CHAPTER 2

Development of Student Perspectives - Initial Studies

I. Introduction

Our initial investigations into student perspectives seek to document and better understand the changes students undergo as they make the transition from learning classical physics to learning about quantum mechanics. We first analyze student responses to pre- and post-instruction surveys at various stages of an introductory physics sequence in order to demonstrate the development and reinforcement of deterministic perspectives during classical physics instruction, as well as the emergence of probabilistic and nondeterministic perspectives following instruction in modern physics. We also find that a modern physics instructor's choice of learning goals can significantly influence student responses: they are more likely to prefer either a *Realist* or *Quantum* (*matter-wave)* perspective in a context where such a perspective has been explicitly taught. Furthermore, a student's degree of commitment to any particular perspective is not necessarily robust across contexts: students may invoke both *Realist* and *Quantum* perspectives, without always knowing when either of these epistemological and ontological frames is appropriate. These studies serve as motivation for a more detailed exploration of variations in learning goals among modern physics instructors, and the associated impacts on student perspectives. [Chapter 3]

II. Studies

The University of Colorado offers a three-semester sequence of calculus-based introductory physics courses: PHYS1 and PHYS2 are large-lecture courses [1] (N~300-600) in classical mechanics and electrodynamics, respectively; PHYS3 covers a variety of topics from modern physics, and is offered in two sections (N~50-100, each). At the beginning and end of each semester, students from several offerings of each of the above courses were asked to respond to a series of survey questions designed to probe their epistemic and ontological perspectives on physics. The first of these surveys was an online version of the Colorado Learning Attitudes about Science Survey (CLASS), [2] wherein students responded using a 5-point Likert-scale (ranging from strong disagreement to strong agreement) to a series of 42 statements, including:

> **#41:** It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.

CLASS researchers do not score student responses to this statement as favorable or unfavorable [2] due to a lack of consensus among expert responses[1]. The myriad ambiguities contained in this statement allow for a number of legitimate (but different) interpretations by expert physicists: they may disagree on what it means to conduct the *same* experiment, what qualify as *very different* results, or even what it means for an experimental result to be considered *correct*.

II.A. Student ideas about measurement change over time.

There is a clear trend in how student responses to CLASS #41 change over the course of this introductory sequence. In a cross-sectional study of student responses from the three introductory physics courses (PHYS1, N=2200; PHYS2, N=1650; PHYS3, N=730) we see a shift first from agreement to disagreement, and then back to agreement with this statement. [Fig. 2.1] At the beginning of instruction in classical mechanics (A), more students will agree (40%) with this statement than disagree (26%); yet the number in agreement decreases significantly (B) following instruction in classical physics (to 30%, $p<0.001$), while an increasing number of students disagree (to 39%, $p<0.001$). This trend then reverses itself over a single semester of modern physics (C), at the end of which a greater percentage of students agree with this statement (46%) than prior to classical physics instruction.

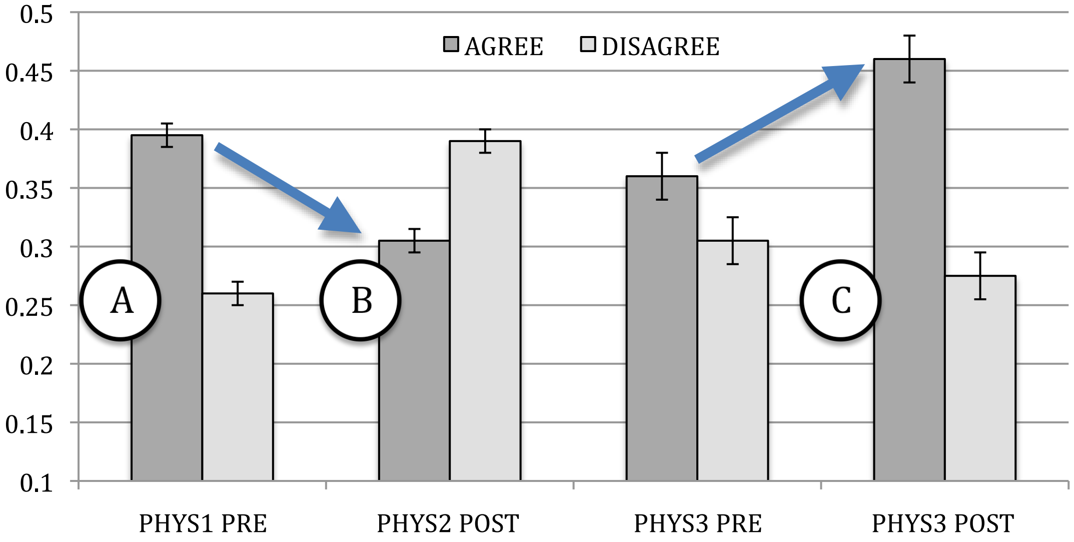

FIG. 2.1. Cross-sectional analysis of student responses to the statement: *It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct* (expressed as a fraction of total responses: PHYS1, N=2200; PHYS2, N=1650; PHYS3, N=730). Error bars represent the standard error on the proportion.

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[1] In informal interviews, physics faculty members at the University of Colorado responded approximately 35% Agree, 60% Disagree, and 5% Neutral.

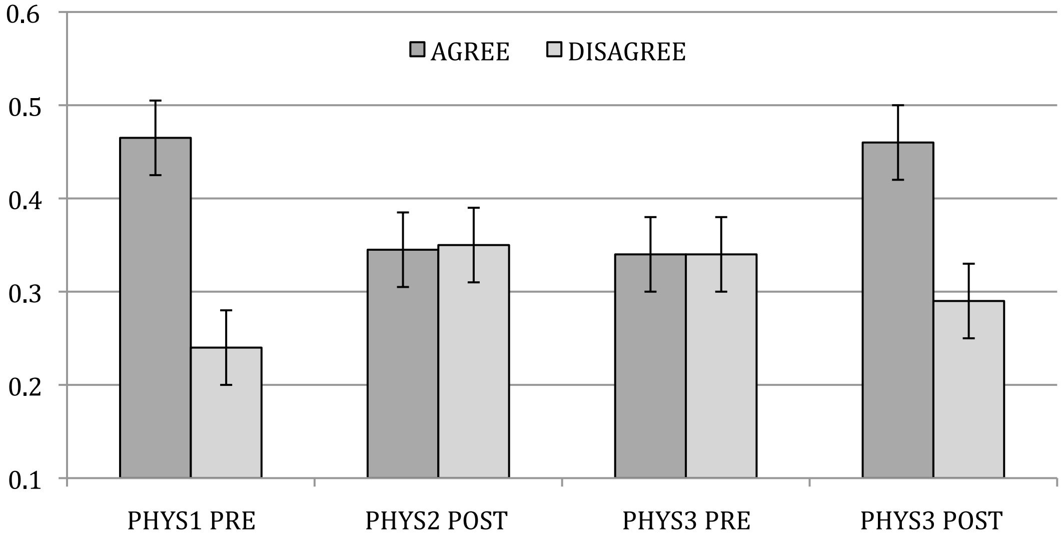

FIG. 2.2. Longitudinal study of student responses to the statement: *It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct* (expressed as a fraction of total responses: N=124). Error bars represent the standard error on the proportion.

In a longitudinal study of 124 students over three semesters, we observe the same trends. [Fig. 2.2]

The distribution of student responses at the end of this introductory sequence is similar to that at the beginning (in terms of agreement versus disagreement); we are naturally interested then in finding out if and how the reasoning invoked by students in defense of their responses changes. We analyzed the reasoning provided by approximately 600 students in an optional text box appended to an online version of the CLASS. These open-ended responses were coded into five categories through an emergent coding scheme. [3] [Table 2.I] The types of reasons offered by modern physics students at the start of instruction was similar to that from students in classical physics courses (pre- and post-instruction), and so the data for both have been combined into a single, pre-quantum instruction group. [Table 2.II]

TABLE 2.I. Categorization of reasoning provided by students in response to the statement: *It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.*

A	Quantum theory/phenomena
B	Relativity/different frames of reference
C	There can be more than one correct answer to a physics problem. Experimental results are open to interpretation.
D	Experimental/random/human error Hidden variables, chaotic systems
E	There can be only one correct answer to a physics problem. Experimental results should be repeatable.

TABLE 2.II. Distribution of reasoning provided by students before and after instruction in modern physics, in response to the statement: *It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.* Categories are as given in Table 2.I. Errors are the standard error on the proportion.

CATEGORY	PRE-QM INSTRUCTION (+/-2%)		POST-QM INSTRUCTION (+/-5%)	
	AGREE (N=231)	DISAGREE (N=199)	AGREE (N=41)	DISAGREE (N=26)
A	10%	5%	32%	27%
B	3%	0%	17%	4%
C	28%	6%	10%	8%
D	59%	20%	41%	19%
E	0	69%	0	42%

Our analysis shows that, prior to instruction in modern physics, 59% of those who agreed with the statement offered Category **D** explanations (experimental error, hidden variables); Category E explanations (physics problems have only one correct answer) were preferred by those who disagreed (69%). These results (in conjunction with other studies [4]) allow us to conclude that most introductory classical physics students who disagree with this statement interpret the results of experimental measurements as an approximation of the true (real) value of the quantity being measured; whereas most of those who agree with the statement allow for the possibility of random, hidden factors to influence the outcome of two otherwise identical experiments.

We find that before any formal instruction in modern physics, few students invoke quantum phenomena, despite the fact that a majority of them reported having heard about quantum mechanics in popular venues before enrolling in the course (e.g., books by Greene [5] and Hawking, [6]). However, a single semester of modern physics instruction results in a significant increase in the number of students who believe that quantum physics could allow for two valid, but different, experimental results. Students shift from 13% to 49% in referencing quantum or relativistic reasons for agreeing with the statement. [Table 2.II] Responses from each population were compared with a Chi-Square test and were found to be statistically different ($p<0.001$).

II.B. Instructional choices influence student perspectives.

To see if different types of instruction and learning goals can significantly influence student commitments to any particular perspective, we examined data from two PHYS3 offerings intended for physics majors. Course PHYS3A was taught by a PER instructor who employed in-class, research-based reforms [7], including interactive engagement and computer simulations [8] designed to provide students with a visualization of quantum processes; course PHYS3B was taught the following semester in the form of more traditional lectures. Both modern physics offerings were similar in devoting roughly one-third of the course to special relativity, with the remaining lectures covering the foundations of quantum mechanics and simple applications (as is typical at the University of Colorado). Notable differences in these two courses included the instructional approaches and learning goals of the instructors. Through informal end-of-term interviews and an analysis of course materials, it is clear that each of the instructors held different beliefs about incorporating interpretive aspects of quantum mechanics into a modern physics curriculum. In the context of a double-slit experiment performed with electrons, the instructor for PHYS3A ("Instructor A") explicitly taught that each electron propagates as a delocalized wave while passing through both slits, interferes with itself, and then becomes localized upon detection. Instructor B preferred a more agnostic stance on the physical interpretation of this experiment, and generally did not address such issues:

> "It seems like there's a new book about different interpretations of quantum mechanics coming out every other week, so I see this as something that is still up for debate among physicists. When I talked about the double-slit experiment in class, I used it to show students the need to think beyond F=ma, but I didn't talk about any of that other stuff. […] We did talk a little about [quantum weirdness] at the very end of the semester, but it was only because we had some time left over and I wanted to give the students something fun to talk about."

Despite Instructor B's self-reported *Agnostic* stance on quantum interpretations, his instructional practices differed in that he explicitly told students that each electron in a double-slit experiment passes through either one slit or the other, but that it is fundamentally impossible to determine which one without destroying the interference pattern (he characterized this *Realist* perspective as the one with which he was "least dissatisfied").

Students from both of these courses were given an end-of-term essay question asking them to argue for or against statements made by three fictional students discussing the Quantum Wave Interference (QWI) PhET simulation's [9] representation of a double-slit experiment with single electrons. [Fig. 2.3] In this simulation, a large circular spot (representing the magnitude of the wave function for a single electron, equivalent to the probability density) (A) emerges from a gun, (B) passes through two slits, and (C) a small dot appears on a detection screen; after a long time (many electrons) an interference pattern develops (not shown).

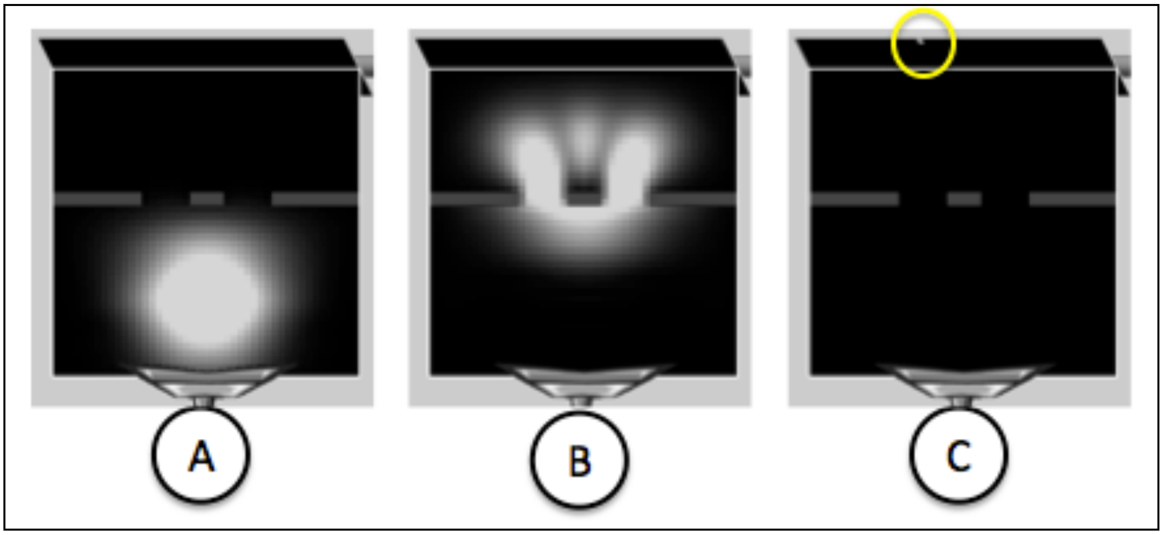

FIG. 2.3. Representation of a double-slit experiment with single electrons in the Quantum Wave Interference PhET simulation; used in the end-of-term essay question.

Each of the following statements (made by a *fictional* student) is meant to represent a potential perspective on how to think of an electron between the time it is emitted and when it is detected at the screen:

> **Student 1**: *That blob represents the probability density, so it tells you the probability of where the electron could have been before it hit the screen. We don't know where it was in that blob, but it must have actually been a tiny particle that was traveling in the direction it ended up, somewhere within that blob.*
>
> **Student 2**: *No, the electron isn't inside the blob, the blob represents the electron! It's not just that we don't know where it is, but that it isn't in any one place. It's really spread out over that large area up until it hits the screen*.
>
> **Student 3**: *Quantum mechanics says we'll never know for certain, so you can't ever say anything at all about where the electron is before it hits the screen.*

In this end-of-term survey question, students were asked to agree or disagree with any (or all) of the fictional students, and to provide evidence in support of their responses, which were then coded according to whether students preferred a *Realist* or a *Matter-Wave* perspective in their argumentation. A random sample of 20 student responses were re-coded by a PER researcher unaffiliated with this project as a test for inter-rater reliability; following discussion of the coding scheme, the two codings were in 100% agreement. The following sample of two student responses is illustrative of the types of responses seen:

> **Student Response (*Realist*):** "We just can't know EXACTLY where the electron is and thus the blob actually represents the probability density of that electron. In the end, only a single dot appears on the screen, thus the electron, wherever it was in the probability density cloud, traveled in its own direction to where it ended up."
>
> **Student Response (*Matter-Wave*)**: "The blob is the electron and an electron is a wave packet that will spread out over time. The electron acts as a wave and will go through both slits and interfere with itself. This is why a distinct interference pattern will show up on the screen after shooting out electrons for a period of time."

The distribution of all responses for the two courses is summarized in Table 2.III (columns do not add to 100% because some students provided a mixed or otherwise unclassifiable response; almost none of the responses favored Student 3). For this essay question, there is a strong bias towards a *Matter-Wave* perspective among PHYS3A students, while students from PHYS3B highly preferred a *Realist* perspective. Virtually no student agreed with fictional Student 3 (which might be consistent with an *Agnostic* perspective); among those who explicitly disagreed with Student 3, most felt that knowing about the probability density was a sufficient form of knowledge about this quantum system.

TABLE 2.III. Student responses to the Quantum Wave Interference essay question from two offerings of PHYS3. Numbers in parentheses represent the standard error on the proportion.

CATEGORY	PHYS3A (%) (N=72)	PHYS3B (%) (N=44)
Realist	18 (5)	75 (7)
Matter-Wave	78 (5)	11 (5)

Students from both PHYS3 courses also responded at the beginning and end of the semester to additional statements appended to an online version of the CLASS for modern physics students, including:

> **QA#2**: An electron in an atom has a definite but unknown position at each moment in time.

It might be expected that students who have learned to view an electron as delocalized until detected in the context of a double-slit experiment would also view it as such in other contexts, such as atoms. Disagreement with this statement on atomic electrons could be consistent with either a *Matter-Wave* or *Copenhagen/Agnostic* perspective, whereas agreement would be more consistent with a *Realist* perspective. While we again observe differences in student responses between the two PHYS3 course offerings [Table 2.IV] there is not the same strong bias toward a single perspective as seen in Table 2.III. Disagreement with this statement among PHYS3A students increased by 22%, and by 13% for PHYS3B students; agreement with this statement decreased by 5% in PHYS3A, while the number of PHYS3B students agreeing with this statement increased by a comparably small amount.

TABLE 2.IV. Student responses to the statement: *An electron in an atom has a definite but unknown position at each moment in time.* Numbers in parentheses represent the standard error on the proportion.

RESPONSE	PHYS3A (%) (N=41)		PHYS 3B (%) (N=36)	
	PRE	POST	PRE	POST
AGREE	44 (8)	39 (8)	48 (8)	54 (8)
NEUTRAL	32 (7)	17 (6)	39 (8)	21 (7)
DISAGREE	22 (6)	44 (8)	10 (5)	23 (7)

II.C Consistency of student perspectives

An important question remains: are there consistencies in student perspectives across domains? The differences in responses from PHYS3A and PHYS3B students are less significant for QA#2 [Table 2.IV] than those seen for the QWI essay question [Table 2.III], but together indicate a possible lack of consistency in their preferred perspectives in different contexts. This inconsistency can be better illustrated by combining matching data for both questions, and then grouping together students from both courses according to how they responded to the QWI essay question. [Table 2.V] In doing so, we see that students who preferred a *Matter-Wave* perspective in the essay question tended to disagree with the notion that atomic electrons exist as localized particles; and the majority of students who preferred a *Realist* perspective in the first case also took a *Realist* stance on the question of atomic electrons. Of particular interest, however, are the students who were not consistent in their responses: 18% of those who disagreed with QA#2, and 33% of those who agreed, offered a response that was inconsistent with their response to the QWI essay question. That is, 18% of students disagreed with the statement on atomic electrons, yet gave a *Realist* response on the interference question; 33% of students were the reverse: taking a *Realist* stance on atomic electrons, but preferring a *Matter-Wave* perspective on the question of electron interference.

TABLE 2.IV. Student responses to the statement: *An electron in an atom has a definite but unknown position at each moment in time,* grouped according to how they responded to the QWI essay question. Numbers in parentheses represent the standard error on the proportion.

QA#2 - POST **QWI**	**DISAGREE (%)**	**NEUTRAL (%)**	**AGREE (%)**
Matter-Wave (N=66)	56 (6)	11 (4)	33 (6)
Realist (N=46)	18 (6)	18 (6)	64 (7)

III. Summary and Discussion

The data presented in this chapter serve as evidence in support of three key findings. First, student perspectives with respect to measurement and determinism in the contexts of classical physics and quantum mechanics evolve over time. The distribution of reasoning provided by students in response to the CLASS survey statement indicate that the majority of those who disagree with this statement believe that experimental results should be repeatable, or that there can be only one correct answer to a physics problem. One could easily imagine that students begin their study of classical physics at the university level with a far more deterministic view of science than is evidenced by their initial responses (after all, most students do arrive with some training in classical science). We take the first significant shift in student responses (a decrease in agreement and an increase in disagreement with this statement, as shown in Fig. 2.1) to be indicative of the promotion and reinforcement of a deterministic perspective in students as a result of instruction in classical physics. After a course in modern physics, student responses shift a second time (an increase in agreement and a decrease in disagreement with the survey statement), although the reasoning behind their responses changed. Students of modern physics are instructed that different frames of reference could lead to different experimental results, both of which are correct (special relativity); they are also taught that the quantum-mechanical description of nature is probabilistic, and that the determinism assumed by Newtonian mechanics is no longer valid at the atomic scale. The impact of this type of instruction is reflected in the significant increase in the number of students who invoke relativistic or quantum phenomena as a reason for agreeing with the survey statement.

Second, we observe that how students develop and apply a particular perspective can depend upon the learning goals of their instructors. The results for the Quantum Wave Interference essay question indicate that how students view an electron within the context of a double-slit experiment can be significantly influenced by instruction. Instructor A explicitly taught students that each electron passes through both slits and interferes with itself, and provided students with an in-class visualization of this process via the QWI PhET simulation. The positivistic aspects of the *Copenhagen Interpretation* [10] insist that questions of which slit any particular electron passed through are (at best) ill-posed, and that quantum mechanics concerns itself only with the probabilistic prediction of experimental results. An *Agnostic* stance might say that the question of which slit an electron passed through is irrelevant to the proper application of the mathematical formalism. Although Instructor B reported personally holding an *Agnostic* stance on questions of interpretation in quantum mechanics, he did not teach this perspective explicitly, but rather was explicit in teaching a *Realist* interpretation of the double-slit experiment; this instructional approach is partly reflected in how the majority of PHYS3B students preferred a *Realist* stance on electrons in this context.

Third, we find that many students do not exhibit a consistent perspective on questions of ontology and epistemology across multiple contexts. While the data shown in Table 2.IV do demonstrate some amount of consistency in responses regarding the question of an electron's location, a significant number of students who preferred a *Matter-Wave* interpretation of an electron diffraction experiment would still agree that an electron in an atom has a definite (but unknown) position. We conclude that students will not necessarily develop robust concepts regarding the nature of quanta, which would be consistent with a resources view of student epistemologies and ontologies in physics. [16-19]

Without passing judgment on any particular set of instructional goals, it is worth acknowledging that significant differences in the teaching of modern physics courses do exist (as with upper-division courses in quantum mechanics[11]), and that these learning goals manifest themselves both explicitly and implicitly (intentionally, or not) during the course of instruction. It is in itself a significant finding that, at least in this regard, students are open to adopting their instructor's explicit interpretations of quantum phenomena (though it may be argued in the case of Instructor B that his explicit instruction was already in alignment with the *realist* expectations of his students); there is substantial evidence that students do not necessarily adopt an instructor's views in other contexts. Previous studies of introductory classical physics courses have shown that, with notably few exceptions, [12-14] students tend to shift to more unfavorable (novice-like) beliefs about physics and about the learning of physics [12, 15]. It has been demonstrated, however, that making epistemology an explicit aspect of instruction in introductory physics courses can positively influence this negative trend. [14] The studies presented in this chapter provide further indication that instructors should not take for granted that students will adopt their perspectives on quantum physics unless such learning goals are made explicit in their teaching.

In the end, it seems that a reasonable instructional objective would be for students to apply a particular perspective (deterministic or probabilistic, local or nonlocal) at the appropriate time. If we are to include these goals for our classes, it is important to understand how these messages are sent to our students, and what instructional practices may promote such understandings. [Chapter 3]

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