CHAPTER 3

Quantum Interpretation as Hidden Curriculum - Variations in Instructor Practices and Associated Student Outcomes

I. Introduction

In physics education research, the term *hidden curriculum* generally refers to aspects of science and learning about which students develop attitudes and opinions over the course of instruction, but which are primarily only implicitly addressed by instructors. [1] Students may hold varying beliefs regarding the relevance of course content to real-world problems, the coherence of scientific knowledge, or even the purpose of science itself, depending (in part) on the choices and actions of their instructors. Education research has demonstrated that student attitudes regarding such matters tend to remain or become less expert-like when instructors are not explicit in addressing them. [1] In this chapter we present similar findings: the less explicit an instructor is in addressing student perspectives within a given topic area, the greater the likelihood for students (within that specific context) to favor an intuitive, *realist* perspective. In other words, the less the interpretive aspects of quantum mechanics are explicitly addressed by instructors, the more they become part of a hidden curriculum. We explore here how modern physics instructors may (or may not) address this hidden curriculum, and examine the impact of specific instructional approaches on student thinking. Figs. 3.1 & 3.2 (where letters refer to specific instructors and their particular approaches, to be discussed below) illustrate how instructional choices can lead to significantly different student outcomes, as well as the mixed nature of student responses across contexts.

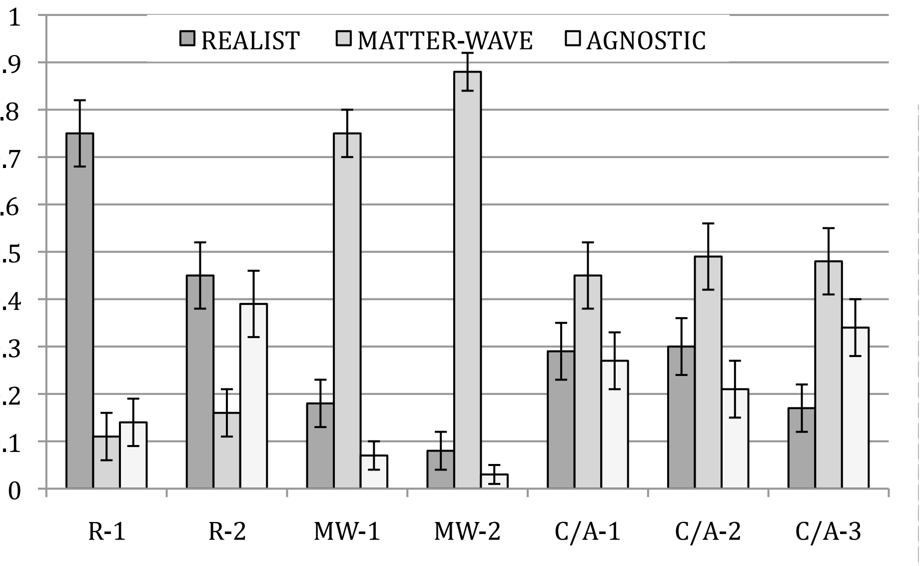


FIG. 3.1. Post-instruction student responses to the double-slit essay question, from seven different modern physics offerings of various instructional approaches [R = *Realist*; MW = *Matter-Wave*; C/A = *Copenhagen/Agnostic*]. Error bars represent the standard error on the proportion; N ~ 50-100 for each course.

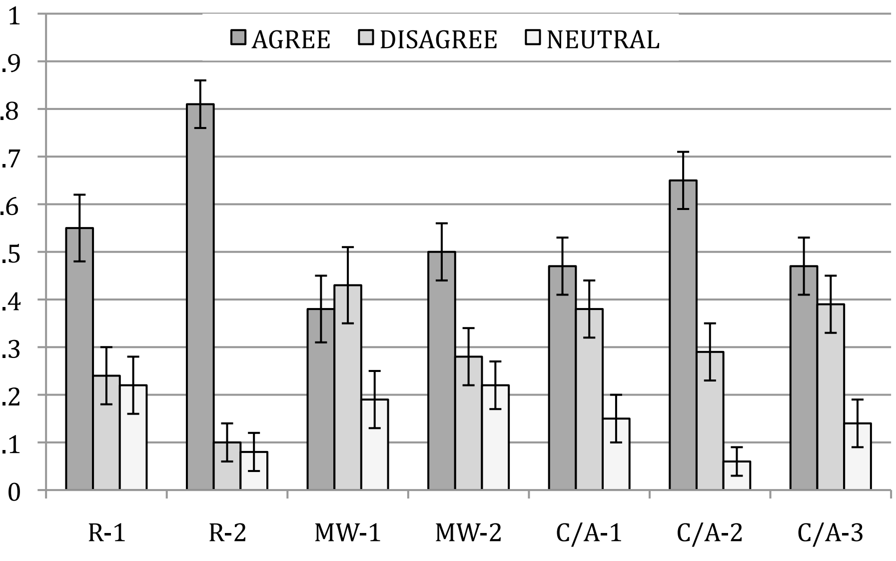


FIG. 3.2. Post-instruction student responses to the statement: *An electron in an atom exists at a definite (but unknown) position at each moment in time*, from seven different modern physics offerings of various instructional approaches [R = *Realist*; MW = *Matter-Wave*; C/A = *Copenhagen/Agnostic*]. Error bars represent the standard error on the proportion; N ~ 50-100 for each course.

II. Instructors approach quantum interpretation differently

This section describes four specific approaches to addressing quantum interpretation in four different modern physics courses recently taught at the University of Colorado, each resulting in significant differences in student thinking by the end of the semester. All four courses were large-lecture (N~100), utilized interactive engagement in class, and devoted the usual proportions of lecture time to special relativity and quantum mechanics. Student responses to the double-slit essay question and statement on atomic electrons described in Chapter 2 are shown in Figs. 3.3 & 3.4, where letters refer to the specific instructors discussed in this section (and their particular approaches to instruction). With respect to the double-slit experiment with electrons, each of these instructors had been explicit in teaching one particular interpretation (*though not explicitly as an interpretation*); student responses in this context were generally reflective of the teaching approaches for each course. [Fig. 3.3]

In two of the four courses (B1 & C) instructors paid considerably less attention to interpretive themes at later stages of the course, as when students learned about the Schrödinger model of hydrogen. Students from all four courses were more likely to agree than disagree with the statement: *An electron in an atom has a definite (but unknown) position at each moment in time*. [Fig. 3.4] What follows is a more detailed discussion of the specific instructional approaches employed in the courses described above, where letters refer to specific instructors, as given in the figure captions.

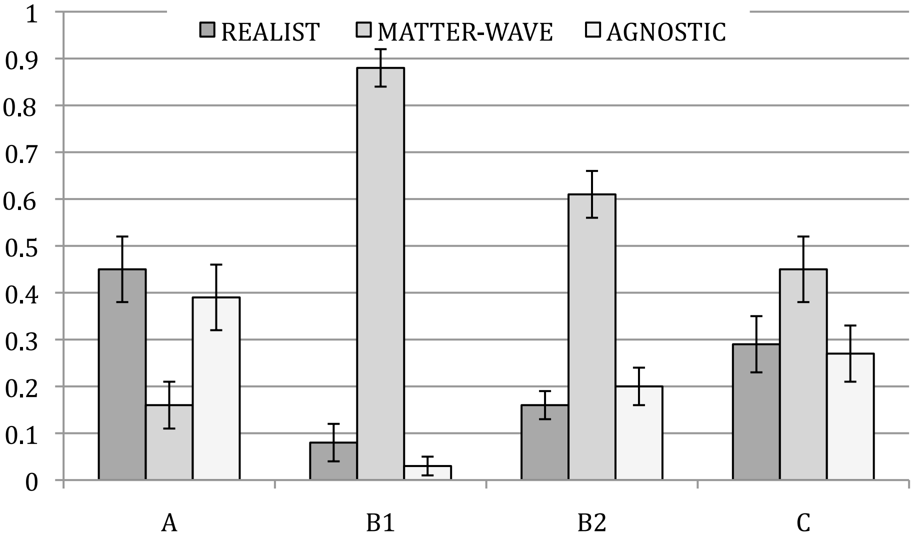


FIG. 3.3. Post-instruction student responses to the double-slit essay question, from four different modern physics offerings of various instructional approaches [A = *Realist/Statistical*; B1 & B2 = *Matter-Wave*; C = *Copenhagen/Agnostic*]. Error bars represent the standard error on the proportion; N ~ 100 for each course.

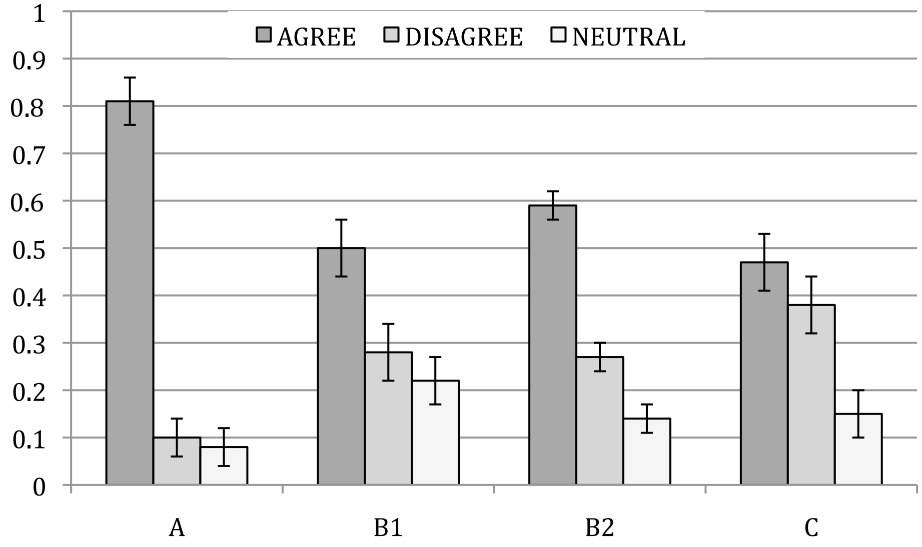


FIG. 3.4. Post-instruction student responses to the statement: *An electron in an atom exists at a definite (but unknown) position at each moment in time*, from four different modern physics offerings of various instructional approaches [A = *Realist/Statistical*; B1 & B2 = *Matter-Wave*; C = *Copenhagen/Agnostic*]. Error bars represent the standard error on the proportion; N ~ 100 for each course.

A. Explicitly teach an interpretation that aligns with student intuition, without discussing alternatives: Instructor A taught this course for engineering majors from a *Realist/Statistical* perspective (though he did not call it such), and explicitly referred to this in class as his own interpretation of quantum phenomena, one that other physicists would not necessarily agree with. Beyond his *Realist* stance on the double-slit experiment, students were explicitly instructed to think of atomic electrons as localized particles, and that energy quantization is the result of their average behavior; there was no discussion of alternatives to the perspective being promoted in class. Student responses from this course in both contexts were in alignment with Instructor A's explicit learning goals: they were the most likely to prefer a *Realist* interpretation of the double-slit experiment [each electron goes through either one slit or the other, but not both], as well as the most likely to agree that atomic electrons exist as localized particles. We believe student responses from this course are reflective not only of this instructor's explicit instruction, but also that this particular kind of interpretation of quantum mechanics is in agreement with intuitively *realist* expectations.

B1. Teach one interpretation (though not explicitly as an interpretation) in some topic areas (particularly at the beginning of the course) and expect students to generalize to other contexts on their own: When first teaching this modern physics course for engineering majors, Instructor B was explicit in modeling single quanta in the double-slit experiment as delocalized waves that pass through both slits simultaneously. He did not frame this discussion in terms of modeling or interpretation, but rather made what he saw as sufficient arguments in favor of this particular interpretation, as he stated in an informal post-instruction interview:

> "This image that [students] have of this [probability] cloud where the electron is localized, it doesn't work in the double-slit experiment. You wouldn't get diffraction. If you don't take into account both slits and the electron as a delocalized particle, then you will not come up with the right observation, and I think that's what counts. The theory should describe the observation appropriately. [...] It really shouldn't be a philosophical question just because there are different ways of describing the same thing [i.e. as a wave or a particle]. They seem to disagree, but in the end they actually come up with the right answer."

Students from this *Matter-Wave* course overwhelmingly preferred a wave-packet description of individual electrons [each electron passes through both slits simultaneously and interferes with itself]. However, these students did not seem to generalize this notion of particles as delocalized waves to the context of atoms, where Instructor B was not explicit regarding the ontological nature of electrons, and where a majority still agreed that atomic electrons exist as localized particles. Students were more likely to prefer *Realist* notions in a topic area where Instructor B was not explicit regarding interpretation.

B2. Teach one interpretation (though not explicitly as an interpretation) in some topic areas, combined with a more general discussion of interpretative themes towards the end of the course: Instructor B later taught a second modern physics course for engineering majors in a similar manner, but this time devoted two lectures near the end of the course to interpretive themes in quantum mechanics, including a discussion of the interpretive aspects of the double-slit experiment (but without reference to atomic systems). Student responses were similar to the previous *Matter-Wave* course (B1) on interpretations of the double-slit experiment, but a majority of students still preferred a *Realist* stance on atomic electrons.

C. Teach a Copenhagen/Agnostic perspective, or de-emphasize questions of interpretation: In this modern physics course for physics majors, Instructor C did touch on some interpretive themes during the course, though he ultimately emphasized a perspective that was more pragmatic than philosophical, as when faced with the in-class question of whether particles have a definite but unknown position, or have no definite position until measured:

> "Newton's Laws presume that particles have a well defined position and momentum at all times. Einstein said we can't know the position. Bohr said, philosophically, it has no position. *Most physicists today say: We don't go there. I don't care as long as I can calculate what I need.*" [Emphasis added]

In an end-of-term interview, Instructor C clarified his attitude toward teaching any particular perspective to students in a sophomore-level course:

> "In my opinion, until you have a pretty firm grip on how QM actually works, and how to use the machine to make predictions, so that you can confront the physical measurements with pairs of theories that conflict with each other, there's no basis for ragging on the students about, 'Oh no, the electron, it's all in your head until you measure it.' They don't have the machinery at this point, and so anybody who wants to stand in front of [the class] and pound on the table and say some party line about what's really going on, nevertheless has to recognize that the students have no basis for buying it or not buying it, other than because they're being yelled at."

Student responses from this course to the double-slit essay question were more varied than with the other courses – students were not only more likely to prefer an *Agnostic* stance [quantum mechanics is about predicting the interference pattern, not discussing what happens between], a significant number of students (30%) preferred a *Realist* interpretation – more than with the *Matter-Wave* courses, but less so than with the *Realist/Statistical* course. Nearly half of all students from this course also preferred a *Realist* stance on atomic electrons.

III. Comparing Instructor Practices (A Closer Look)

The goal of understanding the interplay between instructor practices and student perspectives calls for a more detailed comparison of two modern physics courses with similar content and presentation, but different in their approach to interpretive themes in quantum mechanics (Courses B1 & C from Section II, both of which took place in the semester immediately following the studies described in Chapter 2).

III.A. Background on course materials and curriculum similarities.

Each semester, the University of Colorado (CU) offers two versions of its introductory modern physics course; one section is intended for engineering majors (e.g., Course B1), and the other for physics majors (Course C). The curricula for both versions of the course have traditionally been essentially the same, with variations from semester to semester according to instructor preferences. In the fall of 2005, a team from the physics education research (PER) group at CU introduced a transformed curriculum for the engineering course incorporating research-based principles. [2] This included interactive engagement techniques (in-class concept questions, peer instruction, and computer simulations [3]), as well as revised content intended to emphasize reasoning development, model building, and connections to real-world problems. These course transformations, implemented during the FA05-SP06 academic year, were continued in FA06-SP07 by another physics education researcher at CU, who then collaborated in the FA07 semester with a non-PER faculty member to adapt the course materials into a curriculum appropriate for physics majors (by including topics from special relativity).

The course materials [4] for all five of these semesters (which included lecture slides and concept tests) were made available to Instructors B & C, who both reported changing a majority of the lecture slides to some extent (as well as creating new ones). By examining the course syllabi and categorizing the lecture material for each course into ten standard introductory quantum physics topics, we find the general progression of topics in both classes to be essentially the same (the presentation of content was many times practically identical), with slight differences in emphasis. [Table 3.I]

TABLE 3.I. Progression of topics and number of lectures devoted to each topic from the quantum physics portion of both modern physics courses B1 & C.

CODE	**TOPIC**	**# OF LECTURES**	
		B1	**C**
A	Introduction to quantum physics	2	1
B	Photoelectric effect, photons	5	4
C	Atomic spectra, Bohr model	5	3
D	DeBroglie waves/atomic model	1	1
E	Matter waves, interference/diffraction	3	2
F	Wave functions, Schrödinger equation	2	5
G	Potential energy, infinite/finite square well	3	3
H	Tunneling, alpha-decay, STM's	2	4
I	3-D Schrödinger equation, hydrogen atom	4	2
J	Multi-electron atoms, periodic table, solids	3	3

III.B. Differences in instructional approaches.

While the learning environments and progression of topics for both modern physics courses were essentially the same, the two courses differed in sometimes obvious, other times more subtle ways with respect to how each instructor addressed student perspectives and themes of interpretation. An analysis of the instructional materials used in each of the two courses offers a first-pass comparison of the two approaches. When comparing the homework assignments for each course, there were no (or very minimal) opportunities for students to reflect on physical interpretations of quantum phenomena. Similarly, an examination of the midterms and finals from both courses revealed no emphasis on questions of interpretation. The one place that afforded the most faculty/student interaction with respect to interpretation was in the lecture portions of each course, and so we examine how these two instructors specifically addressed interpretation during lecture.

A first analysis of lecture materials entails a coding of lecture slides (which were later posted on the course website). We employ a simple counting scheme by which each slide is assigned a point value of zero or one in each of three categories, according to its relevance to three interpretive themes. [Table 3.II] These three categories (denoted as *Light*, *Matter,* & *Contrasting Perspectives*) were chosen to highlight key lecture slides that were explicit in promoting non-classical perspectives. Since light is classically described as a wave, slides that emphasized its particle-like 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 (*Contrasting Perspectives* category) were those that addressed randomness, indeterminacy, or the probabilistic nature of quantum mechanics; or those that made explicit contrast between quantum results and what would be expected in a classical system. While most of the slides in Table 3.II received only one point in a single category, many slides were relevant to multiple categories, and so the point totals do not represent the total number of relevant slides from each course.

TABLE 3.II. Categorization of lecture slides relevant to promoting non-classical perspectives, with a point total for each category.

THEME	DESCRIPTION OF LECTURE SLIDE	B1	C
Light	Relevant to the dual wave/particle nature of light, or emphasizing its particle-like characteristics	15	9
Matter	Relevant to the dual wave/particle nature of matter, or emphasizing its wave-like characteristics	15	16
Contrasting Perspectives	Relevant to randomness, indeterminacy, or the probabilistic nature of quantum mechanics; explicit contrast between quantum & classical descriptions.	28	22

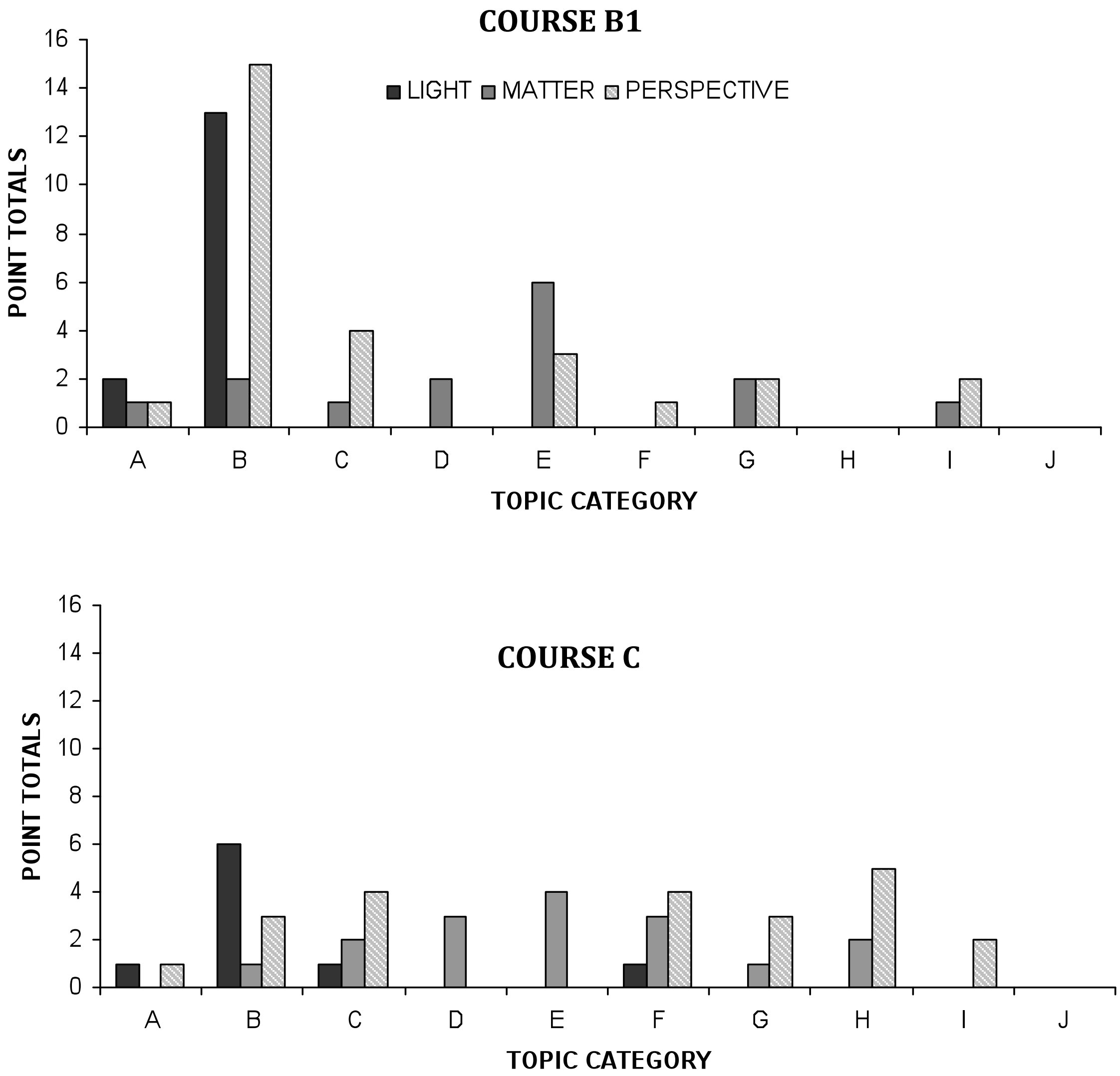


FIG. 3.5. The occurrence of lecture slides for both PHYS3 courses by topic (as describe in Table 3.I), for each of the themes described in Table 3.II.

Course B1 had a greater number of slides that scored in the *Light* and *Contrasting Perspectives* categories, though the graphs in Fig. 3.5 (which group the point totals for each course by topic area, as listed in Table 3.I) show that this difference can be largely attributed to instructor choices at the outset of the quantum physics sections of the two courses, in topic category B (photoelectric effect and photons). That this topic area should stand out in this analysis seems natural if one considers that: i) The photoelectric effect requires a particle description of light; ii) The double-slit experiment with single photons requires both a wave and a particle description of light in order to fully account for experimental observations; and iii) Being the first specific topic beyond the introductory quantum physics lecture(s), it represents an opportunity to frame the content of the course in terms of the need to think beyond classical physics. While both modern physics courses had the greatest point totals in this topic category, B1 devoted a greater portion of lecture time here to addressing themes of indeterminacy and probability (B1 also totaled more points in the *Light* category, though this difference can be largely attributed to Instructor B's brief coverage of lasers, a topic not covered in Course C).

Fig. 3.6 shows the ratio of the point totals for each of the three interpretive themes (from topic area B only) to the total number of slides used during these lectures; the differences between the two courses in terms of the amount of lecture time spent contrasting perspectives is statistically significant (p=0.001, by a one-tailed t-test). We note, finally, that in both courses all three of these interpretive themes received considerably less attention at later stages of the course.

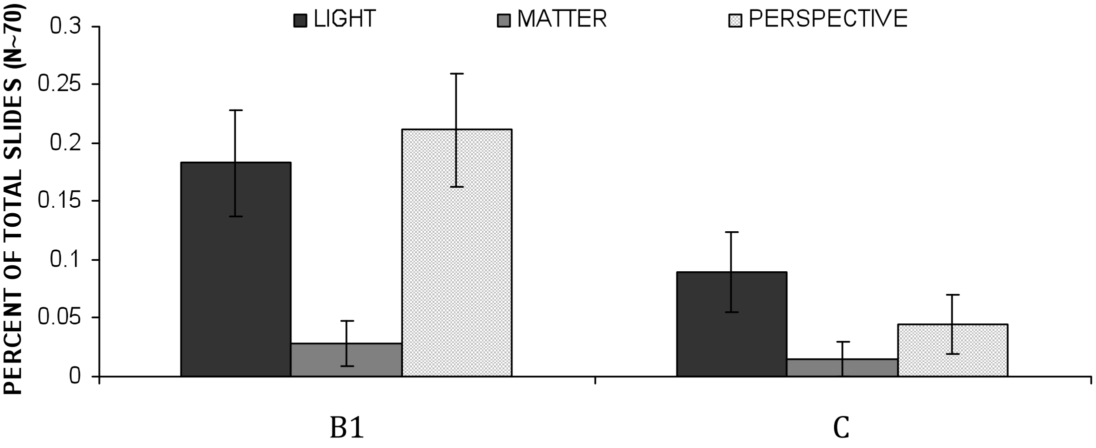
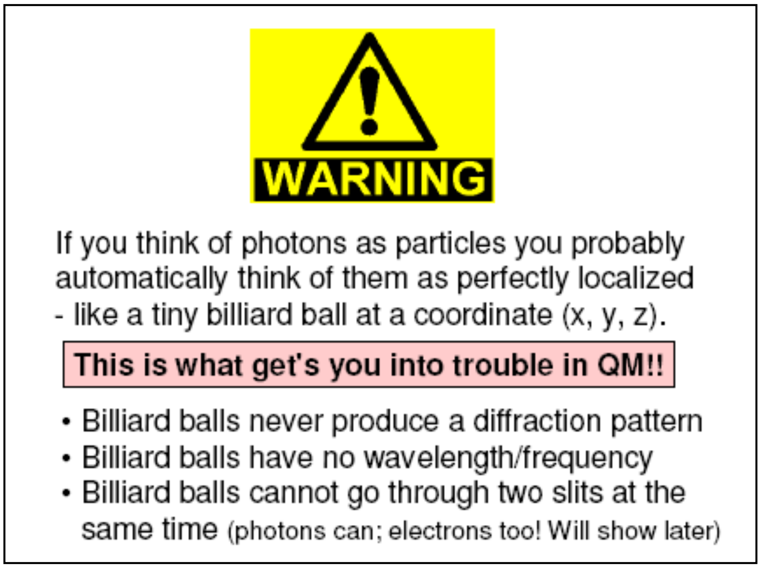


FIG. 3.6. Ratio of point totals from topic area B for each interpretive theme to the total number of slides used during these lectures. Error bars represent the standard error on the proportion.

The lecture slide shown in Fig. 3.7 is one example of how Course B1 differed from Course C in attending to student perspectives during the discussion of photons, by explicitly addressing the likelihood for students to think of quanta as being spatially localized. There were no comparable slides from Course C from this topic category, though this should not be taken to mean that Instructor C failed to address such issues at other times during the semester, or one-on-one with students. We note simply that there were no such explicit messages as part of the artifacts of the course in this topic area (which reflects a value judgment on the part of Instructor C regarding content), and students from Course C who accessed the lecture slides as posted online would have no indication that such ideas were deserving of any particular emphasis.



WARNING

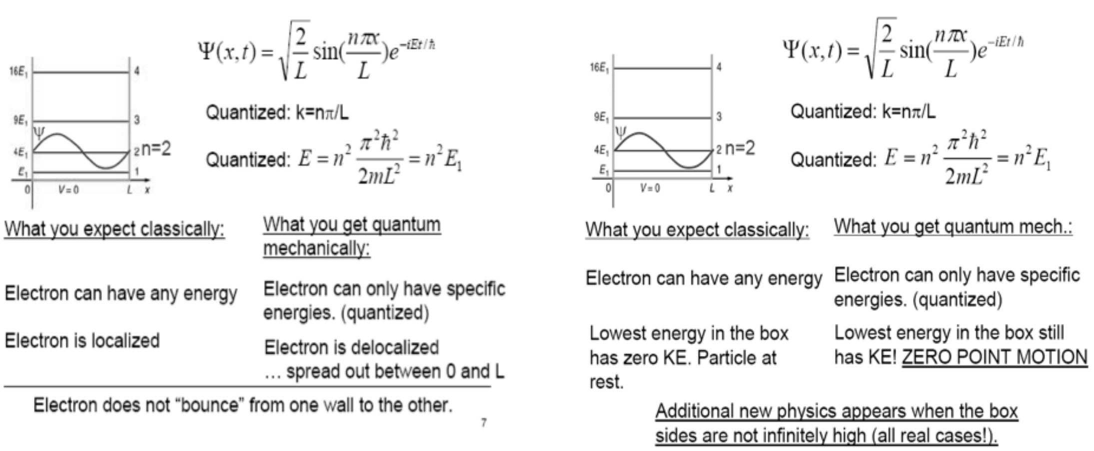
If you think of photons as particles you probably automatically think of them as perfectly localized - like a tiny billiard ball at a coordinate (x, y, z).

This is what get's you into trouble in QM!!

- Billiard balls never produce a diffraction pattern
- Billiard balls have no wavelength/frequency
- Billiard balls cannot go through two slits at the same time (photons can; electrons too! Will show later)

FIG. 3.7. A lecture slide used in Course B1 during the discussion of photons.

While there are coarse differences in how the instructors addressed student perspectives in some topic areas, the instructional approaches sometimes differed in more subtle ways. The two slides shown in Fig. 3.8 are illustrative of how the differences between the two courses could sometimes be less obvious, though still of potential significance. Both slides summarize the results for a system referred to in Course B1 as the *Infinite Square Well*, and by Instructor C as the *Particle in a Box*. At first glance, the two slides are almost identical: each depicts the first-excited state wave function of an electron in a potential well, as well as listing the normalized wave functions and quantized energy levels for this system. 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, whereas an electron confined in a potential well can only have specific energies.



$$\Psi(x,t)=\sqrt{\frac{2}{L}}\sin(\frac{n\pi x}{L})e^{-iEt/\hbar}$$

Quantized: k=nπ/L

Quantized: $E = n^2\frac{\pi^2\hbar^2}{2mL^2} = n^2E_1$

What you expect classically:	What you get quantum mechanically:
Electron can have any energy	Electron can only have specific energies. (quantized)
Electron is localized	Electron is delocalized … spread out between 0 and L

Electron does not "bounce" from one wall to the other.

7

$$\Psi(x,t)=\sqrt{\frac{2}{L}}\sin(\frac{n\pi x}{L})e^{-iEt/\hbar}$$

Quantized: k=nπ/L

Quantized: $E = n^2\frac{\pi^2\hbar^2}{2mL^2} = n^2E_1$

What you expect classically:	What you get quantum mech.:
Electron can have any energy	Electron can only have specific energies. (quantized)
Lowest energy in the box has zero KE. Particle at rest.	Lowest energy in the box still has KE! ZERO POINT MOTION

Additional new physics appears when the box sides are not infinitely high (all real cases!).

FIG. 3.8. Lecture slide from Course B1 (left, *Infinite Square Well*) and a nearly identical one from Course C (right, *Particle in a Box*).

However, Course B1 differed from Course C by emphasizing a wave model of the electron, delocalized and spread out, stating explicitly that the electron should not be thought of as bouncing back and forth between the two walls of the potential well. Instructor C 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 C's choice of language, to speak of a *particle* in a box exhibiting zero-point motion, could implicitly reinforce in students the *realist* notion that in this system a localized electron is bouncing back and forth between two potential barriers. Both of these slides received a point in the *Contrasting Perspectives* category, but only the slide from PHYS3A received a point in the *Matter* category for its emphasis on the wave-like properties of an electron in a potential well.

III.C. The double-slit experiment with single quanta.

As taught in these two courses, the double-slit experiment [Fig. 3.9] consists of a monochromatic beam of quanta that: (1) impinges on two closely spaced slits and diffracts; (2) wavelets spread out behind the slits and (3) interfere in the regions where they overlap; (4) bright fringes appear on the detection screen where the anti-nodal lines intersect.

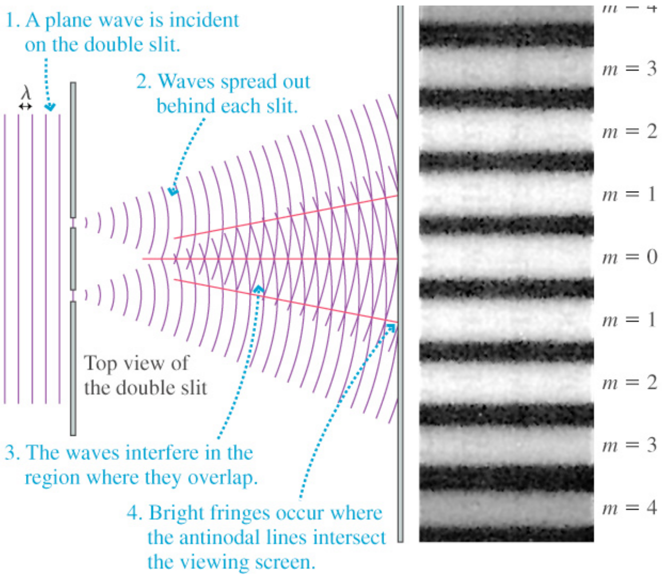


FIG. 3.9. Lecture slide used in both PHYS3 courses describing the double-slit experiment in terms of wave interference.

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 time. A wave description of quanta explains the interference pattern on the detection screen, while a particle description addresses the fact that individual quanta are detected as localized particles; in other words, a single ontological categorization of quanta (particle or wave) is inadequate for explaining all of what's observed in the double-slit experiment. Both instructors addressed during lecture a mathematical description of the interference pattern (how to relate the distance between the slits and the wavelength of the beam to the locations of fringe maxima and minima), and both used the Quantum Wave Interference simulation [5] in class to provide students with a visualization of the process. The approaches taken by the two instructors (B1 & C) with respect to quantum interpretation were as described in Section II; in brief, Instructor B took a *Matter-Wave* approach, while Instructor C was more *Agnostic* in his learning goals.

In the last week of the semester, students from both PHYS3 courses responded to an online survey designed to probe their ontological and epistemological beliefs about quantum mechanics. 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%. Students were also told they would only receive full credit for providing thoughtful answers, and the text of the survey itself emphasized in bold type that there were no *right* or *wrong* answers to the questions being asked, but that we were particularly interested in what the students personally believed.

Instructors for both courses vetted the wording of the items on the survey, and interviews conducted after the end of the semester [Chapter 4] indicate that students interpreted the meaning of the questions in a way that was consistent with our intent. [See Appendix A for the evolution of the survey items (SP08-FA10).]

At the time of this study, the wording of the fictional student statements in the double-slit essay question had been changed in order to better reflect the language and argumentation of actual students (crafted in part from actual student responses from the study described in Chapter 2):

> **Student One:** *The probability density is so large because we don't know the true position of the electron. Since only a single dot at a time appears on the detecting screen, the electron must have been a tiny particle, traveling somewhere inside that blob, so that the electron went through one slit or the other on its way to the point where it was detected.*
>
> **Student Two:** *The blob represents the electron itself, since an electron is described by 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. That's why a distinct interference pattern will show up on the screen after shooting many electrons.*
>
> **Student Three:** *Quantum mechanics is only about predicting the outcomes of measurements, so we really can't know anything about what the electron is doing between being emitted from the gun and being detected on the screen.*

The results for both PHYS3 courses (B1 and C) are shown in Fig. 3.3, where responses are categorized according to which fictional student(s) the respondents agreed with (*Realist*, *Matter-Wave*, or *Agnostic*). While most students chose to agree with only a single statement, there were a few respondents from both courses who chose to agree with both the fictional *Realist* and *Agnostic* students, or with both the *Matter-Wave* and *Agnostic* students; we feel the *Realist* and *Matter-Wave* statements are not individually incompatible with the *Agnostic* statement, since simultaneously agreeing with the latter allowed students to acknowledge that they had no way of actually knowing if their preferred interpretations were correct. The relatively few students (~5%) who responded in this way are grouped together with the other students in the *Realist* or *Matter-Wave* categories, as appropriate.

As might be predicted based on the specific practices of Instructor B, most of his students chose to agree with the *Matter-Wave* statement (the electron is a delocalized wave packet that interferes with itself). The responses from Course C students were more varied: they were nearly four times more likely than B1 students to prefer a *Realist* interpretation; similarly, they were half as likely to favor the wave-packet description. More specifically, 29% of Course C students chose to agree with the *Realist* statement of Student One, and 27% of them agreed with the *Copenhagen/Agnostic* stance of Student Three, while only a combined 11% of students from Course B chose either of these responses.

III.D. (In)consistency of student responses.

As seen in Fig. 3.5, both PHYS3 courses paid less explicit attention to student perspectives at later stages of instruction, as when covering the Schrödinger model of hydrogen. In lecture slides, both courses described an electron in the Schrödinger atomic model as a "cloud of probability surrounding the nucleus whose wave function is a solution of the Schrodinger equation," without further elaboration with respect to interpretation. We are interested in knowing if how students came to think of quanta in the context of the double-slit experiment would be relevant to how they thought of atomic electrons, particularly when they hadn't been given the same kind of explicit instruction in this topic area as with the double-slit experiment or the infinite square well.

In addition to the essay question, students responded (and provided reasoning) to the pre/post online survey statement regarding the position of atomic electrons; the following student quotes are illustrative of the reasoning offered by students in support of their responses:

> **AGREE**: "The probability cloud is like a graph method. It tells us where we are most likely to find the electron, but the electron is always a point-particle somewhere in the cloud."
>
> **DISAGREE**: "The electron is delocalized until we interfere with the system. It is distributed throughout the region where its wave function is non-zero. An electron only has a definite position when we make a measurement and collapse the wave function."

At the end of instruction, B1 students were just as likely to agree with the statement on atomic electrons as students from Course C, [Fig. 3.10] despite the emphasis given in Course B1 to thinking of an electron as delocalized in other contexts. Both courses showed a modest (and statistically insignificant) decrease in *Realist* responses to this statement between pre- and post-instruction, yet students from both courses were still more likely to agree than disagree with this statement in the end.

If responses from both courses to the statement on atomic electrons are grouped by how those same students responded to the double-slit essay question [Fig. 3.11] we see that 70% of students who preferred a *Realist* interpretation in the essay question took a stance on atomic electrons that would also be consistent with *realist* expectations. And while students who preferred a wave-packet description in the essay question were more likely than *Realist* category students to disagree with the statement on atomic electrons, 46% of those students still agreed that an electron in an atom has a definite position at all times. Only in the case of students who preferred the *Agnostic* statement did a majority disagree with this statement, and no students from this group responded neutrally.

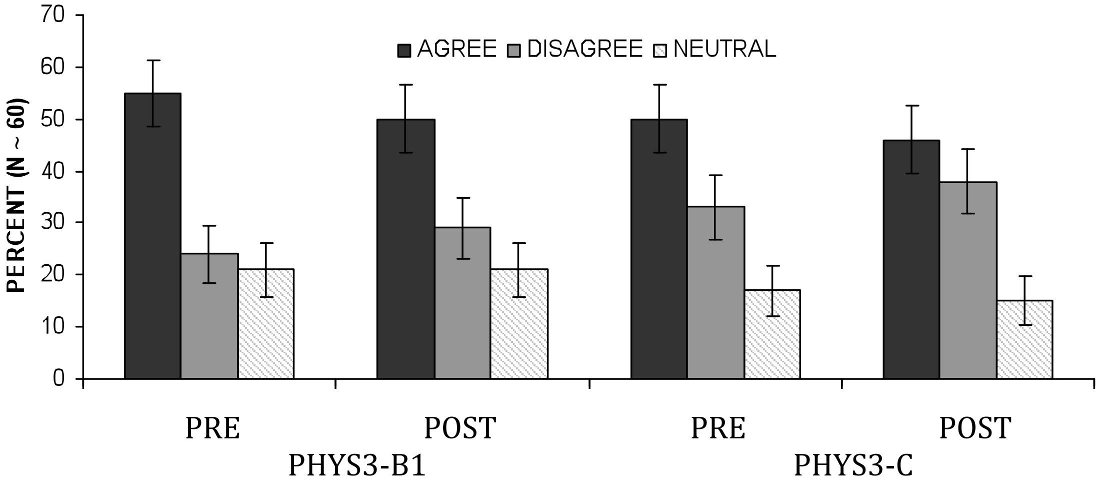


FIG. 3.10. Pre/post student responses from both PHYS3 courses to the statement: *An electron in an atom has a definite but unknown position at each moment of time.* Error bars represent the standard error on the proportion (N~60).

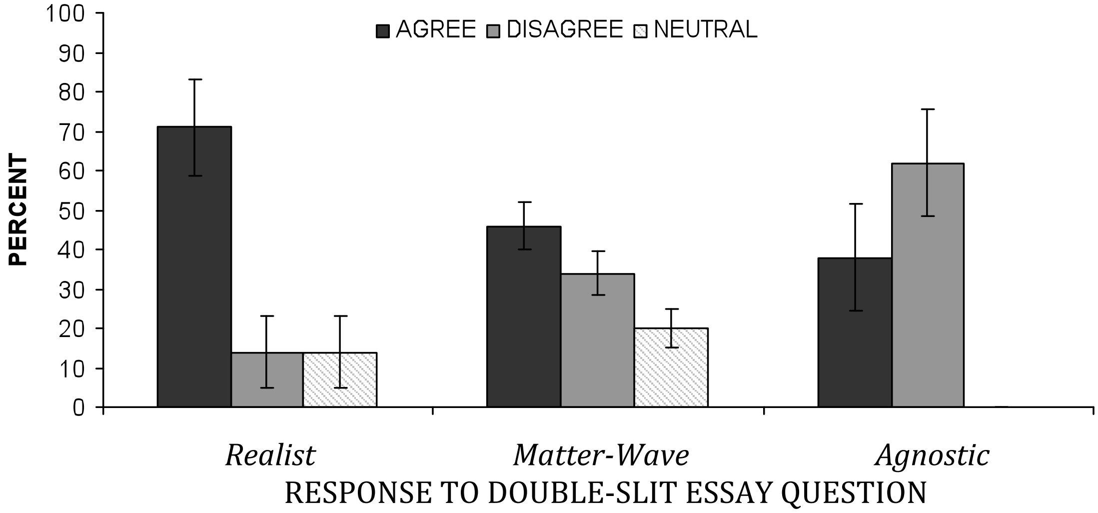


FIG. 3.11. Combined student responses from both PHYS3 courses to the statement: *An electron in an atom has a definite but unknown position at each moment of time*, grouped by how those students responded to the double-slit essay question. Error bars represent the standard error on the proportion (N~60).

IV. Summary and Discussion

Modern physics instructors differ not only in their personal perspectives regarding the physical interpretation of quantum mechanics, but also in their decisions to teach (or not teach) about quantum interpretations in their introductory courses. In this chapter, we have documented significant instructor effects in terms of how students respond to post-instruction surveys; we have also examined in detail two different approaches to addressing interpretative themes in two introductory modern physics courses with similar content.

When comparing these two courses in detail, Instructor B's more explicit approach to teaching a *matter-wave* interpretation of the double-slit experiment had a significant impact on how students said they thought of electrons within that specific context. Instructor C's less explicit and more *Agnostic* instructional approach is reflected in the greater variation of student responses to the essay question; not only were Course C students more likely than B1 students to prefer an *Agnostic* stance (which would be in alignment with Instructor C's instructional approach), these students were also more likely to align themselves with a *Realist* interpretation. In addition, the emphasis given in Course B toward thinking of electrons as delocalized in the double-slit experiment and the infinite square well had no discernible impact on student responses in areas where instruction was less explicit. Both courses were similar in their treatment of the Schrödinger atomic model, and student responses from both courses regarding the existence of an electron's position in an atom were not significantly different, with the majority of students from both courses favoring a *Realist* perspective in this specific context.

We may investigate the consistency in how students apply perspectives across contexts by comparing responses to the double-slit essay question with a statement regarding the position of an electron in an atom. 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, almost half of the students who preferred the wave-packet description of a single electron in the double-slit experiment would still agree with particle-like descriptions of atomic electrons. Such responses evidence the greater likelihood for students to favor *Realist* perspectives in topic areas where instruction is less explicit, and suggest that instructors who wish to promote any particular perspective in quantum physics should do so explicitly across a range of topics, rather than assuming it to be sufficient to address student perspectives primarily at the outset.

These findings also indicate that, just as with topics in classical physics, [6-14] naïve intuition (being congruent with *realist* expectations) can serve as a barrier to conceptual understanding in quantum physics. A major difference between the intuitive barriers in classical physics and in quantum physics lies in the nature of the questions, both ontological (when is a particle a particle, and when is it a wave?) and epistemic (what is the difference between classical ignorance and fundamental uncertainty?). End-of-semester comments from Instructor C support the notion that students who preferred a *Realist* interpretation of the double-slit experiment were not doing so from a simple lack of understanding:

> "Some of the students who I considered to be the most engaged went with [the *Realist* statement. They said]: '…the electron is a real thing; it's got to be in there somehow. I know that's not what you told us, but that's what I'm thinking…' I thought that was just great; it was sort of honest. They were willing to recognize that that's not what we're saying, but they're grappling with that's how it's got to be anyways."

Furthermore, one-on-one interviews conducted with students from these two courses following the end of the semester [Chapter 4] showed that those who had favored a *Realist* perspective in the interference essay question were still able to correctly describe from memory the particulars of the double-slit experiment.

It is also worth noting that the two instructors considered in our detailed comparative study, while sometimes explicit in teaching *an* interpretation of quantum mechanics, were not explicit in teaching these interpretations *as interpretations*. In other words, they did not teach quantum mechanics from an axiomatic standpoint, did not explicitly teach the *Copenhagen Interpretation* (or any other formal interpretation); nor did they frame their interpretations in terms of *modeling,* or *nature of science* (NOS) issues. Instead, instructors for both courses addressed questions of interpretation as they arose within the contexts of specific topics, without making the physical interpretation of the wave function (beyond its probabilistic interpretation, à la Born [15]) into a major topic unto itself. The sense in which quantum interpretation is *hidden* in modern physics curricula becomes apparent when considering how students may default to intuitive *realist* expectations in topic areas where instructors are less explicit; and in recognizing that interpretive aspects of quantum physics tend to remain unaddressed in a way that is meaningful to students.

The studies considered in this chapter suggest that instructors should be aware of the potential impact they may have on student thinking as a consequence of their instructional choices – instructors who spend less time explicitly attending to student knowledge and intuition are less likely to transition students away from inappropriately *realist* perspectives. These studies have also indicated that students may favor a variety of perspectives in a way that may seem contradictory to expert physicists, indicating the need for a deeper exploration into the contextual aspects of student perspectives in quantum physics. [Chapter 4]

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