Characterization of upper-level undergraduate quantum mechanics courses in the U.S.

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Upper-level, undergraduate quantum mechanics (QM) is widely considered a difficult subject with many varied approaches to teaching it and considerable variation in content coverage. For example, two common approaches to undergraduate QM instruction are a spins-first approach, which focuses on the postulates of QM in spin systems before discussing wave functions, and a wave functions-first approach, which focuses on the Schrödinger equation and its solutions for continuous functions in various potentials before discussing spin. These different approaches, along with the content variability in the textbooks used by instructors, may mean students learn different things in QM classes across the United States (U.S.). In this paper, we offer a characterization of QM courses based on survey responses from instructors at institutions across the U.S. With the responses of 76 instructors teaching QM courses (or sequences), we present results detailing their teaching methodologies, use of pedagogical resources, and coverage of QM topics. We find that the plurality of instructors in our sample are using traditional lecture, but many instructors are using interactive lecture or another nontraditional method. Additionally, instructors are using a wide variety of pedagogical tools (e.g., clicker questions). Many instructors in our sample reported teaching single-semester (or single-quarter) QM courses; these instructors report similar content coverage to instructors teaching first-semester (or first-quarter) QM courses, though their responses showed greater variability. We additionally report a comparison of content coverage between instructors using wave functions-first vs spins-first approaches, finding a large degree of overlap with differences in coverage for a few specific topics. These findings can help inform both future research and instructional efforts in QM education.

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I. INTRODUCTION

While quantum mechanics (QM) education has been a core part of the physics curriculum for many decades, it has recently been highlighted as an area of increased national attention due to the rise of quantum information science (QIS). Governments around the world have funneled significant funding into developing QIS technologies such as novel quantum sensors with the potential to unlock new regimes of discovery, and quantum information processors that lay the foundation for realizing scalable quantum computation [1,2]. In the context of this increased attention, there is now a unique opportunity, and perhaps responsibility, for the physics education research (PER) community to reflect on the status of QM education at the undergraduate level to ensure we are preparing both a quantum-literate citizenry and a quantum-ready workforce to support the growing quantum industry [3]. In this manuscript, we endeavor to characterize the current state of upper-level, undergraduate QM education in the United States (U.S.) as a first step toward enabling this reflection.

Previous studies have shown that QM education varies both in what is taught and the methods and perspectives used by instructors [4–6]. One reflection of this variation is the variety of textbooks available for instruction [7–11], though it has historically been unclear how many of these texts are widely used. Another reflection of this variation is the number of distinct QM research-based assessments (RBAs) that have been created to assess learning in these courses, each with different content and emphases [12]. There currently exist six upper-level QM RBAs [13–18] covering topics that are commonly seen in a first-semester, upper-level QM course[1] (QM1), though typical second-semester QM (QM2) topics are largely missing.

Historically, both curriculum and assessment developers in PER have dealt with the issue of variable content coverage by focusing their efforts primarily on the core topics included in all or most courses in a particular core content area. However, a potentially more authentic

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[1]As will be discussed in the Sec. III, here we exclusively focus on upper-level quantum courses, which explicitly exclude lower- and middle-division courses, such as modern physics or dedicated Introductory QIS courses.

approach could be to build materials that accommodate the variety of topical areas covered in an instructor's course. The work reported here is part of a broader effort to fill this gap for quantum assessments, in particular. While this manuscript will not focus on the application of our findings to assessment development, our broader goal of developing a novel QM assessment influenced our methodological choices in meaningful ways (see Sec. III). In particular, a crucial step in both creating our new assessment and developing curricular materials to span the full space of QM content coverage is to understand which topics are actually covered in quantum courses and with what consistency.

This paper focuses broadly on characterizing the current state of upper-level, undergraduate QM courses in the U.S. We designed our methods and analysis to provide a comprehensive snapshot of QM education in the U.S. that will be useful both to inform instructors about common instructional practices (e.g., to promote appropriate expectations regarding the content knowledge of incoming graduate students) and to support the development of curricular materials to target important topics without existing research-based curricula. Specifically, we utilized both interviews with faculty who have taught QM courses and faculty responses to a larger scale survey. In the interviews, faculty were asked to discuss their experiences teaching QM, including the topics covered, textbooks used, and pedagogical approaches. The results of the interviews informed the creation of the survey, which was distributed to physics departments across the U.S. The survey results provide detailed information about instructors' topical coverage, textbook usage, teaching methodologies, use of pedagogical resources, and more.

The remainder of this paper is organized as follows. In Sec. II, we discuss the literature around instruction and content coverage in quantum mechanics and how it relates to and motivates this study. Following this, Sec. III outlines the methods used to design and analyze the interviews and survey and describes some of the limitations of this work. Section IV lays out key findings and implications of this work. Finally, Sec. VI discusses conclusions and future work.

II. BACKGROUND: SCOPE OF QUANTUM MECHANICS INSTRUCTION

There is a large and robust body of research around students' understanding of, or difficulties with, quantum mechanics [19–23]. However, studies investigating the scope of content coverage in quantum mechanics are less common, despite the fact that investigations of faculty consensus regarding content coverage in core physics courses has a long history in PER [24–26]. These studies typically include a combination of interviews and survey responses from instructors teaching courses relevant to the content area in question [27]. This type of domain analysis is particularly crucial in the context of QM education because the field is both very broad—meaning instructors often make choices with respect to what they want to include or focus on—and rapidly changing—particularly with the recent rise of QIS as an area of national focus. Understanding the nature of both what is covered in these courses and with what emphasis is a critical component of ensuring that the development of educational tools is based on robust information on the needs and priorities of the people using those tools [24,28].

The earliest attempt to document the content of a QM1 course was provided by Dubson *et al.* [4]. In this work, the authors interviewed 27 faculty from 6 institutions regarding their teaching methodology and surveyed 20 QM textbooks. They found significant agreement on the list and order of topics but disagreement over the importance of certain key topical areas, such as the QM postulates, the treatment of measurement, and the physical interpretation of the wave function. The results of this work suggest that, historically, there was significant consensus (at least as reflected by presentation in textbooks) in the full topical coverage of QM courses, but perhaps less consensus in ordering and emphasis. However, nearly all of these texts largely introduced the learner to QM by first defining the wave function and laying out the postulates of quantum mechanics in the position basis; this approach is now referred to as "wave functions-first." Since this publication, the landscape of traditional QM education has changed considerably. Townsend, inspired by the work of Feynman *et al.* [29] and Sakurai and Napolitano [30], was the first to write an undergraduate quantum mechanics textbook that began by introducing the quantum postulates using spin systems, rather than wave mechanics [9]. In 2012, McIntyre introduced another "spins-first" quantum mechanics textbook targeting undergraduate students, which follows a similar progression of topics [8]. Certain institutions have reported adopting spins-first approaches; however, it remains unclear how widespread this adoption is, as well as the prevalence with which the various spins-first textbooks are used (see Sec. IV). This fundamental difference in how QM is taught (spins first vs wave functions first) has sparked debate over which method is more effective at producing learning gains [31,32]. Additionally, the explosion of QIS has introduced an entirely new area of focus to what might be taught or emphasized in QM courses [26].

Concerns about continued consensus on QM topics have also been supported via more recent studies in this area. Siddiqui and Singh [5] made the claim in 2017 that "there is no widespread agreement on the essential topics to teach in the college undergraduate QM course for physics majors, the order in which those topics should be taught, and the amount of time that should be spent on various topics." In this study, the authors surveyed 12 faculty members, 6 from the same institution and 6 from different institutions, about various aspects of teaching QM courses, including the goals of a QM course, the order of topics (e.g., wave

functions vs spins first), and challenges faced when teaching QM. They found that QM instructors often had similar goals for an undergraduate QM course, but there were important differences of opinion on how to engage students, the order of topics, which topics they included in their course, and what level of emphasis should be placed on these topics. The results presented in this paper build on Siddiqui and Singh's [5] work by reporting results from a larger, more diverse respondent pool, as well as by asking additional questions regarding prerequisites, pedagogical resources used, and details of content coverage.

Another approach to analyzing the status of QM education was recently presented by Buzzell *et al.* [6]. In this work, they analyzed the course catalogs of 188 U.S. research intensive institutions of higher education to assess the role of QM courses in the undergraduate curriculum. The institutions were selected from the U.S. News Rankings of "The Best Physics Programs" [33]. They found every institution surveyed required at least one course on quantum concepts, 92% required two courses, and 50% required three courses. The authors of this study also found that around 74% of instructors used a wave functions-first approach rather than a spins-first approach. The prevalence of the wave functions-first approach is consistent with the findings of this paper (see Sec. IV).

Our work complements that of Buzzell *et al.* by addressing the question of content coverage in QM courses with a different methodological approach and finer granularity in topical coverage. For a subset of the courses in their dataset, Buzzell *et al.* [6] utilized analysis of course catalogs and syllabi to determine which topics were covered in those courses, whereas our approach directly compiles instructors' perspectives on their teaching of upper-level QM courses via interviews and surveys. Both of these approaches have methodological limitations, such as selection effects (e.g., instructors select whether to respond to a survey or interview request) and data fidelity (e.g., not all instructors include enough information in a syllabus to allow for fine-grained information on their content coverage); however, we believe that together, these two studies have the potential to provide a more comprehensive view on QM education.[2] Throughout our analysis and results, we will provide comparisons between our findings and those of Buzzell *et al.* [6].

III. METHODS

In this study, we employed an iterative, mixed methods research design that consisted of interviews followed by a broadly distributed survey. We also examined publicly available course catalogs for all institutions for which we received responses to our survey. In this section, we will articulate the relevant portions of the interview and survey design, respondent demographics, and limitations of these methodologies.

A. Interview methodology

The majority of the results presented here will pull from the survey described in the next section; however, the design of this survey was based on an extensive interview study. Here, we provide a brief summary of the interviews and participants to frame the survey design and methodology. To solicit participants for the interviews, we compiled contact information for physics departments in the U.S. that offered a QM course ($N = 470$). No institutions were excluded unless we could not find contact information available online or they explicitly did not require any QM courses in their curriculum. In our email solicitation, we asked for faculty who had taught: modern physics; graduate-level QM; graduate or undergraduate quantum information or quantum computation; and/or upper-level undergraduate QM to participate.[3] Overall, 34 faculty participated in interviews. Of our participants, 28 reported having taught upper-level undergraduate QM, 4 had taught modern physics, 2 had taught graduate QM, and 2 had taught a quantum information course (2 instructors had taught two different courses). The 34 interview participants represented faculty from 33 unique institutions.

The interviews were semistructured and each lasted approximately an hour. They consisted of two primary components. The first component, focusing on the instructor's interaction with an assessment creation interface, was the subject of a previous publication [34]. The second component targeted the instructor's experience teaching QM and asked them to identify what from a list of QM topics they would teach and assess in their class. This list of topics was initially generated by the authors but was updated and added to by instructors in each interview. The interview data (including this finalized list of topics) were then used to inform the design of a corresponding survey. Beyond the use of the interview data to inform the survey development, the results in Sec. IV will not include direct analysis of the interview data.

B. Survey design

The purpose of the survey was to solicit information from a broader array of faculty at U.S. institutions offering at least one upper-level, undergraduate QM course. Specifically, we aimed to identify instructors' teaching methodology and the topical areas they consider important, peripheral,

[2]Note that Buzzell *et al.* included modern physics courses among their dataset, whereas we focus only on upper-division QM courses beyond the level of modern physics.

[3]While this analysis is focused on undergraduate QM, we initially solicited participation from faculty members who had taught courses that may have some overlap with undergraduate QM. Including such faculty in our interviews ensured we were not overly restrictive in our scope. The survey results, however, are focused specifically on undergraduate QM.

or extraneous. The complete survey, with all available responses, can be found in Appendix B (Fig. 7). Here, we will cover the aspects of the survey structure necessary to understand and interpret the results. The survey consists of four primary categories: institutional information, course-level data, topical coverage, and optional demographics.

Institutional information: The survey first asked instructors to provide the name of their institution to facilitate later analysis of publicly available course catalogs for information such as prerequisites. Instructors were also asked if their institution follows a semester or quarter system; this information, while available after the fact via online search, was necessary within the survey to facilitate conditional logic on later questions. Of the 76 instructors who responded to our survey, 68 taught at semester-based institutions and 8 taught at quarter-based institutions, suggesting that our results are primarily reflective of semester-based institutions.

Course-level data: Instructors were first asked which upper-level undergraduate QM courses they had taught in the previous 5 years, with slightly different options available for instructors at semester- and quarter-based institutions. Instructors had the option to select multiple courses; however, they only filled out the rest of the survey once (i.e., for instructors who had taught multiple courses, their responses are not differentiated by course). While this presents certain limitations, which will be discussed below, our priority was to limit survey fatigue and maximize the number of complete responses. Instructors were then asked a series of questions about the course(s) they had selected, regarding textbook usage and order of content coverage, teaching style, class size, and changes in teaching due to the COVID-19 pandemic.

Topical coverage: The instructors were then asked about the topical coverage in the QM courses they had taught. They selected topics from a list of 84 topics that were generated via textbook review and revised by instructors in the interviews. The 84 topics were split into five pages to reduce cognitive load. For each of these topics, we presented them with four response options for their level of coverage: *important*, *peripheral*, *assumed prior knowledge*, and *do not cover/use*.[4] At the beginning of each page, we provided them with the following operational definition of these categories:

- *Important*: You teach this topic in depth and assess students' comprehension and retention of it.
- *Peripheral*: You teach this topic but not in depth. That could mean mentioning it in passing or covering it for part of a lecture. It is also something not directly assessed.
- *Assumed prior knowledge*: You do not teach this topic, but you use it, assuming prior knowledge or exposure from your students.
- *Do not cover/use*: You do not teach or use this topic in your class.

Respondents were also provided an opportunity to report any topics missing from our list. Topics specific to QIS were addressed in a prior publication (Ref. [26]) and, thus, were not included in our provided list of topics (with the notable exceptions of the foundational topics of entanglement, measurement, and superposition, which feature prominently in our list).

It is worth reflecting on the overlap between the topics generated by Buzzell *et al.* [6] and those included in our list. As our list was designed to be as comprehensive as possible while theirs was generated from thematic analysis of syllabi, we do not expect complete agreement between the lists. Indeed, we expect that our list will include a number of less common topics that likely would not appear in analysis of syllabi; however, it is valuable to note the degree of overlap, particularly with respect to any topics that might be missing from our list. Buzzell *et al.* [6] generated a list of 59 topics spanning both modern physics and quantum mechanics. In comparison with our list of 84 topics (see Sec. IV), generated through textbook analysis and faculty interviews, there was a significant degree of overlap. Aside from specifically modern physics topics (e.g., the photoelectric effect), almost all topics included on the Buzzell *et al.* list appeared either verbatim on our list (e.g., harmonic oscillator) or were implicitly included in our list of topics (e.g., our list did not include "spontaneous emission" but did include "Einstein coefficients" and "selection rules"). We identify three topics on the Buzzell *et al.* list that do not appear on our list in any form: neutrino oscillations, the adiabatic theorem, and Berry's phase. However, neutrino oscillations and Berry's phase were both supplied by survey respondents as additional topics in our optional "other" box.[5]

Optional demographics: The final section of the survey asked optional demographic questions about the instructor, as well as information about their institution.

C. Participant demographics

The survey was distributed to the same set of institutions from whom we initially solicited interview participants (Sec. III A). We collected a total of 76 complete survey submissions. As the survey was anonymous, we cannot determine if any of the survey respondents had previously participated in our interview study; however, as the results presented here include only the survey data, no participant is double counted. The demographics of the respondents can be found in Table I. Respondents were given an opportunity to provide the name of their institution, and 75 of the respondents provided one, while one respondent instead provided only institutional information. The 76

[4]The use of four levels of coverage was inspired by Meyer *et al.* [26].

[5]We note that Berry's phase is typically introduced with the adiabatic theorem [7].

TABLE I. Demographics of instructor survey respondents. *Respondents could select multiple options.

Race		Gender		Position		Time teaching	
White	60	Male	58	Professor	44	21+ years	40
Asian	10	Female	11	Associate professor	20	16–20 years	9
Prefer not to say	4	Prefer not to say	4	Assistant professor	8	11–15 years	13
Hispanic or Latinx	2	Nonbinary or third gender	2	Other	3	6–10 years	6
Did not respond	1	Did not respond	1	Lecturer	1	0–5 years	8
Total	76*	Total	76*	Total	76	Total	76

instructors represented 74 unique institutions, where we have considered the unspecified institution to be a unique institution for reporting purposes. Information about the represented institutions can be found in Table II. Note that relative to Buzzell *et al.* [6], our dataset has a smaller fraction of institutions with very high research activity, a smaller fraction of public institutions, and a slightly higher fraction of minority serving institutions (MSIs). This suggests that the differing methodologies used in these two studies have indeed resulted in different selection effects.

In Table III, we provide a breakdown of the courses respondents in our sample had taught within the last 5 years. For our analysis, it is important to distinguish between instructors who taught the first course of a multicourse sequence and those who taught a stand-alone course. To address the concern that some instructors might misinterpret the intended distinction between QM1 and QM (single-semester or single-quarter), we cross-checked their responses to the questions asking which QM courses they had taught and which QM courses their institution offers. For any potential inconsistencies (e.g., an instructor stating they had taught QM1 but that their institution only offers a single-semester QM course), we verified the provided information with the institution's course catalog. Based on this verification process, we re-classified three instructors. Table III shows the final, corrected classifications. We note that the majority of survey respondents had recently taught a single-semester QM course, suggesting that a large fraction of the represented physics programs (on the order of half) offer only one semester (or 1–2 quarters) of QM instruction. The next most represented course taught was QM1 of a two semester sequence and then both QM1 and QM2.

TABLE II. Carnegie classification [35], control (public or private), and MSI status for each of the 74 institutions represented by the 76 survey respondents. MSI status was determined using the NASA 2024–2025 List of Minority Serving Institutions (HSI: Hispanic-Serving Institution, AANAPISI: Asian American and Native American Pacific Islander-Serving Institution, PBI: Primarily Black Institution, and ANNH: Alaska Native- and Native Hawaiian-Serving Institution) [36]. One instructor did not provide the name of their institution but self-reported institutional information. For all other institutions, the information was determined by the authors using the institution name. *These categories are not mutually exclusive.

Carnegie classification		Control		MSI status	
Doctoral (R1)	17	Public	42	HSI	11
Doctoral (R2)	11	Private	32	AANAPISI	10
Doctoral and professional	4			PBI	1
Masters (M1)	17			ANNH	1
Masters (M2)	2				
Masters (M3)	6				
Baccalaureate	17				
Total	74	Total	74	Total	16*

D. Analysis

In our data collection, we made the distinction between quarter-based and semester-based institutions. For our topical analysis, however, it is useful to combine the two groups. Where relevant, we have included QM1 from quarter-based institutions with QM1 from semester-based institutions. Similarly, we have included QM2 and QM3 from quarter-based institutions with QM2 from semester-based institutions. This approach has limitations, notably that QM2 from quarter-based institutions potentially shares content with QM1 from semester-based institutions. Part of the rationale for our groupings is that at least one instructor at a quarter-based institution noted that their institution requires a first-quarter QM course but does not require a second quarter QM course. While not perfect, this grouping

TABLE III. Number of instructors at semester-based and quarter-based institutions that taught each course in the last 5 years.

Semester course(s) taught	Number of instructors
QM (single semester)	39
QM1	14
QM1 and QM2	14
QM2	1
Quarter course(s) taught	
QM (single quarter)	1
QM1 and QM2	4
QM2	1
QM3	2

allows for the inclusion of quarter-based institutions in our analysis. Details regarding methodological choices for specific elements of analysis appear in the relevant section. While our analysis choices are informed by our research questions and the nature of the data, we also acknowledge that others may have different questions or priorities that could be addressed by our data; for these cases, we have provided an online, filterable version of our dataset for the interested reader (Ref. [37]).

Throughout our results, we present raw counts or percentages from survey responses. As our goal is focused on understanding broader trends rather than making specific quantitative claims, we do not perform specific statistical tests to investigate statistical significance of, for example, differences between the frequencies of different topical areas. In some cases, we discuss comparisons of these general trends between different types of courses (notably spins first vs wave functions first); however, these should be interpreted as qualitative rather than quantitative comparisons.

E. Limitations

There are several important limitations to consider in interpreting the results of this analysis. First, this study relies on both interview and survey volunteers, which may overrepresent faculty from institutions where the research or teaching loads are more likely to provide space in faculty schedules to respond to such requests. Similarly, interview volunteers may also self-select for instructors who are more likely to know about and utilize active learning techniques. Additionally, our data focus exclusively on the faculty perspective (rather than the student perspective) regarding the content of undergraduate QM courses. This was an intentional choice because undergraduates likely do not have sufficient experience with the topic of QM. However, we note that the student perspective is an important element of any educational reform, and encourage any researcher or instructor utilizing our results to consider the student experience and perspective.

Additionally, we designed our survey to accommodate instructors who have taught any combination of a single-semester QM course, a sequence of QM courses, or only one course within a sequence of QM courses in the last 5 years. However, instructors who had taught multiple courses were not asked to submit separate responses for each course in order to reduce survey fatigue. This introduced several constraints, including that we cannot distinguish where topics were taught for instructors who had taught multiple courses (i.e., we have their full topical focus but not which course introduced it). We have discussed our approach for dealing with this constraint in our discussion of topical coverage in Sec. IV E.

IV. RESULTS

In this section, we summarize data from the full survey dataset along with data from our follow-up analysis of publicly available course catalogs. We first present and discuss results regarding prerequisites, textbooks, teaching methodology, and pedagogical resources used by instructors. Then, we discuss the coverage of various QM topics.

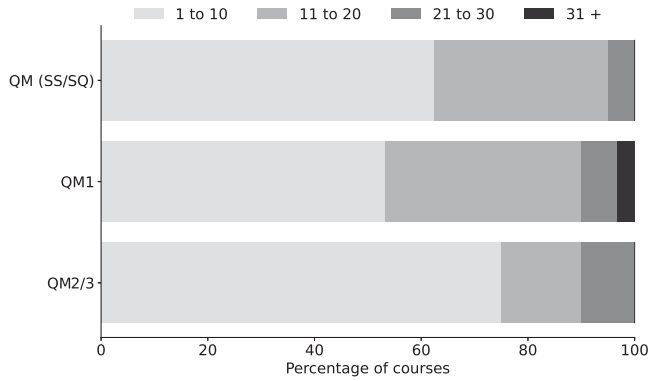


FIG. 1. Distribution of class sizes for courses taught by survey respondents, split into single-semester or single-quarter QM, QM1, and QM2/3. Quarter-based and semester-based institutions are grouped together. Two instructors did not provide class size information, so their courses are not included in this plot.

A. Course-level characteristics

Here, we report the distribution of class size, as well as the required prerequisites. The question asking instructors for their average class size was open-ended, so we have grouped responses into bin sizes of 10. If an instructor reported a range, the average of the range was used for classification. Instructors who reported having taught multiple courses were requested to specify the course size for each class. Figure 1 shows the distribution of class size, split by the type of course. We see that most courses represented in our sample are small, with 10 or fewer students.

Due to potential ambiguity in interpretation, information on prerequisites for the courses included in our dataset was collected using online course catalogs for each institution. When we look at the explicitly listed prerequisites on course catalogs for QM1 and single-semester or single-quarter QM courses, we find the distribution shown in Fig. 2. We see that modern physics is the most common prerequisite followed by ordinary differential equations, mathematical methods for physicists, and linear algebra. It is interesting to note that not every institution required a named "modern physics" course to take upper-level QM. In these cases, some institutions instead required a wave mechanics course or intermediate classical mechanics course. For the 30 institutions that offered a QM2 or QM3 course, the only prerequisite listed for each was the prior QM course. While Buzzell *et al.* [6] noted a tendency in their sample of courses not to require linear algebra prior to a modern physics course, for the upper-division courses that are the focus of our study, it is apparent that differential

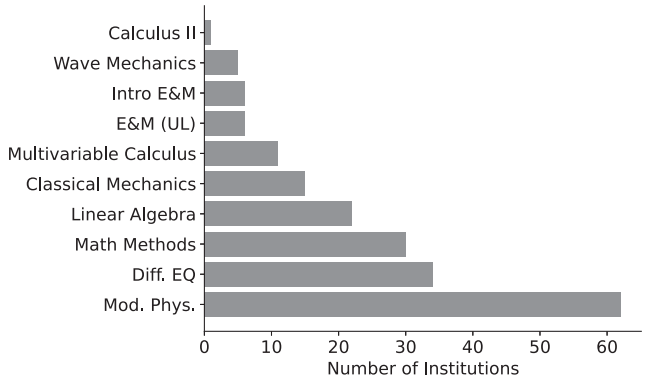


FIG. 2. Distribution of explicitly listed prerequisites for QM1 and single-semester or single-quarter QM courses across all institutions in the sample ($N = 74$). Counts were derived by analysis of course catalogs for each institution in the study. (Mod. Phys.: modern physics or introduction to QM, UL: upper level, E&M: electricity and magnetism, and Diff. EQ: differential equations).

equations, mathematical methods, and linear algebra are the most common math requirements for these courses.

B. QM textbooks

The majority (71 of 76) of instructors stated they follow a textbook, while 4 stated they used only lecture notes, and 1 said they do not use either a textbook or lecture notes. As shown in Fig. 3, Griffiths QM [7] is the most used textbook, followed by McIntyre [8] and then Townsend [9]. However, there are a number of other texts used by multiple instructors (see Fig. 3) along with 11 other texts reported by only one respondent each (see Appendix A, Table VI). This variation in textbook use shows up even when restricting our view to just single-semester and QM1 courses (see Fig. 3), suggesting that the variation is not a result of a preference for different texts when including more advanced QM content.

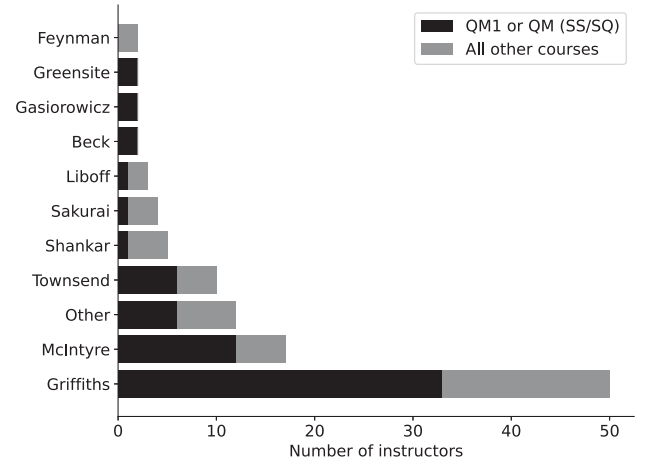


FIG. 3. Distribution of textbooks used by surveyed instructors. Textbooks are included in the other category if they were only used by one instructor (i.e., this category includes 12 different textbooks). The textbooks are labeled by the first author and different editions of textbooks have been collapsed. The entire bar shows the total count from all instructors, and the black portion of the bar shows the contribution from instructors who had only taught a QM1 or single-semester or single-quarter QM course.

The prevalence of Griffiths suggests that a wave functions-first approach to QM instruction is still the most common approach (roughly two-thirds of respondents). This is consistent with the findings of Buzzell *et al.* via their analysis of syllabi [6]. That said, counting both McIntyre and Townsend as spins-first approaches, we also find a significant fraction of courses (roughly a third) utilizing some version of this approach. There is also a long tail of other texts used either in conjunction with a more prevalent text (i.e., one of the texts in Fig. 3) or as the main text for the course.

Since content focus, notational conventions, and consistency of notations such as Dirac notation can vary significantly depending on the text used, this finding has important implications for both assessment and curricular development. Variations in content coverage and focus emphasize the potential value of flexible assessments that can be customized to ensure alignment with the instructor's priorities. It also suggests that modular curricular materials that can be slotted into courses on an as-needed basis would represent a significant resource to the instructional community.

C. Teaching methodology

Our survey also asked participants about their teaching methodology in their classroom. The options they could pick from included: traditional lecture, interactive lecture, flipped classroom/studio, or an other option where instructors could provide their own description.[6] As shown in Fig. 4, the two leading methods were traditional lecturing and interactive lecture, with flipped classroom coming in last. Respondents who selected the other response described a mixture between these teaching styles.

We followed this question with an optional free-response text box for instructors to explain their motivations for using this teaching style. These responses were analyzed to identify common themes among the stated reasons for their chosen teaching style. Here, we will present example quotations corresponding to each identified theme. For traditional lecture (which represented 40% of respondents), some instructors expressed the idea that traditional lecture was simply the most effective. For example,

P6: It seems to work the best.
P10: I feel that lectures combined with problem sets are effective at teaching this material.

[6]This question included operational definitions of each of these approaches to ensure respondents had a consistent interpretation.

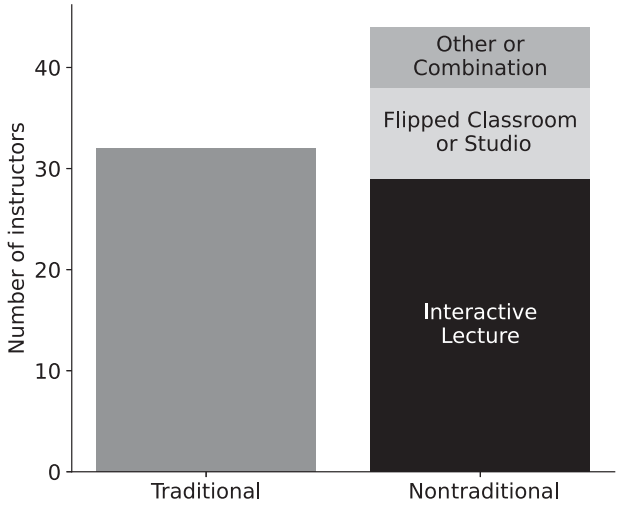


FIG. 4. Number of instructors using each teaching style (single response only). Traditional lecture is defined as lecturing most of the class with notes on a PowerPoint or written on a board, and students ask questions of their own volition. Interactive lecture is defined as lecturing part of the class period, using concept questions, group discussion, tutorials, or student activities. Flipped classroom in a studio format is defined as minimal lecturing with class period driven by students' questions or work on homework or projects.

The majority of other justifications for traditional lecture were logistical in nature. Some instructors noted the difficulty inherent in other approaches:

P2: In general, the flipped scheme has more pedagogical justification and better results. It's just more difficult to do, particularly starting out in a new prep.

Other instructors expressed concerns about the time required for more active methods and the corresponding reduction in content coverage:

P7: It is the most efficient way of delivering knowledge.
P17: There is too much material to cover to use the other methods.

Finally, several instructors noted a lack of institutional support to run their course in any other format than traditional lecture:

P46: No support to run the course in any other fashion.
P49: There are very little resources to apply to courses at this level and our teaching loads have become too high to spend too much time designing custom resources for interactive lectures …

These justifications for a traditional teaching style over other research-based methods are consistent with prior work on instructional change [38,39]. Specifically, these findings are consistent with Henderson and Dancy's [38] finding that instructors often point to situational factors, such as lack of time or institutional support, to justify using traditional lecture.

Alternatively, some faculty argued for the importance of interactive engagement in these courses. For example, some stated that they perceived better student engagement with the material:

P5: It seems to strike the right balance for many of my students between being actively engaged and getting what they are looking for from me.

Additionally, some instructors stated that interactive lecture was more effective at revealing difficulties with concepts and procedures:

P37: I think that it leads to better learning and I can see, in real time, where students are having difficulties.
P59: I find the students understand a lot of the material once they get a chance to discuss the topic.

Difficulties with other methods of instruction were also cited as a reason for using interactive lecture:

P9: More interesting for students and instructors than traditional lecture.
P23: I have done the flipped classroom before, but students have increasingly struggled with that method and so I moved more toward a mix of lecturing and active discussion.

Finally, some instructors cited physics education research as a primary reason for using interactive lecture in their classroom:

P43: Physics education research has clearly shown that students learn more from interactive engagement in the classroom than from traditional lecture, so I use an interactive approach in all of my courses.

For the flipped classroom style of teaching, instructors cited effectiveness as a primary reason for use:

P18: Since there are other good avenues for content delivery ... our time together in the same space is best spent through interactive ... intentional practice—primarily working through examples, problems, and discussion questions.

Some of the instructors who used the flipped classroom methodology stated that they experienced better student engagement in this format:

P75: I've found that this is better than the traditional method in at least one way: the students end up doing much more computation and practice than they otherwise would just reading the book outside of class and "passively" listening to lecture during class time.

Finally, some of the instructors stated that they used a flipped classroom approach because a small class size allowed for it:

P73: Small classes allow it. The availability of online solutions to homework problems has driven me to having students work out problems in class.

D. Pedagogical resource use

After asking the instructors which teaching style they used and their motivations, instructors were asked to select the pedagogical resources and approaches they used in their teaching. Table IV shows the distribution of responses. We see that the top three most used were in-class group work, preclass readings, and simulations. Responses in the other category were primarily clarifications of approaches that combined different elements of multiple options. The only novel element noted in the other responses was the inclusion of computational projects or assignments, which was given by four respondents.

It is notable that research-based assessments (RBAs) were used by only 12 of the 76 instructors who participated in this survey. There could be many reasons for this relatively low uptake of RBAs.[7] For example, this result could suggest that many QM instructors are unaware of RBAs as a potential tool. Alternatively, it could be that many QM instructors know about RBAs but do not find the existing RBAs for QM valuable or appropriate. Either way, this suggests that assessment developers likely need to consider how to both increase awareness of these tools and ensure that they are meeting the needs of QM instructors broadly.[8]

TABLE IV. Distribution of instructors who used each pedagogical resource ($N = 76$). This was presented as a list from which respondents could select multiple items.

Tool	Count (out of 76)
In-class group work	43
Preclass readings	39
Simulations	36
Homework corrections	27
Exam corrections	25
Concept or clicker questions	24
Tutorials	23
Final papers or projects	18
Outside group work	16
Other	13
Research-based assessments	12
Demos	9
Preclass quizzes	7
Group exams	7
Online tutorials	5
Oral exams	4

E. QM topic coverage

The next section of the survey asked each instructor to rate their level of coverage for a list of 84 topics that could be taught and assessed in an upper-level, undergraduate QM course. The full dataset is presented in Appendix C and can be accessed online via Ref. [37]. Here, we report the responses by class type to clarify content coverage for each type of course. We first consider QM1 and QM2 courses and then consider single-semester or single-quarter QM courses. While one could make the case for including single-semester QM courses with QM1 courses, we consider it important to first analyze single-semester courses separately. This way, we can assess to what extent single-semester courses typically cover only QM1 content or if they cover a combination of QM1 and QM2 content.

Throughout this section, we report specific percentages based on instructor responses to our survey. However, we advise the reader to keep in mind the sample sizes (provided in Table V) as they interpret the percentages. For example, topics covered by 100% of QM1 instructors in our sample are certainly not all covered by 100% of QM1 courses in the country. The topic lists we report are intended to serve as a guide when considering topical coverage in QM courses, but they should be interpreted with the appropriate context.

Overall, a total of 14 respondents reported having taught only a QM1 course. To identify core content areas covered in the QM1 courses in our dataset, we focus on topics considered to be important by these instructors. To narrow the focus to topics with a significant amount of consensus, we then needed to select a threshold to delineate topics covered frequently from those covered more sporadically. Different thresholds have been used in prior instructor content surveys (e.g., Refs. [25,26]) and all are ultimately somewhat arbitrary. We decide to use a threshold of 50%, meaning at least half of the instructors in our sample considered the topic to be important. This threshold provides a nice separation between the slightly bimodal

[7]The term RBA was defined for the survey respondents via a link to the PhysPort main assessments page to ensure consistent interpretation from all respondents.

[8]Indeed, as discussed in Sec. I, this work was motivated, in part, to support efforts to develop a new QM assessment featuring flexible content coverage with the goal of ensuring the new instrument can accommodate a wide range of courses, instructional styles, and content priorities.

TABLE V. List of significant topics and percentage of instructors that listed each topic as important for each of our three course types: QM1 ($N = 14$), single-semester QM ($N = 40$), and QM2 ($N = 22$). Only topics listed by at least 50% of surveyed instructors as important for at least one course are included in this list. Tables VII, VIII, and IX presenting the responses from each group of instructors on all topics are given in the Appendix C, and the full dataset can be accessed online via Ref. [37]. Percentages in each column are as a fraction of the instructors for that course only (not relative to the full $N = 76$ dataset). Topics are ordered by the percentage of QM1 instructors that reported them as important. Bolded percentages indicate those topics that reached the 50% threshold for that specific course, with the exception of QM1 topics reported above the threshold by the QM2 instructors, which are provided in italics. This is because 18 of the 22 QM2 instructors were responding for both QM1 and QM2.

Topic	I (%) QM1	I QM (single semester)	I (%) QM2
Normalization	**100**	**95**	*77*
Angular momentum	**100**	**83**	*95*
Hermitian operators/observables	**100**	**93**	*91*
Time-independent Schrödinger equation	**100**	**93**	*91*
Uncertainty principle	**100**	**83**	*91*
Free particles	**100**	**90**	*86*
Harmonic oscillator	**100**	**90**	*100*
Hydrogen atom	**100**	**88**	*95*
Infinite square well	**100**	**88**	*77*
Expectation values	**93**	**88**	*86*
Commutators	**93**	**95**	*95*
Momentum	**93**	**80**	*86*
QM postulates	**93**	**80**	*86*
Raising and lowering operators	**93**	**70**	*100*
Stationary, bound, and scattering states	**93**	**85**	*91*
QM in 3-dimensions	**93**	**80**	*86*
Spin	**93**	**85**	*91*
Hilbert space	**86**	**58**	*86*
Finite square well	**86**	**93**	*82*
Radial wave functions	**86**	**78**	*91*
Spherical harmonics	**86**	**83**	*86*
Eigenstates, eigenvalues, and eigenequations	**86**	**82**	*77*
Linear algebra skills	**86**	**65**	*68*
Probability	**86**	**73**	*73*
Time evolution	**86**	**70**	*86*
Reflection and transmission	**86**	**60**	*55*
Matrix formulation of QM	**79**	**60**	*86*
Time-dependent Schrödinger equation	**79**	**73**	*82*
Minimum uncertainty wavepackets	**71**	30	*50*
Stern-Gerlach experiments	**71**	**65**	*68*
Measurement	**64**	**70**	*82*
Delta-function wells and barriers	**64**	40	*64*
Legendre polynomials	**57**	43	*64*
Energy-time uncertainty principle	**57**	48	*50*
Hermite polynomials	**50**	33	*64*
Addition of angular momentum	43	**50**	**77**
Electron in a magnetic field	43	38	**73**
Infinite spherical well	43	28	**55**
Unitary operators	36	45	**64**
Symmetries and conservation laws	36	25	**50**
Bosons	29	30	**77**
Nondegenerate time-independent perturbation theory	21	33	**91**
Degenerate time-independent perturbation theory	21	23	**82**
Identical particle systems	21	28	**82**
Fermions	21	30	**77**
Zeeman effect	14	10	**59**
Electromagnetic interactions	14	0	**50**

(Table continued)

TABLE V. *(Continued)*

Topic	I (%) QM1	I QM (single semester)	I (%) QM2
Entanglement	14	48	**50**
Time-dependent perturbation theory	7	5	**68**
Transitions	7	8	**64**
Fine structure correction	7	13	**59**
Schrödinger/Heisenberg/interaction picture	7	15	**50**
Exchange interaction	7	3	**50**
Variational principle	0	15	**77**
Selection rules	0	3	**50**
Radiation and emission/absorption	0	3	**50**

distribution of responses shown in Fig. 5. However, the reader can feel free to enforce a stricter or looser threshold depending on their specific interests (see Appendix C). The topics identified as important by QM1 instructors, based on our 50% threshold, are those bolded in the first column of Table V. Together, these topics represent those with a degree of consensus among our respondents as appropriate for inclusion in a QM1 course.

To identify additional topics likely to be included in QM2 (and/or QM3 in the case of quarter systems), we turn to the responses from instructors who had taught these courses. There were only four instructors who responded to our survey that taught just a QM2 or QM3 course without having ever taught QM1. However, there were also 18 instructors who responded for both QM1 and QM2. We combined the responses for these groups, resulting in a total of 22 instructors with experience teaching more advanced QM topics. However, this means that the percentages listed in Table V for QM2 should *not* be interpreted as representing the percentage of QM2 instructors that actually teach each topic in their QM2 course. Rather, we encourage the reader to focus primarily on the bolded topics in Table V, which represent topics that only rise to the 50% threshold for QM2 courses. In this way, we are able to focus on the topics in our list that are consistently taught above and beyond the QM1 level.

Using the 50% threshold, we have identified 35 topics in QM1 and 21 additional topics in QM2. This leaves 28 topics from our original list that do not pass the threshold in either group. Of these topics, two of them (differential equations and complex numbers and functions) were assumed to be prior knowledge by at least half of the instructors in each group. Additionally, there were only two topics on our list where more than half of QM2 instructors reported not covering them at all: group theory and the Hartree-Fock method. Many of the remaining topics were considered peripheral, rather than important, by a considerable portion of instructors. For example, the Stark Effect was considered important by 36% of QM2 instructors but peripheral by 50%. We direct readers interested in topics receiving *any* coverage (i.e., topics considered important or peripheral, rather than just those considered important) to Appendix C.

Next, we consider topical coverage in single-semester QM courses. Figure 5 also shows a histogram of the number of topics binned by the percentage of single-semester QM instructors considering the topic important. In comparison to the equivalent distribution for QM1 instructors (also shown in Fig. 5), the distribution shows slightly less agreement between instructors. This can be quantified by considering the number of topics where at least 90% or less than 10% of instructors consider the topic important. In the sample of QM1 instructors, 42 of the 84 topics were in this range. In the sample of single-semester instructors, 29 of the topics were in this range, showing less agreement among instructors about which topics are important or unimportant.

The bolded entries in the second column in Table V show topics in single-semester QM courses that were listed as

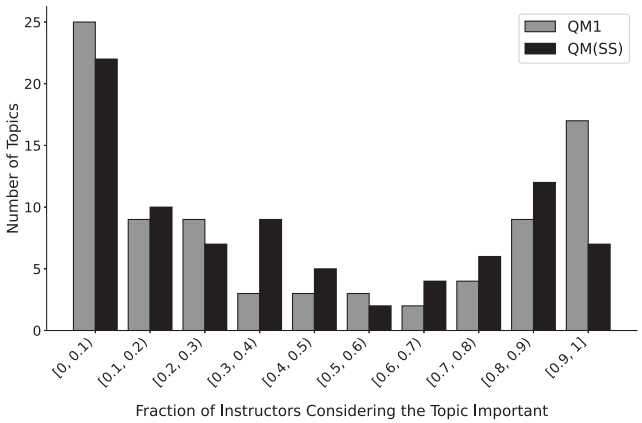


FIG. 5. Distribution of the number of topics reported as important by a given fraction of QM1 ($N = 14$) and single-semester QM ($N = 40$) instructor responses. For example, 25 topics were considered important by less than 10% of QM1 instructors, and 22 topics were considered important by less than 10% of single-semester QM instructors.

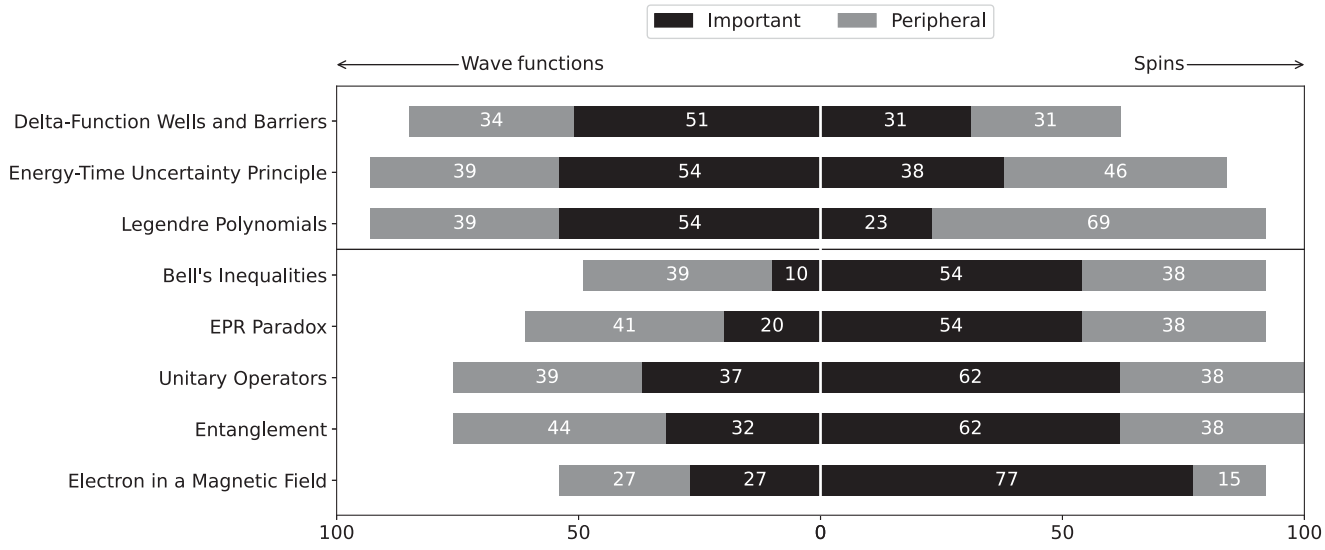


FIG. 6. Plot of topics that were significant for either spins-first ($N = 13$) courses or wave functions-first courses ($N = 41$) but not both, along with the percentage of instructors reporting each topic as important or peripheral in each group. Wave functions-first courses are shown left of center and spins-first courses are shown right of center. Note that QM1 and single-semester or single-quarter QM courses have been combined for this analysis.

important by at least 50% of instructors teaching a single-semester course. When comparing the results of QM1 courses to single-semester QM courses, we note that there is considerable overlap in significant topics. The only topic that was considered a significant topic in single-semester QM courses but not in QM1 courses was Addition of Angular Momentum, while there were five topics that were considered significant in QM1 courses but not in single-semester QM courses. Of course, these regions of overlap would change with a different threshold, and the differences could certainly be sample dependent. However, this analysis supports the conclusion that single-semester courses largely align with QM1 courses in terms of topical coverage, albeit with somewhat more variability between instructors. This indicates that single-semester (or quarter) QM courses should be considered much more in line with a traditional QM course than as some type of accelerated combination of QM1 and QM2.

V. SPINS VS WAVE FUNCTIONS-FIRST APPROACHES

While the previous section only addressed differences in topical coverage between QM1, QM2, and single-semester QM, it is also worth considering potential differences between spins-first and wave functions-first courses. We consider a course to be spins first if it only uses a spins-first textbook (McIntyre or Townsend) or the instructor identified the course as spins first. All other courses are considered to be wave functions-first.[9] Additionally, we focus our attention on QM1 and single-semester or single-quarter QM courses. Based on the results in the previous section, we consider it reasonable to combine those two course categories for this analysis. Thus, the data included in this section include 13 spins-first courses and 41 wave functions-first courses.

Our analysis follows the procedure described in the previous section. We first construct lists of topics considered important by at least 50% of instructors in each group. We observe an overlap of 30 topics, all of which also showed up as significant topics for both QM1 and single-semester QM. We additionally observe eight topics that show up as a significant topic in one group but not the other. To further investigate potential differences in coverage for these topics, we also consider the percentage of instructors in each group considering the topic to be peripheral. These topics, along with the percentage of instructors who considered them important or peripheral in each group, are shown in Fig. 6.

Here, it is not our goal to argue that we see statistically significant differences in topical coverage between spins-first and wave functions-first courses. Rather, it is interesting to consider the trends we observe in our dataset and how they might inform future analyses. We observe notable overlap between the spins-first and wave functions-first courses in our sample: 30 topics surpassed the threshold in both groups, 46 topics did not surpass the threshold in either group, and 8 topics surpassed the threshold in one group but not the other. When considering the eight topics presented in Fig. 6, we note that several of the topics show less discrepancy when considering the percentage of instructors who consider the topic to be either important or peripheral. For example, the energy-time uncertainty

[9]We default to wave functions-first because it has historically dominated QM instruction.

principle and Legendre polynomials see similar levels of total coverage despite being considered important (rather than peripheral) by a greater percentage of instructors of wave functions-first courses. The electron in a magnetic field, on the other hand, is covered by almost all spins-first instructors (the majority of whom consider it important rather than just peripheral) and approximately half of wave functions-first instructors (split evenly between important and peripheral). This result is not surprising, as spins-first textbooks typically begin with a discussion of the Stern-Gerlach experiment, which requires a discussion of electrons in magnetic fields. Bell's inequalities show a similar discrepancy between groups, with 54% of spins-first instructors considering it important, compared to only 10% of wave functions-first instructors, while roughly 40% of both groups consider it peripheral.

Previously, the comparison of spins-first vs wave functions-first approaches has focused on broader conceptual understanding of QM (e.g., Ref. [32]), rather than topical coverage. However, instructors wishing to adopt one approach over the other may be concerned with differences in content coverage. Additionally, it is important for assessment developers to have this information when constructing assessments that might be used to compare spins-first and wave functions-first approaches.

VI. DISCUSSION

In this paper, we reported the results from a study looking to understand the scope and variability in undergraduate quantum mechanics education across the U.S. Utilizing a mixed methods approach, we designed a survey and distributed it to QM instructors across the U.S. who taught an upper-level QM course in the last 5 years, ultimately receiving 76 complete responses. These results highlight several important considerations for the PER community engaged in quantum education research and materials development.

We found that most of the surveyed instructors came from semester-based institutions where a majority of those taught a single-semester QM course rather than one of a multicourse QM sequence. Instructors of stand-alone quantum courses have to make difficult decisions regarding what content and topics they focus on given their more limited timeframe with the inevitable result that they cannot cover all the topics that might be touched on in a multisemester course. Indeed, we found a significant degree of overlap between what is covered in a single-semester course and the first semester of a multisemester sequence, suggesting that in most cases, a single-semester quantum course is not covering more advanced quantum content. This finding has particularly important implications with respect to graduate education. Particularly at larger R1 schools, it is often implicitly assumed that students enter graduate school with a full undergraduate quantum sequence under their belt. Our results suggest that is often not the case, and graduate instructors should carefully consider what they can assume regarding students' background going into their graduate courses.

We found that prerequisites for undergraduate QM courses are fairly consistent, with modern physics, differential equations, mathematical methods for physicists, and linear algebra as the top four most commonly listed prerequisites in our dataset. Additionally, Griffiths' text was, by a large margin, the most common textbook, used by roughly 60% of our respondents. As Griffiths is a wave functions-first text, this finding suggests that a wave functions-first approach is still the most dominant instructional approach. However, the next two most common texts, McIntyre and Townsend, are spins-first texts utilized by close to a third of our respondents. This suggests that spins-first instruction is seeing use throughout the country. Studies comparing the efficacy of these two approaches to QM instruction are rare [32], and do not show a clear signal favoring either approach. Ultimately, the value of one approach over the other is likely tied to deeper goals around QM education. For example, the rise of QISE and the trend toward including quantum computation in undergraduate QM may drive some instructors to favor a spins-first approach. However, the tension between these two approaches can present a challenge for both curriculum and assessment developers. While we observe significant overlap in content coverage between the two approaches, our findings also suggest slightly different priorities in terms of content coverage.

Our results also shed interesting light on the teaching methodologies used in undergraduate QM courses. We found that the two most commonly used methodologies were traditional lecture and interactive lecture, which is likely unsurprising. The frequency of these two approaches, which were used by a similar fraction of our respondents, however, suggests an interesting trend. As an upper-division course taken primarily by juniors and seniors, conventional wisdom might have led one to assume traditional lecture would be the dominant form of instruction. However, we observe more instructors using nontraditional instruction (including interactive lecture, a flipped classroom, or studio instruction) than traditional instruction. Importantly, a survey methodology will tend to oversample instructors who have interest in participating in education research and time available to do so. However, our results still suggest that active engagement has been adopted by a large fraction of instructors even in this relatively advanced course. We interpret this as an encouraging finding particularly in light of previous literature suggesting less consistent uptake of research-based instructional strategies [38].

In addition to information on their overall instructional approach, we also investigated the specific pedagogical resources instructors used in their courses. We found the three most commonly used resources included in-class group work, preclass readings, and simulations of quantum phenomena to aid in learning. The use of exam and

homework corrections was also quite common with roughly a third of respondents reporting each, suggesting that many instructors are incorporating explicit reflective practices within their courses. Concept questions and tutorials were reported at a similar level and many other resources—such as demos, group exams, and oral exams—were reported less often. Overall, our findings suggest that the types of instructional resources used by QM instructors are quite varied and there is potentially demand for new and innovative curricular materials, particularly those that can be inserted into a course without significant modification of the overall course structure.

We also presented a breakdown of topical content coverage of instructors in our dataset, breaking down the topics list into those reported primarily for QM1 and those for QM2 and beyond. This distinction was not aimed at defining what "should" be taught in each of these courses, but rather only to maximize our insight into which topics have a degree of consensus across the full scope of undergraduate QM instruction. This list of topics can serve as a resource for the PER community to help understand the status of QM education, identify gaps in the current resources available to instructors, and guide the development of new curricular and assessment tools.

Finally, we compared content priorities for instructors teaching spins-first and wave functions-first QM1 courses or single-semester courses. Our results showed considerable overlap between the two approaches; however, we observed some variance between the two groups. Of the differences we did observe, some were primarily of emphasis (i.e., whether they considered the topic important or merely peripheral), while a few topics saw different levels of overall coverage. Considering potential differences in topical coverage will be important for future analyses comparing spins-first and wave functions-first approaches, as well as for QM instructors deciding between the two strategies.

This work is an important step in understanding the landscape of quantum education in the U.S. at a time when quantum education is more scrutinized than ever. Now is the time to examine what and how we are teaching upper-level undergraduate QM so we can better prepare a quantum workforce capable of supporting the second quantum revolution.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: ADDITIONAL TEXTBOOKS

TABLE VI. Textbooks not included in Fig. 3 because they were only selected by one instructor.

Textbook	Author
The Meaning of Quantum Theory	Baggott
The Physics of Quantum Mechanics	Binney and Skinner
Quantum Physics: States, Observables and Their Time Evolution	Bohm, Kielanowski, and Mainland
Quantum Mechanics	Cohen-Tannoudji, Diu, and Laloë
Quantum Mechanics	Fitzpatrick
Quantum Mechanics: A Conceptual Approach	Hameka
Quantum Mechanics Non-Relativistic Theory	Landau and Lifshitz
Quantum Mechanics	Merzbacher
Quantum Processes, Systems, and Information	Schumacher and Westmoreland
Invitation to Quantum Mechanics	Styer
The Physics of Quantum Mechanics	Styer

APPENDIX B: INSTRUCTOR SURVEY CONTENT

Q1: Does your current institution use semesters or quarters?

- Semesters
- Quarters

Q2: Which upper-level undergraduate QM course(s) did you teach in the last 5 years?

- QM 1
- QM 2
- QM 3*
- QM single quarter/semester

*Only an option for instructors who had selected "quarters"

Q3: What types of QM courses does your institution offer? Select all that apply.

- Modern Physics/Intro to QM
- Undergraduate QM (single quarter/semester)
- Undergraduate QM (two semester/multiple quarter)
- Graduate QM (single quarter/semester)
- Graduate QM (two semester/multiple quarter)
- Undergraduate quantum information/computing
- Graduate quantum information/computing

Answer the following questions considering all courses selected in Q2:

Q4: Do you typically follow a textbook when teaching your upper-level undergraduate QM course(s)?

- Yes
- No

Yes

Q4ai: Which textbook?

- Introduction to Quantum Mechanics 2nd edition - Griffiths
- Introduction to Quantum Mechanics 3rd edition - Griffiths
- Quantum Mechanics A Paradigms Approach - McIntyre
- A Modern Approach to Quantum Mechanics - Townsend
- Quantum Mechanics - Merzbacher
- Introductory Quantum Mechanics - Liboff
- Principles of Quantum Mechanics - Shankar
- Quantum Mechanics Theory and Experiment - Beck
- Modern Quantum Mechanics - Sakurai and Napolitano
- The Feynman Lectures on Physics Volume III
- Quantum Physics - Gasiorowicz
- Quantum Mechanics - Cohen-Tannoudji, Diu, and Laloe
- Quantum Mechanics Non-relativistic Theory - Landau and Lifshitz

No

Q4aii: If you use different books for the classes you teach, please state below which you use for each.

Q4bi: Do you use your own lecture notes?

- Yes
- No

Q4bii: Would you classify your course(s) as a spins-first course or a wavefunctions-first course?

- Spins-first
- Wavefunctions-first
- Other

Q5: What style of teaching do you most closely adhere to when teaching your QM course(s)?

- Traditional lecture
- Interactive lecture
- Flipped classroom/Studio
- Other

What are your motivations for using this style of teaching?

Q6: Which of the following do you use in your QM class(es)?

- Concept/clicker questions
- Pre-class readings
- Pre-class quizzes
- In-class group work
- Out-of-class group work
- Tutorials or guided worksheets (e.g., QuILTs)
- Online tutorials (e.g., acephysics.net)
- In-class demonstrations of quantum phenomena
- Simulations (e.g., PhET or QuVis)
- Homework corrections
- Exam corrections
- Oral exams
- Group exams
- Final papers or projects
- Research Based Assessments (e.g., QMS, QMCA, QMCS, etc.)
- Other

Q7: How many students do you typically have in your QM class(es)?

Q8: What formal prerequisites do you have for your QM class(es)?

- Linear Algebra
- Ordinary Differential Equations
- Partial Differential Equations
- Group Theory
- Classical Mechanics (upper-level)
- Mathematical Methods for Physicists
- Modern Physics
- Electricity and Magnetism (upper-level)
- Programming for Physicists or Introductory Computer Science
- Other

Q9: Has your teaching of QM changed in any way because of the Covid-19 pandemic? If so, describe below.

The following section will present 5 lists of topics that could be taught in a QM course. The topics are alphabetized and presented in 5 groupings for ease of comprehension. Please assign each topic, regardless of which class it is taught in, to one of the following categories:

- **Do not cover/use**: You do not teach or use this topic in your class.
- **Assumed Prior Knowledge**: You do not teach this topic, but you use it, assuming prior knowledge or exposure from your students
- **Peripheral**: You teach this topic but not in depth. That could mean mentioning it in passing or covering it for part of a lecture. It is also something not directly assessed.
- **Important**: You teach this topic in depth and assess students' comprehension and retention of it.

*Q10: Please enter the level to which you cover the following topics in your QM class(es).***

	Do not cover/use	Assumed prior knowledge	Peripheral	Important
Angular momentum	○	○	○	○
Commutators	○	○	○	○
Time evolution	○	○	○	○
EPR paradox	○	○	○	○
Stark effect	○	○	○	○

Were there any topics you covered in one of your classes that were not present in the previous lists? If so, please include them below as well as the level of coverage you had.

** These are example topics. A full list of topics can be found in the Appendix.

FIG. 7. Complete survey, showing survey flow and answer options. The text under the dashed lines in Q2 and Q10 is provided to help with interpretation and was not present in the original survey.

APPENDIX C: TOPIC COVERAGE PERCENTAGES

TABLE VII. Percentage of QM1 teaching instructors ($N = 14$) who responded for each coverage category. APK stands for assumed prior knowledge, and DNC stands for do not cover. Rows may not add up to 100 due to rounding.

Topic	Important	Peripheral	APK	DNC
Normalization	100	0	0	0
Angular momentum	100	0	0	0
Hermitian operators/observables	100	0	0	0
Time-independent Schrödinger equation	100	0	0	0
Uncertainty principle	100	0	0	0
Free particles	100	0	0	0
Harmonic oscillator	100	0	0	0
Hydrogen atom	100	0	0	0
Infinite square well	100	0	0	0
Expectation values	93	7	0	0
Commutators	93	7	0	0
Momentum	93	7	0	0
QM postulates	93	7	0	0
Raising and lowering operators	93	7	0	0
Stationary, bound, and scattering states	93	7	0	0
QM in 3-dimensions	93	7	0	0
Spin	93	0	0	7
Hilbert space	86	14	0	0
Finite square well	86	14	0	0
Radial wave functions	86	14	0	0
Spherical harmonics	86	14	0	0
Eigenstates, eigenvalues, and eigenequations	86	7	7	0
Linear algebra skills	86	7	7	0
Probability	86	7	7	0
Time evolution	86	7	0	7
Reflection and transmission	86	0	0	14
Matrix formulation of QM	79	14	0	7
Time-dependent Schrödinger equation	79	14	0	7
Minimum uncertainty wavepackets	71	29	0	0
Stern-Gerlach experiments	71	14	7	7
Measurement	64	29	7	0
Delta-function wells and barriers	64	21	0	14
Legendre polynomials	57	36	0	7
Energy-time uncertainty principle	57	36	0	7
Hermite polynomials	50	29	0	21
Infinite spherical well	43	50	0	7
Electron in a magnetic field	43	21	0	36
Addition of angular momentum	43	14	0	43
Special functions	36	50	0	14
Unitary operators	36	43	7	14
Symmetries and conservation laws	36	14	0	50
Periodic table of elements	29	36	0	36
Bosons	29	0	7	64
Degenerate time-independent perturbation theory	21	21	0	57
Coherent states	21	14	7	57
Identical particle systems	21	14	0	64
Frobenius method	21	7	0	71
Fermions	21	0	7	71
Nondegenerate time-independent perturbation theory	21	0	0	79

(Table continued)

TABLE VII. *(Continued)*

Topic	Important	Peripheral	APK	DNC
Born approximation	21	0	0	79
Entanglement	14	57	0	29
Clebsch-Gordan coefficients	14	43	0	43
Scattering	14	29	0	57
Density operators/mixed states	14	21	0	64
Periodic potentials	14	21	0	64
Zeeman effect	14	14	7	64
Electromagnetic interactions	14	14	0	71
Differential equations	14	7	79	0
Complex numbers/functions	14	7	71	7
EPR paradox	7	64	0	29
Bell's inequalities	7	57	0	36
Many-particle systems	7	29	0	64
Schrödinger/Heisenberg/interaction picture	7	21	0	71
Stark effect	7	21	0	71
Transitions	7	21	0	71
Exchange interaction	7	14	0	79
WKB approximation	7	7	7	79
Fine structure correction	7	7	0	86
Hyperfine structure correction	7	7	0	86
Time-dependent perturbation theory	7	7	0	86
Hund's rule	7	7	0	86
Quantum information and computation	7	7	0	86
Bloch sphere	0	43	0	57
Selection rules	0	29	0	71
Variational principle	0	21	7	71
Group theory	0	21	0	79
Fermi's golden rule	0	21	0	79
Molecules/molecular physics	0	21	0	79
Einstein coefficients	0	7	7	86
Hartree-Fock method	0	7	0	93
Partial wave decomposition	0	7	0	93
Radiation and emission/absorption	0	7	0	93
Wigner-Eckart theorem	0	0	7	93
Solids	0	0	0	100

TABLE VIII. Percentage of QM2 teaching instructors ($N = 22$) who responded to each coverage category. APK stands for assumed prior knowledge, and DNC stands for do not cover. Note that 18/22 instructors in this sample were responding for both QM1 and QM2. Rows may not add up to 100 due to rounding.

Topic	Important	Peripheral	APK	DNC
Raising and lowering operators	100	0	0	0
Harmonic oscillator	100	0	0	0
Angular momentum	95	5	0	0
Commutators	95	0	5	0
Hydrogen atom	95	0	5	0
Radial wave functions	91	9	0	0
Stationary, bound, and scattering states	91	5	5	0
Nondegenerate time-independent perturbation theory	91	5	0	5
Hermitian operators/observables	91	0	9	0
Time-independent Schrödinger equation	91	0	9	0
Uncertainty principle	91	0	9	0
Spin	91	0	9	0
QM in 3-dimensions	86	14	0	0

(Table continued)

TABLE VIII. *(Continued)*

Topic	Important	Peripheral	APK	DNC
Time evolution	86	9	5	0
Spherical harmonics	86	9	5	0
Hilbert space	86	5	9	0
Matrix formulation of QM	86	5	9	0
Momentum	86	5	9	0
Free particles	86	5	9	0
QM postulates	86	0	14	0
Expectation values	86	0	9	5
Measurement	82	14	5	0
Time-dependent Schrödinger equation	82	14	5	0
Degenerate time-independent perturbation theory	82	14	0	5
Identical particle systems	82	14	0	5
Fermions	77	18	0	5
Addition of angular momentum	77	14	5	5
Bosons	77	14	0	9
Infinite square well	77	9	9	5
Eigenstates, eigenvalues, and eigenequations	77	5	18	0
Normalization	77	5	18	0
Variational principle	77	5	0	18
Electron in a magnetic field	73	18	5	5
Probability	73	9	18	0
Stern-Gerlach experiments	68	23	9	0
Time-dependent perturbation theory	68	18	0	14
Linear algebra skills	68	5	27	0
Hermite polynomials	64	32	0	5
Legendre polynomials	64	32	0	5
Unitary operators	64	27	9	0
Transitions	64	23	0	14
Delta-function wells and barriers	64	18	9	9
Fine structure correction	59	27	0	14
Zeeman effect	59	23	0	18
Reflection and transmission	55	32	9	5
Infinite spherical well	55	18	0	27
Selection rules	50	45	0	5
Entanglement	50	41	5	5
Minimum uncertainty wavepackets	50	41	5	5
Symmetries and conservation laws	50	41	0	9
Electromagnetic interactions	50	41	0	9
Radiation and emission/absorption	50	41	0	9
Energy-time uncertainty principle	50	36	5	9
Schrödinger/Heisenberg/interaction picture	50	36	0	14
Exchange interaction	50	36	0	14
Many-particle systems	45	45	0	9
Clebsch-Gordan coefficients	45	41	5	9
Fermi's golden rule	45	32	0	23
Finite square well	82	9	5	5
Hyperfine structure correction	45	32	0	23
WKB approximation	45	32	0	23
Scattering	45	32	0	23
Special functions	41	45	9	5
Stark effect	36	50	0	14
Density operators/mixed states	36	45	0	18
Coherent states	32	59	0	9
EPR paradox	32	55	5	9
Einstein coefficients	32	45	0	23
Periodic potentials	32	32	5	32

(Table continued)

TABLE VIII. *(Continued)*

Topic	Important	Peripheral	APK	DNC
Born approximation	32	32	0	36
Differential equations	27	23	50	0
Complex numbers/functions	27	5	64	5
Bell's inequalities	23	55	5	18
Periodic table of elements	23	55	0	23
Solids	23	32	5	41
Molecules/molecular physics	18	50	0	32
Frobenius method	18	41	0	41
Wigner-Eckart theorem	18	41	0	41
Quantum information and computation	18	36	5	41
Partial wave decomposition	18	36	0	45
Hund's rule	9	45	0	45
Hartree-Fock method	9	41	0	50
Group theory	9	32	0	59
Bloch sphere	5	64	0	32

TABLE IX. Percentage of single-semester QM instructors ($N = 40$) who responded for each coverage category. APK stands for assumed prior knowledge, and DNC stands for do not cover. Rows may not add up to 100 due to rounding.

Topic	Important	Peripheral	APK	DNC
Normalization	95	5	0	0
Commutators	95	5	0	0
Hermitian operators/observables	93	5	0	3
Time-independent Schrödinger equation	93	3	5	0
Finite square well	93	3	5	0
Harmonic oscillator	90	5	3	3
Free particles	90	3	5	3
Hydrogen atom	88	10	3	0
Expectation values	88	8	5	0
Infinite square well	88	5	5	3
Spin	85	10	5	0
Stationary, bound, and scattering states	85	8	5	3
Uncertainty principle	83	18	0	0
Eigenstates, eigenvalues, and eigenequations	83	13	5	0
Spherical harmonics	83	13	3	3
Angular momentum	83	8	10	0
QM postulates	80	18	0	3
QM in 3-dimensions	80	13	3	5
Momentum	80	10	8	3
Radial wave functions	78	18	3	3
Time-dependent Schrödinger equation	73	25	0	3
Probability	73	20	8	0
Measurement	70	28	3	0
Time evolution	70	23	0	8
Raising and lowering operators	70	20	0	10
Stern-Gerlach experiments	65	23	5	8
Linear algebra skills	65	18	15	3
Reflection and transmission	60	23	8	10
Matrix formulation of QM	60	20	3	18
Hilbert space	58	30	3	10
Addition of angular momentum	50	23	10	18
Energy-time uncertainty principle	48	43	0	10

(Table continued)

TABLE IX. *(Continued)*

Topic	Important	Peripheral	APK	DNC
Entanglement	48	38	0	15
Unitary operators	45	38	0	18
Legendre polynomials	43	50	0	8
Delta-function wells and barriers	40	38	3	20
Electron in a magnetic field	38	25	5	33
EPR paradox	35	33	0	33
Hermite polynomials	33	53	0	15
Nondegenerate time-independent perturbation theory	33	5	0	63
Minimum uncertainty wavepackets	30	58	0	13
Special functions	30	55	0	15
Fermions	30	30	5	35
Bosons	30	28	5	38
Complex numbers/functions	30	20	50	0
Infinite spherical well	28	43	0	30
Identical particle systems	28	23	3	48
Density operators/mixed states	25	35	0	40
Symmetries and conservation laws	25	33	3	40
Bell's inequalities	25	33	0	43
Differential equations	25	20	55	0
Degenerate time-independent perturbation theory	23	13	0	65
Coherent states	18	33	0	50
Clebsch-Gordan coefficients	18	30	0	53
Hyperfine structure correction	18	13	0	70
Schrödinger/Heisenberg/interaction picture	15	33	0	53
Scattering	15	20	3	63
Variational principle	15	13	0	73
Many-particle systems	13	28	0	60
Fine structure correction	13	15	0	73
Quantum information and computation	10	35	0	55
Zeeman effect	10	28	3	60
Frobenius method	8	33	0	60
Transitions	8	13	3	78
Bloch sphere	5	20	0	75
Born approximation	5	18	3	75
Group theory	5	18	0	78
Time-dependent perturbation theory	5	3	0	93
Selection rules	3	33	3	63
Periodic table of elements	3	30	13	55
Molecules/molecular physics	3	23	0	75
Exchange interaction	3	20	0	78
Radiation and emission/absorption	3	18	3	78
Stark effect	3	13	0	85
WKB approximation	3	13	0	85
Periodic potentials	0	23	3	75
Electromagnetic interactions	0	20	3	78
Fermi's golden rule	0	15	0	85
Solids	0	15	0	85
Hund's rule	0	8	0	93
Wigner-Eckart theorem	0	5	0	95
Einstein coefficients	0	5	0	95
Hartree-Fock method	0	3	0	98
Partial wave decomposition	0	0	0	100

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