Prelecture Questions and Conceptual Testing in Undergraduate Condensed Matter Courses

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Abstract: Prelecture questions have long been used in a variety of courses within STEM to motivate prelecture reading and to help class time be used more efficiently. It is difficult to incorporate prelecture questions into many advanced topics courses and to determine their effectiveness, due to the necessary content knowledge within specialized areas, and due to the small number of students enrolled in these courses. Here, we report on the implementation of a set of approximately 110 prelecture questions over two years of instruction in a special topics course in condensed matter physics. We report quantitatively on student difficulties with different prelecture questions and on their improvement on a survey of condensed matter concepts given at the beginning and end of the course. We report qualitatively on interviews with students in a graduate condensed matter course.
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I. INTRODUCTION

Physics education researchers have a long history of improving physics courses through iteratively developing instructional materials and conceptual assessments to ensure learning goals are being met [1, 2]. This process has been extended from introductory courses to advanced courses [3] such as undergraduate quantum mechanics, and in some cases even to graduate-level courses [4,5]. However, there has been very little work on upper-level special-topics courses such as courses on condensed matter/ solid state physics. One clear challenge (and perhaps one reason for limited work in the area) is the need for specialized content expertise in the topic of study. One of the authors (Porter) has significant expertise in condensed matter, thus this topic is the focus of this study.

The small amount of pioneering work that has been done in studying physics education in the condensed matter context has been focused on laying much-needed foundational work. For example, Sharma et al. [6] describe the potential disconnect between the focus instructors and evaluators in the Indian education system, and the resulting frustration for students. They give an example of a broad topic in condensed matter (crystal structure) and break it down into more specific subtopics and identify expectations that both evaluators and instructors should have of students in these subtopics. A related attempt to formalize expectations of students in a Solid State course (although this time focusing specifically on the underlying quantum mechanics critical to solid state devices and materials) came from DiNardo et al. [7]. In that work, a list of canonical topics critical to the field is presented. There have been a handful of other investigations that focus on a single subtopic (such as the Fermi energy) [8], or that focus on the nanoelectronics applications of condensed matter physics [9]. The preliminary foundational work put forth by these and other authors has enabled us to begin exploratory attempts to use proven pedagogical best practices to improve student learning and assess their conceptual understanding of important course topics.

The goal of this exploratory study is to investigate potential student difficulties with a selection of condensed matter concepts and to pilot test a collection of prelecture questions for an upper-level special-topics condensed matter course. This course typically has low enrollment, thus the number of participants in the study is quite low (about 20). Such low numbers naturally limit the generalizability of this, study but the results can help to provide direction for future study.

II. METHODS

The data collected are a mixture of qualitative and quantitative, falling into three types: (1) preliminary student interviews with three graduate student volunteers, (2) two cohorts' responses to prelecture questions written for the undergraduate condensed matter course, and (3) one cohort's performance on a conceptual assessment

Early interviews of graduate students in the final weeks of a graduate-level condensed matter course at OSU were conducted one year prior to undergraduate investigation. Participants were three students who responded to a course-wide email, and they were compensated with a gift cards. These interviews were recorded with participant permission. Students were first given a brief, 10-question survey, largely conceptual in nature, which typically took students about 10 minutes to complete. Investigators then conducted interviews ranging in duration from 20-40 minutes. In some cases, cursory review of the short survey provided the interviewers with questions, but most interview discussion came from topics identified by past instructors and advisors as being especially important.

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Students were given prompts on those topics and asked to explain a concept or experiment, and were asked to explain their thinking, sketch diagrams, and give examples.

At the undergraduate level, two cohorts were given prelecture questions and the second cohort was also given a conceptual survey of topics important in condensed matter physics. The prelecture questions were designed in consultation with the course instructor to emphasize key points from the reading, and the efforts were also somewhat informed from the misunderstandings observed at the graduate level. The questions were presented to students a day or two before each class, and submissions were cut off two hours before the class began. Questions were largely qualitative and covered basic understanding of the reading assigned to students for the next class meeting. Each assignment typically consisted of about four to five questions, with the total number of questions in the semester being 107 and 110 for the two respective cohorts. The questions ranged from multiple choice (MC), multiple-select / select all that apply (MS), and true/false (TF). Each assignment also solicited student feedback on what topics were most confusing or interesting. These questions were initially given in spring of 2015 (N = 7), and were repeated with minor revisions and a few additions in spring of 2017 (N = 10). Questions were accessed and answered online using OSU's course management system. After every attempt, students were told whether their answer was correct or not, but the correct answer was not provided. Students were allowed to submit answers arbitrarily many times, such that sometimes the number of attempts is a more useful measure of student difficulty than final score.

Students in the second undergraduate cohort (spring 2017) were also given pre and post assessments. These were 23 and 25 questions long, respectively, largely qualitative, and ranged from knowledge one might consider prerequisite knowledge/skills such as basic concepts in quantum mechanics (such as expectation values), to topics emphasized in the course. These assessments were also administered online. Answers were typed in free-response format. Students were instructed not to consult any outside sources and to answer questions using their own understanding. Students received full credit for completing the assessments, regardless of their performance, so there would be little incentive for cheating.

III. RESULTS & DISCUSSION

A. Graduate Interviews

The three graduate students interviewed were able to successfully answer many of the questions, although they sometimes required guiding questions and sometimes vacillated in their opinions. We focus here on three areas of student difficulties that were observed in multiple student interviews. These are the Hall effect, the origins of ferromagnetic ordering (FMO), and band structure. All topics had been covered in class prior to the interviews.

The Hall effect refers to the accumulation of a transverse voltage on a current-carrying slab in a magnetic field, due to the Lorentz force on the charge carriers. It is useful for identifying charge carrier type (hole or electron) and the charge carrier density. Students were prompted with a question about how they would go about determining the charge carrier density of a sample experimentally (with no mention of the words "Hall effect"). If necessary, students were directly asked "Explain the Hall effect".

Students 1 and 2 did not mention the Hall effect as a way of determining charge carrier type or density. When asked to explain the Hall effect, these two students were able to correctly explain the underlying physics and sketch the setup, though they could not connect this to a method of determining the sign of the charge carrier. Student 3 initially stated "You can apply a voltage across the sample and see which way the current goes." This student could not elaborate on how one "sees which way the current goes" and did not mention a magnetic field. The student then began to discuss the spin Hall effect, and was very clear that in that case a magnetic field is necessary. After being asked whether a magnetic field is required for the classical Hall effect, the student thought aloud for a few minutes, sometimes giving conflicting answers. Student 3 eventually said "yes", but was not able to explain why.

Band structure is a map of allowed electron energies in a periodic system as a function of the electron's momentum, and band structure diagrams are a fundamental tool commonly used in condensed matter research. Students were asked to simply explain "What is a band structure?" They were then pressed for details about the meaning of gaps, the meaning of the axes on a typical band structure diagram, and other attributes.

All three students were able to describe band structures, including the meaning of the traditional axes. Student 3, for example, explained "The letters across the bottom refer to high-symmetry point in the Brillouin zone." Further, all three drew structures that had band gaps, a common (but not necessary) feature in band diagrams. When asked whether they had drawn a conductor, semiconductor or insulator, all said either "semiconductor" or "it depends on the size of the gap; could be an insulator or a semiconductor". No student indicated the location of the Fermi level on the diagram, which is necessary for the determination of conductivity. When pressed further "Is there anything else you need to know in order to determine if this material is semiconductor?" only one student finally stated that the Fermi energy must be at the gap.

We also posed a question about FMO, since anecdotally, we have found that students have difficulty with the mechanism for producing FMO. Specifically, FMO is a subtle result of the quantum mechanical exchange interaction and Coulomb forces between electrons, but we have found that students often believe that FMO is due to magnetic dipole interactions or other effects. Thus students were asked whether FMO can be explained by magnetic dipole-dipole interactions between neighboring spins. This question was followed up with “What is the physical origin of FMO?” or “What is another contributor?” if they strongly adhered to dipole-dipole interactions.

Student 1 was initially confident that dipole-dipole interactions could not play a major role, arguing “In many cases, the dipole-dipole interactions would cause neighboring spins to anti-align.” But this student could not say anything about the exchange interaction or Coulomb effects in general. In fact, when pressed, the student replied “Once they all align, there is a net field that helps others align”. The interviewer asked “So a single dipole-dipole pair interaction does not explain it, but that sort of a bulk field produced by many dipoles does?”. The student responded “Yes, it’s like once it happens in a small section, it propagates outward.” This student is apparently using the concept of spontaneous symmetry breaking (which is critical in understanding the direction of magnetization) to justify dipole fields as the driving force behind FMO.

Student 2 said “I think yes, (dipole-dipole interactions) might be sufficient to explain FMO”. When asked whether this was always a sufficient explanation, student 2 replied “I think it isn’t always. I don’t think we talked about it much.” When pressed for an alternative, Student 2 said “I think we talked about Coulomb effects”, but could not explain what that meant or how it could promote FMO.

Student 3 stated: “Somewhat, I know you can make a macrospin approximation. Large spin moments behave more classically and you can treat them like classical spin vectors. Apparently, this student was thinking about the correct assertion that large spins (such as Mn) can often be treated classically in terms of smoothing their projections from the quantized case to a continuous, classical case. But student 3 was confused in stating that this approximation can somehow be used to explain FMO. When asked for alternative explanations, student 3 very clearly explained the exchange interaction, including why fermions energetically prefer spin alignment.

B. Undergrad Conceptual Surveys

One cohort of students in the undergraduate condensed matter course was given a conceptual survey consisting of 23 pretest questions and 25 posttest questions. Course enrollment was low, leaving $N_{\text{pre}} = 10$, and $N_{\text{post}} = 7$. A subset of 11 questions was repeated verbatim on the pre- and posttests. The remainder of the pretest was made up largely of questions relating to prerequisite understanding of quantum mechanics, and the remainder of the posttest was made of content questions that are unlikely to be answerable for people prior to taking a condensed matter course, such as “Explain the difference between Drude Theory and Sommerfeld Theory of conduction”.

The average score on the 11 repeated questions increased from 50% to 65%, which is only marginally significant (paired t-test, $t = 1.7$, $p = 0.06$, $d = 0.89$) due largely to the very small N. Table 1 summarizes concepts/questions that stood out as being either particularly hard for students, particularly easy, or showed particularly high/low changes from pre to post testing. For individual questions, no claims of statistical significance are made. A full list of questions is not provided here due to spatial constraints.

Table 1: Topics from the pre-post concept tests on which undergraduate students performed lowest (red) / highest (green). The four topics offset at the bottom are those with exceptional post-pre gains or losses. Dashes in a column indicate that the topic was not covered on that test.

Topic	Pre (%)	Post (%)
Role of mag. dipoles in FMO	-	5
Phonon modes and molecular motion	-	19
Deficiencies of mean field theory	-	19
Factors determining specific heat	27	-
Thermal energy in electrons vs. phonons	-	29
Sign of charge carrier from Hall effect	30	-
Diff. between ferro- and paramagnets	80	-
Drude vs. Sommerfeld theories	-	95
Taylor expansion application	100	-
Ex. of mat. with high/low therm. cond.	100	-
Explain the Hall effect and applications	100	-
Microscop. origins of therm. expansion	-	100
Factors affecting E_{ground} in square well	57	43
Expectation val. vs. most probable val.	71	62
Conduction properties, given band diagram	19	48
Spatial extent of plane waves	5	62

Note that the three topics for which graduate student difficulties were described in the previous section all show up on the list of topics with low average scores.

C. Prelecture Questions

Students were generally receptive to the prelecture questions, giving comments such as “I do feel that the prelecture questions are helpful.” Students typically made repeated attempts until they answered all prelecture questions correctly. The average score for all students over all questions on their first attempt was 60%. The average score by the final attempt was 94%. Students submitted answers an average of 1.9 times before getting full points or giving up. Figure 1 shows the distribution of attempts. As expected, MS problems generally required more attempts (2.3) than MC (1.5) or TF (1.2). A two sample t test yields for the MS-MC comparison $t = 6{,}0$, $p < 0.01$, $d = 1.2$, and for the MS-TF comparison $t = 7.4$, $p < 0.01$, $d = 1.7$.

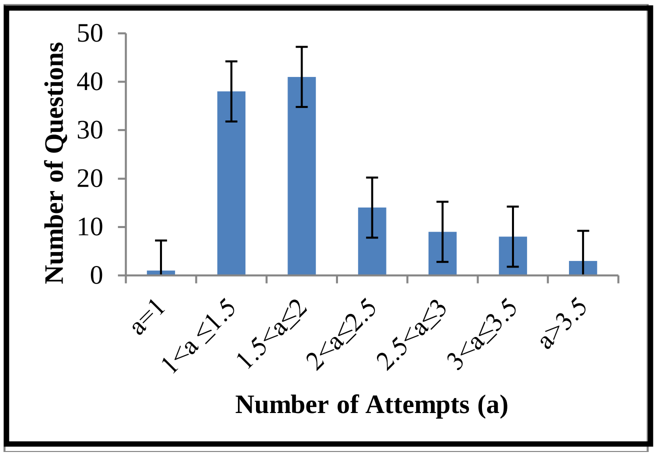

Figure 1: Distribution of average attempts required on various questions, with error bars indicating standard error. There were 110 total questions, with the number of students ranging from 14 to 19.

Care was taken not to include too many answer options on MS questions, as the number of possible permutations would lead to student frustration and complaints. Figure 2 shows an example of a MS question that is an outlier, in that students made many attempts (3.5 on average) and even then, finally scored only 74% on average.

What are Hund's rules used for? Select all correct answers.

(a) The determination of the values of *J*, *L*, and *S* for electrons in an atom.
(b) The determination of the direction of the nuclear spin.
(c) To calculate the sign of the magnetic susceptibility.
(d) To determine whether the atom has a magnetic moment.

Figure 2: A difficult MS prelecture question.

The correct answers are (a) and (d). The most common error was selecting (b) in addition, or instead of (d). The MC question requiring the highest number of average attempts (2.1) is shown in Fig. 3. The average score on this question on the first attempt was 38% and was 100% on the final attempt. The correct answer is (c), since the expulsion of magnetic fields precludes the propagation of EM waves. The most common distractor was (a).

At least for long wavelengths, the reflectivity of a material is higher if the material is in a superconducting state, than if it is in the normal metallic state. This can be attributed to…

(a) Cooper pair breaking and recombination
(b) Temperature changes brought on by the incident light
(c) The expulsion of magnetic fields from the sample
(d) The effects of exceeding the sample's critical field

Figure 3: A difficult MC prelecture question.

IV. CONCLUSION

The findings above indicate that a number of important topics in condensed matter may prove difficult for students from the undergraduate level through the graduate level. Strong candidates for such topics include the mechanism of ferromagnetic ordering, and subtle aspects of band structure. Additional candidate topics can be drawn from Table 1. It is beyond the scope of this paper to give a full accounting of all challenging concepts from the prelecture questions.

Significantly more work is needed to ascertain whether such prelecture questions adequately describe student learning in this context, or whether they improve the effectiveness of lecture through better preparation. But the questions developed as part of this study do seem to be useful to students. They also seem to be of the appropriate difficulty level, since the average score on the first attempt is 60%. They also do not appear to be excessively easy or difficult, since the average number of required attempts was 1.9.

Ideally, future work will involve collaboration between physics departments. Undergraduate special topics classes often have low enrollment, and may not be offered every year. Collaboration would improve the study's statistical significance and ensure broad applicability of the developed materials.

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