reasoning [7–19], these paradigms cannot fully encapsulate all aspects of student thinking about uncertainty. The point and set paradigms characterize students' *procedural* reasoning, the decisions students make as they conduct an experiment and analyze data. They cannot, however, tell us what beliefs or conceptual understanding of measurement underpin these decisions. For example, students may choose to report the mean of a dataset (setlike action) rather than an individual measurement (pointlike action) because they learned this rule of data analysis by rote, rather than because they deeply understand the nature of scientific measurement [7,20]. Thus, more varied approaches to studying students' views of measurement are necessary in order to characterize students' conceptual understanding of uncertainty.

One relevant alternative view relates to the philosophical views that may lead to these procedural ideas and decisions. Research in other instructional contexts has found that attending to students' philosophical views is productive for learning (e.g., considering students' epistemology to support their conceptual understanding [21–23]). In the context of understanding uncertainty, underlying the definitions of the point and set paradigms [7] is the role and existence of a true value, or the idea that, in principle, a quantity measured in an experiment has a single exact value. Students' belief in a true value may vary based on whether they view a physics phenomenon as deterministic or random [2] and, separately, on whether they view the experimental measurement process as deterministic or random.

Coelho and Séré [5] investigated 14- to 17-year-olds' beliefs about the existence of a true value, finding that nearly all students believed an experiment has a unique true value and that it would be possible, in principle, to measure it without uncertainty. The researchers argued that this belief in a true value could be beneficial, as it encouraged students to improve their experiments to increase precision but also detrimental, as it could deter students from reporting uncertainty in their measurements.

We are unaware of any equivalent study that has probed university-level students' beliefs about the existence of a true value. Moreover, Coelho and Séré's [5] study probed students' views of a simple experiment governed by classical mechanics. We might expect more advanced students to express varied views about the existence of a true value in different advanced experimental contexts [4], particularly when knowledgeable about the role of randomness in quantum mechanics.

In this work, therefore, we delve into the idea of a deterministic true value, whether university students at varied academic levels (and experts) think it exists, and why. Our research questions can be articulated as follows:

RQ1. Do students think an object has a true value?

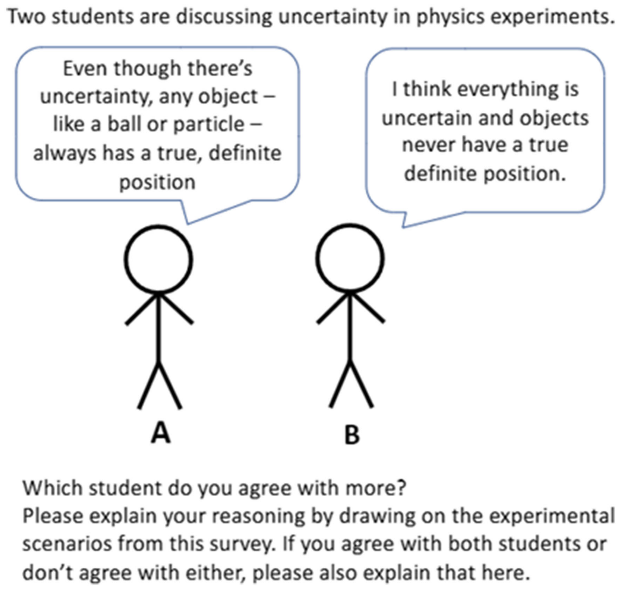
RQ2. What reasons do students give for their stance?

II. METHODS

A. Survey questions

In this work, we analyzed student responses to a single question from a larger survey [3,4,8]. This survey probed student understanding of experimental measurement and uncertainty in multiple physics lab contexts. All student participants were presented with a projectile motion experiment in which a ball rolls down a ramp and lands on the floor. They were then asked several questions from the Physics Measurement Questionnaire (PMQ) [9], asked to list sources of uncertainty in this experiment [3], and were asked how the distribution of measurements would change if more data were collected or if experts, rather than students, conducted the experiment [4]. Students who had taken at least one quantum mechanics course were additionally asked these questions (except the PMQ questions) about one of the three more advanced experiments: Brownian motion, the single-slit experiment, or the Stern-Gerlach experiment.

At the end of this survey, we included a question that directly asks about the existence of a true value for an object's position (see Fig. 1). Participants were first asked



Two students are discussing uncertainty in physics experiments.

Which student do you agree with more?
Please explain your reasoning by drawing on the experimental scenarios from this survey. If you agree with both students or don't agree with either, please also explain that here.

FIG. 1. Two students question administered to student participants. Participants first chose one of the two multiple-choice options, "Student A" or "Student B," to indicate whose statement they agreed with more. They were then provided with an open-response text box to explain their reasoning.

to indicate which of two student viewpoints they agreed with more. They were then asked to explain their answer.

In this paper, we focus on student responses to this "Two Students" question as a measure of students' philosophical views about measurement and uncertainty. We intentionally do not cross examine students' responses across all the question types included in the survey due to limitations of the survey structure. For example, students answered multiple PMQ questions and, based on previous analysis [7,16], students cannot be uniquely labeled as either point or setlike thinkers.

We also asked participants to provide demographic information (race and ethnicity, gender, major, and year) at the end of the survey. We used participants' self-reported majors in our analysis of their responses to the Two Students question. We asked participants to indicate whether their major was closely related to physics:

> Is your primary declared or intended major one of the following? Or, if you are double majoring, is one of your declared or intended majors one of the following?
> (a) Physics
> (b) Astronomy or astrophysics
> (c) Engineering physics
> (d) None of the above
> (e) Prefer not to disclose

For any respondent who selected "None of the above," we then asked a follow-up question in which students could select the category of their non-physics-related major and optionally write in their specific major:

> What is your primary declared or intended major?
> (a) Engineering: _____
> (b) Other physical science (including chemistry, math, or computer science): _____
> (c) Life science or biology: _____
> (d) Other: _____
> (e) Prefer not to disclose

We grouped all participants who answered "physics," "astronomy or astrophysics," or "engineering physics" into a single category, which we refer to as physics for the rest of the paper. Where possible, we manually sorted participants who chose "other" into one of the other major categories (for example, participants who wrote "meteorology" were classified as "other physical science").

B. Data collection

We collected survey data during four semesters from Fall 2020 through Spring 2022 at a total of 12 universities, including private universities, public universities, primarily white institutions, Hispanic-serving institutions, and a historically Black university (see Table I for a full list). To recruit study participants, we contacted instructors who were teaching either introductory calculus-based mechanics or electricity and magnetism courses ("intro" participants) or who were teaching quantum mechanics or more advanced physics courses ("beyond-intro" participants). These instructors shared a link to our survey on Qualtrics with their students and participants were compensated for responding to the survey either through course

TABLE I. Number of complete responses to the Two Students question from the universities represented in our dataset (380 intro responses and 288 beyond-intro responses).

Institution	Intro	Beyond-intro
Auburn University	89	0
California State Polytechnic University Pomona	3	0
California State University Fullerton	2	3
California State University San Marcos	25	19
Cornell University	107	113
Michigan State University	0	30
North Carolina A&T State University	75	0
San José State University	0	10
Texas A&M University	79	7
University of Colorado Boulder	0	102
University of St. Andrews	0	3
University of Wisconsin Stout	0	1

credit or a drawing for a $25 gift card. In total, we received complete responses to the Two Students question (a multiple-choice selection and a nonblank explanation of their answer) from 380 intro participants and 288 beyond-intro participants (see Table II for participants' self-reported demographic information).

C. Coding scheme

Participant reasoning was categorized using an emergent coding scheme (Table III). In developing the coding scheme, one of the authors read most of the explanations and noted recurring ideas. These ideas were shared with the full research team and overarching themes were identified. These themes became the basis for the coding scheme and were refined by one author applying it to a further subset of responses. Once a draft coding scheme had been developed, the full author team independently coded the same 50 responses and compared results. All discrepancies were discussed until consensus was reached and the codebook was updated accordingly. This process was repeated with a further 50 responses until the codebook was comprehensive enough to include the ideas present in almost all responses.

TABLE II. Demographic information self-reported by participants (380 intro participants and 288 beyond-intro participants). Participants who selected more than one race are counted in each race category they selected.

	Intro	Beyond-intro
Year of college		
First year (freshman)	47%	<1%
Second year (sophomore)	37%	12%
Third year (junior)	9%	44%
Fourth year + (senior)	5%	36%
Graduate student	0%	3%
Other	1%	2%
Unspecified	2%	2%
Major		
Physics	16%	89%
Engineering	61%	3%
Other physical science	9%	6%
Life science or biology	6%	<1%
Other	4%	0%
Unspecified	4%	1%
Gender		
Female	36%	24%
Male	59%	70%
Nonbinary	1%	2%
Prefer to self-describe	1%	<1%
Unspecified	3%	3%
Race/ethnicity		
American Indian or Alaska Native	1%	1%
Asian or Asian American	17%	24%
Black or African American	18%	2%
Hispanic or Latinx	14%	13%
Native Hawaiian or other Pacific Islander	1%	1%
White	54%	61%
Prefer to self-describe	1%	3%
Unspecified	5%	4%

The final coding scheme categorized responses into two main categories: experimental and quantum. Responses not falling into either category were labeled as other or as vague. Responses coded as experimental involved any discussion of the experimental equipment or process. This included discussions about experimental limitations due to the experiment being conducted by humans (e.g., human error or the inability of humans to replicate a procedure exactly the same way twice), external factors or variables outside the experimenter's control (e.g., friction and air resistance), and other factors associated with the experimental process (e.g., the fact that tools or technology cannot measure infinitely precisely).

Responses coded as quantum involved any discussion of quantum mechanical ideas. These responses could describe or name quantum physics principles, such as the Heisenberg uncertainty principle, discuss properties of a wave function, or make a comparison between the classical and quantum regimes.

Responses coded as vague generally stated whether or not an object's position is certain and did not provide an explanation. A minority of vague responses included an explanation that did not contain enough information to be codable.

Responses coded as other provided physical explanations that did not fit into the experimental or quantum codes. These were much less common, and most responses within the other category fell into one of three categories: relativity, object size, and moving objects. Responses categorized as relativity involved discussion of relativity principles to describe the uncertainty in the position of the object, including ideas that the object's position can vary based on the frame of reference. Responses coded as object size involved discussion about the size of an object being the main cause of the uncertainty in the position measurements, either on its own or in comparison to the measurement devices that may not have enough precision at smaller scales. Finally, responses coded as moving objects talked about how objects are constantly moving, vibrating, or changing position to describe the uncertainty in the object's position.

After finalizing the coding scheme, two of the authors independently coded all responses. Any disagreements were then independently reviewed by the other two authors. Finally, any further disagreements between the final two coders were discussed by all four authors until a consensus was reached.

D. Expert perspectives

During our investigation, we administered the Two Students question to expert physicists and coded their responses using the same coding scheme designed for our

TABLE III. Definitions and examples of each code.

Code	Definition	Examples
Experimental ($N = 266$)	Participants talked about the uncertainty in the position due to aspects of the experimental process. The responses included uncertainty due to human error, uncertainty due to measurement devices, uncertainty due to external factors (e.g., friction, air resistance), or uncertainty due to other vague factors.	"Measurement uncertainty is not due to objects not having a definite position. It is caused by lack of precision. The marble is not a perfect sphere and each marble is different. Each of the tracks are not going to be exactly the same height. Each of those objects still has a definite position." (Student A) "I believe that no matter how close we get to the object or how precise we are there will always be a percent error of that measurement no matter how small therefore we can never have a definite exact position." (Student B)
Quantum ($N = 211$)	Participants invoked quantum principles or language to describe the uncertainty in position. These principles included (but are not limited to) the Heisenberg uncertainty principle and hidden variable theory. This code also includes responses that compare the classical regime and its uncertainty to the quantum regime and its uncertainty.	"The [Heisenberg Uncertainty Principle] is not about the object's position, but rather our ability to measure it." (Student A) "When the particle is big enough, errors due to uncertainty principle is very small, and we can approximate to 0." (Student A) "I guess I agree with student B since the ball is made up of many quantum particles that have a built in uncertainty due to the uncertainty principle. " (Student B)
Other: Object size ($N = 33$)	Participants indicated that the certainty in measurements depends on the relative size of the measurement scale and object size or that there is a vague inherent uncertainty in the position of the object because of its size.	"The position of objects can still be described, even if there is uncertainty in the measurement. For smaller particles, it is more difficult to describe the true definite position because the uncertainty is larger compared to the size of the object. However, for larger objects, it makes more sense to describe it with a definite position because the uncertainty is small compared to the size of the object." (Student A)
Other: Moving objects ($N = 39$)	Participants discussed movement at the molecular scale or vibration causing uncertainty in position.	"A ball or a particle is constantly moving around there is no definite answer to where the original position of the ball was and same for a particle. A particle is moving up and down and to the sides and if we were to measure, it would be uncertain." (Student B)
Other: Relativity ($N = 30$)	Participants discussed relativity or frame of reference to explain the uncertainty in the position of the object.	"It really depends on your reference frame. In a building, objects can have definite position, however in that same building, looking at the planet from space, the Earth is moving around the Sun therefore the positions are constantly changing. From the perspective of another Galaxy, the Solar System is moving while the Earth is moving through it. No position is ever the same and is always changing." (Student B)
Vague ($N = 167$)	Participants stated that the object's position is certain or uncertain without further explanation or with an explanation that was too vague to categorize within our other codes.	

undergraduate student survey. We use these responses to provide context to our student responses by determining what expertlike responses to the Two Students question might look like.

The administration of the question differed from the student administration in several ways. First, we only asked faculty the Two Students question, without any of the previous questions on the survey. Recall that students were provided with a fictitious dataset that included a distribution of values; faculty were not primed by seeing any such data. In the text of the question, it was not indicated that it was two *students* discussing uncertainty, instead, we used the term *people*. This change was made to try to get answers that reflected our experts' perspective as researchers and physicists and not necessarily as teachers. Additionally, experts were not required to select person A or B, they were only asked which person they agreed with more. As such, many experts did not tell us which person they agreed with more and their answers were best coded as "neither" or "both." The question was administered by email and experts were asked to reply to the email with their answer.

We emailed 119 experts in our professional networks. All experts are physics faculty at colleges or universities. We received a total of 59 responses, 4 of which were received by participants passing the email question on to others. Of the 59 participants, 32 are experimentalists, 21 are theorists, and 6 are physics educations researchers specializing in ideas related to measurement. Two authors coded all responses for their answer (person A, person B, both, or neither) and reasoning using the explanation codes described in the previous section. Any disagreements were then coded by the other two authors. If the final two coders did not agree, then all four authors discussed and came to a consensus.

The expert responses can be seen in Table IV. Of all 59 responses, 18 were coded as agreeing with person A to some degree (either being coded as agreeing with person A or both). About 9 experts indicated they did not agree with either person and 41 were coded as agreeing with person B to some degree (32 of which as only agreed with person B). The distribution of expert responses indicates that there is no single "correct" answer to this question.

In their explanations, 48 of the 59 expert responses received the quantum code, 22 received the experimental code, 6 were coded as other, and 3 as vague. As with the answer option, these coded explanations indicate that there is no single "correct" theme that experts drew on when answering this question. Most faculty discussed quantum mechanical ideas to some degree, but perhaps most interesting is the 11 experts who did not reference quantum mechanical ideas in their answers, indicating that an expertlike response does not need to consider quantum mechanics. The small number of experts coded as other or vague provides confidence that our two main codes, experimental and quantum, capture most expertlike reasoning.

TABLE IV. Expert answers and explanations to the expert version of the Two Students question.

	Number of experts
Answer	
Person A	8 (14%)
Person B	32 (54%)
Both	10 (17%)
Neither	9 (15%)
Explanation code	
Experimental	22 (37%)
Quantum	48 (81%)
Other	6 (10%)
Vague	3 (5%)

III. RESULTS

Our goal in this work was to describe participants' reasoning about the existence of true values across varied populations. We first observed how participants' multiple-choice answers varied based on respondent level, respondent major, and what experiment they saw previously in the survey (RQ1). We then explored how participants' explanations of their multiple-choice answers varied across these variables (RQ2). As per the analysis of experts' responses, we did not interpret any single response as expertlike. Rather, we evaluated the range of student thinking and how that thinking may vary by population or priming from instruction and survey questions.

A. RQ1: Do students think an object has a true value?

We first looked at survey participants' closed-response answer as to which student's view on true values they agreed with more: student A, who believes every object has a true position, or student B, who believes that objects never have a true position (see Fig. 1). We compared answer frequencies based on participants' academic level, major, and what experiment they saw earlier in the survey.

We found that intro and beyond-intro participants expressed different views about whether objects have a true position. Intro students were approximately equally likely to agree with Student A (47%) or Student B (53%; see Fig. 2). In contrast, beyond-intro participants were much more likely to agree with Student B (78%) than with Student A (22%). Thus, beyond-intro participants mostly indicated that objects do not have a true position, while intro participants were split in their viewpoint.

We next explored whether participants with different majors expressed different views about whether objects have a true position. We considered only intro participants for this analysis, as the beyond-intro participants did not represent a sufficiently diverse set of majors to draw conclusions (almost exclusively physics majors). We found

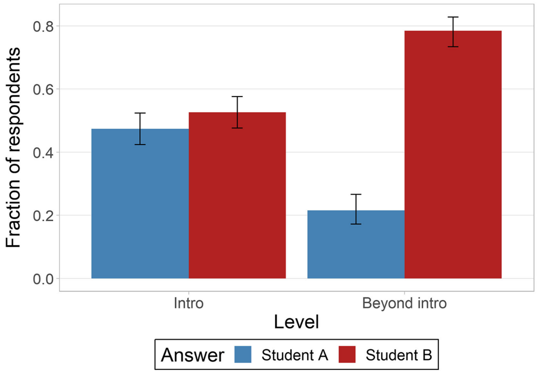


FIG. 2. Respondent answer choices separated by level (intro $N = 380$; beyond intro $N = 288$). Uncertainty bars represent the 95% confidence interval.

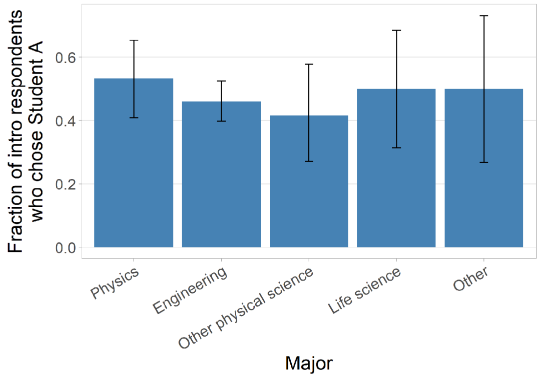


FIG. 3. Intro participants' answer choices separated by major (physics $N = 60$, engineering $N = 230$, other physical science $N = 36$, life science $N = 24$, other $N = 14$). Uncertainty bars represent the 95% confidence interval.

that intro participants' multiple-choice answers did not vary significantly with major, with all majors having between 42% and 53% of intro participants answering student A (see Fig. 3).

Finally, we compared the multiple-choice responses of beyond-intro participants who had seen different experiments (Brownian motion, single slit, or Stern-Gerlach) earlier in the survey. Because the question asked participants to draw on the experimental scenarios presented in the survey (see Fig. 1), we hypothesized that participants who were considering different experiments might answer this question differently. However, we found that beyond-intro students' answers did not vary significantly based on experiment seen, with the proportion of participants answering student A ranging from 16% to 27% across the three experiments (see Fig. 4).

B. RQ2: What reasons do students give for their stance?

After analyzing participants' multiple-choice answers, we then explored the explanations they provided to justify these answers. We first looked at variation in what explanations were provided for answers of student A as compared to student B, considering intro and beyond-intro participants separately (see Fig. 5).

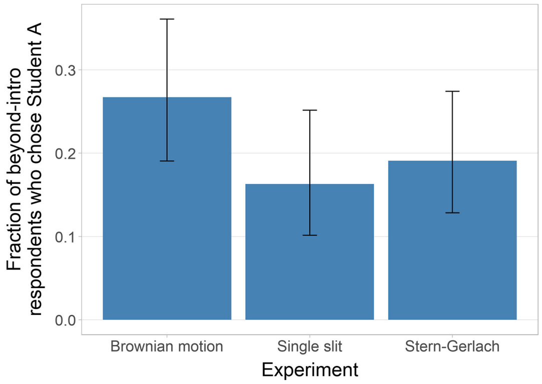


FIG. 4. Beyond-intro participants' answer choices separated by experiment seen (Brownian motion $N = 101$, single slit $N = 92$, Stern-Gerlach $N = 110$). Uncertainty bars represent the 95% confidence interval.

Regardless of their multiple-choice answer, intro participants frequently drew on aspects of the experimental process in explaining their answer (44% of those who answered student A and 46% of those who answered student B). Participants who answered student A often argued that an object has a true position but that experiments always have variability in measurement, for example, due to the precision of measurement devices or external factors such as air resistance. One intro respondent argued,

> Measurement uncertainty is not due to objects not having a definite position. It is caused by lack of precision. The marble is not a perfect sphere and each marble is different. Each of the tracks are not going to be exactly the same height. Each of those objects still has a definite position.

Intro participants who answered student B, in contrast, argued that variability in experiments cause an object not to have a true position, for example,

> While large-scale objects essentially do have definite positions, the ball experiment shows that there can be disagreement over an object's position even when repeated tests to determine it are performed. The ball always lands and you can always see it and point straight at it once the test is done, but determining where exactly it falls relative to its surroundings isn't so easy. It's true that there's one single place it must have landed, but it can't possibly be determined with 100% accuracy, so

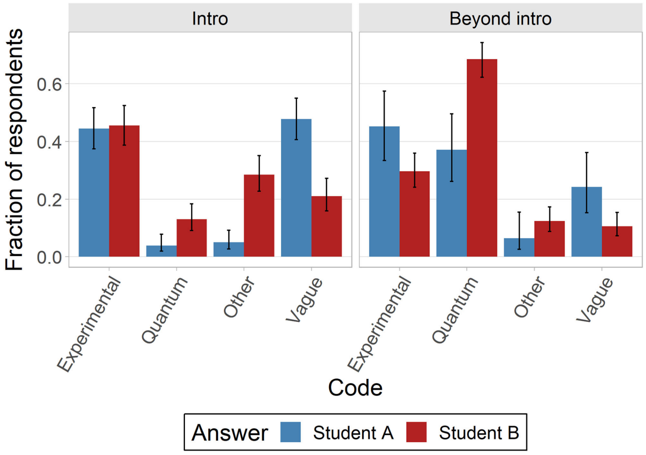


FIG. 5. Codes applied to participants' explanations of their answers, separated by level and answer choice (intro student A $N = 180$, intro student B $N = 200$, beyond-intro student A $N = 62$, beyond-intro student B $N = 226$). Uncertainty bars represent the 95% confidence interval.

> that one single position might as well not exist. It can only truly be described as a range with a likely true value, noting (sic) more precise than that.

Intro participants who answered student B to a lesser degree also drew on quantum mechanics (13%) or other physical explanations (29%) to explain why an object does not have a true position. One intro respondent, for example, argued that the vibration of particles prevents an object from having a true position: "you can never know the true position of an object because on a molecular scale particles are always vibrating—for instance, even in a simple experiment like rolling a ball off the ramp, we can never place the ball at the exact same point." Another intro student simply wrote "Heisenberg uncertainty principle!"

Notably, the most common code given to explanations from intro participants who chose student A was Vague (48%). These participants did not provide sufficient detail in their explanations for us to identify what physics the participants were drawing on in their reasoning, for example "There is always a definite place for an object."

Like the intro participants, beyond-intro participants frequently referenced the experimental process in their explanations of answers of both student A and student B (45% of those who chose student A and 30% of those who chose student B). The nature of their explanations was similar to those discussed above for intro participants.

In contrast to the intro participants, however, beyond-intro participants drew on quantum mechanics much more frequently in their explanations, particularly those who chose student B (37% of those who chose student A and 69% of those who chose student B). Beyond-intro participants who answered student A and discussed quantum mechanics often suggested that quantum mechanics places limits on humans' ability to measure a particle's position but not on the particle's intrinsic properties. For example, one student explained,

> Student A claims that the particle is determinist (sic), despite the quantum uncertainties. This is more intuitive to think about and is actually mathematically sound. The particle could exist in a definite position it the (sic) position is just unknown until it is measured. Such as the uncertainties in measurements in a classical sense do not imply the object is probabilistic, even theoretical uncertainties can only imply that it is impossible to know where it (sic) beforehand due to unmeasurable 'hidden variables' and thus the quantum mechanical universe can still be determinstic (sic).

Another student wrote,

> I think student A is more correct even for a quantum mechanical object. Consider an electron in a hydrogen atom. I am uncertain of where it is, but this is a different type of uncertainty—at least, to a degree. I may not be able to speak with certainty as to its exact position at any given moment, but there is also not really much reason I'd want to. The electron is a different type of thing, and in this scenario, its Cartesian position is not a particularly meaningful way of locating it. I can make a measurement of its position, if I want to. And at that instant in time, I have perfect knowledge of its position, limited only by my instrumentation. This state will soon decay and I will lose my ability to know 'where it is' soon thereafter. I think talking about quantum mechanical objects in this way is not very insightful, though. One can argue from a Bohmian perspective that the electron is always somewhere, and that the wavefunction is a representation of propagation of measurement uncertainties, or from a Copenhagen perspective that the electron *is* the wavefunction in a certain sense, and so on and so on. I think it does not really matter, here, so long as everyone is being precise about what exactly it is that they mean.

Beyond-intro participants who answered student B tended to claim that quantum mechanics prevents a particle from having a well-defined position. One student argued,

> Technically, nothing has a true "definite" position. For things like the first experiment, the quantum mechanical uncertainty in position of the ball is so small that the position is virtually definite but technically has a tiny bit of uncertainty to it. This uncertainty is massively dominated by lab equipment limitations/user error. However, for the second experiment, the distribution created from the single slit diffraction largely comes from the uncertainty in momentum of the particle, which corresponds to uncertainty in position. Here, the Heisenberg uncertainty principle has a large enough effect that user error/equipment limitations are not able to overwhelm it like in the first experiment.

Another student stated,

> Hidden-variable theories have been proven invalid by Bell's theorem. Therefore, an object truly does not have a definite position until the collapse of its wave function, and even then there is uncertainty via the uncertainty principle. The classical scenario has variation by the chaotic behavior of macroscopic forces, ie air resistance

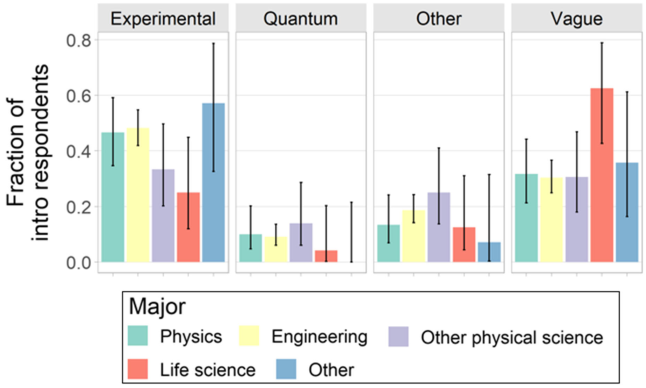


FIG. 6. Codes applied to intro participants' explanations of their answers, separated by major (physics $N = 60$, engineering $N = 230$, other physical science $N = 36$, life science $N = 24$, other $N = 14$). Uncertainty bars represent the 95% confidence interval.

> and friction, by (sic) the quantum has variation by the fact that a state is merely a superposition of all possible places it could be.

As with the multiple-choice responses above, we probed whether respondent explanations varied based on major or experiment seen earlier in the survey. We found that the codes applied to intro participants' explanations did not vary significantly based on major (see Fig. 6). We also found that the codes applied to beyond-intro participants' explanations did not vary based on what experiment participants had seen earlier in the survey (see Fig. 7).

IV. DISCUSSION

In this study, we examined experts' and students' ideas about whether objects have a "true value," which we consider part of a philosophical view about measurement. Answers of both student A (objects have a true value) and student B (objects do not have a true value) were fairly common across experts, beyond-intro students, and intro students. Many of the participants explained their answer to the Two Students question by drawing on the experimental process (45% of intro participants, 33% of beyond-intro participants, and 37% of experts), regardless of which answer choice they selected. Quantum mechanical ideas were also present in many students' and experts' explanations, with 32% of all student explanations receiving this code and 81% of expert explanations. Perhaps unsurprisingly, quantum mechanical ideas were much more common in the beyond-intro population with 62% (178 of 288) of responses coded as including quantum ideas, as compared to only 9% of the intro student responses. As can be seen in Fig. 5, for both populations, quantum mechanical reasoning was more common when justifying student B's statement, although it was still present in some responses to student A, especially at the beyond-intro level.

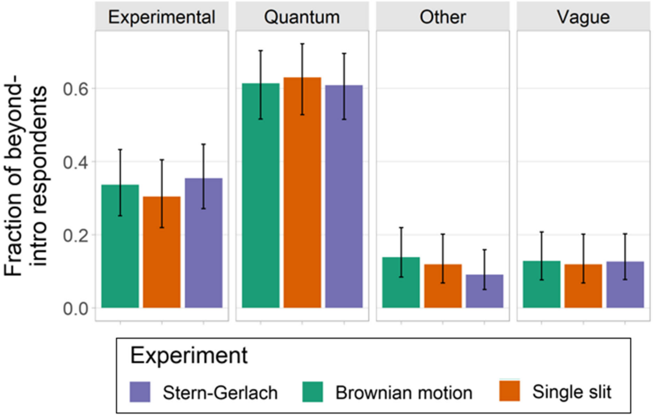


FIG. 7. Codes applied to beyond-intro participants' explanations of their answers, separated by what experiment they saw in the survey (Brownian motion $N = 101$, single slit $N = 92$, Stern-Gerlach $N = 110$). Uncertainty bars represent the 95% confidence interval.

A. Nuance in students' philosophical views

The responses to the Two Students question demonstrate a range of nuanced philosophical views on the nature of measurement and uncertainty, even among experts. We argue that these responses represent a deeper perspective of students' views than can be characterized by either their procedural reasoning [7] or ontological reasoning [2] alone. In fact, we consider a plausible range of philosophical reasonings about measurement (including ontological) that can connect to either pointlike or setlike procedures [7]. Thus, we see multiple combinations of reasonings that may explain a student's pointlike or setlike procedure (Fig. 8).

We found that participants' explanations that discussed the experimental process was similar regardless of whether the respondent argued for or against a true value (student A or student B, respectively). In either case, participants usually indicated that all measurements will have uncertainty that is beyond the control of a human experimenter. Where the explanations differed was in what this uncertainty means for the existence of a true value. Those who used experimental process reasoning when arguing against a true value (student B) typically argued that our inability to measure a true value implies that it does not exist or that its existence is meaningless, drawing only on a random ontology in their explanations. Those who argued for a true value (student A) typically indicated that even if an experiment will always have uncertainty, a true value still fundamentally exists–we just cannot measure it. Thus, these participants considered that experiments have some aspects that are deterministic (a true value exists) but other aspects that are random (experimental uncertainty exists). This example of combined ontologies supplements those in Hull *et al.*, which focused on instances where students treated randomness as incompatible with deterministic predictions and laws [2].

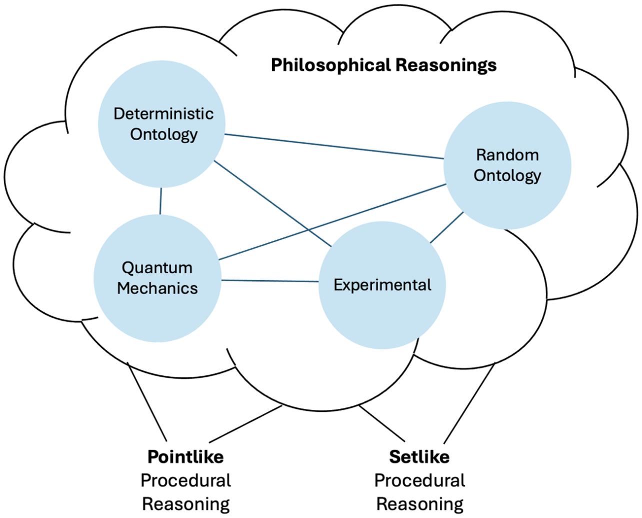


FIG. 8. Student philosophical reasoning about measurement contains influences from multiple ideas including, but not limited to, deterministic ontologies, random ontologies, quantum mechanics, and experimental processes. Students may draw on several of these ideas interconnected with each other or primarily draw on one only. We postulate that these philosophical reasonings will influence students' procedural reasoning, often catagorized as pointlike or setlike (from Ref. [7]).

We observed a greater variety of philosophical reasoning from participants who explained their choice with quantum mechanics reasoning. Some participants who selected student A (there is a true value) described ideas consistent with hidden variables, occasionally explicitly stating that they agree with hidden variables, as with this participant: "The hidden variable theory makes sense to me, because what seems to be random chance macroscopically can usually be found to be deterministic microscopically once you know enough underlying variables. So in QM, perhaps there's an underlying set of laws that makes QM deterministic as well." These participants applied only a deterministic ontology when discussing the connection between quantum mechanics and the concept of a true value.

In contrast, a small number of participants and some experts indicated that while there are many instances where uncertainty in position is unavoidable, it is possible, at least theoretically, for a particle to exist in a position eigenstate, in which case the system is entirely deterministic and quantum mechanical uncertainty in position would be zero. Alternatively, some participants indicated that once you measure a position, you have collapsed the system into a single position eigenstate with zero uncertainty, even if the system was originally in a superposition and thus "random." This group of participants drew on both deterministic (a position eigenstate can exist) and random (position was not well defined prior to measurement) ontologies in their explanation.

This mixture of deterministic and random ontologies also appeared in an entirely different type of response that drew on quantum mechanics. Some participants who selected student A identified that quantum mechanical states contain inherent uncertainty, but chose to answer this question classically, or indicated that this uncertainty would be vanishingly small compared to the macroscopic measurements being taken. For example, one participant stated, "I think, while technically B is correct due to quantum uncertainty, on macroscopic scales this phenomenon can be ignored and we can say that it does have a true position even though we will always be uncertain as to what that true position really is." These participants were comfortable with the idea that the microscopic systems that make up a macroscopic phenomenon may be random but that the macroscopic phenomenon as a whole can still be best described as deterministic.

Across all these varied responses, we see no possible one-to-one relationship between a participant's philosophical views about measurement and the types of procedural reasoning with which we might expect them to engage. For example, we might expect both the experimental-process participants who chose student A and those who chose student B to use setlike procedural reasoning. Both groups of participants expressed that uncertainty is an inherent part of the experimental process, which could reasonably lead to setlike decisions about, for example, taking more measurements and expressing measurements with uncertainties.

In contrast, we could conceive that the participants who discussed hidden variables in quantum mechanics and the participants who discussed position eigenstates may exhibit pointlike procedural reasoning, in which sufficient knowledge could lead to a single true point value measurement. Alternatively, such participants may instead exhibit setlike procedural reasoning, if they, for example, indicate that experimental measurement uncertainty is inherent in practice.

From these proposed connections between the point and set paradigms, we see that there is no clear mapping between students' philosophical views and what procedural reasoning they may use. Students with different philosophical views could fall within the same procedural paradigm, while students with overlapping philosophical views could fall within different procedural paradigms depending on what ideas they drew on in a procedural context. Thus, probes of student procedural reasoning are unlikely to provide us with any information about students' philosophical views of measurement. This lack of one-to-one mapping also has potential implications for instruction, which we discuss below.

B. Implications for future work

In this work, we directly probed students' belief in the existence of a true value in an effort to expand our understanding of student thinking about measurement and uncertainty. We found a variety of philosophical views that both experts and students used when answering the Two Students question. At the end of the previous section, we postulated that many of these articulated views could be consistent with both setlike and pointlike procedural reasoning. Our study did not allow us to directly test this, and so future work should investigate any connections between the belief in a true value, the philosophical views behind their stance, and their procedural reasoning.

Additionally, future work should probe the impact of instruction on student thinking. We found that more beyond-intro students used quantum mechanical ideas in their response to the Two Students question, implying that physics instruction beyond the introductory level shifts students to think in this way. However, these beyond-intro student responses varied in whether they articulated that the position of a quantum particle is (or can be) deterministic or random.

There has been some instruction designed to shift students from using pointlike or mixed procedural reasoning to using setlike reasoning [11,15,16,24–26], with mixed success. Given our finding that both pointlike and setlike thinking can be supported by a variety of philosophical views, it is possible that any instruction aiming to shift procedural reasoning may be more effective if it also considers students' philosophical views. We see this as a parallel to attending to students' epistemologies in developing conceptual physics reasoning [21–23]. Future studies should explore the effect of different types of instruction on the multiple forms of students' thinking about measurement.

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