CHAPTER 4

Refined Characterizations of Student Perspectives on Quantum Physics

I. Introduction

We have thus far seen how *realist* perspectives among modern physics students may translate into specific beliefs about quantum phenomena; e.g., particles are always localized in space, or that probabilistic descriptions of quantum measurements are the result of classical ignorance. We engage here in a more detailed exploration of student perspectives on quantum physics through a number of one-on-one student interviews. The resulting implications for modern physics instruction are particularly significant in that the learning goals for such courses typically include transitioning students away from classical epistemologies and ontologies, to ones that are more aligned with the beliefs of practicing physicists.

Still, it is not always clear exactly what expert physicists believe regarding the physical interpretation of quantum mechanics. [1] A recent survey [2] of quantum physics instructors at the University of Colorado and elsewhere (all of whom use quantum mechanics in their research) found that 30% of them interpreted the wave function as being physically real, while nearly half considered it to contain information only. The remaining respondents held some kind of mixed view on the physical interpretation of the wave function, or saw little distinction between the two choices. And only half of those who expressed a clear preference (matter-wave or information-wave) did so with confidence, being of the opinion that the other view was probably wrong. We find that students also develop attitudes and opinions regarding the reality of the wave function, as well as other interpretive themes from quantum mechanics.

The efforts described in Chapters 2 & 3 at characterizing student perspectives on quantum physics were limited to the application of three coarse labels (*Realist*, *Matter-Wave*, *Agnostic*) which are useful, but in light of the results of these studies, seem limited in terms of capturing the many nuances of student responses, and in particular understanding why students seem to exhibit contradictory perspectives between and within contexts. In this chapter, we therefore address the following:

1) How might our classification scheme be refined to better describe the nuances of student perspectives on interpretive themes in quantum physics?

2) For what reasons do students exhibit mixed perspectives within and across contexts?

From a total of 19 post-instruction interviews with students from four recent introductory modern physics courses at the University of Colorado we find that, though they may not employ the same formal language as expert physicists, students often invoke concepts and beliefs that parallel those invoked by expert physicists when arguing for their preferred interpretations of quantum mechanics. These parallels allow us to characterize student perspectives on quantum physics in terms of some of the same themes that distinguish these formal interpretations from each other. Of particular significance is the finding that students do indeed develop attitudes and opinions regarding a variety of interpretive themes in quantum mechanics, regardless of whether these themes had been explicitly addressed by their instructors. The mixed or seemingly contradictory student responses may be better understood in that: (A) some students prefer a mixed wave-particle ontology (a *pilot-wave* interpretation, wherein quanta are simultaneously *both* particle *and* wave); and (B) students are most likely to vacillate in their responses when what makes intuitive sense to them is not in agreement with what they perceive as a scientifically accepted response.

II. Interview participants and course characteristics

We sought to recruit five students from each of the four modern physics offerings at the University of Colorado from a single academic year (immediately following the studies described in Chapter 2) to participate in an hour-long post-instruction interview. A mass email was sent to all students enrolled in these courses, offering a nominal sum of fifteen dollars in exchange for their participation; students were not informed ahead of time about the nature of the interview questions, only that we would be discussing some ideas from modern physics. There was no real opportunity to select among students since volunteers were sometimes scarce, and so there was no attempt to make the cohort representative of all students from those courses. A total of 19 students were interviewed from these four courses [Table 4.I], either in the last week of the semester or after the course had ended. Interview participants from the courses for physics majors were all physics or engineering physics majors, plus one astronomy major; those from the courses for engineers were all engineering majors (but not engineering physics), plus one mathematics major. The average final course grade for all 19 students was 3.4 (out of 4.0, where overall course averages fall in the 2.0–3.0 range), indicating that participants were generally better than average students, as might be expected for a group of volunteers. Interviews followed the protocol as given in Appendix B. It should be emphasized that our characterizations of instructional approaches in Table 4.I and elsewhere in this chapter come from analyses of course materials and practices, and are not necessarily reflective of each instructor's personal perspective on quantum mechanics, but rather of how that instructor addressed interpretive themes in class.

TABLE 4.I Summary of four courses from which students were recruited for interviews, including a characterization of each instructor's stance on interpretive themes, as taught in that course; instructor labels correspond to those given in Figs. 3.1 & 3.2.

INSTRUCTOR	STUDENT POPULATION	INTERPRETIVE APPROACH	STUDENTS INTERVIEWED
MW-1	Engineering	*Matter-Wave*	3
C/A-2		*Copenhagen*	5
C/A-1	Physics	*Copenhagen/Agnostic*	6
C/A-3			5

The instructor labels given in Table 4.I correspond to those given in Figs. 3.1 & 3.2 (here, the labels MW-1 and C/A-1 correspond to Instructors/Courses B1 & C, respectively, as described in Chapter 3). The labels used for describing instructional approaches have been described earlier, but can be best illustrated by how each instructor addressed the double-slit experiment with single quanta. Instructor MW-1 (B1 in Chapter 3) was explicit in promoting a wave model of individual quanta as they propagate through both slits, interfere with themselves, and then become localized upon detection. Instructor C/A-2 told students that a *quantum mechanical wave of probability* passes through both slits, but that which-path questions change the circumstances of the experiment, making them ill-posed at best. While similar to C/A-2, Instructors C/A-1 (Instructor C in Chapter 3) and C/A-3 ultimately placed more emphasis on calculation (predicting features of the interference pattern) than matters of interpretation.

For the 19 students interviewed for the present studies, there were no discernible connections between a specific instructional approach and the preferred perspectives of the students interviewed from that course, likely due to the limited number of participants. Therefore, discussion in this chapter of specific instructional approaches will be limited to the brief characterizations given above, and a few specific statements below concerning the influence of an instructional approach on that student's individual responses.

III. Refined characterizations of student perspectives

As will be demonstrated below, we find it useful to consider student perspectives in quantum physics in terms of concepts associated with some of the more common (i.e., less exotic) formal interpretations of quantum mechanics. In doing so, we do not mean to imply that student perspectives are as coherent or sophisticated as any formal interpretation (although other research [2] suggests that expert perspectives on quantum physics may be similarly tentative). In fact, our results can best be understood within a theoretical framework that views student perspectives (including the process of *ontological attribution*) as cognitive frameworks that are dynamic emergent processes (as opposed to fixed or static cognitive structures), that are contextually sensitive, and that sometimes simultaneously blend ontological attributions that belong to classically distinct categories. [See Refs. 3-5, as well as Chapter 1, Section II.] Nor do we assume that any one label is necessarily sufficient for describing the nuanced and sometimes inconsistent perspectives exhibited by any particular student; or even that the development of student perspectives on quantum physics follows along the lines of historical developments.

We do, however, find that some formal interpretations of quantum mechanics can be distinguished from each other in terms of a few key themes, and that students do have beliefs or ideas concerning these themes of interpretation, regardless of whether these themes had been explicitly addressed by their instructors. In other words, we have observed that many introductory modern physics students, when formulating a stance on these interpretive themes, employ some of the same epistemological tools used by expert physicists, and will sometimes invoke similar experimental results and intuitive notions of particles and waves as motivation for their preferred interpretations of quantum phenomena. An analysis of all 19 interview transcripts revealed student beliefs and attitudes (of varying degrees of sophistication) concerning the following three interpretive questions:

1) Is the position of a particle objectively real, or indeterminate and observation dependent? [Existence or non-existence of certain hidden variables.]

2) Is the wave function a mathematical tool that encodes probabilities [information-wave], or is it physically real [matter-wave]?

3) Does the *collapse of the wave function* (or *reduction of the state*) represent a physical process, or simply a change in knowledge of the observer?

III.A. Discussion of formal interpretations

We present here a brief summary of some key features of several formal interpretations of quantum mechanics, in terms of the three interpretive themes given in Section II. [Table 4.II] Many aspects of these formal interpretations have been previously discussed in greater detail, [Chapter 1] and it should be emphasized that it would be impossible for these short summaries to be comprehensive, but are offered as working definitions for the sake of clarity when associating these labels with the expressed beliefs of individual students.

Realist/Statistical**:** From either a *Realist* or S*tatistical* perspective, the physical properties of a system are objectively real and independent of experimental observation (observations reveal reality, not create it). The state vector encodes probabilities for the outcomes of measurements performed on an ensemble of similarly prepared systems, but cannot provide a complete description of individual systems. The wave function is not physically real; the collapse of the wave function represents a change in the observer's knowledge of the system, and not a physical change brought about by the act of measurement.

Copenhagen**:** The probabilistic nature of quantum measurements is a reflection of the inherently probabilistic behavior of quantum entities; in general, the properties of a system are indeterminate until measured. The wave function is not a literal representation of a physical system, and the *collapse of the wave function* corresponds to a change in knowledge of the observer, though it does represent a physical transition from an indeterminate state to one where certain properties of the state become well defined.

Matter-Wave**:** Similar to the *Copenhagen Interpretation* with respect to indeterminacy and the non-existence of hidden variables, but also ascribes physical reality to the wave function. Though not described by the Schrödinger equation, the *collapse of the wave function* represents a physical process induced by measurement.

Pilot-Wave: From this perspective, quanta are simultaneously both particle and wave: localized particles follow trajectories determined by a physically real quantum wave. In the double-slit experiment, an electron is all at once both a particle that goes through only one slit, and a wave that passes through both slits and interferes with itself. In this context[1], the position of a particle is objectively real and predetermined based on unknowable initial conditions, so that the reduction of the state represents a change in knowledge of the observer.

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[1] Nonlocal features come into play when other quantum effects (e.g., entanglement) are to be accounted for, in which case the *collapse of the wave function* must be seen as a (non-local) physical process.

TABLE 4.II. Summary of our characterizations of four formal interpretations of quantum mechanics, in terms of three interpretive themes (described in Section II). The *Agnostic* perspective is not a formal interpretation in itself, but is included for completeness.

INTERPRETATION	HIDDEN VARIABLES?	INFO- OR MATTER-WAVE?	COLLAPSING WAVE FUNCTION?
Realist/Statistical	YES/AGNOSTIC	INFO	KNOWLEDGE
Copenhagen	NO	INFO	PHYSICAL
Matter-Wave	NO	MATTER	PHYSICAL
Pilot-Wave	YES	MATTER	KNOWLEDGE
Agnostic	AGNOSTIC	AGNOSTIC	AGNOSTIC

Agnostic: Though not a formal interpretation in itself, we distinguish between this stance and the positivistic aspects of the *Copenhagen Interpretation* (declining to speculate on the unobservable). The *Agnostic* perspective accounts for multiple interpretations of quantum mechanics and their ontological implications, but takes no definite stance on which might correspond to the best description of reality. The utility of quantum mechanics is generally favored over questions of interpretation.

III.B. Students express beliefs that parallel those of expert proponents

We have hypothesized that the perspectives of many modern physics students on quantum phenomena are significantly influenced by the commonplace (and intuitive) notion of particles as localized in space. In classical physics, as in colloquial usage, the word particle generally connotes some small object, so it should not be surprising that students who have learned about particles primarily within the context of classical physics should persist in thinking of them as microscopic analogs to macroscopic objects when learning about quantum physics. This would be an example of *classical attribute inheritance*, in the sense that students may explicitly attribute to quantum particles *all* of their classical analogs, including a localized position (student codes are as given below in Table 4.III):

> "I guess an electron has to [always be at] a definite point. It is a particle, we've found it has mass and it has these intrinsic qualities, like the charge it has, so it will have a definite position, but due to uncertainty it will be a position that is unknown." [STUDENT QR2]

This statement reveals not only one student's belief in localized massive particles, it also suggests a stance on the uncertainty associated with a particle's position: its objectively real value will be unknown until revealed by measurement.

This student (and others with similar attitudes) reported interpreting the probability density for an atomic electron as strictly a mathematical tool used only for describing the probable locations for where that electron might be found once measured; probabilistic descriptions of such measurements were therefore seen as a reflection of *classical ignorance* concerning the true state of that particle just prior to measurement. We thus see how an intuitive notion of particles as localized objects can influence what physical meaning students ascribe to both the wave function and the probabilistic nature of quantum mechanics.

In a similar vein, another student explicitly objected to the idea that wave-packets could represent single particles. Here, this student is discussing the Quantum Wave Interference [6] (QWI) simulation's depiction of a wave-packet's propagation through both of two slits on its way to detection:

> "One electron can't go through both slits at the same time because electrons have mass. Wouldn't it violate conservation of mass and charge if [the electron] were split into two like it shows in the [QWI] simulation?" [STUDENT R1]

Such objections are reminiscent of those made by L. Ballentine (a major proponent of the *Statistical Interpretation* of quantum mechanics [7, 8]) when discussing a thought experiment in which an incident wave packet is divided by a semi-reflecting barrier into two distinct transmitted and reflected wave packets. The reflected and transmitted waves are then directed toward a pair of detectors connected to a coincidence counter. Ballentine argues:

> "Suppose that the wave packet *is* the particle. Then since each packet is divided in half, [...] the two detectors will always be simultaneously triggered by the two portions of the divided wave packet." [Ref. 8, p. 101, emphasis in original]

In this thought experiment (and in practice [9]), single quanta trigger either one detector or the other (and not both simultaneously); Ballentine therefore concludes that, while the wave function may have nonzero amplitude in two spatially separated regions, it cannot be interpreted as describing individual particles, since individual particles are never found in two places at once. In making this argument, Ballentine has implicitly assumed that the *collapse of the wave function* (or *reduction of the state*) represents a change in knowledge of the observer, and not an actual physical process induced by measurement.

In his own book on quantum mechanics, Dirac [10] considers the same type of thought experiment as Ballentine, but provides a radically different explanation:

> "The result of [the detection] must be either the whole photon or nothing at all. Thus the photon must change suddenly from being partly in one beam and partly in the other to being entirely in one of the beams." [Ref. 10, p. 9]

As counterintuitive as this interpretation may be, we find that a number of modern physics students report having accepted such ideas, and have incorporated them into their descriptions of quanta:

> "[T]he electron, until it's measured, until you try to figure out where it is, the electron is playing out all the possibilities of where it could go. Once you measure where it is, that collapses its wave function [and it] loses its properties as a wave and becomes particle in nature." [STUDENT Q3]

Students within this category all explicitly exhibited this kind of flexibility in their ontological descriptions of the behavior of electrons. Other students, like Ballentine, find these types of explanations unsatisfying:

> "[A] single electron is detected at the far screen, and I feel like that really can't be explained for the wave-packet, by one specific detection in a small place like that, if you say [the wave-packet] is the electron. That's really the only discrepancy I have with that: What happens when it hits the screen?" [STUDENT QR2]

Indeed, the question of what happens when individual quanta are detected in a double-slit experiment has played a significant role for some physicists in motivating their perspectives on quantum phenomena, as with Ballentine:

> "[I]t is possible to detect the arrival of individual electrons, and to see the diffraction pattern emerge as a statistical pattern made up of many small spots. *Evidently, quantum particles are indeed particles*, but particles whose behavior is very different from what classical physics would have led us to expect." [Ref. 8, p. 4, emphasis added]

This statement exemplifies a degree of ontological inflexibility in expert thinking: Ballentine is assuming that the detection of electrons as localized particles implies they exist as localized particles at all times. J. S. Bell has also invoked the double-slit experiment when discussing interpretation, but in this particular case as motivation for a pilot-wave interpretation, as proposed by Bohm and others [11]:

> "Is it not clear from the smallness of the scintillation on the screen that we have to do with a particle? And is it not clear, from the diffraction and interference patterns, that the motion of the particle is directed by a wave?" [Ref. 12, p. 191]

This student's discussion of the double-slit experiment echoes sentiments expressed by both Ballentine and Bell – by employing similar argumentation, he reaches similar conclusions:

> "For me, saying that the [wave] represents the electron isn't accurate because an electron, after it's measured on that screen, is a point-particle, you see a distinct interference pattern after shooting many electrons, but you still see one electron hit the screen individually. […] I do agree that the electron acts as a wave because that's obviously what causes the pattern; if it didn't interfere with itself, or create a wavelike function, then you wouldn't see the patterns on the screen also." [STUDENT R3]

Historically, and in our classrooms today, different physicists have offered different interpretations of quantum diffraction experiments. For Ballentine, diffraction patterns form as a consequence of the quantized momentum transfer between localized particles and the diffracting medium. [Ref. 8, p. 136] These patterns are more commonly explained in terms of wave interference, but for some, the wave is guiding the trajectory of a localized particle, while others would claim that each particle interferes with itself as a delocalized wave until becoming localized upon detection. At the same time, a number of *both* expert and student physicists find it unscientific to speculate on that which cannot be experimentally observed:

> "I understand why people would think [the electron] has to exist between here and where it impacts, and it does, but the necessity of [thinking of it] between here and where it impacts as an actual concept like a particle or a wave, I don't see much of the point. We're not going to observe what it is between here and there, so it doesn't seem like a statement for science to make. It seems right now to be entirely unobservable." [STUDENT C2]

The refusal to speculate on unobservable processes is a key feature of the orthodox *Copenhagen Interpretation* of quantum mechanics, which seems to be favored by a majority of practicing physicists, if only for the fact that it allows them to apply the mathematical tools of the theory without having to worry about what's "really" going on (as embodied in the popular phrase: *Shut Up and Calculate!* [12], and the sentiments expressed by Instructor C's [C/A-1, in this chapter] in-class comments from Chapter 3).

We also find it necessary to distinguish between the agnostic or positivistic aspects of an instructional approach, and the agnosticism of those who are aware of multiple interpretations, but are unsure as to which offers the best description of reality:

> "For now, for me, the electron is the wave function. But whether the electron is distributed among the wave function, and when you do an experiment, it sucks into one point, or whether it is indeed one particle at a point, statistically the average, I don't know." [STUDENT QA1]

III.C. Categorization and summary of student responses

We summarize here a categorization of individual students in terms of the interpretive themes discussed above, grouped by overall perspective, as discussed in Section III.A; [Table 4.III] in this section, the label *Quantum* (Q) is used as shorthand for a *Matter-Wave* perspective, for brevity and for consistency with prior published research. [13] A discussion of key findings and commonalities among students within individual categories follows.

TABLE 4.III. Summary of individual student interview responses with respect to three interpretive themes (as described in Section III), grouped by overall perspective. The label *Quantum* (Q) is used as shorthand for a *Matter-Wave* perspective.

STUDENT PERSPECTIVE	CODE	HIDDEN VARIABLES?	INFO OR MATTER WAVE?	COLLAPSING WAVE FUNCTION?
Realist	**R1**	YES	INFO	KNOWLEDGE
	R2	YES	INFO	KNOWLEDGE
	R3	YES	INFO	KNOWLEDGE
Split Quantum/ Realist	**QR1**	NO/YES	MATTER/INFO	PHYSICAL
	QR2	NO/YES	MATTER/INFO	KNOWLEDGE
	QR3	NO/YES	MATTER/INFO	KNOWLEDGE
	QR4	NO/YES	MATTER/INFO	AGNOSTIC
Pilot-Wave	**P1**	YES	MATTER	KNOWLEDGE
	P2	YES/ AGNOSTIC	MATTER/ AGNOSTIC	KNOWLEDGE/ AGNOSTIC
	P3	YES	MATTER	KNOWLEDGE
Quantum (Matter-Wave)	**Q1**	NO	MATTER	KNOWLEDGE
	Q2	NO	MATTER	PHYSICAL/AGNOSTIC
	Q3	NO	MATTER	PHYSICAL
	Q4	NO	MATTER	PHYSICAL
	Q5	NO	MATTER	PHYSICAL/AGNOSTIC
Quantum/ Agnostic	**QA1**	NO/ AGNOSTIC	MATTER/ AGNOSTIC	PHYSICAL/ AGNOSTIC
Copenhagen	**C1**	NO	INFO	PHYSICAL
	C2	NO	INFO/AGNOSTIC	PHYSICAL/AGNOSTIC
	C3	NO/ AGNOSTIC	INFO	AGNOSTIC

We first note that many student responses agreed well with our characterizations of the formal interpretations, while other students provided one or more responses that were not entirely consistent with those characterizations; in the few such cases, a category was assigned based on what would be most consistent with the overall responses from that student. A second, independent physics education researcher coded a subset of five transcribed interviews (all students who were not quoted in this chapter), both by interpretive theme and by overall interpretation, with an initial inter-rater reliability of 93% on individual stances on the interpretive themes, and 100% on overall perspective; following discussion, there was 100% agreement between both coders.

All of the students in the *Split* category were explicit in distinguishing between what made intuitive sense to them (*Realist*) and what they perceived to be a correct response (*Quantum*). Other students offered opinions on specific themes when asked to take a stance, but chose to ultimately remain agnostic for lack of sufficient information (as indicated by the *XX/Agnostic* entries in the interpretive themes columns of Table 4.III). This agnostic characterization of individual responses differs from the overall stance of Student QA1, who said he preferred a *Quantum* interpretation, but expressed a sophisticated overall agnosticism on the legitimacy of a contrasting *Statistical* interpretation.

Realist Category: All three of these students considered probability waves to be mathematical tools used only to describe the probable outcomes of measurements. These students all objected to the idea that a wave packet could represent a single particle, and said they always consider an electron to be a localized object traveling somewhere inside the probability wave describing the system. These students were not classified as holding a *Statistical* perspective because they were explicit in their stance on electrons as localized particles (as opposed to agnostic), and did not have sufficient content knowledge (e.g., consequences of Bell's Theorem [14]) to appreciate why an agnostic stance on hidden variables might be necessary. All three of these students specifically objected to the notion of *wave function collapse*, calling it too counterintuitive or too unphysical to be a correct description of reality. These students all claimed to be aware of at least one alternative to their *Realist* interpretations, but said they hadn't yet been convinced by instructor arguments that their preferred perspective was incorrect.

Split Quantum/Realist Category: While the *Realist Category* students all expressed a measure of confidence in their perspectives on quantum physics (even when those perspectives differed from what they had heard in class), the four students in this *Split Quantum-Realist* category were, by the end of the interview, explicit in differentiating between what made intuitive sense to them, and what they considered to be a correct response. In example, Student QR1 first agreed that an electron in an atom always exists at a definite point, and continued with this line of thinking, both when first describing the double-slit experiment, and again as he began reading the *Realist* statement of Student One from the double-slit essay question:

STUDENT QR1: I would agree with what Student One is saying, that the electron is traveling somewhere inside that probability density blob, and it is a tiny particle. The problem here that I see is that the electron went through one slit or the other. [PAUSE] So, now I'm disagreeing with myself. OK, my intuition is fighting me right now. I said earlier that there should be one point in here that is the electron, and it goes through here and hits the screen, but I also know that I've been told that the electron goes through both slits and that's what gives you the interference pattern. Interesting. [LONG PAUSE] OK, somehow I feel like the answer is going to be that this probability density, it is the electron, and that can go through both slits, and then when it's observed with this screen, the probability density wave collapses, and then only exists at one point. But at the same time I feel that there should be a single particle, and that somehow a single, finite particle exists in this wave, and will either travel through one slit or the other. Why would a single particle be affected by a slit? That I don't have an answer to, other than that it's the wave that's actually being propagated, the wave is the electron.

INTERVIEWER: OK. It seems like you're talking about two different ideas. One is that the electron is a point somewhere inside this wave, and the other is saying the electron is the wave. Do you feel those two ideas conflict in any way?

QR1: Yeah, they do, because one says there is a finite particle at all times, and the other says that there's not, there is just this probability density, and I think the answer will turn out to be that the electron is the probability density, and that's contrary to what I said earlier. But I don't see how it could be the other way, with a finite particle. I don't see how you could get an interference pattern here with the electron being a finite particle the whole time.

INT: OK. What about [the *Matter-Wave*] statement?

QR1: [BEGINS READING] So, that goes off of what I was just saying. [READS] So, I agree with everything up to here, the electron acts as a wave and will go through both slits and interfere with itself, I believe that's true. And that's why an interference pattern develops after shooting many electrons; I guess I agree with that too, because when the blob gets to the screen, it can't just still have a probability density that would look like an interference pattern by itself. It's going to have one finite location. But after multiple electrons, multiple blobs have passed through, they will collectively form an interference pattern. So I would agree with Student Two.

INT: So you're agreeing with Student Two. And did you say that you disagree with Student One, or do you just have reservations about what they're saying?

> **QR1:** Intuitively, I kind of agree with Student One, but I think I have reservations. I don't think, Student One, that they're right.
>
> **INT:** But it appeals to you, what they're saying?
>
> **QR1:** Based upon lecture, and upon those who have greater knowledge of physics than me, I would say that this [second] statement agrees more with that than the initial situation.
>
> **INT:** So you say Student One's statement disagrees more with what you've heard in class?
>
> **QR1:** Yes. But not more with what I envision. This [first] one kind of depicts more of my rational depiction, all that I can wrap myself around and understand, and the second one is more of what I've been told, but don't completely understand. I've been told it's right, so…

This excerpt serves two purposes. It first explicitly demonstrates how students may change as needed between ontological attributions in their descriptions of electrons in order to explain observed phenomena (electrons as particles in order to explain localized detections, electrons as waves in order to explain interference). It also underscores the need to distinguish between the *personal* and the *public* [15] perspectives of students on quantum physics: these students differed from their *Realist* category counterparts in that they explicitly differentiated between what made intuitive sense to them, and responses they perceived as being correct. This finding parallels studies by McCaskey et al., [16, 17] where students were asked to respond twice to the Force Concept Inventory, [18] first as they personally believed, and then as they felt a scientist would respond. These authors found that most every student *split* on at least one survey item, indicating a difference between their personal beliefs and their perceptions of scientists' beliefs. Following a series of validation interviews, these authors reported that students most often explained their personal responses in terms of what made intuitive sense to them, and that split responses reflected how students had learned a correct response from instruction, without having reconciled that knowledge with their own intuition. Similar studies probing the attitudes and beliefs of introductory classical physics students have demonstrated similar results. [19]

Regarding the public perspectives of modern physics students, we would also point out that students will not necessarily identify an authoritative stance based on specific knowledge of what expert physicists believe. Not only may their perceptions of what scientists believe be inaccurate, students may also employ undesirable epistemological strategies learned from their experiences in the classroom:

> “This [*Quantum* statement of Student Two] is more of a complex definition, I think. […] Probably initially I would be confused by this statement if I hadn’t taken this course, but I might be like the public and think the most complicated answer, that must be the right one. Because a lot of times—it’s even happened with the [concept] questions in class—where I think: *That’s got to be the answer*. But then I’ll be like: No, that would be too easy, it’s got to be something else. Sometimes that [strategy] can prove correct or incorrect.” [STUDENT QR4]

Pilot-Wave Category: The responses from these three students indicated an ontology that blends attributes from both classical particles and waves. These students indicated a belief that wave-particle duality implies that quanta must be thought of as simultaneously *both* particle *and* wave. The following student explained the fringe pattern in the double-slit experiment in terms of constructive and destructive interference, and acknowledged that the experiment had been used in class to demonstrate the wave characteristics of quanta, but had his own ideas about the source of interference for localized particles:

> “It seems like the probable paths for the electron to follow interact with themselves, but the electron itself follows just one of those paths. It’s like the electron rides on a track, like a train rides on a rail, but those rails or tracks go through both slits, and the possible paths for the electrons to follow interfere with themselves, create the interference pattern, but the physical electron just rides on the tracks, it picks one. Or maybe switches paths, if two of them cross. I don’t know, it seems that the electron has to be on one of those tracks, but the tracks themselves cause the interference pattern.” [STUDENT P3]

Of particular interest is the way in which this same student demonstrated how his realist (albeit nonlocal) perspective can be employed as an epistemological tool:

> “As [the electron is] traveling it’s going to be somewhere in this [probability density] as it moves along until it’s actually detected. And if it was here [INDICATES POINT NEAR DETECTING SCREEN] then it must have been here at one point in time [INDICATES SECOND POINT NEAR THE FIRST] and if it was here, then it had to be here at one point in time, all the way back to here [TRACES LINE BACK TO NEAR BOTH SLITS] in which case there’s only two places it could be. So yes, I think it went through one slit or the other.” [STUDENT P3]

As another example of the ontological flexibility exhibited in novice thinking, one of these students explained that, while it is necessary to think of an electron in the double-slit experiment as both wave and particle, it was unnecessary to employ a wave description for atomic electrons since, in his mind, there were no wave effects to be accounted for:

> "When I was thinking about [an electron] in an atom, there's really no reason that you have to think about it as a wave, in the fact that it's not really interacting with anything. In [the double-slit] experiment, yes I like to think of it as also a wave, because this is kind of the key experiment of quantum mechanics, to describe this [wave] phenomenon, and so for that reason it is more effective to think of it as both." [STUDENT P1]

With this excerpt, we call attention to the fact that sometimes students employ different models (ontological attribution assignments) in different contexts, without necessarily looking for or requiring internal consistency among them.

Quantum (**Matter-Wave**) **Category:** These five students were consistent in providing responses that indicated a *matter-wave* ontology:

> "I don't think of [the electron] as orbiting the nucleus because it doesn't, it just exists in that region of space. It exists in a volume element that defines the probability of finding the electron in that space […] and that's really what the electron is: a smeared out volume of charge." [STUDENT Q2]

All of these students described unobserved quanta strictly in terms of waves, and discussed the *collapse of the wave function* as a physical process where wave-like quanta suddenly exhibit particle-like properties. According to these students, their personal perspectives on quantum mechanics were in complete agreement with their perceptions of expert beliefs.

Quantum/Agnostic Category: We find it necessary to distinguish this one student from those in the strictly *Quantum* category because, while the *Quantum* category students had all expressed confidence in their *matter-wave* interpretations, this student expressed a degree of sophisticated uncertainty in his own views:

> "The way I think of an electron, I cannot ascribe to it any definite position, definite but unknown position. I mean, it may be that way, but I think that somehow the electron is represented by the wave function, which is just a probability, and if we want to localize it then we lose some of the information. So whether this is true or not is something of a philosophical question. I wish I knew, or understood it, but I don't. For now, for me, the electron is the wave function, so whether the electron is distributed among the wave function, and when you do an experiment, it sucks into one point, or whether it is indeed one particle at a point, statistically the average, I don't know." [STUDENT QA1]

Copenhagen Category: These three students were similar to the *Quantum Category* students in terms of the nonexistence of hidden variables, but saw probability waves as containing information only, rather than representing the actual physical state of a particle. As with student C2 (quoted previously in Section III.B) each of these students stated explicitly that it is unscientific to discuss that which can't be measured or observed. These three students said they considered electrons to be neither wave nor particle; that such concepts were in fact different models for describing the behavior of quanta under different circumstances. These students expressed what we consider to be a moderately sophisticated perspective on both the necessity and the desirability of switching between ontological categorizations.

It should also be noted in our studies that formal instruction is not the only source of information or influence for students regarding quantum physics, as with this student, who explained how his own personal solipsistic philosophy influenced his beliefs about quantum mechanics, and vice-versa:

> **STUDENT C3:** This is more of a philosophical point for me, but if we can't know something, there's no difference between it not existing and us not knowing it. So, for our purposes, it's more useful to say, if we can't know it, where the electron is, then it doesn't have a definite position. […] I believe, so long as we don't measure it, then an electron doesn't have a definite position.
>
> **INTERVIEWER:** What happens when we measure it?
>
> **C3:** Well, we find a position then**…** Then it does.
>
> **INT:** The position we find, is that where the particle was the moment before we measured it?
>
> **C3:** No. We can't know that. So, when we make a measurement, there's the particle. When we look away, the particle goes away. And I sort of felt this way before having learned about quantum mechanics. And it just solidified in my mind that there's no difference between me not knowing it, and it not existing.

In the class-wide online surveys, a majority of students from all of the four courses discussed here reported having previously heard about quantum mechanics in popular venues (e.g., books by Hawking [20] or Greene [21]) before enrolling in the course.

IV. Summary and Discussion

Our more detailed characterization of the perspectives of modern physics students improves upon our previous efforts by addressing the contextual sensitivity of those perspectives, through an exploration of their expressed beliefs about quantum physics across three key interpretive themes. We find that, as a form of sense making, students develop a variety of ideas and opinions regarding the physical interpretation of quantum mechanics, in spite of how their instructors explicitly addressed matters of interpretation in class.

As with past studies, we find that a significant number of students from our interviews (10 of 19) expressed a preference for *realist* interpretations of quantum phenomena. However, the nature of these students' *realist* perspectives were not necessarily of the character we had anticipated from the results of earlier studies. Only three of these students consistently preferred *realist* interpretations of quantum phenomena, while simultaneously expressing confidence in the correctness of their perspectives; whereas four others differentiated between what made intuitive sense to them, and what they perceived to be correct responses. Their particular kind of switching between ontological framings may be best understood in terms of their competing *personal* and *public* perspectives [15] on quantum physics – when responding during interviews, these students frequently vacillated between what they personally believed and the answer they felt an expert physicist would give, without always articulating a difference between the two without prompting. This finding has implications for future research into the ontologies of quantum physics students, who may not always respond to such questions as they actually believe, but rather provide the responses that best mimic their instructors. Such issues are of particular significance with regard to matters of interpretation in quantum mechanics, where the beliefs of practicing physicists are at such variance with each other, which may confuse student perceptions.

The *Realist* beliefs of three other students were of a decidedly nonlocal character: localized quantum entities follow trajectories determined by the interaction of nonlocal quantum waves with the environment. None of these three students claimed to be aware of any formal *pilot-wave* interpretation, and their beliefs in quanta as simultaneously wave and particle were at odds with how wave-particle duality was addressed in class by their instructors (i.e., quanta are sometimes described by waves, and sometimes as particles, but never both simultaneously). The remaining nine of 19 students expressed fairly consistent views that could be seen as in agreement with the (implicit) learning goals of their instructors, whether Quantum or Copenhagen. In other words, these students seemed to have successfully incorporated probabilistic and nonlocal views of quanta and quantum measurements into their personal perspectives, and/or agreed that scientists should restrict discussions to that which can be measured and verified. While these findings are somewhat at odds with previous research into quantum ontologies, which have concluded that student perspectives are rarely in alignment with expert or productive transitional models, we emphasize that the relatively few students who participated in our interviews were generally better-than-average students, and were not representative of an entire class. Ultimately, we believe the value of these findings lies in the demonstration and documentation of a variety of student beliefs regarding quantum phenomena, and not a determination of the relative prevalence of any specific beliefs.

Of equal importance is the demonstration of students employing multiple parallel ontologies, or dynamic ontologies that are flexible and adaptive, each according to their immediate cognitive needs. In one specific case, Student QR1 initially described an electron as a particle localized in space, but wavered in his commitment to this description when he encountered the notion that each electron must have travelled through only one slit on its way to the detecting screen. After a moment of introspection, he concluded that a wave description was necessary in order to explain the observed interference pattern, for he had no explanation as to why a localized particle would be affected by the presence of a slit. He then explicitly stated that the "correct" way of looking at the situation is to equate the electron with the wave itself, which necessitated a corresponding belief in a physically collapsing wave function. Student QR1 was aware of the logical inconsistency in his two competing perspectives, but was able to articulate a need for maintaining both, one in correspondence with his intuition, and one in congruence with what he perceived as an authoritative stance, and which also led to an interpretation of the double-slit experiment that was consistent with observations. We can easily imagine this student's reasoning during the interview briefly recapitulated some of the thought processes he engaged in when first encountering this topic, as he initially seemed unaware of any need to think of electrons as anything other than localized particles, but immediately reconsidered his stance when confronted with an observation that he could only explain in terms of wave interference.

We have also seen how *classical attribute inheritance* will guide the thinking of both experts and novices, through the explicit statements of Ballentine, along with those from Students R1 and QR2: localized detections imply a continuously localized existence, particles are *by definition* localized in space; laws of mass and charge conservation preclude the possibility for particles to be spatially delocalized. These types of epistemological and ontological *resources* are not necessarily wrong in and of themselves, and may be of productive use in classical descriptions of matter, but have enormous implications for what kind of physical meaning students attach to the otherwise mathematically algorithmic process of deriving wave functions and calculating expectation values; and their activation in the context of quantum phenomena may lead students to interpretations that seem paradoxical or are inconsistent with observations.

The demonstration of student flexibility in assigning ontological attributes, switching back and forth (and sometimes blending) them as needed, does more than just explain the contextual sensitivity of student responses; it provides strong evidence of the dynamical nature of the ontologies employed by students when reasoning about quantum phenomena. The students falling into the strictly *Realist* category were the ones showing the least flexibility in their use of ontologies (and even these students were aware of alternative explanations, but hadn't yet bought into them). All of the other students demonstrated varying degrees of flexibility in their use of parallel ontologies: some distinguished between intuitive and normative ontologies; some perceived switches between ontological attributes as reflective of physical transitions; others blended attributes from classically distinct categories, or assigned them separately, all according to their cognitive needs of the moment.

These results are most consistent with the dynamic view of novice and expert ontologies discussed here and in Chapter 1, and are difficult to reconcile with the static, parallel ontologies promoted by Slotta and Chi. First, quantum mechanics describes the *behavior* of light and matter in terms of classically distinct ontological characteristics, and so a rigid (robust) assignment of ontological attributes is not possible for a complete description of electrons and photons. Nor do scientists agree on a normative view of the ontological nature of quanta, and instructors understandably vary in their choices of how to broach this topic in their introductory courses, sometimes fearful of opening a *Pandora's Box* of student questions with no easy answers.

Second, we observe that students frequently modify their patterns of ontological attribution assignment piecewise, both within and across multiple contexts. This type of gradual transition in student thinking cannot be plausibly explained in terms of rigid, parallel ontologies that are developed over the course of instruction, and which then replace the original, intuitive ontologies, unless one were to believe that students develop a whole multitude of parallel ontologies, each specific to the variety of situations they've encountered. In the end, Slotta has conceded that the disagreement between these two opposing views may ultimately be a matter of the degree of ontological flexibility and blending exhibited in both novice and expert thinking, [22] and both sides have made strong arguments in favor of their views on learning and cognition in the context of classical physics; their disparities become all the more apparent, however, in the context of quantum mechanics.

We also find it significant that most every student expressed distaste for deterministic ideas in the context of quantum phenomena, although it had been anticipated that *Realist Category* students might favor such notions. Not only did most every student say they were unfamiliar with the word *determinism* within the context of physics, practically every student believed either that any description of the behavior of quantum particles should be inherently probabilistic, or that the Heisenberg uncertainty principle places a fundamental limit on human knowledge of quantum systems, or a combination of both stances. A superficial analysis showed that the *Realist* and the *Split Quantum*/*Realist* students were more likely than other students to invoke the uncertainty principle when discussing notions of determinism; the remaining students were more likely to state that the behavior of quantum particles (or the nature of the universe) is inherently probabilistic. These responses indicate a need for a more detailed exploration of the uncertainty principle as an epistemological tool for quantum physics students.

These interviews have demonstrated how matters of interpretation are of both personal and academic interest to students, and modern physics instructors should recognize the potential impact on student thinking when choosing to de-emphasize interpretation in an introductory course. Not only do students develop their own ideas regarding the physical meaning behind quantum mechanics, they also develop attitudes (right or wrong) about the positivistic or agnostic stances of their instructors:

> "It seems that there's this dogma among physicists, that you can't ask that question: *What is it doing between point A and point B? You can't ask that!* And I think that the only way we'll be able to make profound progress is by asking those questions. It doesn't make sense that somebody would say, don't ask that, or you can't ask that. I think somehow they're shutting down free seeking of knowledge. But I don't know enough about quantum mechanics. Maybe when I get more understanding of quantum mechanics, I too will be saying: *You can't ask that!* But as a naïve student it sounds like a bad attitude to have about physics." [STUDENT P3]

Although many instructors may argue that introductory students do not have the requisite sophistication to appreciate matters of interpretation in quantum mechanics, we note that several authors have already developed discussions of EPR correlations and Bell inequalities that are appropriate for the introductory level. [23, 24] Questions of interpretation may also be addressed in terms of *scientific modeling*, an aspect of epistemological sophistication that is often emphasized in physics education research as a goal of instruction, as well as in terms of *nature of science* issues. [25] In the end, we argue that modern physics instructors should concern themselves with matters of interpretation, if only because their students concern themselves with these matters, and as educators we should be concerned with what our students believe about physics and the nature of practicing physics. Modern physics instructors who aim to transition students away from classical epistemologies and ontologies may employ our framework for understanding and interpreting the myriad combinations of student ideas concerning the nature of quantum mechanics and its description of the natural world. Such insight may allow us to target instructional interventions that will positively influence student perspectives, and strengthen their abilities to make interpretations of physical phenomena, and to understand the limitations and bounds of these interpretations.

References [Chapter 4]

1. N. G. van Kampen, The Scandal of Quantum Mechanics, Am. J. Phys **76**, 989 (2008).

2. M. Dubson, S. Goldhaber, S. Pollock and K. Perkins, Faculty Disagreement about the Teaching of Quantum Mechanics, *PERC Proceedings 2009* (AIP, Melville, NY, 2009).

3. G. J. Posner, K. A. Strike, P. W. Hewson and W. A. Gertzog, Accommodation of a scientific conception: Toward a theory of conceptual change, *Sci. Educ.* **66**, 211 (1982).

4. A. Gupta, D. Hammer and E. F. Redish, The case for dynamic models of learners' ontologies in physics, *J. Learning Sciences* **19**, 285 (2010).

5. D. Hammer, A. Elby, R. E. Scherr and E. F. Redish, "Resources, Framing and Transfer" in *Transfer of Learning*, edited by J. Mestre (Information Age Publishing, 2005) pp. 89-119.

6. http://phet.colorado.edu/simulations/sims.php?sim=QWI

7. L. E. Ballentine, The Statistical Interpretation of Quantum Mechanics, *Rev. Mod. Phys.* **42**, 358 (1970).

8. L. E. Ballentine, Quantum Mechanics: A Modern Development (World Scientific Publishing, Singapore, 1998).

9. P. Grangier, G. Roger, and A. Aspect, Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences, *Europhysics Letters* **1**, 173 (1986).

10. P. A. M. Dirac, *The Principles of Quantum Mechanics, 3rd ed.*, (Clarendon Press, Oxford, 1947).

11. D. Bohm and B. J. Hiley, *The Undivided Universe* (Routledge, New York, NY, 1995).

12. N. D. Mermin, What's Wrong with this Pillow? *Phys. Today* **42**, 9 (1989).

13. C. Baily and N. D. Finkelstein, Refined characterization of student perspectives on quantum physics, *Phys. Rev. ST: Physics Education Research* **5**, 020113 (2010).

14. J. S. Bell, Speakable and Unspeakable in Quantum Mechanics (Cambridge University Press, Cambridge, 1987).

15. L. Lising and A. Elby, The impact of epistemology on learning: A case study from introductory physics, *Am. J. Phys.* **73**, 372 (2005).

16. T. L. McCaskey, M. H. Dancy and A. Elby, Effects on assessment caused by splits between belief and understanding, *PERC Proceedings 2003* **720**, 37 (AIP, Melville, NY, 2004).

17. T. L. McCaskey and A. Elby, Probing Students' Epistemologies Using Split Tasks, *PERC Proceedings 2004* **790**, 57 (AIP, Melville, NY, 2005).

18. D. Hestenes, M. Wills, and G. Swackhamer, *Physics Teacher* **30**, 141 (1992).

19. K. E. Gray, W. K. Adams, C. E. Wieman and K. K. Perkins, Students know what physicists believe, but they don't agree: A study using the CLASS survey, *Phys. Rev. ST: Physics Education Research* **4**, 020106 (2008).

20. S. W. Hawking, *A Brief History of Time* (Bantam, New York, NY, 1988).

21. B. R. Greene, *The Elegant Universe* (Norton, New York, NY, 2003).

22. J. D. Slotta, In defense of Chi's Ontological Incompatibility Hypothesis, *Journal of the Learning Sciences* **20**, 151 (2011).

23. D. F. Styer, *The Strange World of Quantum Mechanics* (Cambridge University Press, Cambridge, 2000).

24. http://www.colorado.edu/physics/EducationIssues/modern/

25. S. B. McKagan, K. K. Perkins and C. E. Wieman, Why we should teach the Bohr model and how to teach it effectively, *Phys. Rev. ST: Physics Education Research* **4**, 010103 (2008).