

# Faculty Disagreement about the Teaching of Quantum Mechanics

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**Abstract.** To guide research-based transformation of upper-division physics classes, it is useful to identify learning goals that are broadly supported by the faculty. Our efforts to transform our junior-level E&M course have revealed a broad faculty consensus on the content of the course, if not the pedagogical approach. In contrast, we find a range of opinions on both the content and the pedagogy in junior-level QM. We surveyed 27 faculty about their approaches to teaching QM, and reviewed 20 quantum textbooks. Although there is broad agreement on the list and order of topics (Schrödinger equation to matrix methods and spin), we find substantial disagreement in several pedagogical aspects, including (1) the importance of presenting QM on an axiomatic basis (i.e. the postulates); (2) the treatment of measurement in QM (in particular, the collapse of the wave function); and (3) the physical interpretation of the wave function (matter wave vs. information wave vs. something else).

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## INTRODUCTION

Our department at the University of Colorado at Boulder (CU) is engaged in a substantial effort to transform our junior-level Electricity and Magnetism (E&M) and Quantum Mechanics (QM) courses, making them more interactive, with clicker questions, peer instruction, white-board activities, and group-work tutorials [1, 2]. An important step in this process is to specify the learning goals through faculty discussions and consensus [3]. In conversations with our faculty and from a previous study [4], it became clear that, although there is a consensus about the content of E&M, there are a wide variety of opinions about both content and pedagogy in junior-level QM. In an effort to gauge the range of opinions, we developed a survey about the teaching of junior-level QM, and questioned 27 physics faculty (22 from CU and 5 from other schools). At CU, we teach a two-semester junior/senior QM sequence, but the faculty were asked specifically about 1<sup>st</sup> semester, which introduces most of the fundamental concepts of QM.

Interviews were conducted in person for CU faculty and by phone for non-CU faculty. We also examined 20 QM textbooks [5] — both those in current use and those used by the faculty when they were undergraduates — with an eye toward specific

features (described below) which may have influenced faculty opinions.

All 27 faculty interviewed have used quantum mechanics in their research. 16 are theorists; 11 are experimentalists. Faculty ages ranged from mid-thirties to late seventies. All have taught QM courses at some level (sophomore, junior, and/or grad). Eight of the faculty have not yet taught QM at the junior-level, but will teach at this level in the future. Almost all of the CU faculty in the pool to teach junior-level QM (JQM) were interviewed, including one Nobel Prize winner.

Several faculty expressed the view that JQM holds a special place in the physics undergraduate curriculum: it is the most challenging course because students encounter both extreme conceptual difficulties and several new mathematical tools. It is the first course in which the student's classical intuition is often misleading. Some faculty expressed deep pessimism about the achievement of learning goals, a view supported by some research [6]. One of the faculty interviewed said, "The first two encounters between a student and quantum mechanics are completely elastic." Our goal in this study was to elicit faculty views that might inform our efforts to improve this situation.

We present here the most surprising results from our survey of faculty and textbooks. While we find a

growing consensus on textbook use, we find considerable disagreement on three fundamental issues: the postulates, measurement, and the interpretation of the wavefunction.

## TEXTBOOK USE

We asked faculty which textbook they used when they were taught JQM as undergraduates, and found that in the past (~1955 to ~1995), no single textbook dominated the market. 5 of the faculty were taught from Gasiorowicz, 1<sup>st</sup> ed.[7], 4 were taught from lecture notes only, and the remaining 17 faculty used a total of 12 different texts, ranging in difficulty from French & Taylor to Dirac(!).

The textbook situation has changed significantly in the last decade or so. We find that Griffiths' text[8] now dominates the market. We surveyed 68 other institutions (either by contacting the bookstore or by finding current course websites) and found that 44 of those schools (65%) currently use Griffiths. Among the 27 faculty we interviewed, 17 (63%) use or plan to use Griffiths (5 were undecided, 5 use a different text, and 2 use no text). Despite the popularity of this text, we have observed that those faculty using Griffiths seldom follow it closely and rely heavily on their own notes.

## POSTULATES OR NOT?

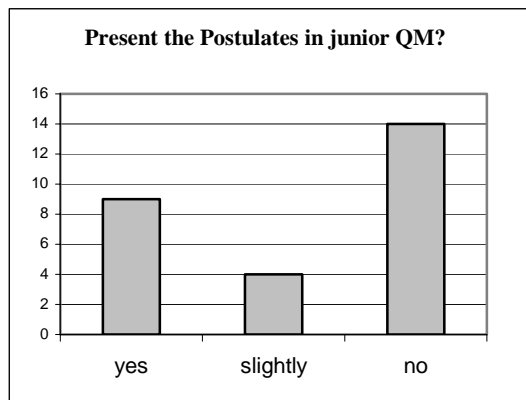
Among faculty and among textbooks, we find a split over the importance of presenting the formal Postulates of QM in teaching JQM.

We asked faculty the following question: "Some textbooks clearly state the Postulates of QM[9], and make some effort to present QM on an axiomatic basis (the way we teach E&M with Maxwell's Equations), but most texts, such as Griffiths, have a more relaxed attitude: they never clearly state the Postulates and make little or no effort to present QM on an axiomatic basis. What is your opinion about the importance of presenting the Postulates in a junior-level course? "

Faculty were divided on this issue, with a slight majority opposed to presenting the Postulates (Figure 1). Four faculty were in an intermediate category because they give brief mention to the Postulates (in one or two lectures) and do not integrate them into the course.

The available textbooks reflect the faculty split. 12 of the 20 books (60%) we examined do not list the Postulates of QM anywhere. Although the texts may contain statements which convey the content of the Postulates, unless the author labels the statements as Postulates or Axioms or informs the reader of the

special status of these assumptions, then we place the book in the No-Postulates category.



**FIGURE 1.** 27 faculty were asked if they would emphasize the Postulates of QM when teaching junior-level QM.

Faculty expressed strong opinions on both sides of this debate. Those in favor of presenting the Postulates argued that students must be clearly informed about which statements must be accepted without proof, based on experimental evidence, and which statements can be derived from more fundamental statements. They argued that students need the framework provided by the Postulates in order to view QM as a coherent structure. Those against the axiomatic approach argued either that (1) the axiomatic approach is misleading, i.e. QM is too complex to be properly axiomatized or (2) the axiomatic approach is not pedagogically useful at this level; few undergrad students can appreciate the axioms and it gets in the way of teaching computational skills.

## WAVEFUNCTION COLLAPSE OR NOT?

One or two of the Postulates of QM describe "measurement". The content of the Measurement Postulates can be encapsulated in two statements:

I. The result of a measurement of observable A will be one of the eigenvalues of the operator  $\hat{A}$ , and the particular eigenvalue  $a$  will be found with probability

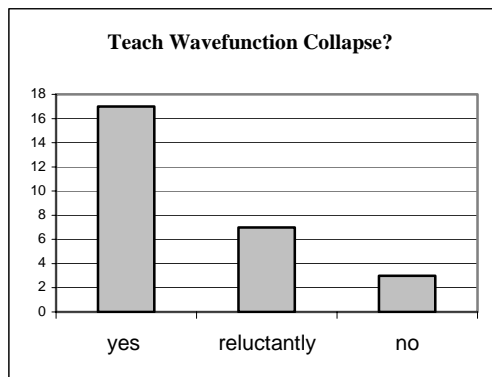
$$\Pr(a) = |\langle a | \psi \rangle|^2$$

II. As a result of the measurement, the wavefunction will "collapse" and become the eigenstate corresponding to the observed eigenvalue

$$|\psi\rangle \rightarrow |a\rangle$$

None of the faculty and none of the textbooks we examined had any issue with statement I. However, many physicists regard statement II as problematic. We asked faculty how much emphasis should be given to the concept of measurement in JQM in general, and

how they would treat the wavefunction collapse (WFC) in particular. The results are shown in Figure 2.



**FIGURE 2.** Most faculty teach the wavefunction collapse, but many do so with some reluctance.

Three of the faculty stated that they would either not mention or only briefly mention the collapse of the wavefunction in JQM. The remaining 24 faculty agreed the WFC was an essential part of QM and needed to be taught and emphasized in the course. However, of these 24, seven stated that they are deeply troubled by the idea of WFC. They suspect that it is "wrong" or "incomplete" on some level, and consequently teach it with some unease. These unsatisfied faculty had thoughtful comments including:

- "This is a pragmatic response to a deep mystery that no one understands."
- "This is the price we pay for pretending that a single particle can exist in an unentangled state."
- "The collapse postulate is implausible; I don't like it. But the coherent story is not there for me if you take it out of QM."
- "I myself am unsure whether the collapse postulate is part of the formal structure of QM. The collapse refers to an ideal quantum measurement that cannot be realized in practice."
- "This can't really be right, because we believe the universe undergoes unitary evolution. So this acausal collapse behavior must be a tentative stand-in for some deeper understanding which we hope will come when we can deal with large numbers of entangled particles. But we have to adopt this view, because it works."

This reluctance to accept the WFC is even more pronounced among QM textbooks. Although Griffiths' text has a careful treatment of WFC, this is not the norm. Six of the 20 texts (30%) that we reviewed contained no clear treatment or no mention of the WFC. Another 8 texts (40%) make only brief, passing mention of WFC, with no equations and/or no homework exercises. Only 6 of the 20 textbooks (30%) contained what we regard as a clear, thorough

treatment of WFC, with enough emphasis that students are likely to appreciate the topic.

How is it possible to teach JQM without mentioning the collapse of the wavefunction? The WFC can be avoided if one only considers single measurements and refrains from mentioning repeated measurements on the same system. This is not entirely unreasonable, since most experiments in the lab are one-time destructive measurements; the particle hits the detector and is then no longer accessible. In such cases, the WFC is not relevant.

This is a rather strange state of affairs. We know of no other case where so many textbooks avoid a topic which is considered fundamental by most physicists.

## INTERPRETATION OF THE WAVFUNCTION

Books have been written about the meaning of the wavefunction (the "state"  $|\psi\rangle$ ), and there is no strong consensus on the issue, so we asked the faculty how they present the physical interpretation of the wavefunction to their students in JQM. In particular, we asked them to choose one of the following two interpretations or to describe an alternative view.

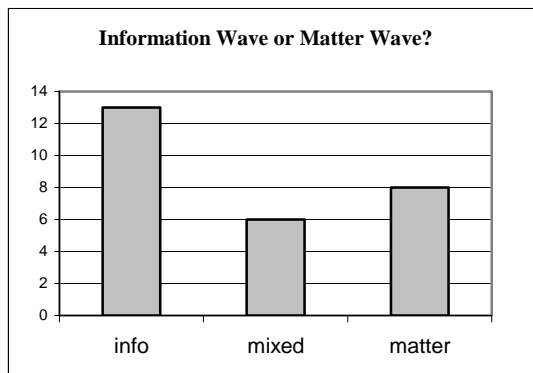
I: Information Wave interpretation: the wave function of a quantum system is a mathematical object which provides information only about the results of measurement, i.e. the interaction between the quantum system and a macroscopic measuring apparatus. In this view, it makes little or no sense to talk about what the quantum system is "doing" in the absence of measurement. The wave function does not describe the system itself, rather it describes the possible results of interactions of the system with the outside world.

II. Matter wave interpretation: the wave function of a quantum system describes the system itself. A matter wave proponent ascribes some kind of physical reality to the wavefunction and would have no problem saying something like "The electron went through both slits."

The wording of the first choice (choice I) was crafted to describe the standard Born Interpretation, for which Born received the 1954 Nobel prize, although this label was not mentioned in the interview. We did not attempt to extract the textbook views on this issue, because we found that few of the texts had any discussion clear enough to interpret.

As shown in Figure 3, faculty are split over this issue (as are the authors of this paper). 13 of the 27 faculty (48%) were in the information wave camp, but 8 (30%) clearly held the matter wave view. 6 others were placed in a "mixed" category, because their statements mixed both views, with no clear leaning

either way, or they stated that they saw little or no distinction between the choices.



**FIGURE 3.** Faculty are split on the interpretation of the wavefunction as an information wave or a matter wave.

This question elicited many thoughtful comments, including the following, all from distinguished theorists:

- "I lean toward the matter wave interpretation. I am partial to ascribing physical meaning to the wavefunction."
- "Well, the matter wave view is wrong."
- "If pressed, I choose the info wave interpretation. But when I talk about the wavefunction, I talk like I believed in matter waves. In fact, I don't care, because it has no effect on the things I calculate."

Of the 20 faculty who expressed a clear preference between choices I and II, only 9 expressed confidence in their attitude and were of the opinion that the other view was probably wrong.

## CONCLUSIONS

In the last half of the 20<sup>th</sup> century, no single undergraduate quantum textbook was widely used. But in the last decade, Griffiths' text has come to dominate the market. One might expect that when a single textbook is widely used, there will be a consensus on course content and learning goals. However, we find considerable disagreement among the faculty on several important issues including the postulates, measurement, and wavefunction interpretation.

Our conclusion is that junior-level QM has a doubly special status. Not only is it the most difficult course for the students, but it is also the most difficult course for the faculty. Quantum Mechanics is a living, evolving field. The community is still working toward a consensus on issues in both pedagogy and fundamental physics. Our survey results highlight the difficulty of identifying consensus learning goals, but also present an opportunity for addressing nature-of-science issues in the classroom.

We suggest that it is important that our students be aware of the debate among the faculty and that faculty should consider presenting the multiple views held by physicists, even if they personally disagree with those views.

David Griffiths (who was one of those interviewed [10]) eloquently expressed this unique situation in the undergraduate curriculum: "Quantum Mechanics is not a finished system, I think. So it is healthy that there are diverse ways of teaching it. I think it would be a catastrophe if everyone taught it the same way."

## ACKNOWLEDGMENTS

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