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Article

Keywords:

Posted Date: October 15th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-7745493/v1>

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Additional Declarations: There is **NO** Competing Interest.

Characterizing the US graduate-level quantum curriculum: Insights into doctoral programs curriculum and comparisons with undergraduate curriculum

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Abstract

Quantum mechanics lies at the heart of physics graduate training, yet little is known about how it is actually taught across US doctoral programs. Here we provide the first national-scale analysis of the graduate-level quantum curriculum, drawing on catalogs from 184 institutions and syllabi from 121 core courses and 91 quantum field theory courses. Using both expert human coding and natural language processing, we cross validate methods for analyzing large-scale educational data in physics. Our results reveal a striking duality: graduate quantum mechanics is anchored by a shared canon, Most often taught with Sakurai's *Modern Quantum Mechanics*, while quantum field theory instruction varies widely, with over one-third of programs offering no formal course. These differences mirror local research strengths but also reproduce inequities in student preparation, particularly in foundational formalisms such as Dirac notation. By mapping the US graduate quantum curriculum, we identify both common foundations and uneven opportunities, raising urgent questions about equity, standardization, and how graduate education should evolve to prepare the next generation of physicists for a quantum-enabled future.

1 Quantum mechanics is central to graduate assessments, such as entrance exams and
2 qualifying exams, with 90% of US graduate programs testing students' quantum knowl-
3 edge [1]. Yet the structure and content of graduate quantum curricula remains largely
4 undocumented. While undergraduate quantum instruction has been studied in detail,
5 there has been no comprehensive effort to characterize graduate quantum training,
6 despite its significance in preparing students for research careers in both academia and
7 industry.

8 This absence of evidence matters. Graduate coursework serves both as a gateway
9 to advanced research and as a barrier for persistence in physics. Variability in curric-
10 ula may reflect healthy diversity across research traditions, but it may also reinforce
11 inequities: students trained at some institutions encounter formalism such as Dirac
12 notation and extensively, while others arrive at advanced assessments with little prior
13 exposure. The stakes extend beyond classrooms. As quantum technologies expand
14 across sectors, equitable preparation at the graduate level will shape not only who
15 succeeds in research but also who is positioned to contribute to the emerging quantum
16 workforce.

17 In this paper, we present the first national-scale map of the US graduate quan-
18 tum curriculum. By analyzing course catalogs and syllabi from 184 doctoral-granting
19 institutions, we identify both shared foundations and striking differences in graduate
20 training. Our dual-method approach, employing both expert human coding and nat-
21 ural language processing, demonstrates a scalable model for curriculum research that
22 can be extended across domains. We find that while core quantum mechanics instruc-
23 tion is broadly standardized, quantum field theory varies in availability and depth,
24 raising questions about equity, local research priorities, and the evolving purpose of
25 graduate coursework in physics.

26 **1 Graduate physics programs**

27 Research on characterizing graduate physics programs has focused on admission prac-
28 tices, such as the use of the physics GRE or rubric-based holistic review [2–6]. Bridges
29 et al. has been working to characterize the landscape of assessments within US grad-
30 uate physics programs [7]. Preliminary findings have demonstrated a strong focus of
31 core course requirements on quantum mechanics and electrodynamics, with quantum
32 mechanics required by all programs in the study.

33 **2 Undergraduate US quantum mechanics curriculum**

34 Two previous studies have characterized the modern physics curriculum [8] and the
35 undergraduate quantum mechanics curriculum [9] at US research-intensive institutions
36 using syllabi for topic characterization. The modern physics study found 94% of the
37 127 research-intensive institutions included quantum concepts in their modern physics
38 courses [8]. With 70% of these courses being required for physics majors to graduate
39 with their four-year degrees, it was concluded that the majority of undergraduate
40 physics students enrolled in US research-intensive institutions are first introduced to
41 quantum concepts within their modern physics courses.

42 The undergraduate quantum mechanics study was a continuation of the modern
43 physics study [9]. This study utilized course catalog data to determine the number
44 of required courses for physics students to graduate when enrolled in US research-
45 intensive undergraduate programs. All of the institutions required one or more courses
46 on quantum concepts, 92% required two or more courses, and half required three or
47 more. The study collected the complete set of required quantum course syllabi from
48 56 institutions. Using this complete data the number of hours spent in the classroom
49 working on quantum concepts was determined to be an average of 63.5 hours with a
50 standard deviation of 28.1 hours required to earn a four-year degree in physics from
51 these institutions. Therefore, it was shown the required time dedicated to quantum
52 concepts with the curriculum at these institutions was highly variable. Additionally,
53 the topics were characterized with the most common themes being the Schrödinger
54 equation and three-dimensional quantum mechanics. One interesting finding, was that
55 despite the literature that students demonstrate a more expert-like understanding of
56 the distinction between physical space and Hilbert space when introduced to the Stern-
57 Gerlach experiment (SGE) [10], only 28% of the course outlines explicitly mention
58 the SGE across their entire four-year curriculum [9]. Dirac notation was also only
59 explicitly outlined in 34% of the institutions' curriculum. Despite ongoing efforts to
60 promote a spin-first approach [11, 12], this study also found the traditional position-
61 first approaches were still more common as they were used by 73.7% of instructors
62 [9].

63 **3 Natural language processing as a novel tool for** 64 **cross-validation in physics education research**

65 Artificial intelligence (AI) tools are increasingly being integrated into education
66 research [13], including physics education research [8, 14]. With this growing inter-
67 est, there is a need to continually and carefully test these technologies using low-risk,
68 manageable data-sets. Being publicly available or requiring little time commitment
69 to obtain from the instructor, course syllabi provide one such dataset. Syllabi outline
70 learning objectives, course logistics, and may also reflect epistemology and pedagogy
71 of the instructor [15].

72 There are many algorithms available for a variety of supervised (requiring labeled
73 training data) and unsupervised (identify patterns without human-provided labels)
74 tasks [16]. Applications include analyzing student work [17], identifying latent themes
75 within textual datasets [18], including textual data generated in qualitative studies,
76 and building theories in qualitative studies [19], and to generate and answer physics
77 questions [20].

78 The aforementioned modern physics study [8] also utilized NLP and human intel-
79 ligence as a cross-validation method. This study found that, compared to independent
80 human-coding methods, human-coding and NLP agreed on topics related to policies
81 and typically outlined structures such as exams within syllabi. However, while the
82 NLP was able to generate the same content topics as the human analysis, such as
83 quantum, atomic, and relativity, the frequency counts of the NLP method were much
84 lower than those of the human-method.

85 While the initial study of the undergraduate quantum curriculum [9] did not utilize
86 NLP for cross-validation with the human analysis, a follow up study did [14]. The
87 follow up study compared AI-generate topics with human-coded themes from syllabi
88 across the four-year curricula at 50 US institutions. The conclusions of this study
89 concurred with those of the modern physics study [8]; while the NLP reliably identifies
90 broad and structural elements of syllabi (e.g., policies, textbook references), the AI-
91 derived topics were often underrepresented in frequency [14]. The NLP used was also
92 limited in its ability to capture the nuanced and context-dependent content typical of
93 upper-level physics instruction, as the AI-derived topics were misaligned with expert
94 human interpretation, particularly in areas requiring deep disciplinary knowledge. The
95 findings support the use of NLP as a complementary tool for theme generation and
96 cross-validation, but emphasize the continued necessity of expert human analysis for
97 rigorous and meaningful educational research.

98 4 Methods

99 Following the methods of our prior work [8, 9], the *US News* rankings of “The Best
100 Physics Programs” was used as a reference list for institutions in this study [21]. This
101 list comprises 190 institutions that are primarily research-focused and offer graduate-
102 level physics education. However, nine of these institutions offered masters degrees in
103 physics but not doctoral degrees, and one institution was a primarily Spanish-speaking
104 institution. Therefore, from the list of 190 US physics programs, this paper will analyze
105 the curriculum of 180 programs.

106 Our research group also understands the uniqueness of Minority Serving Institu-
107 tions (MSIs), and wanted to ensure the experiences at MSIs are better captured in
108 our data. To do so, the entire list of US MSIs [22] course catalogs were referenced to
109 determine which offered doctoral degrees in physics. Of this list, four new institutions
110 were added to our dataset, for a total of 184 institutions analyzed in this paper.

111 From these 184 institutions, 89% of PhD degrees and 53% of exiting masters
112 degrees were awarded in the 2023-2024 academic year [23]. Out of the total enrolled
113 physics PhD graduate students in the US, these institutions had 84% enrolled, with
114 79% of first year graduate students enrolled during the 2023-2024 academic year.
115 These institutions are primarily public (70%) and have very high-research activity
116 (76%) according to the Carnegie Classification of Higher Education Institutions [24].
117 The other institutions in our data set include 21% with high-research activity, and
118 3% whose research activity is not defined by these metrics. Furthermore, 18% are
119 Minority Serving Institutions (MSIs, $n = 31$), including Hispanic Serving Institutions
120 (HSIs, $n = 18$), Asian American and Native American Pacific Islander-Serving Insti-
121 tutions (AANAPISIs, $n = 14$), Historically Black Colleges and Universities (HBCUs,
122 $n = 3$), Predominantly Black Institutions (PBIs, $n = 2$), and Alaska Native-Serving
123 Institutions or Native Hawaiian-Serving Institutions (ANNHs, $n = 2$) [22].

124 4.1 Core courses

125 Core courses were defined as the courses that covered quantum concepts and *all* grad-
126 uate students within a program were required to enroll and pass for completion of their

127 degree, regardless of research track or specialty. To determine the core courses within
128 each program, the institutions' course catalogs, graduate bulletins, physics depart-
129 ment graduate student handbook, physics departmental websites, and/or contact with
130 department administration were utilized to discern graduate-level core course from
131 graduate-level elective courses.

132 Using the list of all core courses in the 184 programs, course syllabi were obtained
133 for all core courses required at 80 institutions. The number of core courses required
134 will later be shown in the results to range between 0 and 3 courses, we will therefore
135 analyze 121 syllabi across these 80 institutions. From these 80 institutions, 44% of
136 physics PhD degrees and 25% of exiting masters degrees were awarded in the 2023-
137 2024 academic year [23]. First-year physics graduate students comprise 39% of the
138 population at these programs, and 41% of the total US physics graduate enrollment.
139 These institutions are 16% MSIs, with HSI ($n = 7$), AANAPISI ($n = 5$), AANH
140 ($n = 2$) represented [22]. These 80 institutions are primarily public (73%) and have
141 very-high research activity (78%) [24]. The remaining institutions are classified at
142 high-research activity (20%), or are not classified by these metrics (7%).

143 The research fields of the 80 programs were also determined for comparative anal-
144 ysis. To determine the research fields offered at each institutions, the department
145 websites were references to determine the main research activities of faculty. After the
146 research fields were recorded, similar research fields were consolidated using the qual-
147 itative codes found in Table 1. Additionally, a heat map was generated to determine
148 the number of core courses and their correlation to the research areas conducted at
149 the 80 institutions.

150 Of the 80 institutions, 68 institutions offered one or more core courses. From these
151 68 institutions, the first core course syllabi within the core course sequence was ana-
152 lyzed to determine the required textbook for the course. To consolidate the results,
153 unique editions of the textbooks were not separated within the data presented in this
154 paper.

155 To determine the topics taught, an emergent coding method was used [25]. All top-
156 ics mentioned in the syllabi were recorded. Using the table of contents from Sakurai
157 [26], closely related topics were combined together. Table 2 below presents the overar-
158 ching themes within the syllabi, along with the topics coded under each theme. Some
159 topics appeared so infrequently that they could not be grouped with others and will
160 appear in the results despite not being included in Table 2. Examples of these topics
161 include the Bohr-Sommerfeld model and quantum hall effect. One institution, which
162 had two core courses, the syllabi did not offer information about the topics covered.
163 Therefore, the topics covered in the core courses were for 67 institutions, across 119
164 unique courses.

165 In addition to the human analysis method, this study used topic modeling, a class
166 of NLP techniques that identify latent semantic structures within a collection of texts
167 [27–29] as a method for potential cross-validation. Topic modeling involves a series of
168 computational steps: converting documents into smaller linguistic units (e.g., tokens),
169 transforming these tokens into numerical representations (embeddings), and then using
170 clustering algorithms to group similar embeddings into coherent topics. Each stage can

171 be configured with different algorithms or models, and the outcome typically depends
172 on both the selected parameters and the structure of the underlying text data.

173 The 119 core course syllabi were again utilized independently for analysis with
174 NLP. The $n = 119$ syllabi documents were comprised of 10 Microsoft Word files and
175 109 PDF files. All files were analyzed. To compare the quantum curriculum from
176 institution to institution, as done in the human analysis of the core courses, documents
177 for different courses taught at the same institution were combined into one single
178 document so that each institution, $n = 67$, had one document associated with it.
179 The 67 documents were then converted to plain text for further analysis using the
180 `pdftotext` utility for PDF files and `pandoc` for the word documents.

181 This analysis utilized `BERTopic` [30], a relatively recent algorithm that builds
182 on transformer-based language models. `BERTopic` begins by embedding the text
183 using a pre-trained model such as BERT (Bidirectional Encoder Representations from
184 Transformers), which captures contextual information by analyzing the position and
185 meaning of words within a broader textual window. These embeddings are then
186 reduced in dimensionality to make the clustering more computationally tractable. The
187 reduced representations are then grouped using `HDBSCAN`, a density-based clustering
188 algorithm that determines the number of clusters automatically based on the density
189 of the data points, rather than requiring it to be set in advance. Finally, representative
190 keywords and example sentences are selected for each topic.

191 Following best practices for `BERTopic`, documents were segmented into sentence-
192 like units using the `sent_tokenize` function from the `nltk` package. This approach
193 ensures that each unit is short enough to be meaningfully embedded by the language
194 model. Unlike traditional topic modeling methods that recommend removing stop
195 words, `BERTopic` leverages these function words as part of its contextual understanding
196 and therefore does not require their removal.

197 As will be shown in the supplemental material, this process of using the plain
198 text syllabi as is provided, NLP identified topics that were concerned with common
199 words or structures of syllabi, and not with the content taught in the courses. To
200 better align the NLP identified topics with the goals of this paper, all sections of the
201 syllabi that were unrelated to the course content were deleted from the plain text files.
202 The information that remained included: learning goals, course outlines, and topics
203 covered. There were 3 plain text files that were not usable with this method so our
204 sample comprised $n = 64$ institutions core course syllabi.

205 4.2 Quantum field theory courses

206 Given the importance of quantum field theory, each of the course catalogs from the 184
207 institutions was used to record the quantum field theory courses offered to graduate
208 students. In order for a course to be considered a quantum field theory course, its title
209 must have contained one of the following: “quantum field theory,” “field theory,” or
210 “relativistic quantum mechanics.” As will be demonstrated in the results, the number
211 of quantum field theory courses offered in the course catalogs will range from zero
212 to five courses at each institution, with a total of 181 courses offered at the 184
213 institutions. We attempted to obtain a syllabus from each of these quantum field
214 theory courses either by contacting a recent instructor of the course or by contacting

215 administrative faculty or staff in the department. Through these communications, we
216 obtained 91 syllabi and determined that 10 courses have not been offered in recent
217 years. Due to graduate school course enrollments being much lower than undergraduate
218 courses, it would make sense that some courses offered in the course catalog have
219 effectively been canceled due to low enrollments or low interests. Students who need
220 this material in graduate school may learn it through informal methods such as self-
221 teaching or working with their advisor, rather than signing up for the formal course.

222 The 91 syllabi were collected from a total of 52 institutions. From these 52 institu-
223 tions, 40% of physics PhD degrees and 6.5% of exiting masters degrees were awarded
224 in the 2023-2024 academic year [23]. First-year physics graduate students comprise
225 31% of the population at these programs, and 35% of the total US physics graduate
226 enrollment. These institutions are 17% MSIs, with HSI ($n = 5$), AANAPISI ($n = 4$),
227 AANH ($n = 1$) represented [22]. These 52 institutions are primarily public (75%) and
228 have very-high research activity (96%) [24]. The remaining institutions are classified
229 as having high-research activity (4%).

230 The 91 syllabi were analyzed to determine the required textbooks for the courses.
231 To consolidate the results, unique editions of the textbooks were not separated within
232 the data presented in this paper.

233 To determine the topics taught within the quantum field theory courses, an emer-
234 gent coding method was used [25]. All topics mentioned in the syllabi were recorded.
235 Using the table of contents from Peskin and Schroeder’s *An Introduction to Quantum*
236 *Field Theory* [31], closely related topics were combined. Table 7 below presents the
237 overarching themes within the syllabi, along with the topics coded under each theme.
238 Several topics did not clearly fall into these overarching themes, and will therefore
239 appear in the results despite not appearing in Table 7. Due to some syllabi not con-
240 taining a list of topics or course schedule, only 85 of the quantum field theory courses
241 were utilized for determining the course content. These 85 courses were offered across
242 52 different institutions.

243 5 Graduate-level quantum requirements and electives

244 From the 184 institutions course catalogs, graduate bulletins, and/or physics depart-
245 ment graduate handbooks, the results of the number of core courses can be found in
246 Figure 1. The majority of graduate physics programs in this study required two core
247 courses (60%), followed by one course (26%). Only some of the institutions in this
248 study did not require any quantum core courses (7%) or required three courses (6%).

249 5.1 Core courses

250 The most frequent research fields across the 80 physics departments analyzed were con-
251 densed matter (84%), high energy (75%), biophysics (70%), and astrophysics (65%).
252 All other research fields were found at less than half of the departments and can be
253 found in Figure 2.

254 Using the data generated from the number of core courses required and the research
255 fields of the 80 institutions, the heatmap in Figure 3 was produced. This map demon-
256 strates the number of core courses required at an institution with the specific research

257 type. The data was normalized horizontally so that the colors would still be dis-
258 tinguishable even for research fields that are less common. For example, only two
259 departments conducted research in the renewable energy sphere. One of these depart-
260 ments required one core course, and the other required two core courses. Therefore,
261 in Figure 3 one course has 50% and two courses has 50%. It can be extrapolated from
262 Figure 3, that fields such as applied physics in this dataset were most likely to have
263 zero core courses, while fields such as computational physics or nonlinear dynamics
264 were most likely to have two core courses.

265 The results of the textbook analysis revealed that across the 68 institutions that
266 required one or more core courses, the majority of the first semester core courses
267 (41.2%) required Sakurai’s *Modern Quantum Mechanics*. The next most common
268 occurrence was to not require or not specify a textbook for the course at all (16.2%).
269 An interesting occurrence that was not found in a similar undergraduate-level quan-
270 tum mechanics textbook analysis [9], was that instructors would utilized a textbook
271 they were working towards publishing themselves (4.4%).

272 From the 67 institutions that were analyzed for themes and topics taught in the
273 core curriculum, it is no surprise that kinematics (99% of curricula), angular momen-
274 tum (91% of curricula), approximations (91% of curricula), and dynamics (90% of
275 curricula) were most commonly included in the course outline of the syllabi, as these
276 are associated with chapters in the first half of Sakurai [26]. The results of the themes
277 analysis can be seen in Figure 4. Both the percentage of institutions that included
278 them within their entire core curricula and the percentage of the total core courses
279 analyzed that included the theme can be seen. There were however, 69 topics that were
280 only introduced within one institution’s curricula, and therefore would only account
281 for 1.25% of institutions. The topics can be found in Table 5.

282 The results of the NLP topics identified by BERT after the syllabi were manually
283 cleaned of all text not directly related to course topics can be found in Table 4.

284 5.2 Quantum field theory courses

285 From reading through the course catalogs of the 184 institutions, it was found that 68
286 institutions offered zero quantum field theory courses, 35 offered one course, 50 offered
287 two, 23 offered three, 4 offered four courses, and one institution offered five courses.

288 From the 91 quantum field theory course syllabi, the most commonly (30%)
289 required textbook was by Peskin & Schroeder [31]. The other required textbooks can
290 be found in Figure 7. Due to some courses requiring more than one textbook, the total
291 percentage in the graph adds to more than 100%.

292 From the 85 quantum field theory syllabi that themes could be discerned from,
293 the most commonly included themes were interacting fields & Feynman diagrams
294 (72%), quantum electrodynamics (71%), and radiative corrections (68%). The com-
295 plete results are shown in Figure 6. There were 34 topics that appeared in only one
296 syllabus and did not have a direct connection to belong as a code in the overarching
297 themes. These 34 topics are displayed in Table 7.

6 Discussion

299 This study provides the first comprehensive national map of graduate-level quantum
300 instruction in US physics doctoral programs. Our findings reveal a curriculum anchored
301 by a canonical set of topics, most often taught through Sakurai’s Modern Quantum
302 Mechanics, alongside striking variability in QFT instruction and the treatment of
303 foundational tools such as Dirac notation. Graduate quantum coursework thus plays
304 a dual role: establishing a shared disciplinary baseline while reflecting the distinct
305 research strengths of individual departments. At the same time, this unevenness raises
306 important questions about equity of preparation, the assumptions faculty make about
307 prior knowledge, and how differences in training shape both student trajectories and
308 the physics community more broadly.

309 Variability in graduate curricula can be interpreted in two ways. On one hand,
310 it may signal inequitable access, as students’ opportunities depend heavily on where
311 they enroll. On the other, it reflects the diversity of research cultures within physics
312 departments. As shown in Figure 2, the number of required courses correlates with
313 departmental research areas: some fields require deep engagement with quantum
314 mechanics for computations and algorithms, while others demand only a foundational
315 grasp. This suggests that variability is not simply noise but a reflection of disciplinary
316 need.

317 Our analysis of course topics shows a clear distinction between universally taught
318 material and specialized, research-driven emphases. Any well-rounded physicist is most
319 likely familiar with the topics in the first half of Sakurai, while niche expertise often
320 emerges from the more specialized topics listed in Tables 5 and 7. Graduate coursework
321 therefore balances two imperatives: establishing a common foundation and equipping
322 students for divergent research trajectories.

323 A particularly revealing case is the use of Dirac notation. At the undergraduate
324 level, only 34% of curricula explicitly introduced this notation [9]. In graduate school,
325 by contrast, Dirac notation is nearly universal, owing to its central role in Sakurai and
326 in graduate-level instruction more broadly. This discrepancy points to a gap between
327 the undergraduate and graduate curricula. Because Dirac notation is fundamental to
328 quantum mechanics, it is imperative that students develop fluency with it [32].

329 Yet even at the graduate level, mastery is not guaranteed. Singh and Marshman
330 found that graduate students often struggled with Dirac notation, giving answers
331 that were highly context-dependent [32]. One reason may be that many students first
332 encounter the notation in graduate school. Moreover, Sakurai’s treatment is abstract
333 and generalized, in contrast to the more concrete style of undergraduate texts, poten-
334 tially compounding difficulties. Students from undergraduate institutions without
335 exposure to Dirac notation thus enter graduate study at a disadvantage compared
336 with peers, highlighting an equity issue. Faculty expectations in graduate courses and
337 assessments may presume prior familiarity, meaning students may struggle not from
338 lack of ability but from differences in preparation. This misalignment may help explain
339 why some students report stress and even trauma around qualifying exams [?].

340 These findings highlight an opportunity to intentionally bridge the undergradu-
341 ate–graduate gap. Graduate programs could integrate targeted modules or refreshers
342 to scaffold the transition to abstract formalisms, while undergraduate programs might

343 expand coverage to ensure students are better prepared. Addressing such gaps is
344 not merely a pedagogical concern but also central to building a more diverse and
345 representative physics community.

346 The treatment of QFT within graduate curricula further illustrates both com-
347 monalities and disparities. Real-world multiparticle systems are governed by QFT
348 [33], making it a cornerstone of modern physics. Yet 37% of graduate programs list
349 no formal QFT course, relying instead on research groups or self-study. Among the
350 remaining institutions, offerings vary from one to five courses. Where QFT is taught,
351 there is strong consensus around a core set of topics: interacting fields, Feynman dia-
352 grams, and quantum electrodynamics, with Peskin & Schroeder [31] as the dominant
353 text. This reflects a shared disciplinary view of QFT as both a calculational frame-
354 work and a theoretical foundation. However, the emphasis on perturbative methods
355 leaves other approaches less systematically addressed.

356 Beyond this core, heterogeneity is pronounced. Some institutions extend instruc-
357 tion to renormalization group methods, non-Abelian gauge theories, or string-inspired
358 frameworks, while others remain at introductory levels. The 34 topics appearing in
359 only a single syllabus—including cosmic inflation, dark matter, and holographic dual-
360 ities—underscore how specialized content reflects local faculty expertise rather than
361 a standardized national curriculum. This mirrors patterns in quantum mechanics
362 coursework and suggests that graduate curricula are shaped as much by institutional
363 priorities as by shared disciplinary norms.

364 These disparities raise broader questions about what graduate students are
365 expected to learn through coursework versus through research. For some, the absence
366 of formal QFT training may be inconsequential. For others, especially those entering
367 high-energy theory or condensed matter fields, the unevenness of QFT instruction may
368 contribute to disparities in preparation and opportunity. Future work could explore
369 how students perceive this variability, how it influences career trajectories, and whether
370 greater standardization in graduate QFT curricula is warranted.

371 Our study also illustrates the potential and limitations of NLP for large-scale cur-
372 riculum research. When applied to syllabi, NLP reliably identified structural elements
373 such as references to textbooks and policies, but it struggled to capture the nuance of
374 instructional content. Compared with human coding, NLP underrepresented the fre-
375 quency of topics and sometimes misaligned with disciplinary meanings. These results
376 echo findings from undergraduate studies, where NLP replicated broad themes but
377 lacked precision and interpretive depth.

378 The limitations emphasize the importance of human expertise: instructors and
379 researchers bring disciplinary knowledge that allows them to distinguish between
380 superficial lexical similarities and genuine thematic overlap. Nonetheless, NLP adds
381 value as a complementary tool. Paired with human coding, it can serve as a form of
382 cross-validation, providing independent evidence of broad curricular patterns while
383 highlighting areas of disagreement for closer inspection. This balance reduces the
384 risk of over reliance on either method alone: human coding captures nuance but is
385 resource-intensive, while NLP offers efficiency but lacks disciplinary sensitivity.

386 Looking forward, domain-specific language models and hybrid human–AI work-
387 flows may improve the reliability of NLP in physics education research. For now, NLP

388 should be viewed not as a replacement for expert analysis but as a way to enhance
389 scalability, transparency, and reproducibility in curriculum studies.

390 Ultimately, the uneven landscape we document is not just a reflection of academic
391 freedom but a structural feature with consequences for equity and access. Students
392 from less-resourced institutions may encounter key formalisms for the first time under
393 the high stakes of graduate coursework or qualifying exams, while disparities in QFT
394 offerings leave some students exceptionally well prepared and others reliant on self-
395 study. These differences risk reinforcing inequities in who thrives in advanced physics
396 and who contributes to the emerging quantum workforce.

397 At the same time, this work demonstrates that large-scale, mixed-method
398 approaches can provide new insights into disciplinary training. Our analysis offers
399 not only the first national map of graduate quantum curricula but also a model for
400 how physics education research can inform equity, curriculum design, and workforce
401 development. Moving forward, physics departments, professional societies, and policy-
402 makers must grapple with what should be considered the “core” of graduate quantum
403 education and how to ensure that all students have equitable access to it. Aligning edu-
404 cational structures with the demands of physics and its increasingly quantum-enabled
405 society is both a disciplinary and societal imperative.

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Table 2: Overarching themes and their associated topics generated from emergent coding of 119 core course syllabi across 67 institutions

Kinematics	Dynamics	Angular Momentum	Symmetry
Fundamentals States	State evolution Heisenberg picture	Angular momentum eigenstates & eigenvalues	Discrete Continuous
Uncertainty	Heisenberg equation of motion	Orbital angular momentum Spherically symmetric potential stationary states	Translational invariance Lattice translations
Operators	Schrödinger picture	Isotropic harmonic oscillator	Rotational invariance
Measurement	Stationary states	Rotation	Space inversion
Stationary distributions	Schrödinger equation	Spin	Time reversal
State vectors	Spin precession	Clebsch-Gordan (CG) coefficients	Rotation group
Observables	Ehrenfest theorem	Pauli-two component formalism	Parity
Postulates	Ehrenfest theorem	Ladder operators	Conservation
Linear Algebra	Time evolution	Spherical harmonics	Kramers' theorem
Hilbert Space	Path integrals	Bell's inequality	
Dirac notation		Wigner-Eckart theorem	
		Rabi Oscillations	
Approximations	Scattering	Identical particles	QFT
Perturbation theory: nondegenerate, degenerate, time independent (TI), & time	Scattering as TD perturbation theory Scattering amplitude Phase shift	Permutation symmetry Symmetrization postulate Two-electron system Helium atom	Relativistic QM Relativistic wave equation Paths to relativistic QM Relativistic TD Schrödinger

dependent cases WKB Adiabatic Berry's phase Fine structure Zeeman effect Stark effect Variational Methods Interaction picture Hamiltonians with extreme TD Applications to interaction with radiation Energy shift Decay widths Dyson series Sudden approximations Effective Hamiltonian Fermi's golden rule Landau-Zener formula Lamb shift	(TD) Born approximation Partial waves Eikonal approximation Low energy scattering Resonance scattering Symmetry in scattering Inelastic electron-atom scattering Lippmann-Schwinger equation Breit-Wigner distribution Rutherford scattering Ramsauer-Townsend effect	Multi-particle states Multi-particle wavefunction Fermions & bosons Indistinguishable particle Density functional theory Two particle scattering cross section	equation Klein-Gordon equation Klein-Gordon fields Dirac equation Dirac fields Quantization of EM fields Negative energies Landau theory Gauge theory Feynman Diagrams Quantum electrodynamics Gauge transformations
Ensembles	Statistical Mechanics	Potentials	Molecular
Density matrices Many particle systems Multi-particle systems Mixed states Bloch sphere Decoherence Entanglement	Entropy Stochastic processes Chaos Von Neumann Entropy Bose-Einstein Fermi-Dirac	Harmonic oscillator Wells Spherical Linear Delta Double well Periodic	Molecules Hydrogen molecules Molecular physics Born-Oppenheimer approximation

Purification Reduced density matrix Two level systems Composite systems Coherence Correlation	Gibbs distribution Renyi entropies Berry-Tabor conjector Fermi gas	Tunneling	
Quantum Information	Tunneling	Quantum Optics	Many-body Theory
Bit versus qubit Quantum information theory Computation Deutsch Algorithm Grover Algorithm	Tunneling through potential barrier Tunneling of particle through quasi-bound state Transmission Reflection	Hong-Ou-Mandel effect Dicke model Quantum theory of light	Green's function & perturbation theory Thomas-Fermi model Hartree-Fock framework
Review of Classical Mechanics	Experiments		
Galilean transformation Hamiltonian mechanics Lagrangian mechanics CM relation to QM Classical optics Lorentz transformations in special relativity	Stern-Gerlach Photoelectric effect Blackbody radiation Davidsson-Germer Double slit		

Table 3: Overarching themes and their associated topics generated from emergent coding of 85 quantum field theory syllabi across 51 institutions

Fundamentals	Klein-Gordon Field	Dirac Field	Interacting Fields & Feynman Diagrams
Lorentz transformations	Classical field theory	Lorentz invariance	Perturbation theory

Lagrangian mechanics Hamiltonian mechanics Green's functions Two-point function N-point functions Correlation function Propagators Complex Integration Pole prescriptions Groups Functional derivatives Generating functional Spectral decomposition Field integrals	Lagrangian field theory Hamiltonian field theory Noether's theorem Noether's current Klein-Gordon equation Poincaré group	Dirac equation Weyl spinors Spin sums Dirac matrices Gamma matrices Dirac field bilinears Dirac propagator Quantization of Dirac field Dirac theory Spin Chiral representations	Perturbation expansion of correlation function Wick's theorem Cross sections S-matrix Feynman rules Yukawa theory Coulomb potential ϕ^4 theory Scalar field theory Vacuum bubbles Connected diagrams Linked-cluster theorem Born approximation Decay rates
Quantum electrodynamics	Radiative corrections	Functional methods	Renormalization
Trace technology Unpolarized cross section Crossing symmetry Mandelstam variables Compton scattering Photon polarization sums Klein-Nishina formula Møller scattering Bhabha scattering Photon field Gauge field Minimal coupling Dielectric function	Soft Bremsstrahlung Electron vertex function Feynman parameters Electron self-energy LSZ reduction Optical theorem Ward-Takahashi identity Wick rotation Running couplings Dimensional regularization One loop diagrams Tree diagrams Tree-level processes	Path integrals Functional quantization of scalar fields & spinor fields Functional formalism symmetry Functional integral Photon propagator Schwinger-Dyson equation Partition function Grassman numbers Grassman variables	Renormalization group Ultraviolet divergences Renormalized perturbation theory Superficial degree of divergence Linear sigma model Goldstone's theorem Effective action Phase transitions Legendre transforms Solitons Wilson's approach

Maxwell's equations	Vertex corrections Kallen-Lehmann form Infrared divergences Cutkosky rules Lamb shift Anomalous magnetic moment Pauli-Villars regularization		Callan-Symanzik equation Coupling constants Evolution of mass parameters Effective mass Screening
Non-Abelian Gauge theories	Quantum Chromodynamics	Topology	String theory
Yang-Mills Lagrangian Gauge-invariant Wilson loop Lie algebras Casimir operator Confinement Non-abelian gauge bosons Faddeev-Popov Lagrangian BRST symmetry Gauge boson self-energy Asymptotic freedom Ghosts	Deep inelastic scattering Distribution functions Hard-scattering processes in hadron collisions Lepton pair production Jet pair production Parton evolution Altarelli-Parisi equations Gell-Mann & Low theorem Strong coupling	Topological defects Topological QFTs Chern-Simons Topology of electronic bands Topological insulators Topological bosonic excitations Topological transitions	Holographic dualities AdS/CFT
Perturbation theory anomalies	Gauge theory spontaneous symmetry breaking	Lattice Field Theory	
Axial current in 2D/4D Vacuum polarization diagrams Current operator equation	Higgs mechanism Glashow-Weinberg-Salam theory Higgs boson	Discrete fourier transforms Deterministic lattice field theory	

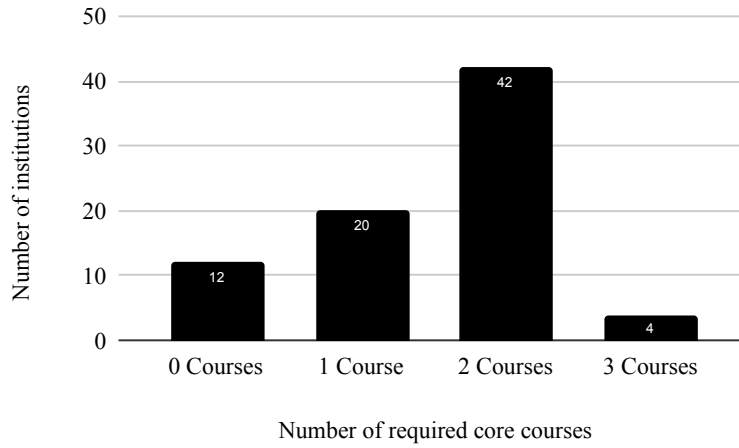


Fig. 1 Number of required core quantum courses at 184 graduate physics programs

Triangle diagrams	Quark and lepton symmetry		
Goldstone bosons	Electroweak theory		
Chiral symmetries	Goldstone boson equivalence		
Chiral anomalies			
Chiral gauge theories			

498 Supplementary information

Table 5: Topics introduced by only one institution core curricula (1.25% of institutions)

Topics introduced by only one institution
Adiabatic gauge potential
Antiferromagnetism
Asymptotic analysis
BCS theory
Berry Conjecture
Berry curvature
Bohigas-Giannoni-Schmit conjecture
Bopp representation
Chern number
Cyclotron resonance
Dirac equation symmetries
Discrete nonlinear Schrodinger equation

EBK approximation
Fermi-Hubbard model
Foldy-Wouthuysen transformation
Fubini-Study metric
Hanbury Brown & Twiss effect
Hellmann-Feynman theorem
Hole theory
Hubard model
Husimi Q representation
Ion traps
Jaynes-Cummings model
Jordan-Wigner transformation
Jump operators
Kubo formula
Landauer theory
Laplace-Runge-Lenz vector
Lieb-Liniger Model
LIGO
Lindblad equation
Local realism
Lorentz group
Many worlds
Masers
Monochromatic perturbations
Moyal product
Nagaoka ferromagnetism
Neutrinos
Noether's theorem
Number-phase representation
Objective reality
Occupation number
Phi-4/Quartic Interaction
Phonons
Photoproduction of hydrogen
Quantum gas microscope
Quantum fields
Quantum Fisher information
Random matrix theory
Renormalization group
Resolvent operator
Schur's lemma
Spontaneous symmetry breaking
Standard Model

String theory
Superconducting quantum interference device (SQUIDs)
Superfluidity
Superoperators
Theory of continuous groups
Time-ordered product
Tonks-Girardeau gas
Two-site Bose-Hubbard model
Wigner-Brillouin perturbation theory
Wigner surmise
Wigner-Weyl transform
Young tableau
Yukawa potential
Zeno effect

Table 1 Qualitative codes to condense research fields of 80 US physics departments

High Energy	QTSE
Particle physics Elementary particles Fundamental interactions Beam/accelerator Phenomenology Dark matter Neutrino Subatomic	Quantum science Quantum phenomena Precision quantum measurement Quantum devices Quantum materials & matter Quantum information Photon activation analysis Quantum computation Quantum error correction Quantum electronics Electronic structure of nanoparticles
Optics & Photonics	Materials
Quantum optics Nano-optics/photonics Nonlinear optics Ultrafast optics Spectroscopy Laser Science	Material science Materials engineering Novel materials Glass/polymer/ceramic electronics Cryogenics Polymers
Nonlinear Dynamics	Biophysics
Statistical physics Chaos Complexity Statistical mechanics	Living matter Membranes Biomedical neuroscience
Nano-scale	Earth Physics
Nano-crystallography Nano-optics/photonics Nano-technology Carbon nano-materials	Atmosphere Climate Geophysics Planetary
Nuclear	Medical
Strong interactions Subatomic Medium energy	Reactors for patient treatment Biomedical Neuroscience
Computational	Observation
Artificial intelligence Machine learning Simulation	Observational astrophysics Observational cosmology Observational astronomy
Cosmology	Applied Physics
Galaxies Galaxy groups/clusters	Engineering physics Applied mechanics
Astrophysics	Instrumentation
Multi-messenger/wavelength Solar physics	Astrophysics instrumentation Remote sensing
Condensed Matter	Fluids
Solid state Single molecule electronics	Fluid dynamics Super fluids
Soft Matter	²³ Space Science
Soft condensed matter	Planetary
Plasma	Quantum/Gravitational Fields
High energy density	Relativity
AMO	Renewable Energy
Chemical physics	Solar cells
Biophotonics	Astroparticle
Mathematical Physics	Physics Education Research
Astronomy	Acoustics

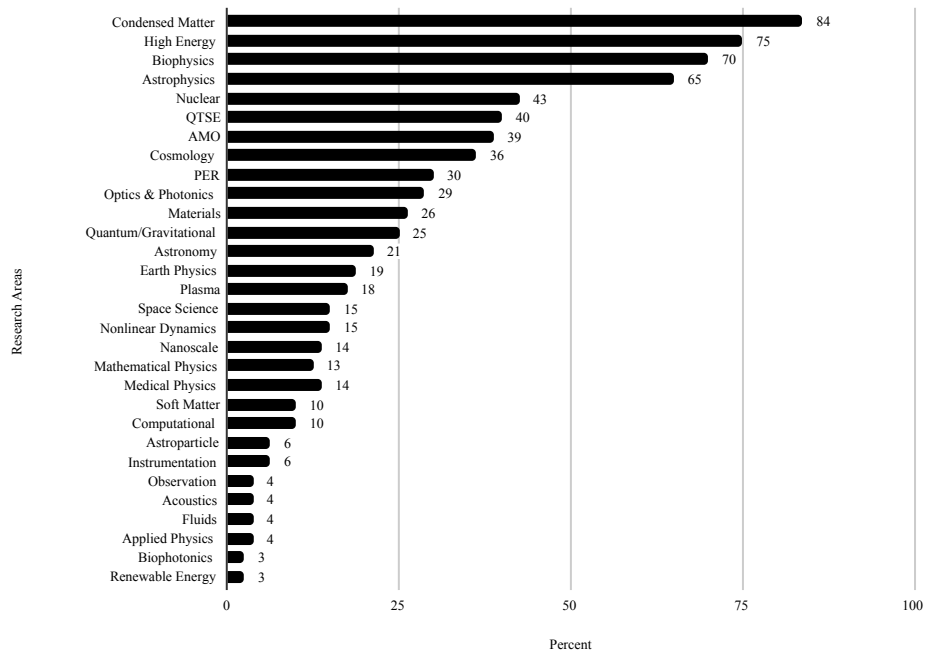


Fig. 2 Research fields across 80 physics departments

Table 4 Five most frequent identified topics by BERT after syllabi were cleaned of text not related to course topics.

Frequency	Ten most relevant words	Prototypical sentence fragment
38	quantum, schrodinger, atoms, scattering, particles, atom, quantization, particle, electron, feynman	topics fundamental concepts quantum dynamics theory of angular momentum symmetry in quantum mechanics chapter approximation methods time independent perturbation theory non degenerate
37	chapters, topics, learning, textbook, outline, math, objectives, prerequisite, books, skills	my aim this quarter is to cover sakurai napolitano sn chapters with some additional material included as needed
32	quantum, qm, introductory, prerequisites, courses, introduction, overview, undergraduate, concepts, physics	course objectives after completing this course and ph you should have a working knowledge of the foundations formalism and basic results of quantum mechanics be able to understand quantum
30	perturbations, perturbation, approximations, variational, approximation, approximate, stationary, methods, transitions, variation	some nuclear physics hydrogen dynamical pdf nuclear jan approximation methods wkb time independent perturbation theory variational method wkb time indepent perturbation theory fine structure h
28	symmetries, symmetry, hamiltonian, invariance, supersymmetry, transformations, lattice, ergodicity, translations, inversions	symmetries in quantum theory conservation laws degeneracies continuous translation symmetry discrete translation symmetry crystal momentum bloch s theorem rotation symmetry angular

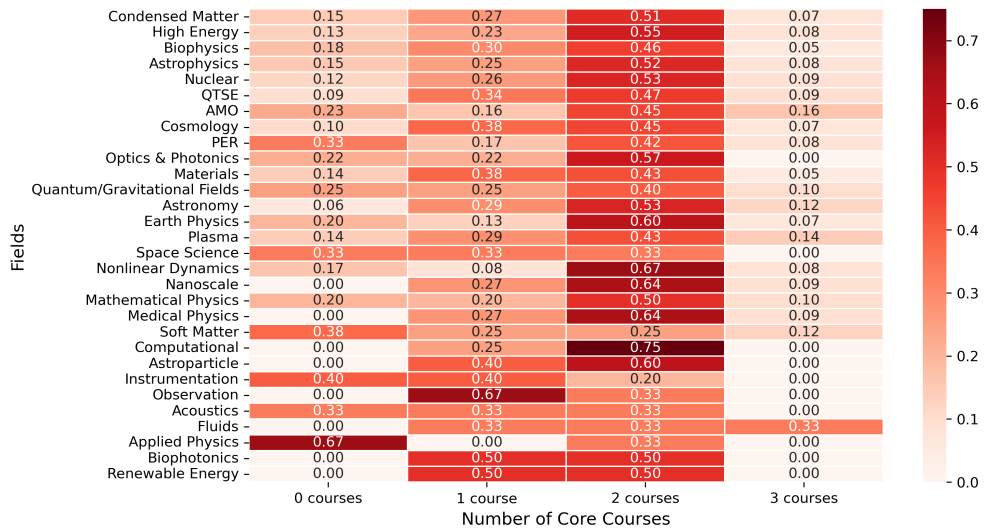


Fig. 3 Correlation between the number of courses required at an institution with research fields

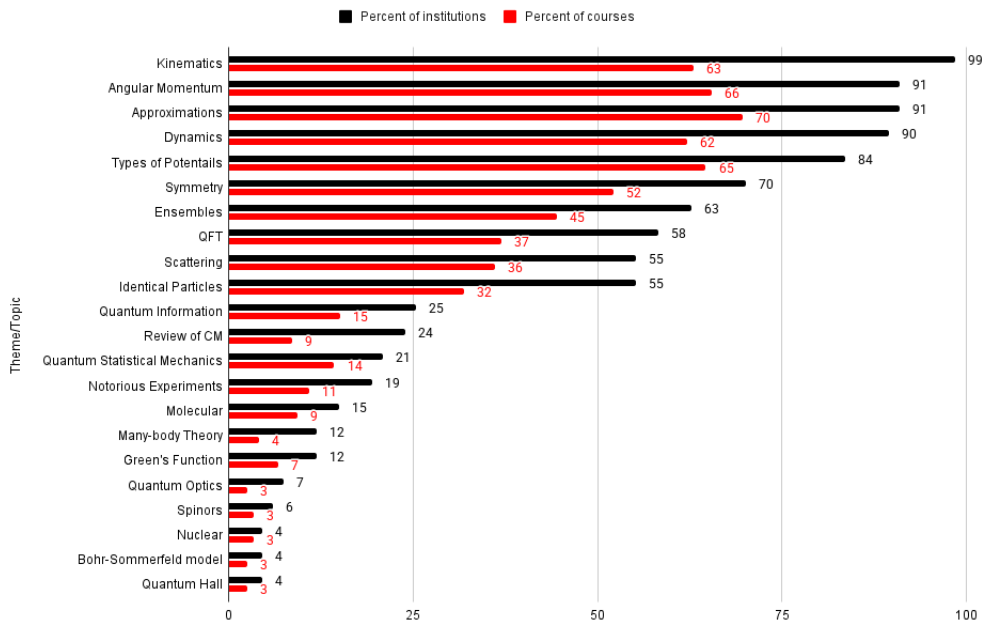


Fig. 4 Themes found in core courses across 119 unique course syllabi and across 67 institutions curricula

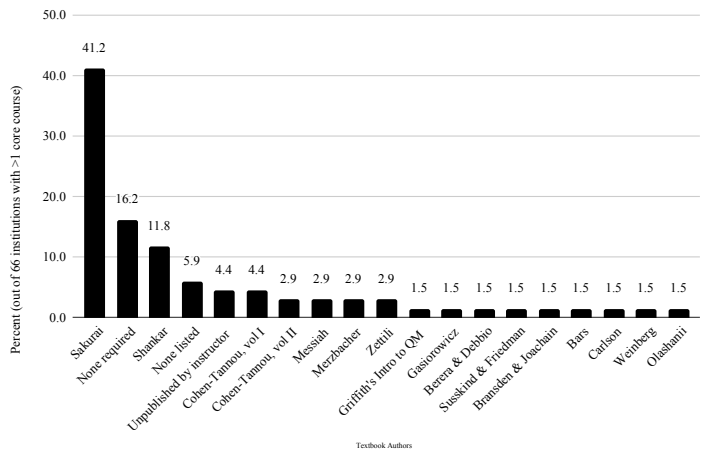


Fig. 5 Textbook required for first semester graduate quantum mechanics courses across 66 institutions

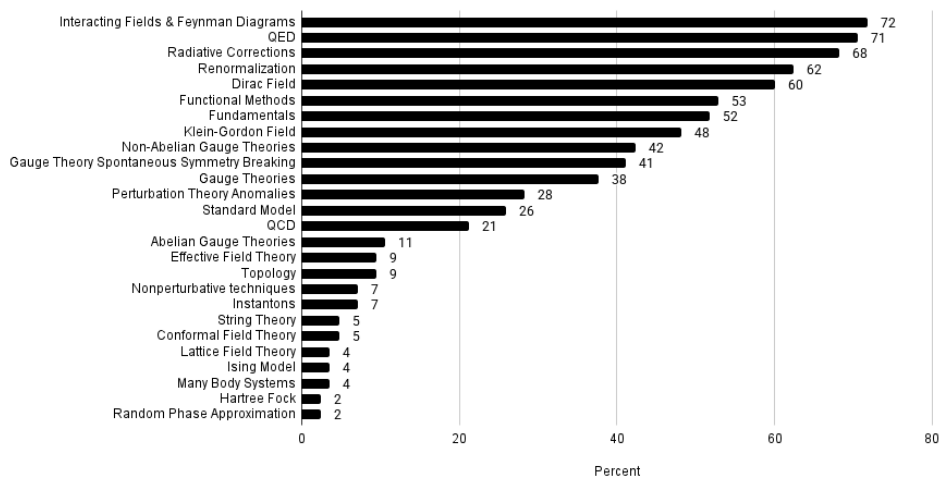


Fig. 6 Themes present in 85 quantum field theory syllabi from 52 different institutions and their percentages.

Table 6 Five highest frequency topics identified by BERT.

Frequency	Ten most relevant words	Prototypical sentence fragment
67	quantum, topics, schrodinger, heisenberg, particles, feynman, scattering, introduction, atom, hilbert	proposed schedule of topics session date topics reading march symmetries and conservation laws april inversion and translation symmetries april time reversal symmetry april april degenerate time
57	lectures, lecture, presentations, topics, discussions, presentation, courses, curriculum, subjects, activities	i will also have occasional student presentations typically on a previously assigned problem small group work and concept questions to help get a discussion started
41	exams, exam, examinations, examination, midterm, midterms, semester, finals, quizzes, tests	exams there will be a midterm exam and a final exam
37	grading, grades, grade, exams, exam, scores, assignments, grader, score, marking	grading policy the final scores will be based on the two exams and the homework with breakdown as follows homework midterm exam final exam the letter grades will be assigned based on the final scores
36	textbook, books, texts, book, chapters, library, bookstore, isbn, bibliography, abebooks	you are encouraged to read the chapters and sections related to the topics from the textbook and reference books and to discuss with your fellow students or the instructor to make clear in concepts

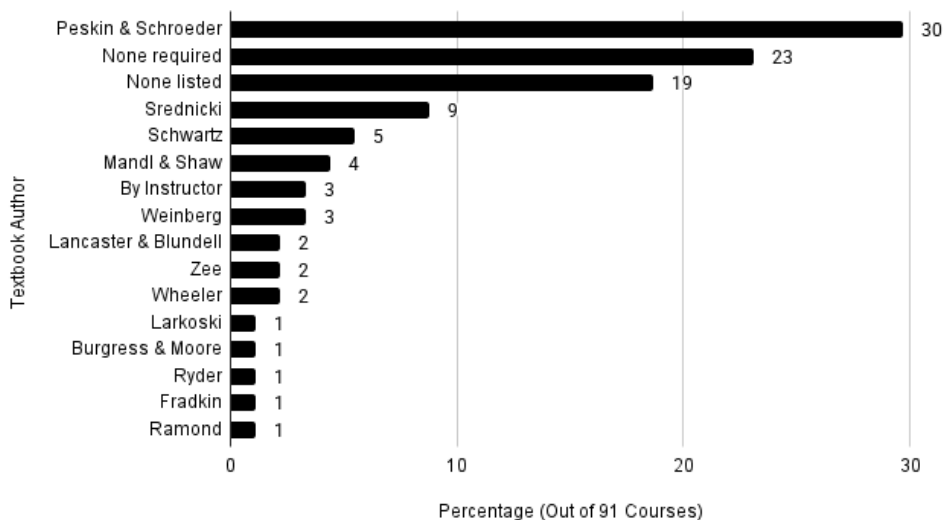


Fig. 7 Textbooks required for 91 quantum field theory courses offered at 52 institutions. The total percentage within the graph adds to more than 100%, due to some courses requiring more than one text.

Table 7 Topics only explicitly mentioned in one quantum field theory syllabi

Quantum hall effect
Spin-waves
Interacting electron gas
Collective excitations
Zero modes
Cabibbo-Kobayashi-Maskawa matrix
Lepton & baryon number violation
Nonperturbative lattice formulation
Blackbody
Froissart bound
Inhomogeneous vacuum field configurations
Gervais-Neveu gauge
Random walks
Mean field theory
Aharonov-Bohm effect
Wess-Zumino-Novikov-Witten models
Dark matter
Cosmic inflation
Quantum gravity & black holes
Bogomol'nyi completion
Matsubara representation
Keldysh-Schwinger formalism
Ballistic versus disordered dynamics
Random matrix theory
Wigner-Dyson versus Poisson level statistics
Quantum dots
Complex nuclei
Spin-glasses
Sherrington-Kirkpatrick
Sachdev-Ye-Kitaev
Theory of localization
Finite-N techniques
Glashow-Iliopoulos-Maiani mechanism
Grand unification