Quantum Interpretations in Modern Physics Instruction

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Abstract. Just as expert physicists vary in their personal stances on interpretation in quantum mechanics, instructors hold different views on teaching interpretations of quantum phenomena in introductory modern physics courses. There has been relatively little research in the physics education community on the variation in instructional approaches with respect to quantum interpretation, and how instructional choices impact student thinking. We compare two modern physics courses taught at the University of Colorado with similar learning environments, but where the instructors held different views on how to teach students about interpretations of quantum processes. We find significant differences in how students from these two courses responded to a survey on their beliefs about quantum mechanics; findings also suggest that instructors who choose to address student ontologies should do so across a range of topics.

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INTRODUCTION

Over the last decade or so, the amount of attention given to quantum mechanics in physics education research (PER) has increased significantly. Yet, the focus of these investigations has been primarily on identifying student difficulties in applying the mathematical formalism of quantum theory. Relatively little attention has been paid to documenting the role of interpretation when teaching quantum mechanics, associated instructional practices, and how differing approaches impact student thinking.

We document two modern physics courses taught at the University of Colorado with similar learning environments, but where the instructors held different views on how to teach students about quantum processes. We find that students are less likely to prefer realist interpretations of quantum phenomena when instructors explicitly promote alternative perspectives, and that this impact does not necessarily transfer to other contexts where instruction is less explicit. This suggests to us that if instructors wish to promote a particular perspective when teaching modern physics, they should be explicit in doing so across a broad range of contexts, and not assume it to be sufficient to address student ontologies primarily at the outset of the course.

Each semester, the University of Colorado (CU) offers two sophomore level modern physics courses, one section intended for engineering majors (PHYS3A) and the other for physics majors (PHYS3B). Historically, the curricula for both courses have been essentially the same, with variations from semester to semester according to instructor preferences.

In the fall semester of 2005, a team of three instructors from the PER group at CU worked to transform the curriculum for PHYS3A [1] by incorporating interactive engagement techniques (e.g. in-class concept questions, peer instruction, interactive computer simulations [2]), and revised content intended to emphasize reasoning development, model building, and connections to real-world problems. These reforms, implemented in PHYS3A during the FA05-SP06 academic year, were continued in FA06-SP07 by another professor from the PER group, who then collaborated in the FA07 semester with a non-PER faculty member to adapt the course materials from PHYS3A into a curriculum also suitable for PHYS3B.

The course materials [3] for all five of these semesters (which include lecture slides and concept tests) were made available to each of the instructors for PHYS3A and PHYS3B in the semester of this study. Although the instructors for both courses reported changing a majority of the lecture slides to some extent, the general progression of topics in both classes was the same, and the presentation of content was often essentially identical; **Table 1** summarizes the progression of topics from the quantum physics section of the two courses, and the number of lectures spent on each topic.

These two modern physics offerings each had a class size of ~75 students, and both devoted approximately one-third of the course to special relativity, with the remaining lectures covering the foundations of quantum mechanics and its application to simple systems. Both courses used the same textbook [4] from which weekly homework problems were assigned, and each offered two midterm exams and a comprehensive final exam.

TABLE 1. The progression of topics and number of lectures devoted to each topic for both modern physics courses from the fall semester of 2008 at CU.

CODE	TOPIC	LECTURES	
		3A	3B
A	Introduction to Quantum	2	1
B	Photoelectric Effect/Photons	5	4
C	Atomic Spectra/Bohr model	6	3
D	de Broglie Waves/Atom	1	1
E	Matter Waves/Interference	3	2
F	Schrodinger Equation	2	5
G	Infinite/Finite Square Well	3	3
H	Tunneling/Alpha Decay/STM	2	4
I	3-D SE/Hydrogen Atom	4	2
J	Multi-Electron Atoms/Solids	3	3

TEACHING QUANTUM PERSPECTIVES

While the progression of topics for both modern physics courses in the FA08 semester was the same, and lecture slides from both courses were often essentially identical, the two courses differed in sometimes obvious, other times more subtle ways with respect to how each instructor addressed notions of quantum interpretation. An analysis of the lecture slides posted on each of the course websites offers a first-pass characterization of the two courses. This analysis entailed a simple counting scheme in which each lecture slide was assigned a point value of zero or one in each of three categories according to its relevance to three specific themes, denoted as *light*, *matter* and *perspective*. These themes were chosen to highlight key lecture slides that explicitly contrasted classical perspectives with quantum perspectives. Since light is classically described as a wave, slides that emphasized its particle nature, or explicitly addressed its dual wave/particle characteristics, were assigned a point in the *light* category; similarly, slides that emphasized the wave nature of matter or its dual wave/particle characteristics were given a point in the *matter* category. Other key slides (*perspective* category) were those that addressed randomness, indeterminacy or the probabilistic nature of quantum mechanics, or made explicit contrast between quantum results and what would be expected in a classical system.

Figure 1 groups the point totals for each course by topic category (as listed in **Table 1**); we find that PHYS3A had a greater number of slides than PHYS3B that were relevant to the *perspective* category, though this difference can be largely attributed to the instructors' treatments of topic category B: the photoelectric effect and photons. While both PHYS3 courses had the greatest point totals in this topic area, PHYS3A clearly devoted a greater proportion of lecture time here to addressing themes of indeterminacy and probability. (PHYS3A also totaled more points in the *light* category, though this difference can be attributed to Instructor A's brief discussion of lasers, a topic not covered in PHYS3B.) We note, however, that each of these themes of interpretation received considerably less attention at the later stages of both courses.

The two slides shown in **Figure 2** are illustrative of how the differences between the two courses could be more subtle, yet still significant. Both slides summarize the results for the system referred to in PHYS3A as the *Infinite Square Well*, but which Instructor B called the *Particle in a Box*. The two slides are identical in depicting the first-excited state wave function of an electron, as well as listing the normalized wave functions and quantized energy levels for this system. And both slides make an explicit contrast between the quantum mechanical description of this system and what would be expected classically, each pointing out that a classical particle can have any energy, while an electron confined to a potential well can only have specific energies.

However, PHYS3A differed in emphasizing a perspective that views the electron in this system as a standing wave, delocalized and spread out between the two walls of the potential well, stating explicitly that the particle should not be thought of as bouncing back and forth. Instructor B focused instead on the kinetic energy of the system, pointing out that a classical particle can be at rest, whereas the quantum system has a non-zero ground state energy. It is arguable that Instructor B's choice of language, to speak of a "particle in a box" having zero-point motion, could easily reinforce for students the notion that in this system a localized particle is bouncing back and forth between the two potential barriers. Both of these slides received a point in the *perspective* category, but only the slide from PHYS3A received a point in the *matter* category for its emphasis of the wave nature of the electron in the potential well.

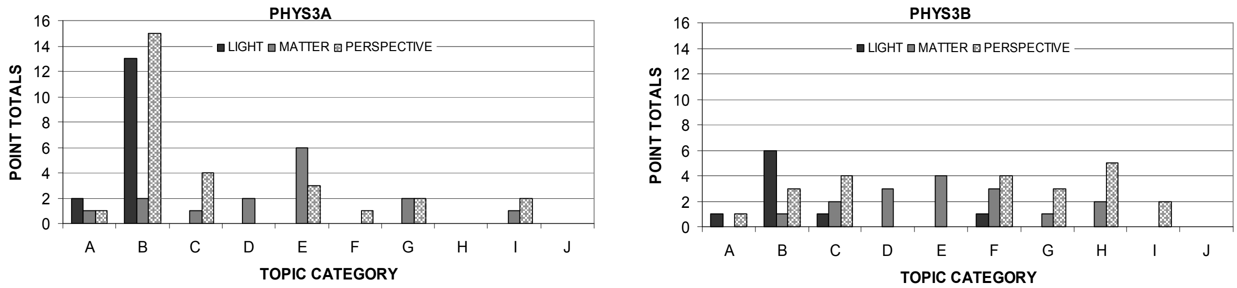


FIGURE 1. Occurrence of lecture slides for both PHYS3A (left) and PHYS3B (right) by topic (as listed in Table 1) for each of the themes *light*, *matter*, and *perspective*.

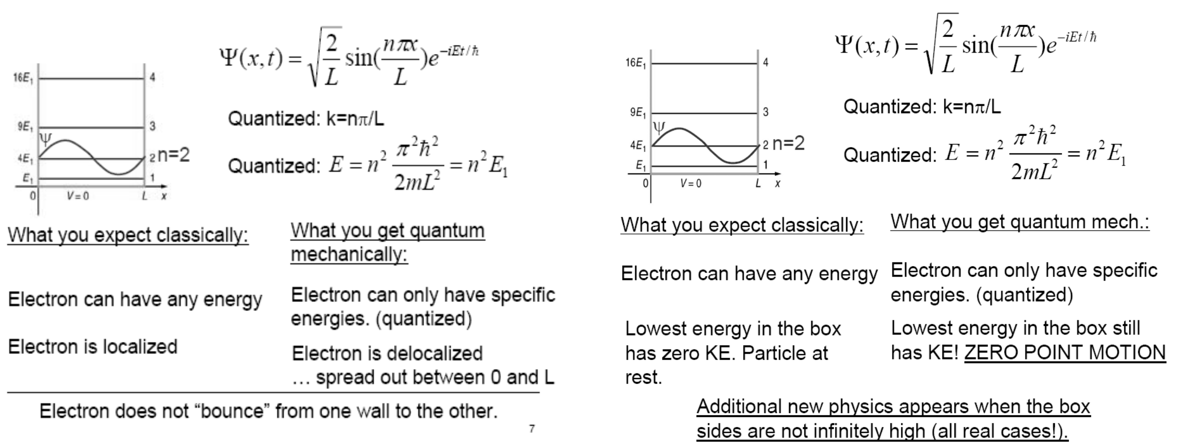


FIGURE 2. A lecture slide from PHYS3A (left, "Infinite Square Well") and from PHYS3B (right, "Particle in a Box").

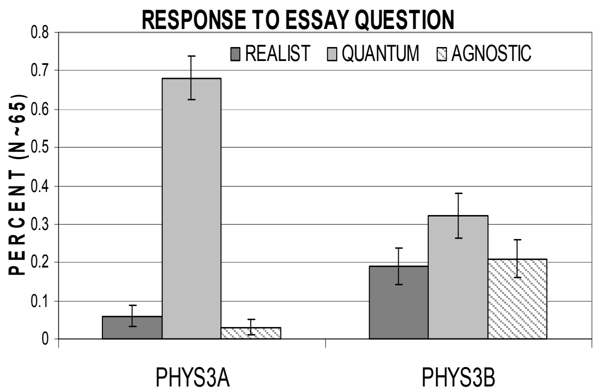
The Double-Slit Experiment

The double-slit experiment is a natural sub-topic in the discussion of photons, since it requires both a wave and a particle description of light in order to completely account for experimental observations. Both courses instructed students on how to relate the distance between the slits and the wavelength of the beam to the locations of the maxima and minima of the interference pattern, and both used the Quantum Wave Interference simulation [5] in class to provide students with a visualization of the process.

Both PHYS3 courses also instructed students that the intensity of the beam can be turned down to the point where only single quanta pass through the apparatus at a time; individual quanta are detected as localized particles on the screen, yet an interference pattern still develops over a period of time. One interpretation of this result, preferred by Instructor A, models individual quanta as delocalized wave-packets that propagate through both slits simultaneously, interfere with themselves, and then become localized when interacting with the detector. Instructor A was quite explicit in teaching this model, devoting several lecture slides to a step-by-step explanation of the process. Instructor B preferred a more agnostic approach, ultimately emphasizing that most practicing physicists are content to make predictions using the tools of quantum mechanics, and don't concern themselves with questions of interpretation.

Variation in Student Perspectives

In the last week of the semester, students from both PHYS3 courses responded to an online survey essay question concerning their interpretation of the double-slit experiment with single electrons. Students received homework credit for responding to the survey (equivalent to the number of points given for a typical homework problem), and the response rate for both courses was approximately 90%.



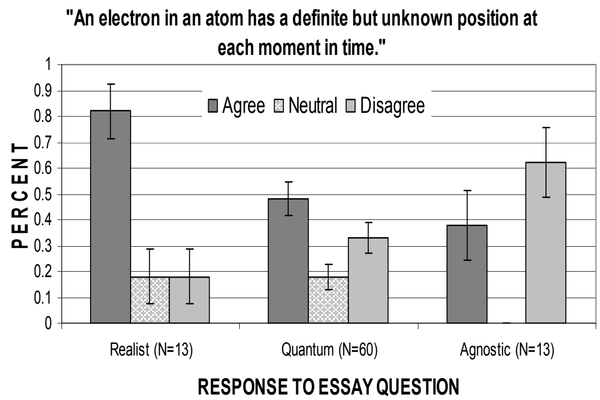


FIGURE 3. Student responses from both PHYS3 courses to an essay question on interpretation in the double-slit experiment (left), and combined student response to an attitudes statement, grouped by how they responded to the essay question (right).

When comparing student responses from both courses (**Figure 3**), we see that Instructor A's more explicit approach regarding the interpretation of the double-slit experiment had a demonstrable impact on how students thought of photons and other quanta within that specific context: most of the students from PHYS3A (~70%) chose to agree with a statement that describes the electron as a wave packet that interferes with itself. Instructor B's more agnostic approach is reflected in the greater variation of student responses to the essay question, and we note that PHYS3B students were much more likely than PHYS3A students to prefer a realist interpretation of the experiment. Specifically, 19% of PHYS3B students chose a realist interpretation, agreeing with the statement that each electron must pass through one slit or other, but not both; and 21% of PHYS3B students preferred an agnostic stance, agreeing with the statement that quantum mechanics is concerned only with predicting experimental results. In comparison, fewer than 10% combined of students from PHYS3A chose either of these responses exclusively. This result expands on an earlier study [6] which suggested that students have a greater tendency to prefer realist interpretations of quantum phenomena when instructors are not explicit in promoting alternatives.

Interestingly, the emphasis given in PHYS3A toward thinking of quanta as delocalized in the double-slit experiment and the infinite square well did not seem to transfer to a context where instruction was less explicit in addressing student ontologies. We were able to investigate the consistency of student perspectives across contexts by comparing responses to the double-slit question with student responses to a statement concerning the position of an electron in an atom (**Figure 3**). In this case, both courses were similar in their discussion of the Schrodinger model of hydrogen (topic 'I', see **Figure 1**). We find that most every student who preferred a realist interpretation of the double-slit experiment also took a realist stance on the question of whether an electron in an atom has a definite position. On the other hand, about half of the students who preferred the wave-packet description of an electron in the double-slit experiment still agreed that an electron in an atom must have a definite position at all times. This suggests that if instructors wish to promote a particular perspective when teaching modern physics, they should be explicit in doing so across a broad range of contexts, rather than assuming it to be sufficient to address student perspectives primarily at the outset of the course. The contextual dependence of student perspectives is a subject for future study.

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