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Mixed methods Analysis of Undergraduate Quantum Mechanics: An Exploratory Case Study

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MIXED METHODS ANALYSIS OF UNDERGRADUATE QUANTUM MECHANICS:

AN EXPLORATORY CASE STUDY

by

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ABSTRACT

One key goal of Physics Education Research is providing research-based instructional techniques and tools to help assess the complex learning goals associated with a mature understanding of physics. Characterizing faculty expectations is important to produce a comprehensive understanding of knowledge students should acquire before and during a quantum mechanics course (QMC). Semi-structured interviews have been conducted with faculty members and students entering a QMC in the Physics Program at a Large Public Research University (LPRU) in the Southeast. The interviews examine perspectives of different evaluation techniques, ideal preparation, course content, and expected conceptual models of students. A post-course survey was offered to the students that took the QMC in the Fall of 2012 and to those who completed the course in the past three years. The survey addressed similar questions on evaluation, course content, and preparation. Using Classical Content Analysis and Key-Words-In-Context coding methods, contradictions and similarities within and between faculty and student populations are presented. These results are presented in an effort to highlight predictors for success in the QMC, identify common-core perceptions, and strengthen course evaluation. In all data, findings suggest that student perceptions shift towards those of faculty over the course of the QMC. Evaluation data indicate that on average the faculty members, like students, are open to a varied array of evaluation techniques, if it is within the goals of the course and does not interfere with other faculty responsibilities. In perceptions of preparation and course content, faculty have a uniform perspective of what should be prerequisite, and the student survey data strongly recommend that the second semester of Linear Algebra offered at the LPRU will help with the mathematical complexities of the QMC. Through triangulation of qualitative and quantitative results contradictions of preparation and content are exhibited through multiple media for the use course content such as the Hamiltonian.

INDEX WORDS: Physics education research, Mixed methods, Evaluation, Quantum mechanics, Qualitative analysis

MIXED METHODS ANALYSIS OF UNDERGRADUATE QUANTUM MECHANICS: AN EXPLORATORY CASE STUDY

by

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DEDICATION

To my family, without whom I'd be nowhere near the "well–rounded" individual that I am.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Richard Feynman has famously stated that "I think I can safely say that nobody understands quantum mechanics." [1] Normally, this might be interpreted as a testament to the mathematical complexity of Quantum Theory, but he was referring to the unintuitive foundational aspects of Quantum Theory. Quantum mechanics is very often one of the final courses that a student will take in their undergraduate career. Quantum Theory draws on a great deal of other upper-level mathematics and physics that the student will ideally have already experienced in some capacity. Quantum Theory also flies in the face of classical intuition that students have been developing over the course of their undergraduate career. This difficulty motivates the research to determine if there are ways to improve the preparation students have before they attempt to learn one of the more abstract and complex topics in a physics curriculum.

This dissertation is organized as follows. **Chapter One** outlines the research questions and motivations, and theoretical framework for this line of research. **Chapter Two** situates this work within the context of Physics Education Research. Details of the methodology employed to collect and analyze data are described in detail in **Chapter Three**. **Chapter Four** provides the results of analysis of perspectives on evaluation techniques, prerequisite and course material for an upper-division course such ans Quantum Mechanics. Finally, conclusions, implications, and future studies are discussed in **Chapter Six**.

This investigation describes the perceptions of faculty and the perceptions of undergraduate students taking a Quantum Mechanics course (QMC). Through interviews, surveys, document analysis, and diagnostics, we have identified predictors for success in student preparation and have compared faculty expectations of the course content, preparation, and evaluation for the course to those of students. Using the results we have developed a series of suggestions to help undergraduate students be better prepared for taking a QMC. Based on the methods employed in this research, the entire course schedule for physics majors in a physics program can be analyzed and sets of basic principles can be generated to guide student preparation for each class. This research is conducted in the form of an exploratory case study, or pilot study. This research is most useful in refining questions for a deeper or broader research questions. An exploratory case-study is used to inform a complete research design that can last several years or decades [2].

1.2 Research Questions

My interest in the particular course stems from my own difficulties in learning quantum mechanics, and discussions of the course with colleagues at different universities. The purpose of this research is produce data-driven guidance for students and instructors that will allow students greater success in a particular class. A comprehensive description of all perspectives on a course can provide insight to the parties involved in what is often referred to as the "Educational Milieu" and allow faculty members and students to make more informed decisions in their preparation for a course [3]. This body of work seeks to answer the following research questions:

- What are faculty member and student perceptions of alternative evaluation techniques?

- What are faculty member and student perceptions of QMC preparation?
- What are faculty member and student perceptions of QMC content?
- How do these preceptions compare within and between groups? Is there a "common-core" of ideas?
- Does this data suggest action that could improve student preparation for a one-semester quantum mechanics course?

These questions are addressed by triangulation of faculty and student coded interviews, survey data, and document analysis of course materials. Methods used to collect data involve acquiring data from the course in the form of recorded lectures, student assignments, and student class–notes. Interviews were conducted with students and upper-division faculty members.

1.3 Motivations

Quantum Mechanics is one of the last courses that an undergraduate student will take before they complete their Bachelor's degree. The course draws a significant amount of material from other upper-division courses in mathematics and physics. Quantum mechanics is a topic not only considered conceptually difficult, but also mathematically difficult. Institutions and instructors have their own goals for what a QMC should teach [4]. Finally, quantum mechanics is a stepping stone to a myriad of current research topics in physics. Fields such as solid state and condensed matter physics make use of quantum mechanics and provide research opportunities in academia as well as in the private sector. There is value in research that can identify preparation, content, and evaluation that can potentially strengthen students' ability to work with quantum mechanics.

A focus on evaluation of student knowledge is motivated by several points. This type of research has been conducted and published in other fields such as Chemistry Education Research, yet it has not been explored fully in the context of learning physics material [5, 6]. Evaluation also reflects the values of the instructor of the course. This is a form of data that can be used to determine the epistemological perspective of the instructor and what skills should be honed in a particular course. Research indicates that evaluation directs students perspective on what materials and skills are most important to focus on in a course [7–9].

For a vast majority of physics students, the first time they encounter an alternative evaluation technique, such as an oral examination, may be as graduate students, or in a job interview. Oral examinations provide the student with an opportunity to practice presentation and oral communication skills, while avoiding some of the issues of academic integrity. There is This type of evaluation, as well as written responses, allow the student to explain course material in their own words, which may make student thinking and prior knowledge more visible to instructors. Often this type of evaluation will be informative for both the educator and the student, and avoids the student success based on rote memorization. The instructor also has a greater degree of freedom in the depth and breadth of knowledge they choose to probe.

If instructors and students see the inherent value of oral, mathematical, and written forms of self-explanation of physical phenomena, then it should be possible to implement periodic oral exams, presentations of course material, or problems with short answer or essay components. These forms of self-explanation improve the depth of student understanding of course material [10]. One of the motivations for this work includes a better understanding of faculty members' perception of different kinds of evaluation as well as motivations or barriers to alternate evaluation techniques. By offering varied methods of evaluation to these students, Physics departments will be strengthening skills that will aid the students beyond their undergraduate education. This paper examines values of Large Public Research University (LPRU) in the Southeast faculty members and undergraduate students in the form of thirteen interviews and a survey based on the interview data. Participants' beliefs regarding what methods of evaluation are appropriate for upper-division courses are addressed in the interviews and survey. With the interview and survey data, we seek to determine if student beliefs of evaluation align or disagree with what faculty members think, and if either party believes a more comprehensive type of evaluation is needed. One goal of this research is to generate a data-driven argument for the way instructors evaluate students in upper-division courses. These students are ideally becoming expert members of the physics community with a mature understanding of physics, and their evaluation should be based on the professional skills of a physicist.

This research also examines values of faculty members and undergraduate students at the same LPRU. The student perception of course activities and material is often forgotten in education research [11]. Participants' beliefs regarding what material should be prerequisite and contained in a QMC as well as expected conceptual understanding are addressed in the interviews and survey. With the interview and survey data, we seek to determine if students' beliefs align with what faculty members actually think, and if students are informed about what they will encounter in a QMC. One goal of this research is to influence the way instructors address students in upper-division courses. A proper understanding of the foundational knowledge students possess will help if an instructor wishes to tailor their course, and this data will provide a list of important skill students should focus on as they prepare to learn quantum mechanics. A faculty members' perceptions on these topics also is indicative of their epistemological stance [12].

1.4 Research Elements

It is important to define the particular epistemology, theoretical perspective, methodology, and methods that directed how this research was conducted. These four elements of research, inform one another as shown in figure 3.1. Methods, as defined by Crotty, are the techniques or procedures used to gather and analyze data related to the research [13]. The methodology is a strategy or plan of action behind the choice and use of methods based on desired outcomes. Theoretical perspective is the philosophical stance that defines the criteria and logic employed in a methodology. Epistemology questions the nature of knowledge; how it can be acquired, and the extent to which a topic or entity can be known. Theoretical perspective is the philosophical stance that informs a range of methodologies.

Objectivism is the epistemological view that things exist as meaningful entities independent of consciousness or experience. These objects have inherent meaning, or truth that exists within them, and through careful experimental design and analysis objective truth can be obtained. Post-positivism is a theoretical perspective that posits

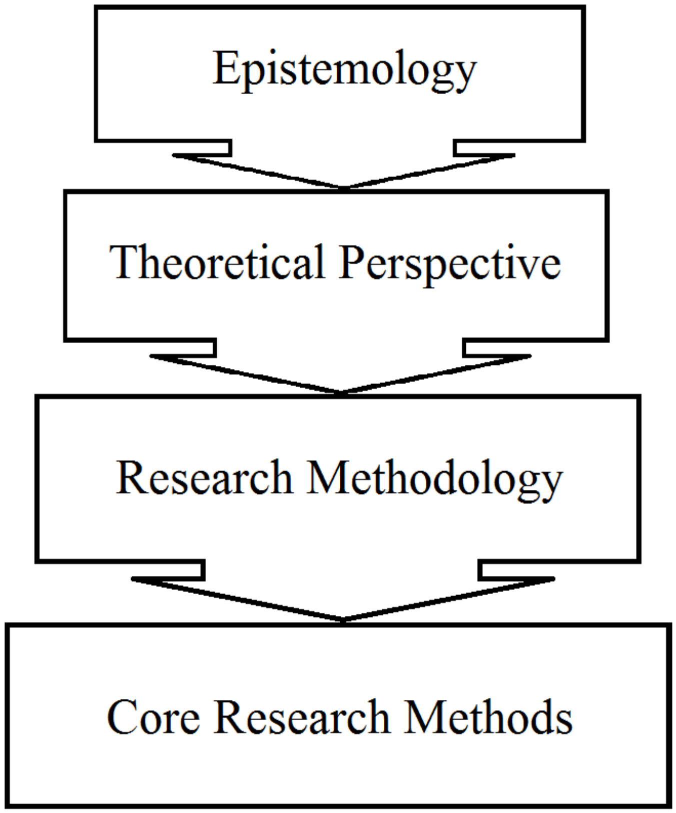

Figure 1.1: Crotty defines four elements of research; each informed by the previous element.

that an objective reality exists, but it can only be know imperfectly or probabilistically. This combination of epistemology theoretical perspective defines the perspective in which most natural science takes place. Methodologies associated with perspective are experimental research and survey research and methods include sampling and measuring, statistical analysis, and data reduction. This set of research elements informs the quantitative work associated with this mixed methods research, specifically the statistical analysis for diagnostic scores and response data.

Crotty defines Constructionism as an epistemological stance that claims all knowledge is contingent upon human practices, being constructed in and out of interaction between human beings and their world, and developed and transmitted within an essentially social context [13].This is often confused with Constructivism, which focuses on the meaning-making activities of the individual. The qualitative components of this research are framed within the Constructionist epistemology and the theoretical perspective of Interpretivism, which looks for a culturally derived and historically situated interpretation of the world. Due to the nature of this qualitative data, methodology of this work is ethnography. Methods used to collect and analyze data are case studies, interviews, document analysis, and theme identification. In this research, it is crucial to note that this set of research elements is employed to focus on the perspective data for faculty and students, as this data is more socially constructed and value–laden.

CHAPTER 2

HISTORY AND LITERTURE REVIEW

Although the topic has been discussed for over forty years, in the past twenty-five years, the field of Physics Education Research (PER) has grown tremendously as researchers study student comprehension on various physical phenomena, create models to describe student thought processes, develop curricula to improve student mental models, and evaluate the effects of research-based instruction methods. A great deal of this work has been focused on student comprehension of topics in the introductory physics sequence with a growing population shifting their interest towards the more advanced courses in a physics program. There has also been an interest in the way that perception and mental models affect the teaching and learning of material. There is a tremendous breadth of research tools, topics, and methods that are employed by researchers studying Physics Education. The focus of this introduction will be on the research leading to the work in this dissertation.

2.1 Education Research

The beginnings of education research are associated with the period of the late nineteenth century when the first research universities, such as Johns Hopkins University or Stanford University, were founded. Research institutions such as these were considered the main force in generating and disseminating knowledge. In this period of history, the dominant belief was that scientific practices could act on the social sciences in controllable ways [14]. John Dewey is one of the most well-known education researchers of this period that broke away from the belief that education was a passive endevor. Dewey's perspective argued that education and learning are social and interactive processes, and therefore the school is a social institution through which social reform can and should take place [15]. In addition, he believed that students ultimately succeed in an environment where they are allowed to experience and interact with course material, and all students should have the opportunity to be involved in these learning experiences [16]. There was a need for a theory based on principles of interaction and continuity. This highlighted the idea that experiences can be educative or miseducative, and those experiences strongly effect learners that are engaged in the material. Dewey's educational theories were all published in the early twentieth century and his perspective on education carries through those works. Dewey's educational reform ideas were also politically motivated, encouraging students to not only acquire skills in a classroom, but use them for a greater good. Education was considered, by Dewey, to regulate the processes associated with being a productive participant in social reconstruction. Many future research draw from Dewey's work the importance of the student experience with material being learned. Dewey's work suggested that it was not enough that materials and methods have proven effective with other students in different places and times [15].

Through the middle and end of the twentieth century, there are several prominent researchers that changed the way education research is conducted. Piaget was one of these individuals, and is best known for establishing genetic epistemology [17]. This work does not use epistemology in the traditional sense of the term, but in a way that takes into account the development or changes in epistemology. This can be interpreted as epistemological changes such as those exhibited by physicists' understanding shifting from popular scientific determinism to the Copenhagen Interpretation of quantum mechanics at the beginning of the twentieth century. This example cites an epistemological change over the course of a career, but this can be and was applied to child cognitive development.

Elliot Eisner also contributed to education research through curriculum development theory. The term educational "milieu" was coined to describe the combination of content, rewards, faculty members, and facilities that describe a learning environment [3]. The more noted interpretation on genetic epistemology is the development of childrens' cognition. The process by which development and formation of a new cognitive stage is key. The subject performs an action that classifies the action and its effects, and through repeated actions with variations or changes in context, the subject is able to differentiate variations and their effects. As the previous step is occurring, the subject is also identifying objects as defined by the way different actions effect them. The ultimate goal of this general exercise is for the subject to construct new actions, objects and effect with growing complexity. the work of Piaget inspired transformations in the American education system leading to a more "student-centered" approach to instruction.

David Ausubel worked in the field of Developmental Psychology and is most well-known for his work creating advance organizers [18]. Advance organizers can be divided into two categories, comparative and expository organizers. Comparative organizers are used to activate an existing schema that the student already possesses, and encourage the use of memory of material that is already known and its relevance to the material being taught. Expository organizers provide new information and schema for material that will be taught. For, material that the student may not have encountered, the expository organizer attempts to anchor new material to terminology and topics that are more familiar. Ausubel's work informs a great deal of education research that deals with students creating schema for material being taught to them [19]. Ausubel also developed Assimilation Theory, which focuses on the assimilation hypothesis, which assumes that new learning experiences are always integrated into preexisting knowledge structures. Accordingly, the assimilation theory of learning states that new information is incorporated into an anchoring structure already present in the student [20].

Joseph Novak and his research team at Cornell University developed teh technique of concept mapping in the 1970s [21]. David Ausubel's Assimilation Theory also informs the techniques of concept mapping. Concepts are typically enclosed in circles or boxes, and relationships between concepts are represented by connecting lines that link them together. Words on the linking line explain the relationship between the concepts. Concepts are also represented in a hierarchical fashion with the most general concepts at the top of the map and the more specific concepts arranged below. The inclusion of cross links makes explicit relationships between concepts in different domains within the concept map. Cross-links show how a concept in one domain of knowledge shown on the map is related to a concept in another domain shown on the map. Inclusion of specific examples of objects can help to clarify the meaning of a given concept.

Michelene Chi, with University of Pittsburgh, has contributed tremendously to the study of cognition and work with representations of experts and novices. In this work categorization and mental model differ drastically, and direct problem solving attempts [22]. Chi divides student shifts in representation into three categories, from least to most difficult to address; belief revision, mental model transformation, and categorical shift. This work has flourished into Categorical Change Theory(CCT), discussed further in Chapter 3 [23, 24]. Andrea diSessa, with UCLA Berkley, is another such researcher, who holds advanced degrees in physics, yet works in an education program. His work on the epistemology of physics has garnered acclaim from both Physicists and Behavioral Scientists [25]. diSessa's work focuses on generating a theoretical framework that provides a stronger foundation for experimental work [26]. This work coins the term "p-prim," or phenomenological primitives, analyzes data on organization schema of students, and investigates how these systems of ideas develop. The p-prim is a fundamental, tautological idea from which other more complex ideas are built, and diSessa combines p-prims with CCT to address the fragmentation in novice mental models of introductory material [27]. The representation of competencies themselves have been investigated, with some patterns emerging. The way in which a novice-like representation changes into a expert-like representation has shown patterns depending on instruction.

Other researchers who are outside physics departments have taken steps to improve the quality and effectiveness of teaching physics. Arnold Peltzer published work that focused on trends in physicist responses to what factors contribute to successful physics students [28]. David Kember has also contributed by reassessing conceptions of what teaching is, but for academics of differing fields and at different institutions [29]. This work results in a high degree of consensus on categories that describe perceptions of teaching in higher education. How the categories are related is still an open question in the field. If conceptions are situated in discrete categories or occupy a continuum has yet to be determined. Joan Stark has investigated the importance of course planning and the under represented topic of the process by which instructors plan classes [30]. In education research there is also a precedent for research into the beliefs and perceptions of classroom participants. Lin Norton has investigated self-reports of educational beliefs and intentions in higher education [11, 31]. Michigan State University has conducted research on mathematics instructors to determine how their beliefs about how to teach effect their actions in the classroom [32].

2.2 Physics Education Research

2.2.1 Foundations

Physics Education Research (PER) had its foundations established in the 1960's and 1970's by Robert Karplus, Fred Reif, and Arnold Arons and the other founders of the American Association of Physics Teachers (AAPT). These men were informed by the early work of Jean Piaget and John Dewey and focused their research on students learning in high school classrooms. Many of these early papers were formatted as essays on the authors experiences and ideas of "best practices" for teaching general science or specifically physics [33, 34]. Karplus and Arons publications shifted towards collecting data and creating Piagetian exercises for classroom environments [34]. Fred Reif's work in the late 1970's is some of the first that treats the classroom as a laboratory to investigate instructional techniques [35]. These founders of the AAPT essentially generated the initial interest, and participated in foundational research in PER that spurred the growth of the field.

2.2.2 Current Work

The field flourished in the latter part of the twentieth century as researchers focused on the educational practices at the college level. Since the mid-1980's Lillian McDermott, whose background is in experimental nuclear physics, has been involved in education research associated with introductory coursework, and better methods of teaching kinematics, optics, and electricity and magnetism [36]. Investigations of student mental models of velocity were conducted using interviews and diagnostics [37]. McDermott was also involved a panel that generated opinions of physicist on what the goals, content, and methods of instruction should be for an undergraduate program [38]. These notions of qualitative and quantitative data used in conjunction to generate the state of a classroom was new to the field.

Edward Reddish, a theoretical nuclear physicist by training, began involvement in PER in the late 1980's though research associated with the use of computers in teaching college physics at University of Maryland [39]. Later Redish turned his focus to active engagement and the implications that cognitive studies had on teaching strategies [40]. This work reinforced the fact that students do not enter a class *tabula rasa*, but struggle to shift to new mental models, have greater success when one model can build of an existing foundation, and that fundamentally all cognition is based on patterns. Redish set the tone for integrating cognitive science and pure qualitative research to the body of PER.

Since the 1980's, David Hestenes, at Arizona State University, has been involved in modeling theory associated with cognition and science instruction. His work lead to the development of a pedagogy that integrates mathematical modeling of physical systems as a central component to physics instruction. Modeling instruction is designed to engage students in many aspects of generating a model. This includes testing, analyzing, and evaluating the model. The modelling theory has extended to highschool students as well as all levels of undergraduate students. Hestenes and his students also developed the Force Concept Inventory (FCI) in 1992 to measure the relative effectiveness of curricula to teach Newtons Laws [41]. Since that time, other researchers developed diagnostic tools to cover a broad range of topics [42].

The Mazur Group, at Harvard, pioneered an instructional strategy for teaching called Peer Instruction (PI). PI involves students in the teaching process by fostering in-class discussion and using ConcepTests, questions designed specifically to highlight common misconceptions. Results of the PI instructional strategy included increased benefits from pre-class reading, increased engagement in class discussions, and increased student understanding of material [43, 44]. This innovation has been found to reduce student attrition in introductory courses and students demonstrate similar gains regardless of background knowledge in post-secondary classes from Harvard to two-year colleges [45].

2.2.3 Research at the Upper-Division

In the past fifteen years, a number of physics education researchers have turned their focus from the introductory courses to intermediate and upper-division coursework.

The transition for novice to expert learner is of great interest to researchers and practitioners alike. Physical Review Letters: Special Topics Education was also launched during this period in 2005. Corrine Manogue, with Oregon State University, outlined an experimental curriculum for physics, what defines thinking like a physicist, and investigated the way the curriculum changes affected cognitive changes about classical mechanics and electricity & magnetism [46, 47]. The program, known as Paradigms in Physics, modifies the final two years of a B.S. degree in physics where topics are taught by phenomenon rather than by discipline. The students were receptive to the format, as indicated by 20 minute exit interviews and TA commentary [48]. Other group members have chosen to work in conceptual quantum mechanics research through interviewing students and observing their work with operators, eigenstates and quantum measurements or defining the epistemology of physics students [49–51]. Chasteen and co-authors used active engagement and learning theory from PER to develope new course materials and conceptual assessments. Students supported the changes to the class, and data indicated that students developed work habits that are similar to expert problem-solvers [52].

Wittmann's work with University of Maine, makes use of classroom observations, multiple-choice diagnostics, interviews and assigned classwork to determine student mental models for various topics in upper-division coursework. One example of this is how students struggle with the quantum nature of light. Student explanations suggest that the notion of what is oscillating and waves "fitting" through a slit in a diffraction experiment [53] Other topics such as inconsistencies in students' conceptual, mathematical, and graphical models quantum tunnelling have been addressed by developing course materials that focus on consistency between these models [54, 55].

Papers have also been published that address faculty perspectives on course content, epistemology, and instructional methodology. Charles Henderson and Melissa Dancy have written many papers through University of Minnesota on faculty interpretation and use of research-based instruction strategies (RBIS). Their work focuses on the complexity of instructional change and what motivates instructors to attempt to use RBIS [56]. A survey of 722 physics faculty members resulted in data for twenty possible predictor variables that were investigated to determine if there were significant paramters that correlated with the use of RBIS [57]. Nine statistically significant parameters were reported, and faculty age, institution type, and percentage of job related teaching were not barriers to RBIS use. Henderson has reported on other findings, such as the beliefs and values of physics instructors regarding student problem solving capabilities and choosing features to problems at the introductory level. Both studies are based on artifact based interview techniques of faculty teaching calculus-based introductory physics. The studies conclude that instructors will choose problem features that value clarity of presentation and minimizing student stress over those that align with RBIS [58–60].

The PER group at University of Pittsburgh, led by Chandralehka Singh, is one of the most prolific groups on the topics of PER in quantum mechanics courses. For over a decade, they have been writing papers that address the issues associated with learning junior and senior level quantum mechanics as well as perceptions associated with teaching quantum mechanics. One major topic addressed is how expert-like behavior is developed in senior-level students. When given identical problems on a mid-term and final exam, most students in the class demonstrated a lack of reflective practices that would allow them to achieve a higher score on the final exam [61]. Another paper documents the attitude towards problem solving that graduate students have. The research in this paper indicates that the graduate students often display expert-like attitudes towards introductory material problem solving , but their approaches to solving graduate-level problems are similar to introductory students solving introductory problems [62]. There has also been work done interviewing and surveying faculty to determine their approaches to teaching material in undergraduate quantum mechanics courses [63].

The University of Colorado - Boulder has also made impressive strides in determining best practices in education at the upper-division level. Noah Finkelstein and Charles Baily have lead efforts to probe the way students understand the phenomena of quantum physics and how instructors beliefs shape that understanding [64,65]. Sam McKangan designed a conceptual diagnostic survey for students between the junior and senior level courses in quantum mechanics call ed the Quantum Mechanics Conceptual Survey (QMCS) [66]. This tool has been created based on extensive research of student misconceptions and the assessed strengths and weaknesses of other such diagnostic tools [67, 68]. Stephanie Chasteen and Rachel Pepper have all focused their research on the difficulties students encounter in the upper-division electricity and magnetism course. These difficulties manifest as struggling with mathematical and spatial representations [8, 52, 69].

2.3 Evaluation Techniques

Undergraduate students are usually assessed on their learning and understanding of course material by means of written examinations, homework, and quizzes. These methods can sometimes promote using mechanisms such as rote memorization and pattern recognition to answer questions correctly [61]. This often takes precedence over an in-depth appreciation of the conceptual underpinnings and mathematical logic of physics [22, 70]. Written examinations and problems are almost exclusively used in physics evaluation, and are generally viewed as an effective way to gauge the cumulative learning of a large number of students in a timely and uniform fashion [71]. These evaluations often lack the ability to improve misunderstandings and assess a limited depth of student knowledge [6]. Moreover, academic dishonesty during written exams and on homework assignments is sometimes an important problem that educators must address. Students that are in smaller classes may have the opportunity to be evaluated on oral presentations, writing exercises, or poster presentations [5]. For large classes or for faculty members that have a large teaching load, these approaches are often impractical. Stewart reports on writing exercises implemented in introductory physics classrooms to address conceptual change and improve critical thinking skills [72]. The use of language in physics problems is consistently and positively correlated with exam performance and conceptual understanding [72]. A less common form of evaluation appears to be the oral examination [6, 73]. Boedecker and Ehrlich each report implementing oral exams as an extra-credit exercise successfully at the introductory level [74, 75]. Investigations of the effectiveness of presentations and oral exams have been carried out in chemistry education research, but few if any analogs in physics education research. Students perceive written and poster examinations to be equally fair, are more comfortable discussing conceptual material, and instructors receive fewer complaints about grades assigned [5]. In another case, oral examinations resulted in higher scores than written examinations on similar material and increased student knowledge and motivation to study. Oral exams can also uncover weaknesses in instruction and offer tudents performance related feedback and experience presenting technical material under pressure [6, 73]. Overall, self explanation is an evaluation tool that is underused in physics courses, and has show evidence of improved understanding of material in courses for other scientific fields [10].

There is a significant body of literature that documents how, why and to what extent instructors use research-based instructional strategies [56, 57, 60]. The typical model for dissemination of a new technique involves informing the faculty members of the change, convincing them that the change is necessary, and providing them with the materials necessary to change their course. The faculty members' rationale for alternative evaluation methods appears to be the same as the rationale for research-based innovations; instructors are often willing to try them, but report that they cannot invest the time required to make a major instructional change or will edit out essential components. This model had effectively informed many instructors about research-based innovations, however, it does not lead to effective changes in classroom practices [56]. The majority of this work has been done for research-based innovations for the introductory physics courses, which confirm potential variables to implementation such as correspondence with peers about teaching and departmental encouragement for improved instruction [57]. Post-secondary education is known for allowing academic freedom to the faculty members instructing a particular course, so the perspective that a faculty member has regarding a specific technique or tool strongly influences if it will become a routine part of the curriculum. A significant amount of research has been done to investigate attitudes and beliefs of all participants in a classroom. The methods used by professors to validate work, evaluate students vary between pure and applied fields of study [63,76,77] If instruction and evaluation operate under field-specific rules, students should be provided with a sense of what these rules are.

2.4 Course Preparation

For over twenty years, education research has used the beliefs and perspectives of faculty members and students as data to better characterize the motivation for instructional practices and course content. Gortzen, at Florida International University, reports on the perspectives and epistemological beliefs of a teaching assistant to better define what types of professional development benefit other teaching assistants [78]. Dumon provides Likert scale data for laboratory grading preferences of instructors and students and how they differ with respect to approach and logistics [76]. Work published by Cotten focuses on out-of-class interactions and how they effect the learning environment [79]. The majority of this research has been conducted at the introductory course-level with a few exceptions [61–63, 65, 80]. Data of this type can be taken to compare faculty member and student perspectives or to gain a deeper knowledge of the beliefs of one group and how that affects their actions in a learning environment.

Faculty beliefs regarding course material, instructional practices, and philosophical stance on course content have all been explored in published research. Faculty views on knowledge, validation, and methodologies have been linked to classroom practices to determine if these beliefs aid student learning and to determine the motivation behind such instructional choices [32, 77, 81]. Teaching conceptions have been shown to be related to measures of the quality of student learning [29]. Result of this type of research include the need for clearer definitions of critical thinking and more descriptive strategies to teach critical thinking [82].These lessons can be translated to better instruction for physics students in a QMC. Henderson reports on faculty beliefs and values on teaching and learning problem– solving skills in introductory physics courses determining a set of "core concepts" that define faculty thinking. This is accomplished through the development of interview codes and concept maps based on the codes [60]. Instructional practices are a compromise between an instructors conception of teaching is as well as the academic and social context in which they teach [31].

Student beliefs regarding course content and approaches to learning physics material have been documented for introductory physics courses, this is often accomplished with large numbers of students taking attitude surveys such as the Colorado-Learning Attitudes in Science Survey (C-LASS), Epistemological Beliefs Assessment for Physical Science (EBAPS), or the Maryland Physics Expectation Survey (MPEX) [83–85]. Data has been taken through coded interviews for investigations of junior and senior level courses [52,62,65,80]. The goals associated with this type of data range from validation of research-based instructional tools and strategies to identifying and correcting novice–like conceptual views that should be addressed before a student enters graduate studies.

All the tools used to perform this analysis have been used by the PER community, and by combining different tools, a more comprehensive picture of the condition of the course can be constructed. The QMCS has been used to gauge student conceptual understanding for a wide range of students [66, 68, 86]. In analysis of assignments, the design and use of rubrics have been employed to assess complex competencies in a credible way [62, 87, 88]. Mason reports that student performance on assignments and exams suggests that even upper-division students do not use their incorrect solutions as an opportunity to repair, organize, or extend their knowledge structure [62]. Mason also uses a survey in a separate paper that suggests even graduate students' approach and attitudes towards solving problems can sometimes be novice-like when solving graduate-level problems [61]. These results are confirmed in this research and informs the analysis of student persepctives. Investigators also use some form of Bloom's Taxonomy to assess the difficulty of an item and express them in terms of complexity and modality of knowledge structure [89, 90].

This work uses triangualtion to examine the values of faculty members and undergraduate students in the form of thirteen interviews, a diagnostic survey, and document analysis. This data is analyzed to locate contradictions in the faculty and student perspectives and actions in the learning environment. Participant beliefs regarding student knowledge of prerequisite material, and course content in the QMC are addressed in the interviews. With the interview, diagnostic, and assignment data, we seek to determine if substantial contradictions or conflicts in perception arise in the QMC. With this information, faculty and researchers can generate a hypothesis about if there are ways to improve delivery of material or how to better prepare students for the expectations of the instructor. One goal of this research is to influence the way instructors address students in upper-division courses. A proper understanding of what foundational knowledge students possess will help if an instructor wishes to tailor their course, and this data will provide a list of important skill students should focus on as they prepare to learn quantum mechanics.

CHAPTER 3

THEORETICAL BACKGROUND AND METHODS

3.1 Educational Theories

3.1.1 Zone of Proximal Development

The work of Lev Vygotsky deems social interaction critical for cognitive development. Related to this idea, the zone of proximal development (ZPD) is defined by Vygotsky as the distance between the actual developmental level determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers [91]. The ZPD views interaction with peers and experts as an effective way of developing skills and strategies to solve problems. Vygotsky suggests that when a student is at the limit of the ZPD for a particular task, providing appropriate assistance will allow the student to complete the task as well as providing scaffolding for similar exercises. This socio-cultural theory is invoked in educational research related to the organization of course content and delivery as well as learning environments [92]. Vygotsky refers to Montessori's idea of 'sensitive periods' as optimal points of departure for instruction.

> "She found, for instance, that if a child is taught to write early, at four and half or five years of age, he responds by 'explosive writing', an abundant and imaginative use of written speech that is never duplicated by children a few years older. This is a striking example of the strong influence that instruction can have when the corresponding functions have not yet fully matured." [91]

Another common interpretation takes the zone of proximal development as a rationale for creating social situations or environments where instructional support is given to children, thus enabling children to acquire new skills in a new way, through joint problem solving and interaction. The notion of 'scaffolding' is a product of this line of interpretation.

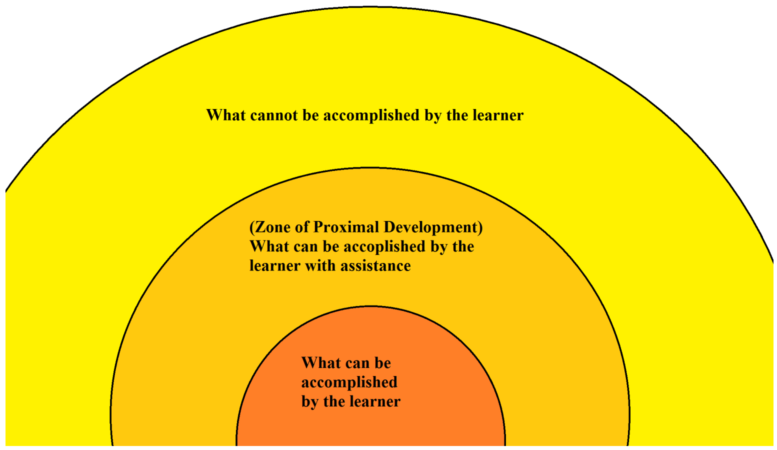

Figure 3.1: The visualization of the ZPD concept.

3.1.2 Conceptual Change Theory

Conceptual change theory arose to handle the phenomenon of learners having prior incorrect knowledge that is resistant to change. This theory is based on the Constructivist Theory, by Jerome Bruner, which asserts learning is an active process in which learners construct new ideals or concepts based on current knowledge. In an ideal situation, the learner will abandon their prior conceptual framework because explanations of their framework are inconsistent with correct scientific explanations. Overall, it is the goal of conceptual change theories to understand and propose methods to overcome resistance to change, resulting from both assimilation and rejection.

The theoretical background used in this research is Conceptual Change Theory first created by Michelene Chi [24]. Learning complex material, such as material encountered in physics, can occur under at least three conditions. First, a student may have no prior knowledge of the material that will be learned, although they may have some related knowledge. Second, a student may have some correct prior knowledge about the material that will be learned, but that knowledge is incomplete. In the third situation, the student has acquired some ideas about the material that is in conflict with the material to be learned, these ideas can come from previous learning experience in the classroom or every day experience.

According to Chi's theory, conceptual change manifests itself in three forms, belief revision, mental model transformation, and categorical shift. Belief revision corresponds to ideas that can be expressed as single statements. Chi uses the term belief to discuss ideas that students have assimilated into a conceptual framework. If students' ideas are incomplete, simply telling that student the information will add to their current framework of ideas. For conceptual change to occur at this level, prior knowledge must conflict with new information. When the unit of information is a statement or idea, instruction can be designed to refute false information and correct it resulting in revision of that idea. Chi reports evidence that false ideas can be revised even when instruction did not explicitly refute incorrect information. In the example, eight grade students who exhibited the idea that the heart oxygenates blood were given the information that lungs oxygenate blood.

An organized collection of ideas can be viewed as forming a mental model. The mental model is an internal representation of a concept, or system of concepts that corresponds in some way to an external structure that it represents. These models can be use in a predictive nature to determine outcomes for a given situation. As with ideas, mental models can conflict with a correct scientific model to varying degrees. Mental models can be non–existent or incomplete. For example, students entering an introductory physics course could have prior conceptions of physics that are so sparse and disconnected that it is difficult to classify if their mental model is incorrect or in agreement with the correct scientific model. In this situation, ideas can be added in an effort to fill gaps, but this is not conceptual change. A mental model can be flawed, this means that it is coherent but incorrect. For example, if a student can use a mental model to provide similar and consistently incorrect explanations or predictions to questions, this would be considered a flawed mental model. Efforts to correct a flawed mental model are usually through a series of belief revisions. Students will either augment their currently flawed model, or a significant amount of new information refutes prior knowledge and the mental model is transformed. In the first possible outcome, whether or not a flawed model is transformed depends on if critical false ideas are confronted. Knowing or correcting many false ideas does not guarantee a successful transformation of a mental model. If students do not see a contradiction between their model and the correct one, or if critical false ideas are not confronted, their mental model for the topics will not be transformed.

The category is the final grain size of idea in Categorical Shift Theory. These categories that are created by the student have different properties that often can not be expressed in another context. Incorrect information at this level is referred to by Chi as a robust misconception [23] A simple example of this is to define the categories of an object and a process. An object, like a baseball bat can be described as made of wood. This is due to the fact that objects have the property of be composed of some material. It does not make sense to describe a process, like a baseball game, as made of wood. The category of processes does not have a property such as composed of a material. If a person were under the impression that a baseball game could be described in such a way, the revisions to the idea that need to be made are at the core of their framework associated with these ideas. Shifting across lateral categories, which is to reassign a concept from one ontological category to another, has not had research conducted at the time of this work. Analysis of simpler examples of categorical shift indicate that there are two instructional steps associated with the shift. The first is to have the student be aware that there is a mistake at the level of a ontological category. This is means that the student must understand that the category they have assigned information to does not have the appropriate properties to support it. The second element to this shift is that the student must have a correct category to which the information belongs.

3.2 Methods

3.2.1 Setting and Sample

For students at the LPSU, Modern physics I is the first course that focuses on the material associated with quantum mechanics. This course addresses several conceptual elements associated with quantum theory, as well as the phenomenological motivation for developing quantum mechanics. Modern Physics I introduces students to experimental motivations for quantum theory such as blackbody radiation, the photoelectric

Effect, quantization of states, and Wave-Particle Duality. Elements of quantum mechanics are covered such as particle scattering, distribution functions, special relativity, and the Schrödinger's Equation in one–dimension. Though not required, the majority of students that take quantum mechanics also take Modern Physics II. This course is a survey of statistical physics and applications of material covered in the first semester Modern Physics course including semi-conductor, nuclear, and particle physics. Both modern physics courses are taught out of the book Modern Physics by Tipler and Llewellyn [93]. The LPSU offers a single semester senior-level course that covers the basic theoretical underpinnings of quantum mechanics. A course on ordinary differential equations and Modern Physics I are prerequisite to register for the QMC. Due to the small number of students that register for the class, it is cross-listed as a senior-level undergraduate/first-year graduate course for the entire department. Topics covered include, the infinite and finite potential well, radial wave functions, raising and lowering operators, spin matrices, and perturbation theory.

The format of the course is a traditional 75 minute lecture three times a week. The instructor implements homework assignments every two weeks, a mid-term exam, and a final exam as the evaluation for the course. In the fall semester of 2012, fifteen students registered for the QMC. The students who are of primary interest in this research are the twelve undergraduate students. This semester was of particular interest to the researchers, due to the large ratio of undergraduate to graduate students. This group is composed of nine physics majors, one mathematics major, one chemistry major, and a post-baccalaureate student. Two of the nine physics majors were female. Of the twelve undergraduate students that registered for the QMC that semester, seven were interviewed before classes began in the Fall of 2012 for this research. This group of seven students was composed of students in their final or next to final year of the undergraduate program and includes both female physics majors, the post-baccalaureate student and the mathematics major.

Faculty participants were selected as those who taught upper-division physics courses and courses prerequisite to the QMC offered at the LPSU. It is important to note interview data demonstrates that there is little, if any communication regarding curriculum or course content between faculty. The faculty members that teach the upper-division course work were chosen due to their more clear perception of what material will benefit students that are finishing their undergraduate career. Six faculty members were interviewed. The faculty participants are a diverse population with a range of teaching experience of 3 to over twenty years, and have varying levels of university and departmental involvement.

3.2.2 Data Collection

Quantitative and qualitative data have been collected as part of a larger project that sought to build a comprehensive picture of how members of the LPSU Physics & Astronomy Department view particular types of evaluation and what preparation will best prepare students for a QMC. Based on the information taken from all the interviews, published literature, and popular quantum mechanics texts, a survey instrument was designed in an effort to question a broader segment of the department and to provide a finer gradation to some of the responses given in the interviews [94]. Email addresses of all the students that have taken the QMC in the past three years were collected and the survey was offered to them.

There are 12 respondents and the survey covers three main topics. The first is what types of evaluation are appropriate for a QMC, and their rationale for that answer in the form of a short open response. The second topic covered is what physics and mathematics topics they believe should be prerequisite for the QMC and the rationale for those responses. Choices that are based on interview responses, popular textbooks, and literature were ranked from most important to least important. Finally, the last topic addressed was what material they think should be covered in the QMC. Those choices, that are based on the previously mentioned research material, were ranked from most important to least important.Categories were defined in the following way:

- Not Applicable is defined as a topic that has no bearing on the students understanding of quantum mechanics.
- Prerequisite is defined as having a student be “Familiar” or have “Mastered” the topic in a course taken before the QMC.
- Introduced is defined as having knowledge of vocabulary and being able to use equations associated with a topic.
- Familiar is defined as knowledge of a topic that is greater than only vocabulary and definitions, and involves manipulating equations and explaining results.
- Mastery is defined as having in-depth knowledge of a topic including its conceptual and mathematical origins.
- Beyond Scope is defined as a topic that should expect to be “Familiar” or “Mastered” in a course taken after the QMC.

Assignments, two sets of class notes, and the mid-term exam were collected and copied so that they could be analyzed multiple times and by multiple coders. Over the course of the semester there were four assignments, a mid-term exam, and a final exam to which the researcher did not have access. It is important to note that the mid-term exam offered five questions, and the student selected three to complete for credit. This selection process can be viewed as a possible indicator of confidence at the middle of the semester. Before the first lecture of the semester, a diagnostic survey, the QMCS, was offered to the class. All of this data was taken in an effort to characterize the student knowledge and perspective before learning anything from the QMC which could be compared to evidence from assignments as the semester progressed.

Interviews were scheduled as semi-structured, one-hour conversations for all participants and the main goals of the interview were to determine student and faculty perception of different evaluation types and what material should be prerequisite to and covered in a QMC. Interviews conducted with students were scheduled before they had taken the first lecture in Quantum Mechanics in an effort to understand their initial perceptions of the course and student rational before seeing any course material. It was explained to all interviewees that the evaluation questions were focused on upper-division courses, and that our research interest was in quantum mechanics. Interviewees were asked what evaluation techniques they believed were appropriate for that course and for the upper-division in general. The questions on evaluation techniques are as follows:

1. "How appropriate do you think multiple choice (MC) questions are for evaluating student knowledge?"

2. "How appropriate do you think student presentations (SP) are for evaluating student knowledge?"
3. "How appropriate do you think oral examinations (OE) are for evaluating student knowledge?"
4. "How appropriate do you think written problems (WP) are for evaluating student knowledge?"
5. "How appropriate do you think short answer questions (SA) are for evaluating student knowledge?"

The goals of the interview were to determine student and faculty perception of evaluation, course content, and prerequisite material in a course in quantum mechanics. Interviews conducted with students were scheduled before they had taken even the first lecture in quantum mechanics to better understand their initial perceptions of the course before seeing any in-class material. It was explained to all interviewees that our research interest was focused on quantum mechanics. Faculty interviewees were asked what their perceptions were as well as what they thought a students perception would be. This body of work focuses on the questions associated with student and faculty thoughts on preparation, material covered in the QMC, and what conceptual knowledge students possess before taking the class.

3.2.3 Data Analysis

Qualitative research focuses on systematic inquiry instead of mathematical abstraction. This data is collected in open–ended questions and through interview protocols providing participants the opportunity to freely articulate their ideas and beliefs. In analysing data generated in this format, responses are not grouped according to pre-defined categories, rather salient categories of meaning and relationships between categories are derived from the data itself through a process of inductive reasoning. The constant comparative method offers the means whereby by the researcher may access and analyse these articulated perspectives so that they may be integrated in a model that seeks to explain the processes under study, in this case student perception of a QMC.

The constant comparative method involves breaking down the data into discrete units and coding them to categories. Categories arising from this method generally take two forms: those that are derived from the participants language, and those that the researcher identifies as significant to the projects focus-of-inquiry [95]. Language based categories are used to reconstruct the perspective used by subjects to conceptualize their own experiences. The goal of the latter is to assist the researcher in developing theoretical insights into the processes operative in the site under study. Ultimately, the process of constant comparison leads to both descriptive and explanatory categories.

This is an iterative process, and categories undergo content and definition changes as units and incidents are compared and categorized, and as understandings of the properties of categories and the relationships between categories are developed and refined. By continually comparing specific incidents in the data, the researcher refines the these categories, identifies their properties, explores their relationships to one another, and integrates them into a coherent explanatory model.

All the interviews were divided into statements, which consist of a single sentence or idea. Groups of statements were assigned a topic based on the subject of the discussion in which they were located. We consider the tone of the comment as the expression of meaning, feeling or spirit. The codes for comment tone are as follows:

+ For a comment that is positive with respect to the subject.

N for a comment that is either neutral or mixed positive and negative with respect to the subject or off-topic.

- for a comment that is negative with respect to the subject.

Interviews were also divided by interviewee group and a separate coding was performed based on the content of responses to interview questions. Statements that had similar language in response to a question or statement were built into categories. All participants had their names and identifying information removed from the transcripts. A colleague who is unaffiliated with the research performed identical coding on a sample of the transcript data in an effort to qualify the consistency of the codes generated. A meeting was arranged to compare individual coding of the sample data, and differences were discussed and mitigated. When a consistency reached 95% of the sample content, these codes were considered adequate and applied to the entire body of transcript data.

The first step of qualitative analysis is the implementation of the Constant Comparison method. The Key-Words-in-Context (KWIC) method of category development followed for qualitative analysis of the interview data [96, 97]. All the interviews were divided into statements, which consist of a single sentence or idea. Groups of statements were assigned a topic based on the subject of the discussion in which they were located. Interview codes were developed for both interviewee groups at the same time based on the content of responses to interview questions. Statements that had similar language in response to a question or statement were built into categories.

These categories are very straightforward for prerequisite material; necessary, a "good idea", and not necessary. For conceptual questions, all responses were collectively grouped into common responses as codes. Identifying information was removed from the transcripts, and pseudonyms were assigned. A colleague who is unaffiliated with the research performed identical coding on a sample of the transcript data in an effort to qualify the consistency of the codes generated. Individual codings of the sample data, and differences were discussed and mitigated. When a consistency reached 95% of the sample content, these codes were considered adequate and applied to the entire body of transcript data. Data from the survey is organized by topics in physics, topics in mathematics, and QMC content. In order to compare the survey data to interview data, the topics needed to be categorized by the course were they would most likely be seen. This categorization was conducted with the assistance of a different unaffiliated colleague who was more familiar with content of the undergraduate mathematics courses. When categories were in at least 95% agreement, the categorization was considered valid. This allows a comparison of the courses that are mentioned by faculty and students in the interview data to be compared in a meaningful way to the survey data taken after students have completed the QMC. For the course content data, topics were listed by the number of times the topic was suggested to a given category.

All the interviews were divided into statements, which consist of a single sentence or idea. Groups of statements were assigned a topic based on the subject of the discussion in which they were located. Interview codes were developed for both interviewee groups at the same time based on the content of responses to interview questions. Statements that had similar language in response to a question or statement were built into categories. For questions of preparation and confidence, all responses were collectively grouped into common responses as codes. All participants have had their names and identifying information removed from the transcripts. A colleague who is unaffiliated with the research performed identical coding on a sample of the transcript data in an effort to qualify the consistency of the codes generated. Ant differences were discussed and mitigated. When a consistency reached 95% of the sample content, these codes were considered adequate and applied to the entire body of transcript data.

Using the student responses and a correct solution to each problem, rubrics were generated from mathematics and physics content. Each problem was also rated using a revised version of Bloom's Taxonomy [88, 90]. Bloom's Taxonomy was meant to be used as a common categorization to determine the cognitive goals of an exercise, curriculum, or sequence of courses [89]. This allows analysis of frequency of individual rubric points and math and physics oriented scores on each problem. Student notes were also collected in an effort to determine the amount of coverage various topics had over the course of the semester. Anecdotal evidence suggested that the course material had not changed appreciably in the past 5 years. To validate this claim, three sets of notes were compared for pacing, and content, and the contents is identical for 89% of topics in the notes. The pacing was the same within one week for all three sets of notes. This was deemed acceptable continuity between instances of the QMC.

Research associated with the QMCS suggests that it is best used at a junior level and that there is little conceptual knowledge gained in senior-level or graduate QMCs [66, 86]. This data motivated the use of the QMCS as a pre-instruction diagnostic for the QMC and a post-instruction diagnostic for the modern physics course at the LRSU in the southeast. Other such tools have been created, but are to specific in content or ask questions at a level that is not expected of students entering the QMC [67]. Classical test theory (CTT) was used to determine the reliability and validity of using the diagnostic to evaluate student conceptual knowledge after taking Modern Physics I and before Quantum Mechanics. The QMCS was considered a strong diagnostic tool for the population of students that had completed junior–level quantum mechanics material, but had not yet begun a senior–level quantum mechanics.

There are four metrics commonly used in PER and other fields to determine the validity and reliability of a diagnostic tool; item difficulty, item discrimination, point biserial coefficient, and Ferguson's delta. The expressions for these metrics are shown in equations 3.1–3.4.

$$P = \frac{N_1}{N} \tag{3.1}$$

$$D = \frac{N_H - N_L}{\frac{N}{4}} \tag{3.2}$$

$$r_{pbi} = \frac{\overline{X_1} - \overline{X_0}}{\sigma_X} * \sqrt{P * (1 - P)} \tag{3.3}$$

$$\delta = \frac{N^2 - \Sigma f_i^2}{N^2 - \frac{N^2}{K+1}} \tag{3.4}$$

The difficulty (($\overline{P}$)) of a question should practically range between 0.3 and 0.9, depending on what fraction of the students tested are expected to answer correctly [98]. Discrimination ($\overline{D}$) is the measure of how well as question discriminates a high achieving student from a low achieving student. This is accomplished by the number of correct responses in the upper and lower quartile of the population divided by a quarter of the population. The point biserial coefficient (r_{pbi}) is a measure of individual item reliability. This can be interpreted as how well success on the item will predict success on the entire test. Finally, Ferguson's Delta (δ) is a measure of reliability of the entire test. This is accomplished by determining how broadly scores are distributed over the range of possible scores on the test [98].

CHAPTER 4

RESULTS

4.1 QMCS Diagnostic

The distribution of scores on the diagnostic was normal for both the post-instruction test offered in Modern Physics I and the pre-instruction test offered in Quantum Mechanics. Due to the normal distribution and statistically significant similarities of scores, both populations were combined to increase the N value for analysis. Table 4.1 shows the measures calculated and compares them to the optimal values as indicated by literature [98]. These values are better than the values suggested by the current literature for every measure except the average item difficulty. These metrics suggest that the QMCS is an appropriate test for the students entering the QMC in this study. This is agrees with data taken by other universities that have used the QMCS [66–68].

Table 4.1: Classical Test Theory Metrics for the QMCS administered in the fall semester of 2012 compared with ideal values of the metrics.

CTT Metric	Fall 2012	Ideal Value
Average Difficulty ($\overline{D}$)	0.46	0.50
Average Discrimination ($\overline{P}$)	0.61	≥ 0.30
Average Point Biserial Coefficient(r_{pbi})	0.38	≥ 0.2
Ferguson's Delta (δ)	0.97	> 0.90

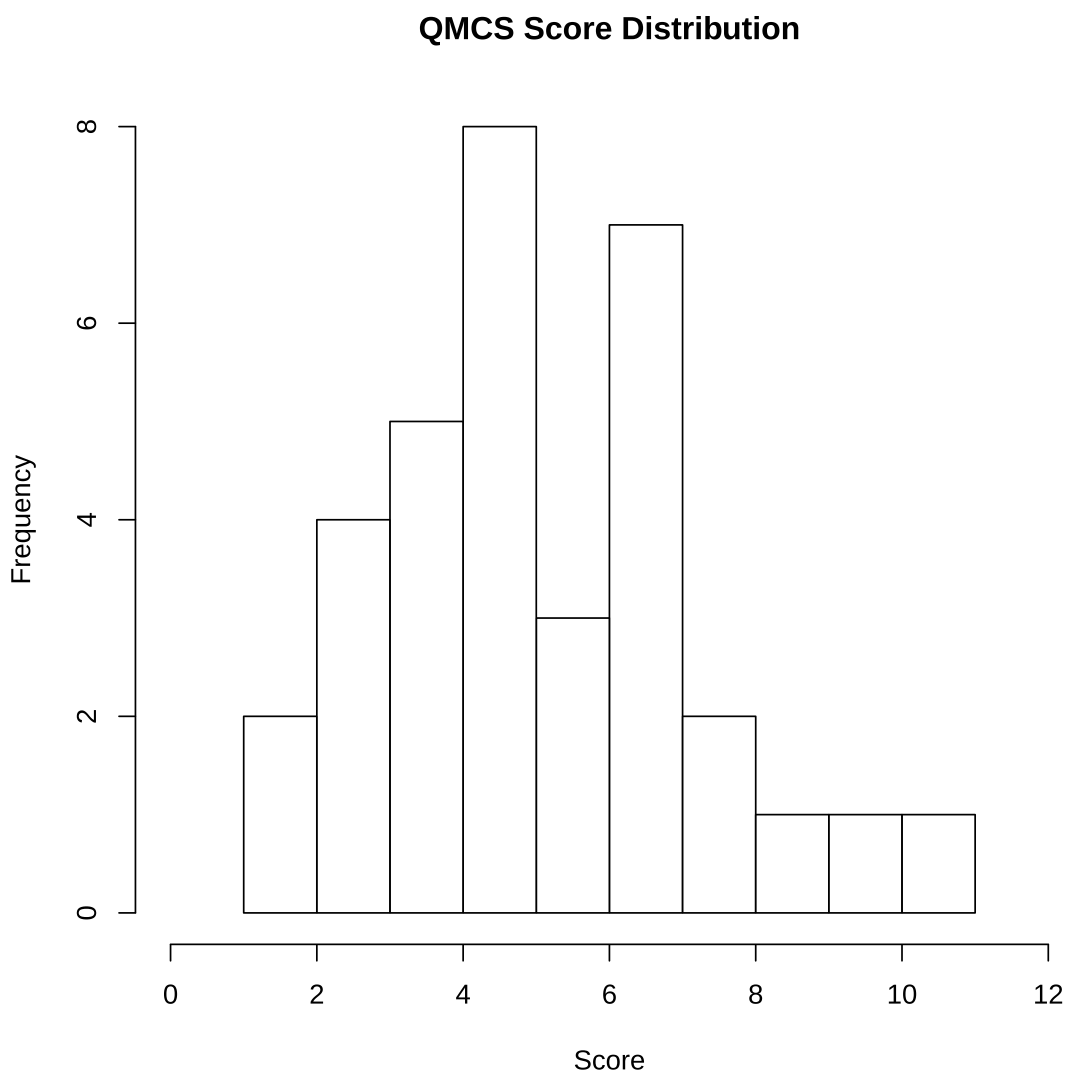

Figure 4.1: Total score distribution for students prior to taking the QMC used to support themes noted in interview data.(N=32)

Figure 4.1 shows the distribution of scores for the combined population of students that have not tkaen the QMC, but have taken a course in modern physics. Of the 32 students that took the QMCS, only three have a score above 66%. These scores oppose category of statements in the interviews in which students self-identify as comfortable with the conceptual aspects of modern physics, which will be discussed further in 4.3.4.

4.2 Assessment Perspectives

4.2.1 Multiple Choice Questions

Figure 4.2 compares the tone of faculty and students for the five different evaluation techniques discussed in the interview schedule. One can see from figure 4.2, that student and faculty members have a similar negative tone. In response to the question referencing the multiple choice format, 70% of faculty comments and 58% of student comments are negative. The average amounts of negative comments are significantly higher than the neutral or positive comments for either interview group. This result of significantly negative responses mirrors results on multiple choice questions described in Yerushalmi's paper on faculty perspectives on problem features [99]. Student interviewees have a greater number of neutral comments, on average, than the faculty interviewees. The individual number of statements and tone of statements is more uniform for the students than for the faculty. The students also spoke more on average about multiple choice questions than the faculty.

Table 4.2 lists the multiple choice content codes derived from interview and survey results. Only one of the seven students, and one of the six faculty members interviewed

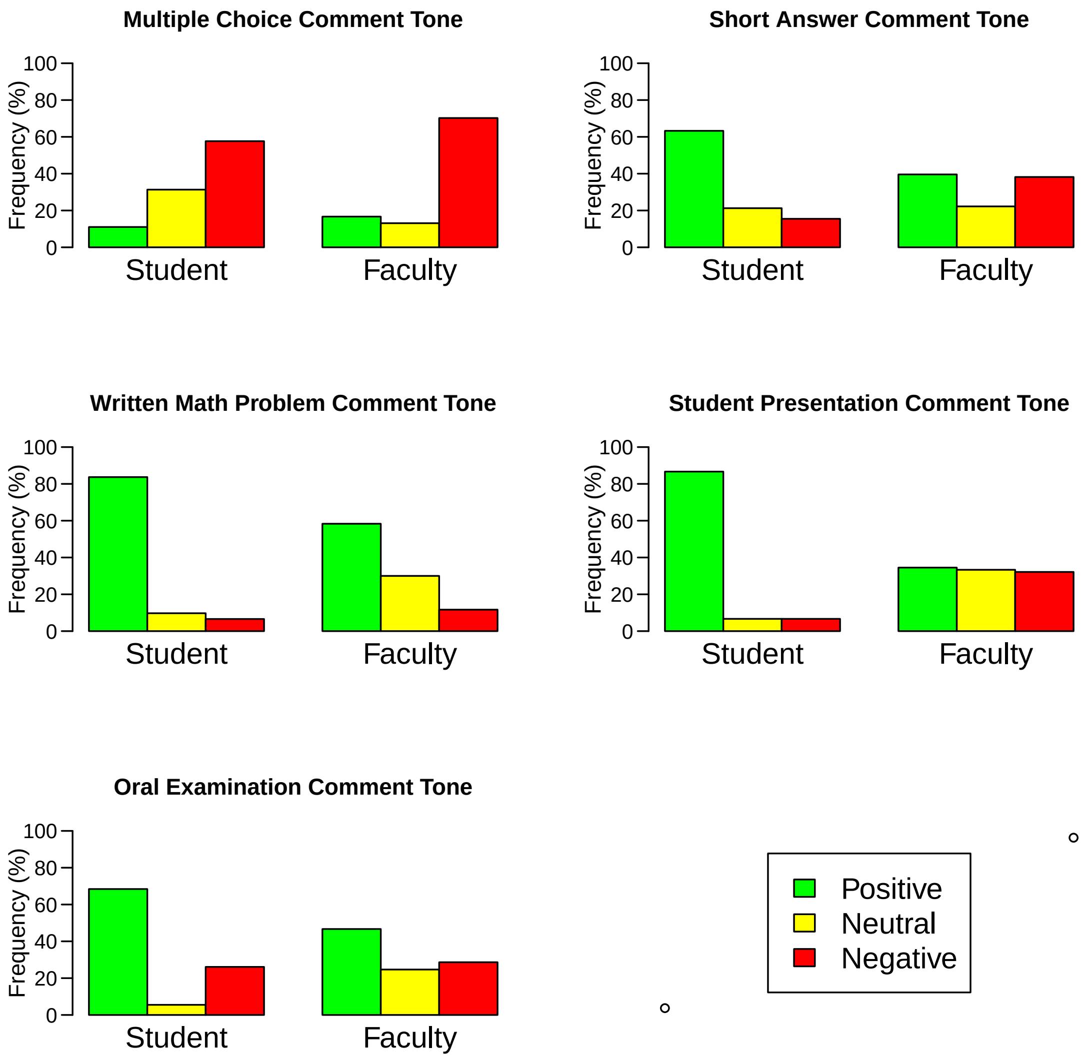

Figure 4.2: Comment tone comparisons between students before QMC instruction and faculty members. Data are also sorted by evaluation type.

Table 4.2: Multiple Choice Questions Codes

Code	Description
NO	Not Useful
GUE	No: Can Guess/Use Strategies
CON	Yes: For Concepts/Basics
DEM	No: Must Demonstrate Knowledge

explicitly stated that multiple choice questions were useful without applying a condition [YES]. The condition that arose in interview and survey data was that these types of questions are acceptable for "basic" information, which was defined in the interviews as concepts, vocabulary, or historical context [CON]. The most common reason given by faculty for why multiple choice questions should not be used was that the student can not demonstrate depth of knowledge [DEM]. This code was seen in the survey data taken after the course, but not in the student pre-instruction interview data. Faculty members acknowledge that there is a very limited range of applicability for multiple choice questions at the senior-level; typically for superficial ideas, concepts or vocabulary in the subject. They also acknowledge that this format is used occasionally due to the speed and uniformity of evaluation. This is not mirrored by the students response, which is that one can use test-taking strategies or guess answers to get the right answer. There appears to be a consensus of perspectives regarding multiple choice questions, which is that there are very few reasons or situations where this format of evaluation should be used for a quantum mechanics course. The post-instruction surveys indicate that the reasons for negative tone shift towards those of the faculty.

Interview quotes from faculty members demonstrate a range of beliefs, though the majority of interviewees are in agreement:

> *"Actually it's about understanding of the process or understanding a particular problem... and yes or no answers, [Multiple Choice Questions are] not the best choice. In fact ...I don't think a multiple-choice question is even good for freshman courses."* -Dr. Blue

> *"Yeah, because in order to decide whether a student understand something I have to see his work and this absolutely precludes me seeing his work...I understand that it's easier, but never in 45 years have I given a multiple-choice test"* -Dr. Yellow

> *"If you are asking someone to write out as much as they can, then choose one of the multiple choice answers, maybe that's a little better, because that gives them a guide to whether the answer they got is anywhere near one of those choices or not."* -Dr. Red

Similarly, the students have a uniform set of beliefs regarding the multiple choice format as well:

> *"Normally, a lot of times you have to solve issues, or solve a situation, basically...I don't want to say it's a problem, but it's a problem. So, I'm figuring out the situation and I don't think a multiple choice question can necessarily do that for you."* -Clark

> *"Well, I don't think that multiple choice questions are very good at evaluating what I know. I definitely like them sometimes, because they make tests easier, and I have a better chance of getting the answer right...if I were a teacher, I would not do it."* -Doris

4.2.2 Short Answer Questions

The average tone of faculty comments is 21% lower than that of students with positive tone 61%. Faculty members demonstrate a more even tone, on average, but it should be noted that two faculty interviewees were strongly opposed to the use of short answer questions, even in conjunction with written mathematical problems. All student interviewees, except one who did not respond to the question, considered short answer questions appropriate for the QMC and half of those respondents highlighted the fact that they would be good for concepts. Survey data suggests that student perceptions of utility especially for concepts does not change over the course of the semester. Table 4.3 lists the most common short answer content codes derived from interview and survey results.

Table 4.3: Short Answer Question Codes

Code	Description
YES	Useful
CON	Yes: For Concepts/Basics
WMP	Yes: With Math Problems

4.2.3 Written Math Problems

Students have an overwhelmingly positive tone when discussing written math problems. The positive tone percentage for students is 84%, which is similar to that of the student presentations. Table 4.4 lists the most common short answer content codes derived from interview and survey results. Student interview data implies that the utility of written questions is conditional in that these types of questions would be best with a short answer component that focuses on the physical meaning of the result calculated [WSA]. There was also a majority that stated the importance of demonstrating knowledge of the material through solved problems [DEM]. No negative content codes existed for written math problems. A majority of both faculty and student responses focus on ideas such as mathematics is crucial to physics, that the student must demonstrate knowledge through this type of evaluation.

Table 4.4: Written Math Problem Codes

Code	Description
YES	Useful
DEM	Yes: Must Demonstrate Knowledge
WSA	Yes: with Short Answer
CMU	Yes: For Complete Understanding
MAT	Yes: Math Crucial to Physics
PRI	Yes: Primary Goal of Physics

4.2.4 Student Presentations

There are significant differences in tone for student and faculty member comments when they are asked about student presentations. It is important to note that the core physics courses offered at the LPRU typically do not use this form of evaluation, and it is most often seen in elective courses such as Modern Physics II or Nuclear and Particle Physics. Comments made by students are 86% positive about the use of presentations in upper-division courses like quantum mechanics, as seen in Figure 4.2. The comments made by students are the most uniform for this evaluation format. The faculty comments are the most balanced in tone for this format of the five investigated, where 35% of comments are positive, 33% are neutral, and 32% are negative with respect to student presentations.

Table 4.5: Student Presentation Codes

Code	Description
SCI	Yes: Career/Scientific Skills
LOG	No: Logistics/ Time
NO	Not Useful
LRN	Yes: Learning Experience
YES	Useful
FUN	Yes: Enjoyable Experience
DEP	No: Focus on Foundation
FOU	No: Other Group Work Preferred

Table 4.5 lists the student presentation content codes derived from interview and survey results. The majority of student interviewees believe that the experience was both enjoyable[FUN] and a positive learning experience[LRN]. One interviewee acknowledged that the opportunity to be creative in a physics lecture is rare, and another student recalls a revelation:

> *"I was like 'Oh, science. So I wont have to write papers and talk in front of people or do any of that,' but then as you progress you realize that science is all-encompassing of all skills. You have to be able to write, read, present, communicate, do math, and logic."* -Adam

The class most often referenced for the applicability of presentations is the second semester of Modern Physics, which is an elective. This course is designed as a survey of practical applications of material from Modern Physics and Statistical & Thermal Physics. A minority of students claimed that quantum mechanics is not the right venue for that type of evaluation, because the goals for the course are different. Two students indicated that the QMC should focus building a foundation of tools and concepts as preparation for graduate level courses and that they may not be ready to present that material.

> *" I'd be all for it, I guess, if there was enough substance there that I could intelligently talk about [in the] quantum [course]"* -Eric

The presentation format also relies on the student to challenge themselves. As with all evaluation techniques, the material must be tailored to the course. One student took advantage of a pertinent topic in the Modern Physics II course.

> *"I chose to punish myself and pick the topic that was as hard as possible on the list of topics. I mean it was rewarding, because I decided to do this one, but some of the topics were on Quasars and stuff, and it just would have been kind of simple. The one I had to do was really tough and helped me figure out the language of bras...er...bras and kets."* -Bill

Faculty indicate that specifically for quantum mechanics, presentations may not be a useful tool. This is due to the belief that this course should be focusing on creating a strong foundation of mathematical tools to prepare students for the rigors of the graduate level course[FOU]. Presentations are better left to courses that survey a broad range of topics without great depth, but the general belief that the goals of the course should be assessed before choosing an evaluation method is common in all faculty interviews [DEP].

> *"In your first semester of QM you want the basic tools, so I think it needs to be somewhat more traditional..."* -Dr. Red

The survey data codes may indicate a shift in student thinking with respect to presentations in class. The most common ideas expressed are that the presentations are not useful for quantum mechanics due to the logistics of allowing every student to make a presentations [LOG], or that other group work is preferred [OTH]. It is also common to cite their uses for more basic material [CON], and it was equally common for a student to be undecided on the applicability of a presentation [UND]. These comments are similar in tone and content to those made by faculty interviewees.

4.2.5 Oral Examinations

Students discussing oral examinations respond positively 68% of the time, on average. Negative responses are seen 26% of the time and the remainder are neutral responses as seen in Figure 5. Faculty members respond positively 47% of the time, and while this is significantly less than the students positive responses, it is also significantly greater than faculty responses that are negative or neutral. It should be noted that one student interviewee had 100% of her oral examination comments coded as negative, and one faculty member had comments that were 50% negative and 50% neutral.

Table 4.6 lists the oral examination content codes derived from interview and survey results. Three students indicated that it would be "nerve-racking"[NER] or "intimidating"[INT]; one of whom was opposed to the idea of an oral examination completely. Others that claimed they would be nervous, but were open to the idea of an oral exam, if it was structured and they were made aware of the type of material that would be covered[STR].

> *"I would feel nervous at first. but it would motivate me to know what Im talking about, because if Im going to go talk to the person whos been standing up there teaching, I dont want to give the impression that I wasnt listening and you know...daydreaming in class..."* - Adam
> *"I think that's a good way to do things, because I think when you talk to instructors... instructors a lot of times can really pick up on where students*

Table 4.6: Oral Examination Codes

Code	Description
YES	Useful
COM	Yes: Better Communication
INT	No: Intimidating/Depends on Professor
NO	Not Useful
STR	Yes: If Structured
20M	More Than 20 Minutes Needed
MNC	Yes: Combines Math and Concepts

aren't as comfortable, because... like I know from personal experience talking to people and doing it myself, that we dodge certain concepts." -Eric

The two female physic majors both indicated that this would make them nervous or intimidated. Research has been conducted at the introductory level focusing the idea that stereotypes can shape intellectual identity and performance [100, 101]. Kreutzer reports that interactive engagement (IE) techniques improve gains on diagnostic tests [102]. This supports the fact that pedagogical tools such as Peer Instruction and self-explanation improve student learning and change the way under-represented students feel about their place in physics [10]. Student interview codes indicate common reasons behind the positive remarks are improved communication with the instructor[COM] and citing oral exams as a scientific career skill[SCI]. Oral examinations are considered to be helpful for determining students strengths and weaknesses, and addressing the weaknesses by student and faculty interviewees. Two faculty members claimed this would be most useful at the beginning or throughout the semester[SEM] as opposed to a replacement for a final exam. They indicated that this would be best as a structured series of topics as opposed to an open conversation[STR]. It was also common for faculty to mention that they do informal oral assessments throughout the semester. The two most common themes that emerge from the data are that oral examinations would be unconditionally useful and that if a condition were imposed it would be that the exams lasted longer than twenty minutes [20M].

> *"I think that [oral examinations] would be important and that would get you to those people who struggled under some time limit to get to get to a correct written answer, yet you could still probe their knowledge and concepts."* -Dr. Red

> *"It seems to me that [the oral examination] is a confluence of their understanding plus their personality, and that is why I would not put too much weight in it. "* -Dr. Yellow

> *"I think it should be our expectation that the students can communicate the ideas."* -Dr. Indigo

Two of the six faculty members interviewed were opposed to using oral exams, one of whom believes that, if offered regularly throughout the semester it may distract from other elements of the course. The main limiting factor cited for faculty members using oral examination is the time constraints that are on them during the semester [LOG]. The most frequent code in the survey data is that an oral examination would be unconditionally useful. Students claimed that it would improve communication with the instructor [COM] and address both mathematical and conceptual understanding[CNM]. The logistics of administering oral examinations to the entire class and nervousness about speaking with the professor [INT] were the most common codes. The code that appears in all data sets is that oral exams would be useful. The survey data may indicate that the utility of the oral exams and the possibility of increased or better communication are unaffected over the course of the semester.

4.3 Perspectives on Course Preparation

4.3.1 Course Content

Some faculty members were hesitant to discuss course content during interviews. This may be reflected in the fact that many interviewees had not conducted a QMC before, even though they were instructors of other upper-division courses. Those that did not immediately respond to the question of appropriate course content in a QMC commonly stated that it would take time for them to think about exactly what material they would include in the course. Questions were re-framed as to what material they recall as important from their own experiences in an undergraduate QMC, and what quantum mechanics concepts and mathematical tools they would expect students to know from a QMC that are pertinent to the course they conduct. For example, one professor was asked what topics they would want a student to take away from the QMC, as it pertains to the course they teach.

> *"For [COURSE], basic quantum mechanics like Schrödinger's Equation and some knowledge with the Dirac Equation…Unfortunately when I gave the course a couple of years ago…several of the students dropped out after the first couple of lectures because I [was assuming] good knowledge of the Schrödinger's Equation then the second part with Dirac equations kind of surprised the students. So for the course I am teaching…the time is very, very limited and [it takes] a lot of effort on the part of the students if they dont understand quantum mechanics."*

In light of course content they had greater familiarity with, faculty members were more able to address the question of what material should be in the QMC. The faculty members that were more directly involved with the course sequence and quantum physics content of the undergraduate courses had more input without prompting.

> *"What [we] need them to understand or to be able to do is the following: [we] need them to be able to solve ordinary differential equations. [we] need them to understand that the solution by series...that they are not thrown for a loop by that...'Cause if they can't solve, if they can't understand the solutions of differential equations, since the Schrödinger's Equation is a differential equation...I mean they are ...I can't say it on this ..."*

Goals suggested by the faculty for those who complete the course focus on the ability to solve simple problems and approximate the solutions to more complex problems. When prompted to elaborate on what defines simple and complex, examples were offered. Problems that would be considered simple are potential well and barriers with simple geometry, normalization and computation of observables for one-dimensional systems, and working with raising and lowering operators. The complex problems fell into the category of Time-Dependent Perturbation Theory, specifically 2nd order perturbations and use of the variational method to solve for energies of a system. It was also expressed that all of these problems were designed so that they could be completed in a reasonable amount of time if they were included on an in-class exam. Student perception of what material would be covered in the QMC was neither strong nor consistent, and responses were often vague. One might expect that with a strong undergraduate community and Society of Physics Students (SPS), upper-division students would have conversations about what material is covered in various classes. Membership in the SPS at the LPSU has increased from 22 to 55 active members in the past two years. Interview data and anecdotal evidence suggests that the difficulty of a course is discussed much more often than the content of the course. Students consistently mentioned potential wells as material that would be addresses, as well as Heisenberg's Uncertainty Principle, and Schrödinger's Equation. One question on the survey asked the survey taker to rate each of the topics presented on a numerical scale from 1-6, where these values are defined in section 4.1.2.

Table 4.7: List of topics from interview results, research literature, and popular textbooks for material that should be included in a one-semester quantum mechanics course.

QMC Topics	
Angular Momentum	Quantum Measurement
Dirac Equation	Reflection and Transmission
Experimental Origins	Scattering Theory
Fermi's Golden Rule	Schrödinger Equation in a Magnetic Field
Harmonic Oscillators	Spinors
Matrix Mechanics	Systems of Identical Particles
Operators and Eigen Functions	Time–Dependent Perturbation Theory
Particle–Wave Duality	Time–Independent Perturbation Theory
Postulates of Quantum Mechanics	Uncertainty Principle
Potential Well Problem	Wave Mechanics

The final question asks what material should be covered in a one-semester QMC. Of the topics offered in the survey, none were considered Not Applicable and none were selected more than three times as "Introduced" or "Beyond Scope." This suggests that the topics selected from the literature and interview data were suitable for a QMC. Because there were only ten responses, any topic with five ratings was considered significant. The most highly rated topic was the Postulates of Quantum Mechanics as being "Mastered." Evidence in assignments, notes, and the mid-term exam suggests that the postulates are a point of focus for the course. All other significant topics had five responses, and they respond to topics covered explicitly in assignments and exams. Topics considered "Mastered" and "Familiar" align chronologically from the syllabus of material to be covered in the course with "Mastered" material earlier in the semester followed by material considered to be "Familiar."

Table 4.8: Topics from post-instruction survey expected to be "Mastered" sorted by frequency (N = 10).

Frequency	Topics "Mastered"
7	Postulates of Quantum Mechanics
5	Operators and Eigenfunctions
5	Potential Well Problems
5	Angular Momentum

4.3.2 Preparation

Faculty members were questioned about what material a student should see before they enter a quantum mechanics course. All faculty agree that the prerequisite courses in ordinary differential equations and modern physics are necessary, and a majority also mention that the "basics" are also crucial. When asked to define what they consider the basics, all faculty referred to the ability to integrate and differentiate functions,

Table 4.9: Topics from post-instruction survey expected to be "Familiar" listed with frequency (N = 10).

Frequency	Topics "Familiar"
5	Systems of Identical Particles
5	Scattering Theory
5	Fermi's Golden Rule
5	Schrödinger Equation in Magnetic Field
5	Time–Dependent Schrödinger Equation

make use of trigonometric identities, and one faculty member included in their definition the ability to use arithmetic. The rationale behind these choices focuses on the fact that Schrödinger's Equation is a differential equation and must be mathematically manipulated, and that modern physics provides the motivation for the development of quantum theory. Three of the six interviewed faculty members suggested that it is a good idea for students to have encountered linear algebra and partial differential equations before taking a QMC as well. The instructors that mentioned partial differential equations also noted that they believe that was covered adequately in the course for what is necessary, however this did not stop more than half of the faculty members from recommending partial differential equations as a good idea to be taken before the QMC.

> *"We don't require them to take PDE's, but we're leading them right up to the edge of it, because they have ordinary differential equations...you're right there on the edge, and you teach them a little on the way. I would think that if somebody didn't take PDEs and came out of the quantum mechanics class [they] would find PDEs easier, and the other way around...I hope."*

The notion expressed above, that previous courses will lead the student to the edge of what is necessary for the QMC, is prevalent in half of the faculty interviews. The familiarity that is expected from the faculty members is often not met by the incoming students. This appears to be related to the amount of knowledge the faculty member has about the specific courses offered at the LPSU. Linear algebra was also listed as necessary or as a good idea by more than half of the faculty interviewees. The faculty members who made these statements cited the need to diagonalize matrices and finding eigenvalues to eigenfunctions as the main benefit of this course for taking a QMC.

> *"If they have done [ordinary] differential equations...maybe partial differential equations. Partial derivatives are covered in that, so maybe that should be something. We use a little bit of matrix diagonalization for the rotation of rigid bodies, again, this is not some thing we go through in the Classical Mechanics course. "*

Classical Mechanics was mentioned by more than half of faculty interviewee as a good idea. When prompted for a reason why they expressed this belief, all but one faculty member stated that there are mathematical tools that can be practiced and applied in the QMC. More than half of the faculty interviewees also suggested that electricity & magnetism would either be necessary or a good idea, due to the abstract nature of fields for students entering the upper-division and experience with wave equations.

> *"In my mind ideally, you would go to classical mechanics, more concrete, but highly mathematical level at that point. Then youd do electricity & magnetism, now youre moving to something more abstract, and has a different nature because its a vector quantity that you are dealing with... and then you move to quantum mechanics, which youre dealing with a quantity that is not a vector quantity, its a complex quantity and is not directly measurable and so the level of abstraction is moving up as you go through"*

The approach described in the quote above appears to be a strong rationale for a sequence of courses. Though diagnostic and assignment data suggest that students who have completed classical mechanics performed better in class, the size of this population of student is to low to determine any statistical correlation between performance and specific course history. Other courses were mentioned when faculty members did not have topics or courses to suggest from an open-ended question. Courses such as Electronics, Statistical & Thermal Physics, were mentioned by the interviewer as options, but none had a significant number of responses. Only half of the faculty commented on the actual preparation of student as they enter the QMC, and the responses mirror published data [63]. Faculty generally represent the students as mathematically under-prepared or average, but those that believe that the mathematics can be separated from the conceptual in upper-division courses stated that the students are conceptually ready for the QMC.

Student interviewees were questioned about the preparation that they believed was expected of them as well as their confidence level in their previous coursework. Students responses to questions of confidence were generally positive. One strong theme in responses was the notion that whatever was not understood could be learned quickly during the semester. Actual interviewee course history can be seen in Figure 4.3. The figure indicates that the prerequisite courses are obviously finished, and that the majority of students are taking Electricity & Magnetism and Partial Differential Equations at the same time as the QMC. Courses such as Classical Mechanics and Statistical & Thermal Physics have not been taken yet by this group of students. Note that very few students have taken any linear algebra courses, because in the post-instruction survey, several students indicate that this course would be very helpful. Apart from linear algebra, it appears that some of the courses recommended by the faculty are the most popular courses taken in conjunction with the QMC. Questions that focus on the methodology and input for courses taken were not part of the interview schedule.

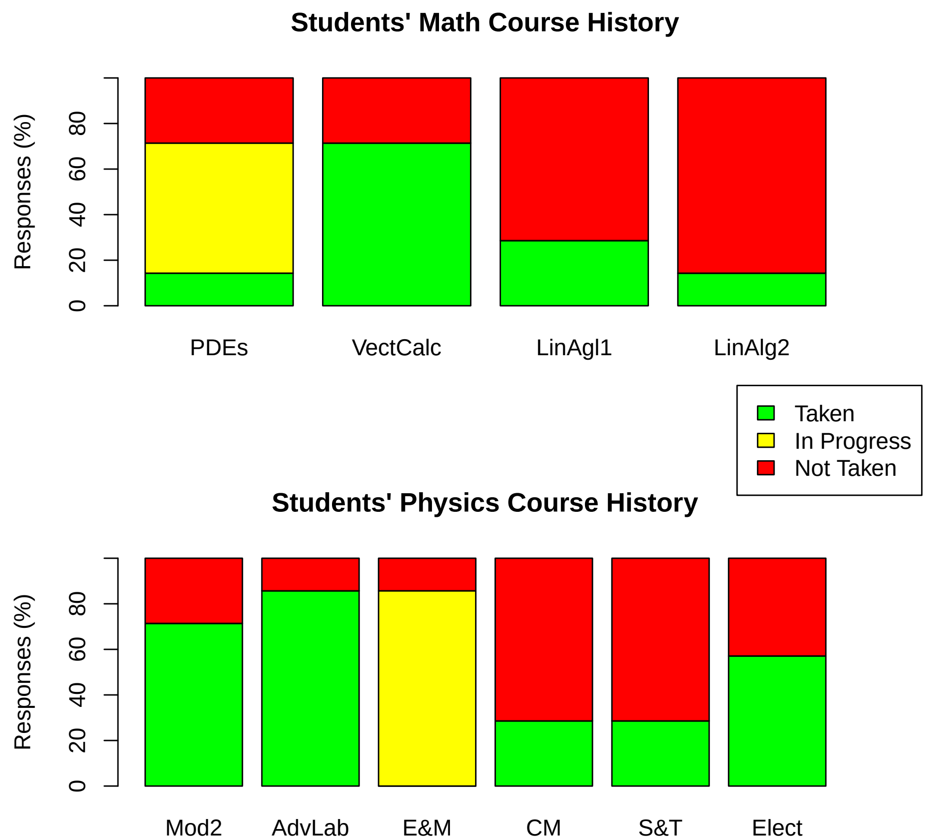

Figure 4.3: (color online) Post-instruction survey responses to questions on what topics are most important as prerequisites for taking a QMC.

The post-instruction survey used questions to have students rank topics as most to least important as preparation for the QMC offered at the LPSU. Participants were asked to rank physics concepts followed by a prompt to explain the reasoning behind their choices. Another series of questions follows an identical format with mathematics tools or topics, followed by prompts to explain those choices. The topics with greater than 3 instances in the first, second or third choice from each subject were analyzed and their motivations were compared. The first, second and third choices in physics and math preparation can be seen in Figure 4.4. Students who have completed the QMC indicate that their first choice for preparation content is the experimental motivation for developing quantum theory (4) and the interpretation of the wave function (3). Both of these topics are assigned to categories for the Modern Physics course. The remaining responses (2) are for wave mechanics. Wave mechanics was coded as a classical mechanics topic. The second choice distribution is wave mechanics (4), the interpretation of the wave function (2), and the Hamiltonian (1). The Hamiltonian was coded as Classical Mechanics material. The third choice distribution was again focused on the experimental motivation for quantum theory and the interpretation of the wave function, in identical occurrences to the first choice position. The remaining occurrences are for the Hamiltonian (2). These results would indicate that the students believe that a course in modern physics and classical mechanics would be most beneficial to a student, as it would address the most popular of the suggested topics for preparing for a QMC. This does assume that the course in Classical Mechanics has time to fully address the Hamiltonian, which is often covered as the end of the semester approaches in Classical Mechanics. The final topic in the physics list is “Idealizations, Generalizations, and Assumptions,” and was added to the list to determine the perceived value of the nature of designing mathematical models of physical systems, a skill that is crucial to all natural science. This topics is one that the majority of faculty interviewees report that emphasize the inherent value of in lecture. This category was ranked once as in the top three choices and three times in the last place position by students who have taken the QMC. This suggests that the topic is not viewed as important to success in the course, but warrants further investigation. The rationale behind the choice displayed in Figure 4.4 and discussed above show a change in the perception from students who have been interviewed before stepping into the QMC and those who have completed the course and taken the survey. Responses range from eloquently to blunt:

> *"One of the basic motivations behind quantum mechanics is that matter is a wave. This explains the experimental evidence of atomic structure in was that no other explanation can."*

> *"Wave functions will be dealt with all semester long, and they are neither intuitive nor familiar to a new student."*

The rationale for the most popular topics, experimental motivation and interpretation of the wave function, highlight that the reasons why the theory was developed are important to understand the usefulness and need of quantum theory and that the wave function is central to quantum theory. Wave mechanics and the Hamiltonian were content categorized as classical mechanics materials that were also popular choices for prerequisite materials. Several students expressed the need to understand the Hamiltonian before they could understand Schrödinger's Equation as well as other assigned problems in the course. Wave mechanics listed due to the reasoning that one must know the basics of waves to work with wave functions and understand probability distributions. This may be indicative of pervasive misconceptions about wave functions and distributions in general.

Mathematics recommendations offered by students who have taken the QMC again have only four topics that are mentioned more than three times as a first, second, or third choice. The topics that has the most occurrences is partial differential equations,

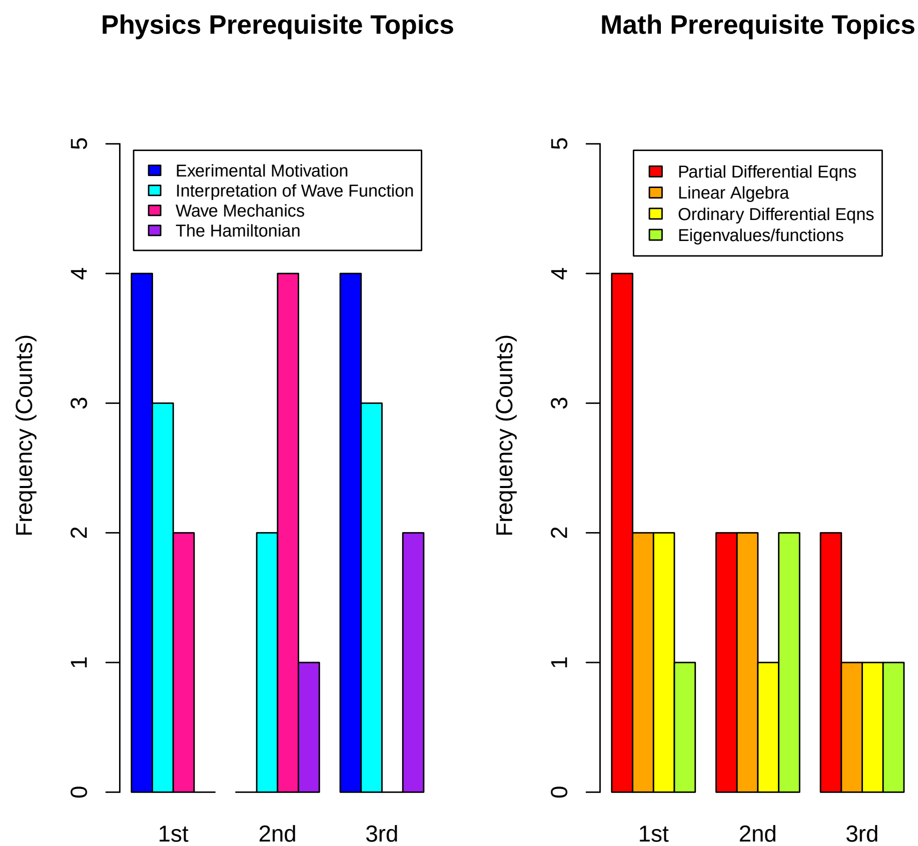

Figure 4.4: (color online)Interview data of math and physics courses taken and in progress for undergraduate students entering a QMC.

both in the first choice (4) and across the top three choices (8). The next most popular choice for mathematics preparation is Linear Algebra (5), and students make a point on several occasions in the survey to differentiate the introductory linear algebra course from the second semester of the course, as the second semester has more material that is pertinent to the QMC. Working with eigenvalues and eigenfunctions is mentioned (1) once in as a first choice, twice (2) as a second choice , and once (1) again as a third choice. This material is also covered in the second semester of linear algebra at the LPSU. Finally, ordinary differential equations are suggested twice (2) as a first choice, and once (1) as a second or third choice. These results when coded for particular courses that address the topics point to the course in Partial Differential Equations and the second semester of Linear Algebra. These two courses address three of the four most popular topics chosen by student to better prepare for a QMC. The comments that explain the choices discussed and displayed above are much more focused on the practical applicability of finding solutions and suggestions for future students.

> *"Though the Schrödinger Equation is a partial differential equation, the course mainly deals with one position variable for the sake of simplicity. Basically knowing how to solve ODE's is a must, PDEs is nice if you want to include more coordinates."*

The necessity of a course in partial differential equations is stressed by many respondents. One common theme in comments made is the utility of the second semester course in linear algebra.

> *"Linear Algebra is frequently used in the lectures, so it' a good idea to understand it's main concepts, theorems, and rules."*

> *"Most of the notation I was constantly tripping over in PHYS4810 (Quantum Mechanics) was explained in MATH4435 (Linear Algebra)"*

> *"I took Linear [Algebra] one and two because I am a math major and I felt I had a major advantage in the class."*

The LPSU provides a Introduction to Linear Algebra that is a precursor to this course, but students explicitly state that the second semester course is more pertinent to the QMC.

4.3.3 Quantum Physics Concepts

Faculty interviewees were asked to express their impressions of how familiar students would be with the conceptual topics mentioned above. Faculty members display very uniform beliefs about students' conceptual understanding of quantum physics topics addressed in the interviews. For the PEP, faculty believed that the students would be familiar with it by name, and how it is used in solutions to problems, but not why it exists. With regards to Wave-Particle Duality, they have a correct response to what it is, but ultimately just use the appropriate equation for a given physical situation. When discussing HUP, all faculty members cited that the students would address the inherent uncertainty in position and momentum, but not what this means with respect to measurement. More responses were elicited when discussing the Bohr Model than with any other conceptual topics. Faculty members suggested that the majority of students would reference an electron cloud around a small, dense nucleus when asked about atomic structure. Only one of the faculty interviewees suggested that a planetary model would be prevalent. Additionally, the faculty members were asked how they felt about the Bohr model as an instructional tool. Responses were unanimous that it is a good tool for transitioning from a classical perspective to a quantum perspective and that its historical context is also important in teaching the motivation for quantum theory.

> *"It's an excellent instructional tool because, the most important thing is that is shows that within this model not all values of physical variables are allowed...at least in a bound state. So, it gets that idea, and that is a crucial idea in quantum mechanics. The idea that certain physical quantities under certain circumstances can only take on prescribed values. That's the 'quantum' of quantum mechanics."*

> *"I would [use the Bohr Model]. I would start out with what they should have learned in Modern Physics, because who knows when they took that, and re-emphasize some of the rules that people came up with experimentally to lead you to this point. So again a little bit more historical approach where we have all these rules that people were discovering experimentally and trying to understand why these things came about...and how they came about . Because if you just jump right into Schrödinger's Equation, it's like going into fantasy*

land."

"But it is also... one of the things you learned along the way as far as historical or the process of science is how to adopt a model that has some really good features even though you know it has some holes, and you might know right away that there are some holes... somethings that there are some features that we cant explain. Bohr had no idea why is there a ground state. There was no reason for that until you get to DeBroglie."

Students were asked about five common topics in modern physics that pertain to quantum mechanics; the Pauli Exclusion Principle (PEP), atomic structure, Heisenberg's Uncertainty Principle (HUP), wave/particle duality (WPD), and the notion of a wave function. Students tend to have strong superficial knowledge of these concepts, but do not demonstrate a knowledge of the motivation or reason for their existence. The PE is recognized by all but one of the students, and with a small hint, that student quickly finished the definition of the PEP. Of the seven interviewed students, only two required a hint to begin their answers, which were correct. That student's answer was the following:

" It's from experiment, right? Because it's a principle, it's from the wave functions...it's not in the math that we had to add in."

Five of the seven had a correct concept of what the PEP was, but only one student could give an answer to why the PEP holds true. Only six students responded to the question about atomic structure. Of those six, five made a point that there is a nucleus surrounded by an electron cloud, as opposed to orbitals. The five that mentioned the electron cloud also made reference to the fact that the nucleus is incredibly dense. Half on the students included information such as the particles that compose the nucleus and that there is a significant amount of empty space within an atom. All students knew HUP by name and all but one discussed its general relation to measurement without any prompting or a hint. Five of the seven discussed the relationship between the momentum and position observables, but none recalled the relation between energy and time. Two of the seven students made a point to recite the equation and it's relation to $\hbar$. All of the students knew the concept of wave/particle duality by name, and cited the results of many electrons incident on a s double slit. Six of the seven mentioned that this property applies to all matter, and of those three made explicit reference to the de Broglie wavelength. The last topic addressed was that of wave functions, and all but one of the students was able to describe the method necessary to normalize one. It was most commonly referred to as "related to the probability that a particle is on a given location." None of the students knew what the units of a wave function were, or if it represented more than just a probability distribution.

4.4 Document Analysis

The assignment, textbook, and notes, there is evidence of a contradiction in expectation involving the time development operator. In this work an activity diagram was used to map out elements needed to understand how the subject interpreted the objectives in the QMC. The subject for the first activity system was the population of undergraduate students taking the QMC. For example, the object of the both activity systems is being able to correctly use the time development operator (TDO) to describe a physical situation. The rules for this system included the academic and behavioral codes set in place by the university, course requirements, and the rules outlined in the syllabus. There were also rules dictated by social norms in the population of undergraduate students. Other rules included the structure and format of the class and are mentioned above. The community of the classroom was composed of the instructor, the graduate students registered for the class, the teaching assistant whose sole responsibility is to grade assignments, and the undergraduate students. This list also represented the hierarchy of the system as well. The instructor is the leader and expert in the topics being addressed. Because the teaching assistant was involved in determining grades, that person was directly below the instructor in the class hierarchy. All of these elements affect how the students interact with notes and assignments.

The graduate students and undergraduate students behaved as two separate populations both in and out of the classroom. There is no indication that the two student groups shared information. The activity system for the instructor differed only in the professional standards set in their rules, artifacts, and object. The artifacts were the lecture material and textbook and the object was to communicate the necessary information to mathematically describe various quantum systems. In the QMC textbook, Foundations of Quantum Physics, Burkhardt and Leventhal listed the TDO, as the sixth postulate of quantum mechanics. At the undergraduate level, it was expected that students understand how using separation of variables, the solution of the time-dependent Schrödinger Equation (TDSE) reduces to the time-independent Schrödinger Equation (TISE) multiplied by an exponential time factor. The ability to perform this separation required that the Hamiltonian is not time-dependent. The text limited the discussion to time-independent Hamiltonians, as that is the usual case. The text addressed the TDO in the context of the time evolution postulate, a spreading wave-packet, and the harmonic oscillator potential. There was no exposure to the TDO in the modern physics textbook used at the LPSU. The focus at that level was on solutions of stationary states in one dimension and total mechanical energies that are not time-dependent.

Document analysis of coursework and notes from students suggested that this topic was taught, but not understood well. The notes taken by students indicate that the TDO is only explicitly covered in one in-class correction session for the homework assignments. Assignments had four problems over the course of the semester that used the TDO. The first question gave the student a stationary state of the wave function and an expression for the Hamiltonian and asked that the student find the expression for the TDSE. The final example that was accessible was from the midterm exam, where given (x) at t=0, the student must determine (x,t) for a free particle.

Table 1 shows selected rubric codes regarding TDO from the analysis of the first homework and midterm exam. On question 1.4.D, the student must know that the problem needs only have the oscillating time-dependence multiplied into the wavefunction. Question MT.2 asks that the student know that the free particle has integrated energies instead of a sum. The number of students that presented a correct use of the TDO was over 90% on the first homework but only 10% on the midterm. This trend was evident from other problems that are similar in form to question 1.4.D. The first problem required executing a procedure to determine an outcome. The codes that for question MT.2 suggest that the TDO cannot simply be multiplied by the wave function given in the problem and often needed to be transformed to momentum space. This midterm problem required that the student make judgments about the problem based on criteria that may or may not be presented.15 The student performance suggested that their knowledge of how to use the TDO is incomplete.

4.4.1 The Hamiltonian

Interviews have been conducted with the faculty members who teach classical mechanics and the first semester of modern physics. These faculty members were asked about what the students' exposure is to the Hamiltonian, and it is usually one time in the lecture notes for the modern physics course, and mentioned at the very end of the classical mechanics semester, as evidenced by interviews and class notes. Only two of the seven students interviewed took classical mechanics before registering for quantum mechanics, and the topic is only mentioned in the final week of the course. These students statements regarding the Hamiltonian are that they have heard of it, but are not familiar enough with the concept to discuss it further. It is important to note that the Hamiltonian operator is covered in the modern physics lectures and the assigned text.

> *"I just introduce Hamiltonian and say the next step from Lagrangian is this. And that you will come through this in Quantum Mechanics in more detail."*

> *"It's in the table when we do operators and they can see how...the things that we are using, we are calculating, are connected to the Hamiltonian, in the simplest case. I show it and mention it and talk about it and then say that you'll see this a lot more when you get to QM. So they get about five minutes on it."*

The instructor for the quantum mechanics course was interviewed and had developed very specific expectations of what mathematical and physics knowledge the students should possess before entering the QMC. It is also important to point out that the instructor is aware that some students will have only met some of these goals. One very specific topic is the Hamiltonian. Goldstein describes the Hamiltonian as an expression for the total energy of a system, the sum of kinetic and potential energy, and it is an artifact associated with the activity of solving Schrödinger Equation problems, as well as some perturbation theory problems [103].

> *"They hafta have a good grounding in Classical Mechanics (CM). When I say the word Hamiltonian, they should not stare at me blankly. They need to know what a Hamiltonian is...classically...we'll take it from there."*

Understanding how to generate the Hamiltonian as well as well as what it describes for a given system in considered crucial to understanding Schrödingers Equation. Students were also asked about their exposure to the Hamiltonian, and the results corroborate the responses from the faculty members.

Table 4.10: Codes generated from student responses to the question "How familiar are you with the Hamiltonian?"

Frequency (N=7)	Hamiltonian Codes
5	Do not recall the Hamiltonian
5	Recall the Lagrangian, but not Hamiltonian
2	Studied Hamiltonian independently

Responses to the question above fall into three main themes: not recalling the Hamiltonian, recalling the Lagrangian, and studying it independently over the summer. This seems to align with other data associated with knowledge of the Hamiltonian. Given the historical context of students exposure to the Hamiltonian, one might expect that questions that deal with the Hamiltonian or related topics such as various potentials in the Schrödinger equation are very difficult for students. QMCS questions 8-10 are defined as questions that deal with the Schrödinger Equation, but these questions do not link the total energy to the Schrödinger Equation or the Hamiltonian, so there is no comparison between this physics concept and the QMCS score. When the Hamiltonian is encountered in an assignment, it is constant with respect to time and used to calculate energy eigenvalues or it must be generated by the student. These questions do not adequately address how the Hamiltonian is related to the development of the Schrödinger Equation. The activity system that uses the course material and other resources as an artifact with the objective of understanding what the Hamiltonian is in a quantum mechanical system and how it is used in finding eigenvalues and solving Schrödingers Equation has a conflict arising from the difference in perceptions of previous knowledge. For the student there is little if any exposure to this idea before the QMC, and may be outside of the zone of proximal knowledge, but interview data suggest that the amount of guidance sought by students is very little.

4.4.2 Uncertainty Principle

Faculty and student interviewees were questioned about what knowledge of Heisenbergs Uncertainty Principle (HUP) was expected before taking a QMC. All students interviewed were familiar with the name of this principle and the fact that it addresses the minimum uncertainty in a measurement of momentum and position. None of the students, however, were familiar with the uncertainty in a measurement of energy and time or were familiar with the mathematical reasoning behind why the Heisenberg Uncertainty principle exists. Faculty expectations of student understanding were correct in almost all cases. On the QMCS, problems 3 and 6 are categorized by the author as relating to Uncertainty, but not the mathematical use or proof of the HUP. They are similarly not comparable to the interview data or assignments as was the case with the Hamiltonian. Assignment data indicate that the students had the capability to use and manipulate the HUP, but did not as a group understand its origins. The second assignment had a single problem that asked students to determine the expectation values of x,p,x^2, and p^2, and use them to compute Δx and Δp and determine if the results agree with the HUP. Three-quarters of the class succeeded in that problem, suggesting that the group did nto have significant difficulty with manipulating and reasoning with the HUP in that context. One of the questions students could chose to answer on the mid-term was to derive the HUP from the definitions of (ΔA) and (ΔB), and five of the twelve undergraduate students attempted that question. Three of five were able to produce the correct result, but none used the Cauchy-Schwarts Inequality, which is necessary to complete the derivation correctly. Based on interview codes and mid-term results it is possible to claim that student understanding of the HUP does not reach the point where the foundational ideas are understood. Chapter 3 results indicate that the HUP was not indicated by the survey results as material that should be “Mastered” or “Familiar,” though in course content it is mentioned as one of the prominent ideas in quantum theory.

4.4.3 Time Development Operator

In Foundations of Quantum Physics, Burkhardt and Leventhal list the time development operator (TDO), which is sometimes referred to as the time evolution operator, or the propagator, as the sixth postulate of quantum mechanics. At the undergraduate level, it is expected that students understand how using separation of variables, the solution of the time-dependent Schrödinger Equation (TDSE) reduces to the time-independent Schrödinger Equation (TISE) multiplied by an exponential time factor. The ability to perform this separation requires that the Hamiltonian is not time-dependent. The text limits the discussion to time-independent Hamiltonians, as that is the usual case [104]. The text addresses the TDO in the context of the time evolution postulate, a spreading wave-packet, and the harmonic oscillator potential. There is no exposure to the TDO the modern physics textbook used at LPSU [93]. The focus at that level is on solutions of stationary states in one dimension and total mechanical energies that are not time-dependent.

Document analysis of homework assignments, the mid-term exam, and notes taken by students has suggested that this topic in the course is taught, but not understood well. The notes taken by students indicate that the TDO is only explicitly covered in the in-class correction session for the homework assignments. Assignments had four problems over the course of the semester that used the TDO. The first question gives the student a stationary state of the wave function and an expression for the Hamiltonian and asks that the student find the value of the TDSE. The second example gives the student the TISE for a particle in a box and is asked to find the TDSE. A third example is a harmonic oscillator in the ground state with the "spring" cut at $t = 0$ and the student is asked to determine the TDSE. The final example that was accessible was from the mid-term exam, where given $\Psi(0)$, the student must determine $\Psi(x, t)$ for a free particle.

The data in table 4.11 indicates that students are able to use the TDO in the context of adding a multiplicative term to a wave function as done in the first two pairs of codes. The codes that follow afterwards are from problems where the TDO cannot

Table 4.11: Chronologically organized assignment rubric elements that make use of the TDO.

Question	Date	Rubric Element	Frequency (N=12) *(N=10)
1.4.D	09/06/12	Determine correct TDSE	11
1.4.D	09/06/12	No Attempt	1
2.1.B	09/18/12	Determine Correct TDSE	11
2.1.B	09/18/12	No Attempt	1
2.4	09/18/12	Correct Solution	1
2.4	09/18/12	Correct Wave Function	6
2.4	09/18/12	Correct Use of TDO	0
MT.2	10/30/12	Attempt to use TDO	8*
MT.2	10/30/12	Correct Solution	1*

simply be multiplied by the wave function given in the problem. The complexity level of these problems is higher than the first two by the assigned Bloom's classifications. The first pair of problems are category 3 problems. These problems require executing a procedure to determine an outcome. The latter problems are category 5 problems, which require that the student make judgments about the problem based on criteria that may or may not be presented [89]. The student performance suggest that their understanding of how to use the TDO is incomplete.

4.4.4 Student Confidence

Interviewees were asked how confident they felt in the material that they had covered in previous mathematics and physics courses. The math questions centered on upperlevel courses such as Ordinary Differential Equations, Partial Differential Equations, Vector Calculus, Linear Algebra, and Introduction to Linear Algebra. Physics questions were more limited, since students had taken fewer of them. Modern Physics I and II, Electricity & Magnetism, Statistical & Thermal Physics, and Electronics were the most prominent choices. Students were often glib when recalling material from any courses and often claimed that they could "pick it up during the course" or that they "were not familiar with the names, only the formulas or ideas." Five of the seven interviewees are consistently confident in their background in mathematics and physics.

These statements are compared to the QMCS results and homework rubrics to validate or refute the student perspective. Students were offered the QMCS as a post-instruction diagnostic for Modern Physics I and as a pre-instruction diagnostic for those registered for the QMC. The distributions of both QMC and Modern Physics I were significantly normal $p = 0.02$ & $p=0.03$ respectively and score distributions were statistically similar($p = 0.05$). This prompted the combination of all data in an effort to increase the N value for analysis ($N=32$).

Figure 4.1 displays the range of scores for the entire population of undergraduate students that took the QMC as well as those completing Modern Physics I. The performance on the QMCS was not as strong as expected. The average score was a 46% with a standard deviation of 19% and a standard error of 3%. The content of the QMCS has been included in Appendix D. This is corroborated by the assignment analysis for the first two assignments. The content of the first two assignments aligns with the content covered in the QMCS. The average percentage of rubric points earned for the QMC ranged from 62% to 75%, with a standard deviation of 15% and a standard error of 3%. Rubrics were broken down by math and physics score, and evidence suggests that 2/3 of students consistently had higher math scores than physics scores on the rubrics.

4.5 Result Summary

One faculty member said the following during the course of the interview:

> *"The question you should ask yourself is 'why do we evaluate?' What are we trying to do when we evaluate? We are not trying to see who is good and who is bad. We're trying to differentiate between who understood and who did not -you know understanding is in degrees, it's not black and white, zero and one...for senior students, for even graduate students, understanding is more involved. Understanding more complicated processes, it becomes even harder to judge."* -Dr. Blue

We present evidence that both faculty and students in the the LPSU physics program under investigation have similar perspectives on what types of evaluation methods are most appropriate for an upper-division course, such as quantum mechanics. We argue that both parties respond positively to the idea that a comprehensive understanding of physics should be tested orally and mathematically, as these formats are crucial to participants in any scientific research discipline. The faculty data suggests that if they had the time, oral examinations would be beneficial to both students and teachers. Many faculty members do this informally as a formative evaluation as they lecture. This data also suggests that the intended goal of quantum mechanics should not be broad topical knowledge, but to lay the conceptual and mathematical foundation for further study in quantum mechanics at the graduate level, as seen in the perspective on student presentations in that course.

Students as a group changed their responses after taking the QMC. The belief that multiple choice questions are not useful remains, and the rationale offered becomes more similar to the faculty rationale of demonstrating knowledge or using these questions only for concepts or the basic material. Students shift beliefs about in-class presentations as well, citing some of the same reasons as the faculty for why they may not be appropriate. The most prominent reason is the scheduling and logistics of presentations. Student perspective on oral exams remains unchanged over the course of the QMC according to survey and interview data. The desire for better communication remains a common code as well as the unconditional utility of the oral exam and importance of being able demonstrate knowledge of necessary mathematics and concepts. Students exhibit significant positive commentary about student presentations (86%) and oral examinations (68%), especially when compared to multiple choice questions (11%). This indicates that the LPSU students may recognize the importance of skills associated with participation in a scientific discipline or the importance of a deeper evaluation of their knowledge. Generally, students are open to a diverse evaluation of their knowledge of physics, and believe that it benefits them during and after their undergraduate experience. Faculty demonstrate similar trends in commentary when questioned about multiple choice questions, but have a more balanced tone than students when discussing the other evaluation techniques.

The data and analysis presented indicates that there are few, if any, ideological barriers for students to diverse evaluation in physics and that the faculty members would generally be open to such an idea, if certain criteria are met. The most common criterion being that the evaluation did not impose on time in the classroom. The findings of this small, exploratory study would be best used for the generation of a theoretical construct that can be tested rigorously in a larger more focused study. This body of information could lead to reforms of assessment in upper-division courses at a variety of institutions by including various forms of self-explanation in examinations or using oral examinations to serve as formative assessment for instructors. These tools develop the students' communication skills and serve them beyond their undergraduate careers.

We also present data that suggest faculty members and students in the LPSU physics program have dissimilar perspectives on what material should be prerequisite and covered in a QMC. This difference is due to student interviewees' apparent lack of knowledge about what content to expect in the course, and is understandable if students that are wholly unfamiliar with the QMC. There were little if any indications of any communication with students who had taken the course previously and all student interviewees acknowledged the utility of the interview process in focusing them on what material might be important for the course that they were about to take. This condition may have lead to student beliefs about the preparation or content for the course. We argue that students' perspective on both preparation and course content shift towards those of faculty members based on survey data taken after the QMC. Themes from survey responses include the need for Linear Algebra, Modern Physics, and Partial Differential Equations. The majority of faculty members indicate that the students do not need more than strong foundational skills, or "the basics," a course in ordinary differential equations, and a course in modern physics to succeed in a

QMC. This data also suggests that the intended goal of a QMC for half of the faculty interviewees is to solve "simple" problems as defined above, the other half include the ability to convey understanding through both writing as well as mathematics.

The interview data suggests that the faculty view of what conceptual knowledge students posses as they enter a QMC is accurate for the topics covered in the interview. Students demonstrated knowledge of atomic structure, the PEP, or HUP. But the majority of students could not respond correctly to questions focusing on the foundations or development of these ideas. Students knowledge of the wave function focuses on probability distributions and normalization, and omits a broader meaning on what the wave function describes and how it does so. According to the familiarity criteria defined in the Data Collection section, the responses commonly given would be considered "Introduced;" which could be expected depending on the depth and breadth of material covered in the modern physics course.

The faculty perspective on what material will foster a strong understanding of quantum mechanics is an important starting point for creating a comprehensive course in quantum mechanics. as the student perspective after taking such a course. The survey responses offer insight for future physics students as to course sequences that are optimum, material that may be addressed in courses, and material to revisit in preparation for approaching a QMC. Faculty interviews and conversations highlight the fact that if a student struggles with the mathematical tools necessary to describe quantum theory, this will only obfuscate the quantum physics that the instructor is trying to help the student learn.

The data acquired from this departmental research could ideally be used for the generation of a framework for curriculum development for QMC's and the methodology can be applied to any subject or course level. Offering insight from both previous students and faculty in a structured format as opposed to the oral tradition that is typical of most departments could be mutually beneficial to all parties involved. Students who are motivated could have material that they can being to assimilate before the beginning of the semester and even those who are less motivated could be warned of what will be expected of them if they decide to register for the course. By having strict and meaningful descriptions of course content and goals for courses at all levels, assessment of student learning and instructional methods will be more clear and measurable. This would ideally prevent students who are unprepared from taking a course that they may not be prepared for conceptually or mathematically. On a larger scale, perceptions of preparation and course content could be further categorized by variables associated with institutions at which they are held. Though the majority of faculty express that there is little communication about course content or instructional technique between them, yet there is internal consistency in beliefs of LPSU faculty members. This case study applied to institutions all over the county could help determine a statistically significant "common core" of beliefs to guide curriculum development for QMC's.

A goal of this research is also to address conflicts of perspectives on course content, and perspectives on student confidence in the prerequisite material for a QMC. This relates back to the foundational work by Chi and diSessa regarding how students build a scaffolding for information being taught [22, 26, 27]. Prerequisite materials can be further investigated and build from phenomenological primitives, or p-prims.

For an upper-division course, these p-prims can be less intuitive than those found in introductory courses. The data acquired over the fall semester of 2012 have been used to crystallize an authentic image of the quantum mechanics class. This work highlights the importance of communication between faculty members regarding course content and class sequences. The students also need to be active members in their own preparation and education. A clear set of goals and tools needed appears to be a possible solution to contradictions of objective for all the cases described in this chapter.

Faculty and student interviews suggest that there is little coverage of the Hamiltonian for any students before they reach graduate school. This statement has been confirmed though the student notes and assigned text for Classical Mechanics as well as Modern Physics. Document analysis of assignments in the QMC indicate that while the Hamiltonian is a fundamental concept in quantum theory it is mentioned most often in the context of finding energy eigenvalues. If knowledge of what the Hamiltonian is and what it does is as crucial in the development of quantum theory as is indicated by faculty members, steps should be taken to encourage students to study this outside of class, or address it in a pertinent course. The TDO is an important element for dealing with non-stationary states of a quantum system. The TDO is not covered in the Modern Physics curriculum due to the rational that simplified examples of the Schrödinger Equation should be studied. Coursework evidence suggests that the TDO is understood for the TISE as a multiplicative element, but not for SDSE systems. This concept is only evident in one student's work from the assignment data collected. The HUP is material that is addressed in both Modern Physics I and Quantum Mechanics, but student knowledge of the HUP does not reach the stage of "Mastered" as defined in chapter 3. Mid-term exams show that of the students that attempted to derive the HUP, none could do so. The questions in the QMCS associated with the HUP also showed poor performance.

Any of these topics can be addressed in terms of building understanding from the fundametal unit of a p-prim. Treating knowledge of the Hamiltonian as a p-prim involves the understanding of partial derivatives, the total energy of a system, Lagrangian Mechanics, and even the Legendre transform. Correct use of the TDO requires that the student know the difference between discrete and continuous energy and what that implies about the system being studied. For the HUP, the concepts associated with quantum measurement and the observer effect, because all data collected indicates students do not discern between the two concepts.

Data collected indicate that confidence that students have entering the QMC is unfounded and the course should be taken quite seriously, as it draws material from many different upper-division courses in both math and physics. The assignments of the first two weeks show a lower rubric score in physics than in math suggesting that students may be using their mathematical capabilities as a crutch for deeper learning of the conceptual components of quantum theory. Faculty members, including the instructors of modern physics and quantum mechanics, have been interviewed regarding their perspective on what the goals for a one-semester QMC should be.

> *"its equally important is to understand the conceptual aspects of quantum mechanics that is a very important aspect of this course, because we don't do it in the next course. 'Cause we assume they understand the concepts...we're just delving deeper."*

The subject of this statement is Modern Physics I. Based on analysis of the material from the students in the class and from interview data, conceptual content is addressed more in Modern Physics I than in the QMC and this is expected by faculty interviewees. The majority of faculty interview data indicates that the focus of a QMC should be to create the foundation for graduate level study in quantum mechanics, which is often reduced to the mathematical foundation for solving problems. If this is the case, clear goals for the modern physics and quantum mechanics courses could easily be communicated to students and allow faculty a solid list of goals by which to evaluate student performance.

CHAPTER 5

CONCLUSIONS AND IMPLICATIONS

5.1 Case Study Overview

At the beginning of this dissertation, the following questions were asked:

- What are faculty member and student perceptions of the following:
  * Alternative evaluation techniques
  * Course preparation
  * Course content
- How do these perceptions compare within and between groups? Is there a "common-core" of ideas?
- Does this data suggest any predictors for success in a one-semester quantum mechanics course?

These questions are addressed by triangulation of faculty and student coded interviews, survey data, and document analysis of course materials.

In an effort to address these questions, semi-structured interviews with faculty members and senior-level students entering a QMC at a LPRU in the southeast have been conducted. Interviews probe the perceptions of different evaluation techniques, expected conceptual models of students, and expected and ideal preparation for learning quantum mechanics. In addition, a survey was offered to students that completed the QMC at an LPSU. The survey also addresses similar questions of course content, preparation, and evaluation. Finally, a new analysis method was implemented to determine conflicts in expectation and perception by utilizing the cultural-historical activity theory framework. Using traditional coding of interview responses and document analysis, researchers highlighted conflicts associated with student confidence in conceptual material, prerequisite knowledge, and course content for the QMC. The following sections summarize the results presented and suggest projections on which future research should concentrate.

5.2 Results

The interview and survey results together support several recommendations for implementing evaluation techniques at the upper-division. The most prominent result is the fact that faculty and student opinion, as well as the post-instruction survey results are overwhelmingly against the use of multiple choice questions at the upper-division. The rationale for this statement from faculty and post-instruction survey results focuses on demonstration of knowledge, while the rationale from pre-instruction students focuses on the ability to circumvent content knowledge with test taking strategy or by chance. Another implication of the data analyzed is that the majority of faculty members and students see the utility in a combination or written and mathematical explanations for physics problems. This aligns with research in PER and more general education research [23]. It has been determined that the utility of student presentations relies heavily on the nature of the course and the instructor's goals. Some classes will need to focus on a strong foundation of knowledge that requires less freedom to explore material, while other courses offer a broader array of topics studied in less depth. It is the instructors' prerogative to choose what the goals for a course are and how to achieve those goals. The final result that this analysis suggests is that oral examination is some form are acceptable to the majority of faculty members and students, under the condition that the examination is structured and the process does not impinge on the faculty member's time and other responsibilities.

Faculty members were hesitant to recommend course content without careful consideration. Reframing the question based on their experiences and courses that they have taught recently provided some limited success. Student perspective on what content would be covered in the QMC was not consistent and often referred back to material seen in the modern physics course with more elaborate mathematics. Though a majority of faculty members recommended courses such as Partial Differential Equations and Linear Algebra as a supplement to the QMC, they all agree that the course in modern physics and ordinary differential equations would be enough to succeed in the class. Faculty perspectives on student conceptual knowledge mirrors the knowledge that is indicated from student interviews for almost all cases. Students demonstrated knowledge of atomic structure, the PEP, or HUP. But the majority of students could not respond correctly to questions focusing on the foundations or development of these ideas. Students knowledge of the wave function focuses on probability distributions and normalization, and omits a broader meaning on what the wave function describes and how it does so. Students seem to choose courses that the faculty members recommend most strongly without consulting faculty members. Post-instruction survey data strongly suggests that student who are preparing to take the QMC register or have taken the course Linear Algebra II due the significant overlap in notation and foundational mathematics knowledge.

Conflicts in perception are present in prerequisite knowledge, course content and student confidence in material. Evidence from interview codes and assignment data builds a case for deeper instruction at some point int the upper-division sequence for the Hamiltonian and the TDO. Assignment highlight the fact that the TDO is missused through the mid-term exam in the QMC. The topics is covered in the text, but not addressed in a significant way, according to notes taken by students in the class. The Hamiltonian is mentioned in the classical mechanics and modern physics courses, but interview data demonstrates that the majority of students enter the QMC with very limited knowledge of the Hamiltonian. Student confidence in conceptual and mathematical knowledge is very high, but this is not generally supported by the diagnostic or assignment scores. Taken together these findings support a recommendation to focus and increase communication within the department. This can take many forms; the least invasive being more precise course descriptions and listed skills that will assist in learning the material. This could ultimately help students plan their sequence of courses, prepare for a course that might otherwise be very difficult, or know that they do not have the base knowledge to take a particular class. The data in this body of work also suggests that the mathematical and physics background needed to succeed in upper-division course work are applicable, despite the facts that students do not immediately see the connection and faculty members are not inclined to mention it explicitly. Faculty being more aware of what material is and is not taught in the program can possibly help students see the connected nature of the mathematical tools used to model physical systems.

This research emphasized the importance of communication between all members of this learning environment regarding course content and preparation. The course materials and assignments implied that the instructor may have expected the students to be able to make the leap from a simple problem that used a TDO as a component multiplied onto the spatial wave function to something more like a free particle that could absorb any amount of energy, therefore energies must be integrated instead of summed. Some goals for the course may not explicit enough. The historical context of the students coursework provided an explanation for misunderstanding the TDO, which has been seen in other recent work [80,105]. Survey and faculty recommendations of Linear Algebra II are well founded, and this is corroborated in the course assignments. Survey results also recommend more exposure to the interpretation of the wavefunction and the Hamiltonian. Both of these topics contribute to students conceptual model of the TDO. This line of research provides a list of important material students should focus on as they prepare to learn quantum mechanics.

5.3 Future Directions

A number of possible future studies using a similar methodology could follow this exploratory research with minimal experimental difficulty. One option is to further investigate documents associated with the class in question. Notes taken by students would be indicative of what material they believe the instructor is trying to emphasize [7]. Another data form that can be used are audio recordings of lecture material. The instructors aims in the class could be triangulated with a combination of these notes, instructors' lecture notes, syllabus, and assignments. The assignments provide evidence to instructor epistemology, pedogogical preference, and mode of assessment as well as insight into students' competencies with the assessed material. A thorough analysis of these documents and audio material would provide evidence of the ways that different instructors present material and assess student progress in a particular course and provide data-driven suggestions for course preparation. These materials could also suggest different modes of assessment or changes in material or content delivery. This data would require a more rigorous qualitative coding scheme.

Information on the structure and pace of the course could be combined with concept maps generated by faculty members and periodically by students. This would provide insight into how the expert scaffolding is arranged for the course material as well as how the novice builds and corrects their scaffolding of the course material. This exercise could be a experiment to verify the Categorical Shift Theory in physics as opposed to the research conducted in Physiology courses [23]. Concept mapping as outlined by Novak would offer a more concrete representation of student conceptual knowledge and how they assume the material is organized [21]. This requires a discussion of how to create and change concept maps. Interviews would be conducted with faculty members in an effort to characterize the expert scaffolding of the course material, or topics within the course. Topics such as the TDO or the Hamiltonian as identified by this research would be topics that may show significant promise in identifying expert scaffolding and measuring a change in student scaffolding over a the course. This would most easily be accomlished by assigning exercises in class to create the concept maps. Diagnostics offer a binary response to if a student understands a concept, but not how they see that concept interacting with other information in the subject. In a larger study, statistical significance can be added to concept maps for students, generalizing misconceptions in modern physics and prerequisite mathematics. This methodology was employed successfully by PER researchers at University of Minnesota for a different topic with a population of introductory students [59,60]. This would allow interventions in courses prior to quantum mechanics to build a stronger foundation in the modern physics material.

Data collected and previous research support the notion of a “common core” of ideas held by faculty members as well as the suggestion that instructor beliefs direct evaluation and teaching strategy. Because the course is offered on a regular basis, acquiring data from more survey participants is straightforward and non-invasive. Determining the perceptions of evaluation held by faculty members an important component of assessing how institutions respond to research base instructional strategies. This also provokes conversations related to what goals are set for individual courses and for students exiting a program. Having concrete goals for courses and for exiting the program produces stronger physics students, and alleviates pressure on the instructor for rationalizing grading choices. A similar study should be performed to determine prerequisite material for courses of all types. For introductory courses, instructor perspectives could identify common core ideals for preparation and content. This is beneficial to the department that has created a uniform evaluation standard for the course, and for the physics education researcher that has a more uniform population of students for investigation. This methodology could be extended beyond physics courses, as experts in any field will have strong opinions of what material is necessary to learn as a student moves through the course sequence.

In order to determine the statistical significance of findings, a database would need to be created that stored various parameters that describe any participating institutions. Investigating the significance of variables such as department size, funding, undergraduate population, location, and research specialty would be the first step to a strong categorization of evaluation practices at different types of institutions. The same body of data would support surveys that focus on course content or preparation as well. Cluster analysis or primary component analysis would easily categorize or identify correlated variables respectively. Anecdotal evidence suggests that public and private universities or engineering programs and liberal arts programs will teach a different course sequences for the same topic, but detailed analysis could form the cornerstone of a categorization that guides concrete learning goals for any institution. Programs that seek to strengthen or change their program could use this data to investigate different implementations based on an established category that their institution falls into or seeks to be in. A survey item is already in development to be sent to physics faculty at a variety of institutions. An appropriate scale for the survey study would be a national scale. Even if participation was low, this would allow several types of institutions to contribute data. In summation, this body of information could be the beginning of reforms in the upper-division courses offered at a variety of institutions and include, at the very least, detailed course descriptions to benefit students, written components to examinations, and ideally periodic oral examinations, all to help inform instructors and prepare student develop the skills that will serve them beyond their undergraduate careers.

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APPENDICES

Appendix A: Faculty Transcripts

A.1 Dr. Red

CO: I find this works best if I start off by asking you about your experience as an undergrad in Quantum Mechanics (QM).Okay, its been a long time.

DR. RED: So, um...I was a student here at Georgia State. I dont know if you knew that. I had no idea. So, Atlanta is my home town. I was here from 75-79. Quite a long time ago, and I took QM with Dr. Manson and hes still on our faculty. Thats excellent. So, as I recall, I thought it was a great experience. Hes very animated and likes to give his opinions You bet. but also I thought he was an excellent teacher. I do remember sort of being a little intimidated by QM. Modern Physics set me up for it a little bit...So the sequence was the same...Modern I, Modern II Actually I think we only had...I think we had two Modern [Physics] classes, but we were on a quarter system.

CO: Are there any topics you remember being really difficult to wrap your head around?

DR. RED: Well, I mean. Just the whole terminology was new to me...Schrodingers Equation [SE] and complex variables. So was it more of a mathematical complexity or a conceptual one. It was a little of both. Yeah. Its sort of a whole new mind set for a lot of people. To go from classical Mechanics and E&M to QM is just different.

CO: That being said...lemme look at my list. If you were evaluating students for an upper-division course, like QM...Im going to run through a handful of different types of questions and Id like your opinion on how good they would be at evaluating students knowledge. For example, Multiple Choice Questions. How do feel about those at the upper-division level?

DR. RED: I think for most upper division physics courses, it's not appropriate. Could you elaborate a little? Well, I just think that theres lots of ways to give partial credit and to evaluate the thought processes of students and Multiple choice doesnt really allow you to do that. If ou are asking someone to write out as much as they can then choose one of the MC answers, maybe that s a little better, because that gives them a guide to whether the answer they got is anywhere near one of those choices or not. Yeah. Otherwise, I think most other physics professors would agree with me that its inappropriate.

CO: What do you think about short answer questions...just one or two sentences?

DR. RED: I think those could be useful, , traditionally but as you know, most of the test for the upper-division courses are solve these problems written problems...show your work. I can see that that might be useful in testing for some basic jargon that you should always incorporate into your work. You need to know what these words mean, for example. Or, lets say you went over a few things like experiments for example related to QM,...it might be good to know the key figures in the field. It could be appropriate.

CO: It;s funny you mention that, because Ive always said I wish there a history of Physics course at the undergraduate level. I feel like you are inundated with a lot of math and concepts, and you learn about SE and you hear a bunch of different names, but you really dont know who those people are. Sometimes the story also helps you remember whats going on with the idea.

DR. RED: Thats right, and its also good sometimes to see how things progress. You can see how people thought about things...there are never any easy answers, and its presented to you as this is the way it is. How did it get to the way it is? There are probably Its not all being hit on the head with an apple and figuring out gravity Right, which didnt happen either.

CO: But...the Written problems are sort of the bread and butter for upper-division physics courses.

DR. RED: Yeah, traditionally thats what people tend to do. But theres always room for change.

CO: I know that some of the upper-division courses, like Modern or Modern II, they do presentations at the end of the semester where everybody picks a topic and go deeper with that topic. What do you think about that in the context, I know QM is more basic, so its not so much interesting research topics within that field. Do you think that kind of think could work?

DR. RED: Its possible...without thinking about it too much. Im not sure. I think its great for Modern; we didnt do that when I took Modern, but its possible. In your first semester of QM you want the basic tools, so I think it needs to be somewhat more traditional, but in more advanced classes, even in my grad classes I use short answers and presentations.

CO: This is sort of the other end of the spectrum...having a one-on-one conversation with a student, instead of a 3 hour exam block...Im assuming that time is not a constraint, if you could divide that 3 hour block into 15 minute chunks and spend the time with a student and ask them in a conversation type format and have that be their grade eval.

DR. RED: Sure, if you are asking for their opinions about how things are going, no. If you are actually testing their knowledge to some extent...kinda like mini oral exam Thats what I was thinking of. I think that would be important and that would get you to those people who struggled under some time limit to get to get to a correct written answer, yet you could still probe their knowledge and concepts. I know in terms of oral quals thats always been interesting and finding where peoples knowledge is really strong and spots where its not so strong, and you can gauge where their weaknesses are and address that. If you are doing it for credit though, fifteen minutes might be too short. I EXPLAIN THE ORAL EXAMS IN LANGUAGE CLASSES I think you're gonna have to spend 45 minutes with someone to really understand what they know and what they dont know.

CO: Im going to ask you about how you think a student would respond to a couple different questions...some conceptual topics...the first one being if we ask the student what the structure of an atom is how do you think they'd respond?

DR. RED: When they are at the QM level. Before they get into QM, sort of post-Modern[Physics] Thats a good question, Im not sure how to respond because Im not sure what is being taught in Modern these days, but theyd probably give you the Bohr Model of the atom. And Im not so sure theyd go too much beyond that...a nucleus, draw you an energy level diagram. they might be able to give you an equation or two about energy difference levels according to principle number. EXPLAIN THE PURPOSE OF INTERVIEW

CO: Same question, but dealing with Heisenbergs Uncertainty Principle [HUP]. Do you think that students going into QM have a grasp...what kind of grasp do you think they have? A better way to ask the question might be if you were going to tell a student about what HUP is, where would you start that conversation? Assuming theyve taken Modern [Physics] already.

DR. RED: Well, you can always start with the cat in a box. Laugh. Yep. Its been a long time for me but I think that...what would I expect them to know? Yeah. I think that Id expect for them to remember that there is this inherent uncertainty between position and momentum ...so Id expect them to remember that... not so sure how much more modern does with that...other than some basic explanation of why due their wave nature why particles behave like this. I wonder how much understanding there is about how that deals with measurement. Theyve probably heard of the effects of the observer on a measurement. Its not clear whether QM will give them a better understanding of that or not. I guess it would in terms of really emphasizing the wave nature of particles.

CO: Same question for the Pauli Exclusion Principle [PEP]. Do you think that if you said hey what can you tell me about this PEP...how do you think theyd respond

DR. RED: Hopefully, theyd know that you can only squeeze a given number of electrons in to a quantum state. They may not remember exactly why that is. That would be sort of reinforcement...I think that might be a much deeper understanding, but yeah.

Something they remember , probably understand certain [???] but look at some basic understandings...

CO: If you were teaching QM...I know this is backtracking... you mentioned the Bohr model, would you use the Bohr model as an instructional tool if you were teaching the course?

DR. RED: I would. I would start out with what they should have learned in Modern Physics, because who knows when they took that, and re-emphasize some of the rules that people came up with experimentally to lead you to this Motivation? point. So again a little bit more historical approach where we have all these rules that people were discovering experimentally and trying to understand why these things came about...and how they came about . Because if you just jump right into SE, like going into fantasy land. Its a shock to the system You can understand slabs going down inclined planes, you see that kind of stuff everyday, but when you get into QM you dont have any physical reality Theres no intuition. Thats right. I would think youd need to build some kind of background...why looking at SE is important. Lets take a step and see how we got to that point.

CO: Since you brought up SE, the next think I was going to ask you was what do you think student understand about wavefunctions? Before they get into the QM class...

DR. RED: They probably have heard about it in Modern Physics, again I really dont know how Modern [Physics] is taught these days, but I would hark back to my Modern [Physics] days and remember that yes, waves behave like particles and particles behave like waves. Remember something about you can only squeeze electrons into certain orbits because they are waves and need to connect with themselves in a certain orbit.

Isnt this strange.

CO: How much background do you think they have when we talk about Particle-Wave Duality? What kind of understanding of that idea do you think they have?

DR. RED: I guess it depends not only on what they learned in Modern [Physics], but maybe in some earlier courses, like in Astronomy. We do this quite a bit, we talk a lot about photons, waves and particles, its very crucial to introductory astronomy students. how photons can behave like waves in certain situations and particles in other situations. So, I think its pretty variable. Depending on their background and how much popular literature theyve read. Cause theres a lot out there, right? I think that QM is one of those things that is addressed...I know Stephen Hawking has made a pretty penny off... Exactly. A Brief History of Time or more fun basic physics stuff as they were coming up through school that . That's one of those things that you hear about a lot.

CO: What do you think would be the ideal preparation for a student going into QM...Ill ask you in terms of math and what physics you think they should have.

DR. RED: Okay, so I haven't looked this up for our students... Ill tell you right now they prerequisite for QM is Partial Diff. E-Q. [PDEs] is Modern Physics No Math? As far as I am aware. And the prereq[uisite] for Modern Physics? Im not sure if it is Differential Equations [ODEs] or multivariable calculus. Okay. It seems by the time you get to QM you better have some differential equations.

CO: Considering that SE is a differential equation that seems like a good recommendation. Right. Are there any other math ideas or math classes that you think would be really important.

DR. RED: Well, itd be really nice, but I dont know if it is required to have some linear algebra.

CO: I dont think its required, but I know its Linear Algebra comes in handy.

DR. RED: It definitely does. Of course, Modern [Physics] I...I can't remember if we had a Modern [Physics] II when I took it. I think they just stretched it out. I know that right now its Modern [Physics] I, is the requirement...then theres an Advanced Laboratory, and I know a limited amount about that, then theres Modern [Physics] II,is sort of special topics within QM So I think they need Modern [Physics] I, and the laboratory would be nice, but I dont know if its absolutely required. I wouldnt make it a prereq, but it would be nice to have it.

CO: What about other upper-division courses? I know that at UGA Classical Mechanics was prerequisite for QM.

DR. RED: I see. As far as I can recall, I wouldnt think it would have to be...unless its being taught differently than thirty years ago.

CO: I dont think thats the case. Just to make sure Im straight on this...in terms of Mathematics, Differential Equations and Linear Algebra ar the big ones Yeah.. Um...In terms of Physics. Modern [Physics] is definitely number one Yeah. and the advanced lab behind that. Yeah, I think that would be nice depending on [?prereqs?] Okay. So, in your mind, if you were to put together the course Oh no....bear in mind you can say That takes some preparation Obviously it takes a lot of preparation, I couldnt imagine it where Im at. Are there any topics you think would be important to hammer on for those students who were taking QM? Sort of a greatest hits thing?

DR. RED: Wow...its been a long time...and like I said, I havent looked this up ahead of time. So I haven't taught any physics its all been Astronomy. But, how about ideas that are pertinent to your area of research, right? Yeah, well Theres definitely QM going on there This is true...so thats an interesting...if I was setting someone up to take one of my grad classes...its cheating a little bit...Well, Im trying to get at... Id want to give them a general experience...I definitely have some basic Modern/Quantum stuff in my interstellar medium class. We come across these concepts that they have probably were exposed to, but dont remember so they actually have to go look them up. One of them is multi-electron systems and L-S coupling and all that kind of thing. Cause what were studying in the graduate interstellar medium class are specific emission or absorption lines coming from various levels and why some levels are permitted and why some are in combination and some are forbidden. So you gotta remember all that, or at least refresh yourself on why you have these rules about all these transitions. Its critical for actually understanding the physical conditions in the gas that we study. Yeah, so L-S Coupling and total angular momentum and the various ways that levels are split, and what sort of transitions are permitted and forbidden...which happen. Theyre forbidden and in Astronomy they happen because the densities are so low. In the text book that I use, theres actually an appendix in the back called Nebular QM. Its basically what you should remember or brush up on to understand some of these transitions. That makes sense. So maybe some of the ideas that lead up to that aswell? Right. Modern [Physics] will take care of a lot of it, but QM will give you a much more basic understanding. Okay, why are we stuck with these rules The guy that I learned undergraduate QM from like to use the term greater mathematical elegance. Wow.

Im not sure I could do that. If was going to teach from my experience, which I do a lot of...I would make some connection to astrophysics, transitions and interstellar gas. that seems to be the rule instead of the exception in my experience on the other side of the lecture. it normally times into someones passion for their research. Normally its pretty useful as long as you dont go too far. As long as you dont go too deep into your specialty and people are going Why is this relevant to me? but to give them some relevance to your field and why its important and I think thats good.

CO: Okay, that would be the diea preparation, this is just your perception...do you feel like the prep that students are getting as they come up through the program is meeting this ideal? are there any places where you think they might have more difficulty.

DR. RED: I never hear any bad stuff. [Laughter.] Assuming as Chair now, there's not any real egregious...Yeah... Knowing our students from interacting with them, in SPS or whatever, Id say they seem to be prepared. Listening to things from their end, I havent heard any huge complaints about preparation? or coursework. Thats always good.

CO: Do you think the students that ...let me frame this. A lot of our students that take QM have not taken Classical Mechanics yet, you mentioned that you don't think that sort of thing should be prerequisite. Do you think that students have an adequate grounding in CM before they get to that point or I know we dont have an intermediate Cm, so theyll have the 2000 level background.

DR. RED: Based on my experience, it was sufficient the way the course was taught...that was a few decades ago, but...so if things are taught differently then maybe the answer should be different. It sort of restricts their choices too. They are trying to put all these courses together to graduate in a certain amount of time. Too many prerequisites in front of classes makes it harder to get done. So, practically speaking, I think it should be the way it is, but my opinion is you dont need it. Sure. Now the QM instructor may tell you differently...I think every instructor wants you to everything before you get to where theyre at. Yeah. Its not possible.

CO: So, you mentioned in QM they definitely should be seeing a refresh of everything that is Modern [Physics]. What do you expect students who took the class after a year to retain from this type of course...and the way I look at this is that there are students who will go on to become academics and go to grad school and there are students that will go off into some sort of career path. What material do you think theyll retain from the class?

DR. RED: Well, those students that are sort of more interested in industry jobs and not going to grad school , theyre motivation is different so I wouldnt expect them to retain too much of the technical ability for solving problems...those specific problems. So, maybe familiarity with concepts? Yeah. Weve trained them to solve problems in general, thats why people hire Physicists. So, QM helps in that sense of learning how to solve problems, and theyll retain a lot of the concepts, but maybe not remembering exactly how to Solve SE. For the other group thats going into grad school, Theyll probably not retain too much more that that, but theyll know they need to go back and refresh themselves. People usually are not going to go back and refresh themselves on concepts unless they are needed, but if they are just going to encounter them more so, itd be easier to go back and refresh themselves.

CO: If there was one piece of advice you could give to a student that is about to take

QM what would that piece of advice be?

DR. RED: After theyve taken it? No, before. Id tell them to go back and look through all their Modern Physics stuff...make sure they understood what was going on there and got sort of the basic concepts, because if they dont...When they get hit with SE theyre not going to know where its coming from...I think its easy to get lost really fast. Unless the teacher specifically goes back and reviews a lot of those concepts.

CO: One of my motivations for doing this line research is that I struggled with QM the most, but once you get a strangle hold on it, its pretty awesome. That feeling of mastery is intense. Ive read about 5 or six introductory QM books. I was always the person who was looking for a text book that made the material jive with me.

DR. RED: For me it was just so foreign, even after taking physics...even after taking Modern [Physics], it was very foreign. I think you can only buy in so much to some of the ideas without having a little more exposure to it. I believe that. You have to abandon all this classical training youve got.

CO: If there was a top three courses you could suggest... a top three for math and for physics what would they be?

DR. RED: Okay, I think we covered this already. ODEs, and partial couldnt hurt, and linear algebra. For physics, Modern [Physics] I is key. I dont think you need much more other than the basic 2000 level classes for that.

A.2 Dr. Orange

CO: So...starting off, weve already covered some of this, so it may be a bit redundant MmmHmmm. In your opinion, Id like to ask some topical questions in Quantum Mechanics (QM). How do you think the students would respond when asked to consider an atom, what model do you think theyd put forth in their mind?

DR. ORANGE: You mean undergraduate students? Yes, thats correct. Students that have completed the Modern (Physics) sequence and are about to start quantum mechanics. Yeah, I think they are okay. They have Decent understanding of what the conventional models were. They may be shy to respond to your questions, but they understand.

CO: As an instructor do you think the Bohr Model is a solid model to use for that level of course?

DR. ORANGE: Yeah. thats good...theres no other options. It also gives students a historical perspective.

CO: How much would you say they know about Heisenberg's Uncertainty Principle?

DR. ORANGE: Probably zero.

CO: The same question for Wave Particle Duality...do you think they come into the class with any type of...

DR. ORANGE: Well, I think they understand what it means, on a conceptual level its okay, but I dont know how practically they know, when working on an experiment, how to relate the wave particle duality. At least theyve heard of it.

CO: Do you think they are familiar with the Pauli Exclusion Principle?

DR. ORANGE: About atoms? I think they are aware (of it). Probably they dont know why(it exists). Very few people probably know why.

CO: Sure, I think we have to understand that the abilities of students will cover some distribution, no one will be the average students. And Wave functions, how strong do you think their understanding of wave functions is?

DR. ORANGE: Its hard to say, I think mathematically they are capable of following the math and to use the wave functions...how to use them as mathematical tools to describe processes are maybe far away. I dont know. I didnt ask any to work on specific QM problems.

CO: What tools do you think are most important for the students that are going to be going into QM...what mathematical tools?

DR. ORANGE: Mathematical tools? I think that Differential Equations should be the minimum requirement. Sure. and to have a brain.

CO: I know in the past, integration and trigonometry have been mentioned absolutely.

DR. ORANGE: If they cannot trigonometry, they should not be in physics. That is a no-brainer. just ask them, do you have legs or hands. Physics students, if I ever needed to ask trigonometry questions, I would be sad. Yeah, thats a bad sign. A bad sign. They should never be in college to me, but unfortunately that happens. For Physics Majors, nobody should ask those questions.

CO: In your impression, do you think the students are adequately prepared to take that course?

DR. ORANGE: I dont know. I never taught Quantum Mechanics. The best person to talk to is probably Dr. Manson or who is teaching...He teaches both 6810 and 4810. Okay, so he may give you some real answers.

CO: Could you recommend top courses a student should have in math? You mentioned Ordinary Differential Equations.

DR. ORANGE: Thats right. Anything else? Probably not, Algebra is important.That makes sense

CO: In terms of Physics preparation, do you think that in the physics background, students are prepared going into QM?

DR. ORANGE: I think they should. I dont...qualitatively I have no clue. if by that time they should finish the Modern too.

CO: Would you recommend a top two or three physics courses the students absolutely should have before they take QM?

DR. ORANGE: I guess that is part of our curriculum, you take modern...you know... thats the preparation. Thats our standard practice. Yes. Is there any extra? Could you rant the importance of...obviously everyone who is moving through the program takes CM, and E&M, they get the first Modern Semester and the second Modern...I believe. Theres a handful of upper-division courses that they all take as they move through the program. I think our curriculum is okay. I think they start with CM, and E&M and move on to Modern Physics and that...Even though it is traditional, it is still necessary preparation.

CO: Okay, do you think that the CM and E&M of the same importance as Modern [Physics]? Are they ...

DR. ORANGE: they are very important, thats part of the training. 9:12 They way I look at it is if, for example, to be able to work with a Hamiltonian is important in QM. so, CM ideally teaches how to work with a Hamiltonian. Thats right. I think having a rigorous training, try to analysis problem, are very important, are very practical , application is probably more practical that the QM. So, prepar[ing] them to understand the classical physics and be able to move on to Modern Physics which typical people dont see and feel. I think thats a good sequence to follow.

CO: Could you give me your impression of students grounding in CM when they get to QM?

DR. ORANGE: I dont know. You have no idea? No idea. [CO Babbling] Over the past, We do have a very fine undergraduate student that did well, as an example do you know THIS STUDENT? Yes. I think he did extremely well, but unfortunately he was not able to his higher level degree[s?] We have really good, smart undergraduate students. Absolutely. The other students I dont know.

CO: Those topics being out of the way, I just want to talk to you about the QM course, itself. This is not the 4810 that is offered here, this is more hypothetical...if you were in charge of a classroom. Im asking how you would approach the classroom. Can you tell me about your experience in undergraduate QM?

DR. ORANGE: I guess its very...I have not taught the QM, but it probably should cover the traditional topics. Start from...review the classical physics...to me good instruction is [where] you put the content to the historical perspective, thats very important, then you bridge the new concept coupled with practical application and rigorous mathematics. I think you have to go through this step by step. With a proper homework assignment to reinforce student learning. Other than that, you just do a decent job.

CO: Do you have idea what the student expect to get out of the course?

DR. ORANGE: They want to get an A [Laughter]. Its hard to say. I think its difficult to get instructors to put themselves in the position of a student. Its not that difficult, we were students at one time. You cant say because you are an instructor, you cant understand students. We were students, but at a different time. The settings may be different, the background may be different, and I think as a student, if youd just like to take an easy path and [just] walk through, I dont think thats a good student. You have to expect the hard work and do your share of the...contribute a fair amount of effort. I think thats [what a] student should do. And theres no free lunch...you have to contribute.

CO: Could you comment on what you think the goals for a quantum mechanics class should be. What topics should absolutely be covered? As someone who has taught Nuclear and Particle [N&P] [Physics], what material would you hope that the got from QM before they enter N&P?

DR. ORANGE: Well, I guess you should understand how to solve the quantum theories...simple classical Schroedinger Equation [SE]...be able to interpret the results...thats it, theres no more. Understand the simple applications, be able to understand the quantum principles [?postulates?] and the simple SE thats it. Okay, excellent.

CO: Do you have any impressions about what the students get out of the Modern Physics courses...sequence?

DR. ORANGE: That is difficult. I dont know. A lot of times, actually, you dont think whether students take Modern Physics a lot. Because you start CM and E&M, then you dive into QM...Modern Physics is not necessarily a prerequisite for QM. Okay. Majority of the modern physics part should be covered in the intro 2000 course already. Okay. Sure. Modern Physics probably is just to give students some kind of brief [???] on a variety of topics...lets say...who do not want to take Nuclear physics or something else Sure. So, students get almost a taste of several different fields. Thats right. To me that course is not critical.

CO: the last set of questions are more general and hypothetical. If you could evaluate your students any way you choose, what do you think is the best way to evaluate students understanding of course material, and I mean this in general.

DR. ORANGE: Problem solving skills. Give them a problem and see how they approach it. That is the only way. [To] talk to them doesnt help much.

CO: So, that would be the idea, and its practical as well?

DR. ORANGE: Yes. Exactly. That is how we...everything we test. How do you know if this car is built beautifully? you drive in it. Yes. RIght?

CO: Just out of curiosity, how often do...in your experience... do faculty members talk about what they are teaching in the courses they teach?

DR. ORANGE: Not much. Not much in our department, I dont think we have that.

CO: I guess the last question I would ask is if you could give a student about to take QM any piece of advice what would that piece of advice be?

DR. ORANGE: Work hard. Thats right. read. That makes sense. Work hard and [to] read themselves.

CO: Is there anything else that you think you could say to help students in QM?

DR. ORANGE: [Laughter]Work hard and read the book. And do problems, thats part of the work hard. Thats very important.

A.3 Dr. Yellow

CO: Basically, we're interested in talking about is 'What are instructor's expectations of students that are coming into Quantum Mechanics (QM)?'

DR. YELLOW: Which QM are we talking about? The undergraduate class? Yes. And are we talking about the undergraduate students ONLY coming into the class?That's correct. Yes. Because, as you know it is a 4000/6000 class.Yes.

CO: This is...Everything we are going to be talking about right now is going to be directed at the 4810 students.

DR. YELLOW: Okay, okay, okay...I just wanted to understand. Absolutely. Now...

CO: I'll probably want to do the same thing where I want to be crystal clear on something you say. Mmhmm. So...Basically, we're interested in finding out what types...what do student's understand about QM before entering the class?

DR. YELLOW: Precious little. What I need them to understand or to be able to do is the following: I need them to be able to solve ordinary differential equations (ODEs). I need them to understand that the solution by series...that they are not thrown for a loop by that. Mmhmm. It would be nice... there are things that that's absolute requirement. Sure. 'Cause if they can't solve...if they can't understand the the solutions of a differential equations, since the Schroedinger Equation is a differential equation...I mean they are ...I can't say it on this ...I understand ...deep trouble. but they are S.O.L.

DR. YELLOW: Okay, it would also be nice if they knew something about partial differential equations (PDEs). However, we actually do that. We show how you solve a PDE by separation of variables

It would also be nice if they actually knew what a Fourier Series was, but we do go over that because we don't have a uniformity of backgrounds. So, that's on the math side.

DR. YELLOW: But that's like...But as you know, Mathematics is the vocabulary of Physics. And so, you've got to have. Not matter how you. When you are learning a foreign language, no matter how well you know the rules of conjugation, if you don't have any vocabulary, you can't do nuthin'.

CO: Yeah. Sure

DR. YELLOW: So, um...that's the math. On the physics side, they need to know the phenomenology of modern physics. That is, the idea of the Compton Effect, they Photoelectric Effect, um...what else? The ideas of relativity. Special relativity, of course Mmhmm. 'E' equals 'mc' squared...that kind of thing.

DR. YELLOW: They hafta have a good grounding in Classical Mechanics (CM). When I say the word Hamiltonian, they should not stare at me blankly. They need to know what a Hamiltonian is...classically...we'll take it from there. But the most important is understanding the phenomenology of modern physics that made it necessary to move beyond classical physics.

DR. YELLOW: So, good mathematics preparation and a good course in modern physics. Now in modern physics, typically you introduce the Schroedinger Equation...you introduce it phenomenologically and and you solve it for simple cases uh, but that's not crucial. The crucial thing is the idea s of theses processes which showed that the classical understanding could not possibly be right.

CO: Sure.

DR. YELLOW: That's what we need to successfully make the transition to QM. Then, we take it from there.

CO: So...the historical grounding kind of...

DR. YELLOW: Well, it's not necessarily, it doesn't need to be taught historically. It is, in a sense, because it came...it was the impetus from which we said 'Well, CM cannot be right.' You know, starting with black body radiation...That's another one.

DR. YELLOW: So, it's real difficult...If I had to give in the course the first lecture or lecture and a half is devoted to that, but it should be review. If it is new, it's too hard for them to learn all that brand new. So, they should have that already.

CO: Sure. Excellent. I think you've jumped through a series of these I'm sorry. No, it's okay.

DR. YELLOW: Cause I thought about this a lot since I tell students what I think they need to have and if they don't have that background, they really need to come and talk to me.

CO: Okay, but if a little bit of this is redundant, humor me. That's okay. One of the things I was going to ask is how would a student respond when they are asked what an atom looks like?

DR. YELLOW: I think they would tell me it looks like the planetary model.

CO: In that same vein, do you think that the Bohr model is a good instructional tool?

DR. YELLOW: Yes. It's an excellent instructional tool because, the most important thing is that is shows that within this model not all values of physical variables are allowed...at least in a bound state. So, it gets that idea, and that is a crucial idea in QM. The idea that certain physical quantities under certain circumstances can only take on prescribed values. That's the quantum of QM.Sure.

DR. YELLOW: You know the text book we are using, [Foundations of QM by Burkhardt & Leventhal] it starts off with a chapter called Wave Mechanics and the first section of the chapter is What's doing the Waving? It's important it explain that. Well, in QM what is quantized?

CO: Sure. Definitely. To shift a little bit, do you think students have a complete understanding of Heisenberg's Uncertainty Principle? No. Absolutely not. I what capacity do you think they understand it?

DR. YELLOW: They understand that you can measure both exactly and simultaneously, they don't have a good grounding in what exactly that means. They don't have...the important thing...the crucial aspect that they are not taught earlier has to do with commutation of operators. And as I explain to the class, Isn't it amazing that this mathematical property of operators actually translates into something physical which is measurable...or not, as the case may be. Unless you have seen a derivation having to do with operators that don't commute, because if you commute that greater-than-equal is equal to zero. Mmhmm And that they have no understanding of before . Why can you measure p_x and p_y but not L_x and L_y simultaneously? Because p_x and p_y commute and L_x and L_y do not commute. I'm pretty sure that is not covered in the Modern Physics course.

CO: Okay. A few more quick ones...How do you think a student would describe the principle of Particle-Wave duality?

DR. YELLOW: That's a good question. I think at the level of the Modern Physics course before they come into QM they would not. They would say that if it's a particle like property I'll do the calculation this way, and if it's a wave like property I'll do the calculation that way. I think they have no real understanding of it. We try to give that to them in the QM course.

DR. YELLOW: And the way we try to give it is using the photon as particle, because we all know from optics how you describe light waves and , by they way, that's how we heuristically develop the Schroedinger Equation. We say Okay. We know something about light. We use DeBroglie's hypothesis with the relation of momentum to wavelength and we also then use the relativistic business of how frequency is related to energy from the Photoelectric effect. So we replace in the optics expression, which is well known, e to the i, k, x minus omega, t ...or you can do it real. It's easier to do it that way cause you don't have to remember which has a positive derivative and which has a negative derivative...it's easier to deal with the exponential notation...and you replace k, which is two-pi over lambda with momentum and you replace omega with energy divided by h-bar and so then you have particle properties and you find that that obeys the Schroedinger Equation.

DR. YELLOW: What you then get them to understand is that nature is made up of particles that have waves associated with them..How do we know that this wave is associated with them?...that is a very good question and that they come in with no understanding of...and I'll tell you one way we explain that. We explain that using the idea of total internal reflection. Now you know, if light goes from a medium of higher to lower index of refraction at some angle, it's called Brewster's angle(Double Check), you get total internal reflection, however, if just above this, you have another medium with the same index of refraction some of it gets through. The question is if you send a light beam how does it know if it's(the third medium) there? Because there's no extra time. When it gets there it already knows whether it goes through or not. We define how it knows as the wave function...it's a definition. It has something associated with it that knows whats going on up there. We call that the wave associated with it. You can also do this now with solid state electronics with an electron and a barrier. it's the same kind of thing if the potential stays up nothing gets through. If the potential goes down...and this is much easier to do because you can do it with very slow electrons, and you can see does it take any time to get through, and the answer is as soon as it gets there it knows whether it can get through or not. It's quite interesting. So, there is something associated with a particle we call it the wave function. So they begin to see this thing doesn't flip up between a particle and a wave, it is a particle that has a wave associated with it and the wave has something to do with the probability of finding the particle at different places.

While they learn that in the earlier course. They learn Psi absolute squared has something to do with that, what they don't learn is how to actually describe it. How can it be both?

Because, you know, there are somethings in the world that are just paradoxes. That it cannot be both. Something cannot be A and not-A or like A and -A, the only way they can be equal is if A equals zero.

CO: Keeping in line with the wave-function, do you think the students understand what the dimensions of a wave-function is. Do you think the dimensional analysis component of it comes into play at all. Yes it does it does indeed... Okay.

DR. YELLOW:That's why, in one sense, it makes it a little difficult to use One-Dimensional problems that they can actually solve, because there the dimensions are different than they are in ordinary three-space. Of course, if you are talking about a system of more than one particle, the actual Psi absolute squared has dimensions of$L^{-}6$ instead of $L^{-}3$. But I think dimensional analysis is very useful in a whole bunch of different ways not just merely with the wave-function.

CO: Do you think the students come in having any kind of understanding of the dimensions of that wave-function? No.

DR. YELLOW: Well...any kind of understanding is a rather broad term. Not the understanding..nowhere near the understanding I hope they have when they get out of the course. Sure. You bet.

CO: One last element talking about the Pauli Exclusion Principle (PEP). Do you think the students understand that PEP...do you think students understand how the PEP works?

DR. YELLOW: How it works? Yes. Why it works? No. It's a different thing. Because here, it's simply a law of nature that fermion...the wave function for system of many fermions must be anti-symmetric. There's no reason for that...there's no way to prove that it just happens to be the case. And that's a little bit difficult to convey that here we have something that is simply a fact of nature. Whereas another type of particle the wave-function has to be symmetric...and those are the only two kind of particles we have. Heheh. So, I would say, even when they get out of this course they don't have a truly good understanding...the understanding really comes with the graduate course in QM. Now perhaps that should be changed, but I do not think that they truly understand the PEP.

And there are some historical reasons... You know much of QM was developed in Germany. Think of the names, Schoedinger, Heisenberg, Pauli...however in the late twenties and early thirties, the Nazis took over and they wanted to obliterate anything that came from Jews. Pauli was Jewish. So, the concept was kind of obliterated...for a while...of course it didn't get them very far. Also Bohr and Einstein were Jewish that did not help. Heheh. In many ways, scientists there tried to develop things without using the PEP. There was actually a famous boo...infamous book, a German text book of Physics written in 1936 called Deutsche Physik. Now, literally the translation means German Physics, but it actually means more colloquially Arayan Physics. And so, in the preface it pointed out that Jewish physicists tried to pull the wool over the eyes of Aryan physicists...so they were throwing all those things out. That made it extremely difficult, so the next generation of German scientists were not trained very well. But you see, since the biggies in the field except... the ones who stayed there, couldn't teach this, it fell into disrepute not dis people forgot about it for a while... Anyway, that's an interesting sidelight. Yeah.

CO: You started talking about math at the very beginning(of the interview). What would you say, generally speaking, of the students mathematical grounding coming into the course?

DR. YELLOW: Let me state it this way. They have taken the requisite minimum courses, do they have it? That's a different question, you understand.Absolutely Most of them do have , but not all. Some of them find ODE's a challenge, and when they find that a challenge, the find all of QM a challenge...because of that.

CO: Sure. You've basically already addressed this, but what mathematical tools do you think are the most important to learning the material in QM?

DR. YELLOW: Well, differential equations, and a related thing is how to do integrals. You know, there are a lot of integral tables around, but there are methods. Like, I try to show what you can actually do without having to resort to integral tables. It's good to use your head and figure these things out.

CO: I specifically remember my experience, that was something that was a revelation to me.

DR. YELLOW: Yeah, you really can do these integrals. Some of them are messy, but they are not terribly difficult. You just have to think about it a little. For example if you have a integral from minus infinity to infinity, it's probably not good to use a trigonometric substitution like sine or cosine which do not go from minus infinity to infinity. It's probably best to use something like Tangent which does. You know, little things like that. Sure.

DR. YELLOW: Oh, and on that point. One of the things I try to convey is not to intimidated by integrals and many of them are. Which indicates to me their preparation or what they got out of the preparation was not entirely sufficient. At that level, you don't want them getting hung up on the mathematics.

CO: Going in that direction, are there a top three math courses that you would recommend for a student coming in?

DR. YELLOW: Differential Equations One, Differential Equations Two ,Differential Equations Three. Essentially. Now, it would be nice to have something about Matrix Algebra...that's another thing. They need a basic grounding in matrices and determinants, they have to know that. They don't have to have a full course in Linear Algebra, but that and...because we do diagonalize matrices and we expect them to understand what that means. And it would be really nice if they knew, as I mentioned, something about partial differential equations and some things about Fourier series. But that's not...we will teach it there, so it's not absolutely required but it would be good if they knew a little bit about Sure.

CO: In terms of the Physics background, what do you expect of the students that are coming into the QM course? I ask this sort of realistically...what do you expect?

DR. YELLOW: I expect them to have had...to understand the phenomenology of modern physics, and to have had an intermediate course in E & M and Mechanics. For example, I give them a problem that has electrical charges in it and they have to figure out the Hamiltonian. In other words, they have to figure out what the forces are...electrically...they have to know that.

CO: That sort of answers my next question. What courses would you have them take before they enter the course. E & M, Classical Mechanics, and Modern Physics. Okay. This is also something you have addressed more than once, but your impression of the students grounding in Classical Mechanics prior to taking the course.

DR. YELLOW: Fair at best on the average.

CO: Sure. So, are there parts of the Mechanics background that could be stronger?

DR. YELLOW: Yeah. They have to have a better idea of what the Hamiltonian is and what the Hamiltonian means. Because that is so crucial in QM. MmmHmmm.

CO: What are your goals in teaching the course? Broadly, in terms of what material you think is the most important to convey.

DR. YELLOW: What are my goals in teaching? Lemme give you a little anecdote. This is from the graduate course. When I was taking the equivalent of the graduate course in QM, a two semester course. Near the end of the second semester, somebody asked the professor what we were responsible for for the final and the professor looked at him and said QM.

Well, at this level, you can't expect that but I guess an understanding of the general phenomenology predicted by QM and the ability to solve simple problems and approximate the solutions to more complex problems. That is about the best that I can do. It's hard to articulate.

CO: I specifically remember the syllabus for the 4810/6810 course being pretty lengthy. UnHnn

DR. YELLOW: there's a lot of individual pieces...like I wanted people to learn how to do perturbation theory, which was just developed before QM as a way of solving Differential Equations that you couldn't solve exactly. Also, its equally important is to understand the conceptual aspects of QM that is a very important aspect of this course, because we don't do it in the next course. 'Cause we assume the understand the concepts...we're just delving deeper. But here, the idea of a wave-function, what normalization means, and all the things like that. We expect that to be understood. Excellent.

CO: Would you say that , generally speaking, the students that are coming through the course are getting that material out of it?

DR. YELLOW: That I have to think about...Some do, some don't. If you look at the grade distribution, the ones that get A's and high B's do, the ones who get C's don't. Now, some of them may be getting part of it. They may be getting the conceptual part, without being able to do the mathematics. It's very difficult to tell. The people who get A's and B's are doing okay. They are getting what they need to get out of it. People who get below that are missing something, it's difficult to tell exactly what. Since there's only a mid-term and a final, there's a limit to the number of questions you can ask. So you don't' really have a good feeling to how much hi s being missed.

CO: If you encountered one of your undergraduate students a year later would you expect them to have that same material under their belt...understood? Do you think they would retain that information?

DR. YELLOW: I would think they would certainly retain the conceptual information. Depending upon what they were doing. If they went on to graduate school I would certainly expect them to retain all of it and build upon it. If they then got a job in the electronic industry or the computer industry after that, I would expect only the conceptual part to be strong and then just some of the other part, but thats just a guess. Sure. That makes sense.

CO: What are your impressions of what the students have taken from the modern sequencethat we offer? Modern Physics I & II?

DR. YELLOW: Its variable. Some come in with a really good grounding there and some do not, even though they have apparently take the same course. Like two people seeing the same car accident and coming up with different stories. So, I dont know exactly what can be done about that, but those who come in with a poor grounding have more difficulty for obvious reasons. Sure.

CO: Okay. I just want to reflect back on one or two quick things. Sure. You mentioned thatin terms of physics courses E&M, Mechanics, and the Modern are the three crucial ones. In reverse order. I was going to ask you if you would order them that way. MechanicsJust the opposite order. No problem. Okay. Excellent. I mean, all three are important Suretheir pertinence when dealing with the material in class.

DR. YELLOW: You know, as Jesus said, The three most important virtues are faith, hope and charityand charity is the most important of those. Gotcha.

CO: In terms ofsame typesame type of question for the Mathematics material:

DR. YELLOW: I would say the most important thing is ODEs, and thenI dont know if I should even say thisdoing integrals, because thats a lower level than ODE. But that If its a concern, its a concern. But thats on par with ODEs and just below that would be Matrix Algebra and determinants. Below that would be PDEs and Fourier

Series. Excellent. That would be my ordering there. Excellent, I appreciate it.

CO: And do you thinkIm trying to think is there any other information that youd like to convey about the QM course? Do you think theres anything we havent touched on?

DR. YELLOW: HmmmmWell, one of the things that students do, which they do to their detriment, is they come to lecture, they take notes, and they do nothing else until they have a homework assignment or a exam or something. And what happensin any given class we dont do that much, but if you let it slide for two or three weeks, all of a sudden weve build a towering edifice and theyre just too far behind to ever catch up. And I dont know how to make them stay current. I certainly dont want to give pop quizzes in QM heheh. Sure. Its nothowever, itd be so much easier for them in the long run.

CO: Sure. I think that doing work outside class is somethingI know that for myself it had to be a learned behavior. It wasnt something I did naturally.

DR. YELLOW: This is not just QM, this is general. Many undergraduates have not yet come to the realization that they are responsible for their own learning. The instructor is there to help them where the instructor can, but they are responsiblenow they should have really learned this in high school or even before, but they havent. Many of them have not and if they dont do well, it must be because the instructor was bad. Now, it is certainly true that some instructors are better than others, some are clearer than othersand its even more complicated that that, because you might have one person in the class that thinks instructor A is terrific and instructor B sucks and another person who thinks just the other way around. Because not every instructor really matches every single student, nor is any one way of instruction the best way.

Thats one of the reasons I object particularly to the short answer part of the teacher evaluations. When you havent even described what your goals are in teaching, to have an instrument that measuring something you havent defined yet is absurd. Heheh. What it is, is a popularity contest. How much do I like this teacher? and I can prove that. Its very simple. You know, I have had in the past, at the Physics 101 level classesdouble sections and it turned out one time the better students were in one of the sections and the worse students were in the other. And they met entirely together except for independent recitations. And so, the ones that were doing okay gave me good grades, gave the book good grades, etcetera. The ones who were doing bad gave me bad grades, the lab bad grades, the same bookbad grades by a difference of about 1.5 points out of five which is absolutely huge. Thats when I learned that the only useful of the student evaluation is the essay part, which occasionally told you something that was useful to know. But the ones where its just numbersI never found them useful, because no matter what it said it never gave me anywhere to go. Id say Okay, what should I do differently? Soum Like I sayI dont know how to make students keep up, because that would really help them. Sure. That makes a lot of sense.

CO: Thats all I haveIve found this particularly enlightening. Okay. Thank you very much.

DR. YELLOW: If you think of any more questions youd like to ask, feel free to come by.

FOLLOW UP ON 4/30/2013

CO: I've asked our faculty about five different types of evaluation and Id kind of like to go through the five types with you and see what your impression is of each one. For example, the first one we usually discuss with everybody is the idea of multiple-choice, using multiple-choice questions by themselves at the at the level of quantum mechanics or another 4000 level-type course...

DR. YELLOW: I don't even believe in it for a freshman course I believe they should in a science course that should never ever be used I do not see the point in it.

CO: Sure could you elaborate on the reasons why you think that's...

DR. YELLOW: Yeah because in order to decide whether a student understand something I have to see his work and this absolutely precludes me seeing his work so I think it is nonsensical I understand that it's easier but never in 45 years have I given a multiple-choice test except in the sense that sometimes I'll give on a final exam six problems and say pick four... If you can think of that does multiple-choice laughter but no never if this wasn't always sometimes never that isn't always never

Gotcha. Another type of evaluation we've I've talked about with other faculty is the idea of a short answer or an essay type of question where you would have either a few sentences or more than that in terms of describing a solution or something like that how appropriate do you think this would be The wrote answer component

DR. YELLOW: Again never because what we do in physics we take the real world and cast it into mathematical terms if they can't be cast into mathematical terms that we cannot deal with it and so I don't see again I don't see the point of trying to do this it's very unnatural expressing it non-mathematically. guess it must be with that and that's an equation it's not an essay

DR. YELLOW: It must be explained mathematically that's an equation that's not an essay

Okay so another element is the idea of a roadmap medical problem that's our bread and butter so to speak and as you said that's what we do

DR. YELLOW: Well again you have to think of what the what is the aim what are we trying to do in order to really discuss evaluation you have to discuss what your goal is and it seems to me our goal is infinite in the physics course is two for the student to look at a situation be able to put down what they know mathematically decide what they need to know mathematically and find some relation or relationships mathematical relationships that relate those things the only way to tell if they can do that is to give them a problem and see what they can do so when I grade that sort of thing if they have the right method but forgot to divide organ forgot to carry it to out of 10 points they might lose a half of a point something like that I want them to convince me that they know what's going on and so the only way they can do that is mathematically

CO: Alright but for students that are able to perform that matter is there a chance that they missed the physics somehow and...

DR. YELLOW: I know math is just a tool and that's why the word problems then I know there's a disconnect that this is not a mathematics course I don't write down here are some equations find X and Y I don't do that we say about his traveling and the river is moving south at 4 miles an hour the boat it's modeling you want them to take what could be a really situation but it's not because it's frictionless approximation and translate that message about medical terms solve the problem and then translate the answer okay the boat will be going at an angle of 36 to the... Something you could actually look at

CO: Okay so this should be interesting for the next two there are some courses where they do student presentations with students present material usually in the semester or something like that do you think that that's appropriate in the quantum course

DR. YELLOW: It's not inappropriate but it just takes too much time out of the classroom there is that a something of value because in order to essentially teach something you have to really learn so that's probably not a bad idea except we can for the time

CO: Okay so logistically it's...

DR. YELLOW: If we could do it in parallel somehow but logistically I don't think that the game justifies the time

Okay that some people there different types of goals are different Excorcist I think that some courses are more of a survey course and some courses are more...

DR. YELLOW: Well even in a survey course you still want them to be able to abstract real-world material into with meta-mountain with mathematical tools the mathematics can be very simple sure but that's what we want people to do in physics so

CO:The last type of evaluation that I want to talk about with you is the idea of an oral exam a one-on-one do you think that is applicable for the senior-level students that are taking for those little courses like one

DR. YELLOW: It could be yes it is applicable again it takes too much time and there's some students who get very tongue-tied under such situations so I'm not sure if it is a truly accurate measure of their abilities some students are doing and they can do that sort of thing quite well others or not and you would like to it seems to me that is a confluence of their understanding plus their personality and that's why I would not put too much weight in it I've known some very good physicist who gets a very bad talks

A.4 Dr. Green

CO: Okay. Like I said what were gonna do isbasically this will come in four pieces. Id like to ask you what you think the Mathematical preparation is for a student coming through Classical to Quantum, and the Physics content as they come through to Quantum, and umI wanted to ask you your opinion of how you think are prepared versus how they should ideally be prepared. So, starting at the beginning, what mathematical tools do you think are most important for students entering Quantum Mechanics (QM)?

DR. GREEN: I guess the basic math knowledge is needed, and I think that that is an acceptable level of exposure is there when they come to Classical Mechanics (CM). Beyond that, one issue might be at the stage of people taking CM, some people have not done Differential Equations or Partial Differential Equations. So when I do LaGrangian Mechanics, I have to go through a little bit of Partial [Differential Equations], but if they dont do that well, then they are going to have issues in QM.

[Phone Call interrupted recording]

CO: So, you mentioned Differential Equations and Partial Differentials. Is there some place that students may need more preparation?

DR. GREEN: See, if they have done Differential Equationsmaybe Partial Differential Equations and partial derivatives are covered in that, so maybe that should be something.

CO: I know very little about the CM course. Is there any matrix Mathematics used in that course?

DR. GREEN: We use a little bit in matrix diagonalization for the rotation of rigid bodies, again, that matrix part is not something that we go through in the CM course. This time around, maybe 80% of the class said they did that, but always they come up with some other statement after that saying we dont remember it. Sure. But the prerequisite, the majority have covered that.

CO: What courses are prerequisite? Do you know the number off the top of your head? If not, I can look it up.

DR. GREEN: NoNo I dont know.

CO: Ill check into that, because its easy to say Oh, theyve taken Differential Equations, but who knows what the content of the course is Yeah. sometimes.

[MATH3260: Differential Equations, is required for CM as well as PHYS2212: Principles of Physics II. MATH3260 is typically taught by Dr. Alexandra Smirnova and requires MATH2215: Multivariable Calculus.]

So you would say your general impression of their grounding in mathematics is strongor umI dont want to say strong Okay. Maybe somewhere Fair? Yes. More towards the lower end.

CO: In terms of calculus and integration, how would you sayis it not a problem? Their ability to perform the integration of a function, is that okay?

DR. GREEN: If I think back to the last semester, there were about 15 or 16 students. I think there were about 5 people who did not have problems. The majority have taken the calculus class, but struggled had problems. Just by sitting in class is not the

CO: If you could pick the top 3 courses that students should take before as they progress towards QM the top three mathematics courses. Which three would you recommend?

DR. GREEN: Calculus II Obviously That assumes they all know trigonometryDifferential Equations. You brought up a point about matrices.

CO: In terms of the students physics background, how strong would you say their physics background is as they progress through classical towards QM. I guess we should evaluate in terms of the courses

DR. GREEN: I think the connection here is the Modern Physics. Half of the people have not done Modern Physics, but have heard some things here and there form a lab or othersbut photoelectric effect half of the people have some vague idea saying Einstein has something to do with it. So, general physics parts are ok, but the connection moving from classical to quantum not properly covered for all students.

CO: By the time they finish CM how skilled would you say they are using the tools of CM , like using the LaGrangian, and understanding of rotating rigid bodies.

DR. GREEN: I make it a point to cover Lagrangian, but it usually happens in the last two or three weeks. So this is something that I am going back and forth saying do I want to rush through the beginning and have more time for Lagrangian or should I take a little more time explaining the beginning parts to make sure that their foundation is right. If I do that, the Lagrangian is going to have two weeks. Gotcha. So this time

I asked the students, and the said they want a good background. So I went through oscillations, different kinds of linear harmonics oscillators, and all that, in a little bit more detail. And then, at the end Lagrangian was two weeks, and it looks like from the comments, now they dont like that about the thing, saying Oh, we should have spent more time on Lagrangian. One reason they think is it looks easier than everything else. So maybe we should have done moreI think the grass is always greener on the other side. So from that point of view, I think they arethe basic mathematical skills are covered and I make sure they know how to do the partial derivatives even if they havent done the differential equations classes but again, maybe half of the class can really do it at the end and the other halfstruggles? Yes.

CO: Its been a while since I have been in Classical Mechanics, do you cover the Hamiltonian as well, or is that beyond the scope?

DR. GREEN: I just introduce Hamiltonian and say the next step from Lagrangian is this. And that you will come through this in Quantum Mechanics in more detail. Well, there we go.

CO: This may seem kind of obvious, but what do you think are the most important that the students take before they enter quantum? I know you mentioned Modern [Physics I]. Physics courses? If there were a top two or three that you think they must take before they re entering

DR. GREEN: I think E&M should be done too. Sure. So thewe taked about these two now and the other onesyou only want physics not the math ones? Thats correct. Maybe a better way to say it is topics in physics they should have covered. Absolutely I think those two should be enough, but they will have to read about other areas. So, I dont think we want to put requirements saying you need to sit for this course and that, but Modern and E&M needs to be done.other than Maths. Because, Nuclear Physics has some connections, so people can go through different parts of that so maybe you dont need to sit through the whole Nuclear physics course, but some parts of that will be useful. The same with molecular or atomic physics. Okay. so there are some parts that are useful if you have some previous idea

CO: This is more hypothetical. What do you think the goals for the QM course should be? I ask this as if you were to teach QM.

DR. GREEN: I think I dont want to answer that in an affirmative way, because I havent done the QM at all after I took the courses as a graduate student. Sure. But, on the other hand, Uncertainty Principle... Sure. is something whether you are a QM person who has taken different course or not, should have some idea. So, there are some basic things like that which you need to know like Uncertainty principle and Probability. Because the probability is also main thing in QM to go through. So, those probably should be there somehow, but if you go further, Fermi Golden Rule and all that...the angular momentum, those things are important too. But they should have seen a little bit of that before, now you convert that to the Quantum case. I dont want to say anything more specific because I have not thought about that at all for years now.

CO: What do you think the students expect from QM? In your opinion, if you were to say Our undergraduate student think theyll cover X, Y, and Z in the class...

DR. GREEN: I think they have expectations like the Schrodinger Equation and I think some people think that relativity and the$E = mc^2$ ...that is something they know...the equation even before coming to Physics. So, sometimes some people think that Oh that should be in thin, then they say Oh, the only connection is Einstein's Photoelectric effect at this stage. I think other than that, maybe especially if they have done Modern Physics, they have some idea saying what is the change, why can we not use CM with everything and be done. SO, that part is there for the people who have done Modern Physics.

CO: From my understanding, everyone who takes QM has taken Modern Physics beforehand. I think...but I cant guarantee it.

DR. GREEN: I dont know, because the classical mechanics class said No, they havent done modern yet. So, I dont know how much later they are going to do that and take QM too. That sounds like a question for the undergraduate advisor. Definitely

CO: If you...after the course is done, how much material do you think the students will retain from QM?

DR. GREEN: Are you asking for an average? Obviously different people will respond in different ways On average...maybe fifty percent.

CO: I think thats as far as I can go with that question, seeing the amount of interaction you have with the undergraduate students.

DR. GREEN: No, unless they come to graduate school, I dont have too much interaction with them because I do only the CM, and they do that very late. The last two semesters, so after they do that, Either thy are gone or they have one more semester.

CO: Id like to ask you how you think students understand a couple of topics within quantum mechanics. How do you think a student would respond when asked what an atom looks like?

DR. GREEN: I dont know how theyd respond, but Id assume they know since theyve gone through the basic principles in Chemistry and all that. So, they know the nucleus and the electrons going around and all that so majority is empty and there is a probability of the electron in different places...I think they should know that. Okay.

CO: How much would you say they understand about Heisenburgs Uncertainty Principle? That it exists...or...

DR. GREEN: Yeah. I think everybody knows that there is something like that, but I dont know whether everybody knows what that means. Again, if they have gone through the Modern Phsyics then they should have some basic idea. Sure.

CO: And the same question again, in terms of particle/wave duality, do you think that the exposure they have in modern...how much exposure do you think they have as they progress through?

DR. GREEN: I think maybe even before that (Modern Physics) they go through the diffraction experiments in the lab. SO they have some idea, they know that there is something like this, but Im not sure they really understand what that means.

CO: In the same line of questioning, do you think that culturally people on the street, if you ask them about light being a particle and a wave, do you think theyd say Oh, Ive heard something about that.? I think that is an idea that is kind of pervasive

DR. GREEN: I think more than that, E is equal to mc squared is something more widely known than the particle wave duality. Excellent.

CO: What about the Pauli Exclusion Principle? I know that they talk about it...

DR. GREEN: That a lot of people know because of Chemistry. Sure. So the majority of the people take chemistry so...they understand it within that context. (DR. GREEN nods.)

CO: Do you think that the students could describe the dimensions of a wavefunction?

DR. GREEN: Maybe very few. Yeah, that makes sense.

CO: Last question in terms of topics in QM, if you were to teach the course, would you use the Bohr model as an instructional tool?

DR. GREEN: Yeah, I guess. Any particular motivation behind that? That is, maybe Im biased...semiconductors...for SP different (levels) Silicon...its a big thing and we can exlain that with this (model). So, If I have some bias, that is why.

CO: In terms of evaluating students, I mean this generally. What do you think is the best way to evaluate a students performance in the course. Practically, I know if you have 200 students in a course there are ways having a conference with each student is just impossible. Practically and ideally.

DR. GREEN: Ideally is, I think, have some discussion with a student after exams, practically, I dont know if that is possible. So, I think we should not ...this is my way of doing things. We should not just ask them to derive something that is in the books and all that, that type of problems are not the way to see if theyve understood. So, maybe the problem can be a very simple problem, but somehow that the student should have understood the principles behind that. Problems like that, this is what were were talking about in the Studio mode and other understanding Physics ?edumajors? simple newtons laws questions...what is the tension, is this higher than the other one?

Connecting light bulbs in different ways. So maybe something like that is some way to see if they understand the principles. Yes, and I know that some courses do a presentation at the end of the semester...

DR. GREEN: I do that in a graduate course....were you in...I didnt take Solid State. That one, I ask them to do them to do a presentation. I think the undergraduate courses, with the material to be covered...thats not possible.

CO: Yes, from what I am gathering it is a balancing act for everyone.Trying to cover all the material in an appropriate way. Thats it...do you have any comments about QM?

DR. GREEN: So, I think there should be some options...If a student doesnt not want to go to graduate school and do Physics, then their preparation can be a little different than the other people who want to go to graduate school. So the people who want to do something else can spend more time on understanding principles rather than deriving angular momentum coefficients of some situation or Clebsch-Gordon coefficients, the Golden Rule and all that. But just to give that idea what is wave particle duality, and how uncertainty principle works and why it is...that type of difference is useful for general population and that leads to your previous question when you talk to somebody on the road. Those type of people will be talking about that if they come across it.That makes sense. Thats all.

A.5 Dr. Blue

CO: What type of mathematics do you expect from students going through that senior level mechanics class?

DR. BLUE: Quantum MechanicsKeep in mind I never taught QM. I usually teach Introduction to Nuclear and Particle Physics which requires introductory level Quantum Mechanics Sure. Generally, I think for students to go to Quantum Mechanics, I think Matrix Algebra is necessary, Mathematical Physics, a modern physics course is neededwith all three of these this is a very good introductionthat is a good background for QM.

CO: Okay and if you talk about mathematical physics. Is thereare there some particular tools or abilities that students should have from that Mathematical Physics class?

DR. BLUE: Well, the problem is, for example, Schrdinger Equation and solutions to Schrdinger EquationIt requires the ability to deal with differential equations, and so on. Also relativity is very important for QM. Although maybe not QM I, but QM II when you move on to the Dirac Equation. Pretty much, in general this is what I think are the basic requirements. Although, I think if you ask about QM since Dr, Manson is teaching this course, he has a more intimate knowledge of how students perform in it.

CO: Sure. Were just interested in your opinions as an upper-division instructor. Sure. Umlet me ask youin terms of the physics backgroundWhat physics coursesyou mentioned Modern Physics...are there any other physics courses that you think are an absolute requirement for the students that are coming into QM?

DR. BLUE: I believe just some knowledge with matrices algebra and some knowledge of Modern Physics, some basic mathematical physics. And of course, Relativity for QM II Special relativity but I think other courses are notnot

CO: Okay, for example, likeClassical Mechanics.

DR. BLUE: II dont think its a requirement for that course. Thats excellent. Umif you dont mind me asking why? Because we are dealing with the quantization of things, we are not dealing in a classical sense, so I think it would be nice if you has some basic knowledge of classical mechanics just for to carry out a comparison. Thats how we deal with it classically, when we use QM thats what we have.

CO: Excellent. So, um... Im going to ask you about a couple of topics and how you think the students think before they come into the class.

DR. BLUE: I think some heavy core we teach a little bit of atomic physics, which helps imagining in Physics II, I think 2212. Okay, and so it helps them imagine somy hope is that when you say an atom, they will imagine a heavy nuclear core and electrons in orbit around it.

CO: Okay, just to elaborate on that I would ask you your opinion of the Bohr model as an instructional tool. DO you think its a good tool? There are some people who think its a good tool for teaching

DR. BLUE: I think its a good tool, because it gives the students a transitionyou cantits a good transition in their thought process. Usually students come in with a classical sense of things and you want to transition them slowly through the process. So I think its important. If I teach, I would go through it, although not in details with a lot of history. I think its important Excellent. for undergraduate students.

CO: How much do you think the students understand about Heisenbergs Uncertainty Principle (HUP)? Do you think they have a stronger

DR. BLUE: I dont knowThis is something you would have to ask the students. Were interested in what the instructor thinks Im comfortable with the level after they take QM because I think Steve Manson is a good teacher, at least from my conversations with himhes knowledgeable and convincing. So, that all depends. I think the course they take first is Modern Physics with Dr. Mani.

CO: If you were instructing the QM course, if you were the person who was in charge I guess the way I should frame this question is How would you introduce HUP? What would you expect from the students before you tell them about the Uncertainty Principle?

DR. BLUE: Well, they would require some knowledge of momentum and energy. I guess that brings up the Classical Mechanics like you were saying, but these concepts are actually taught in Physics I & II. Basic knowledge of these some special relativity might also be very helpful in introducing this.

CO: Same type of questionIf you were to introduce the students to wave-particle duality, what knowledge would you expect them to come into the class with?

DR. BLUE: They need to understand what it means to be a wave, and what is wave mechanics in general. Which is also a course that we teachthis is the end of the semester and I spend about the last few weeks talking about wave mechanics on an introductory level. I dont think we teach wave mechanics in classical mechanics. In introductory physics we do, but unfortunately that might be dropped in the future. Okay

CO: One last question, in terms ofhow much do you think the students understand about a wave function before they enter the class?

DR. BLUE: This is a questionI dont understandits based on the level of the students, its based on the introductory courses that the students took and how much that instructor at that time focused on it. I mean in some classes they dont even catch waves and vibrations. Even when you study Physics II, they actually dont get to the point where they discuss Maxwells equations and start thinking about waves. Light and electromagnetic wavesSo, this kind of has a lot of variables Of course, I understand. and of course based on the student who took the course was trying to understand whats going on or just took the course as a so

CO: But if you were teaching the class, you would introduce the material expecting that the student understand

DR. BLUE: I would have to spend some time introducing what a wave is, you know? Sure. Its always important to refresh the information for the students. Mmhmm. Sure. That makes sense. But of course it also depends are you teaching the course to undergraduate students or graduate students

CO: YesIm only interested in undergraduatesSo just to recap, if you were to rank the mathematics skills that are absolutely necessary for students entering QM in order of most important to least important, could you give me thatyou mentioned Matrix Algebra, Differential Equations

DR. BLUE: I think it depends on what level of is it Quantum I or Quantum II. Like the Introductory, it needs differential equations. Thats very very important. I think without it, the students would be completely lost, because that is the very first thing you start to studySchrodingers Equation. Yeah. As you move on, and you start using matrices, then you need matrix algebrabut thats for math. As you go even further youll start needing special relativity. So, it depends what level you are and what stage were talking about here. Okay. That makes sense.

CO: In terms of Physics, its important that they have that Modern Physics grounding?

DR. BLUE: I think its important, unless we have to extend it and make it QM one and two and threeI noticed that if you dont have the physics introduction to QM, most of the students gain is kind of based on pure mathand not understanding.

INTERVIEW INTERRUPTEDSECOND FILE

CO: Okay, sowe were talking about grounding in physics from the modern classHypothetically, if you were creating a QM class, what material would you expect the students to get out of the class? What topics within QM? And Im thinking for undergraduates.

DR. BLUE: Id need to look at what syllabi generally have in the course, but in generalunderstanding of microscopic level quantum mechanics, especially the hydrogen atom with all the needed tools, maybe some perturbation theory. I tell you, Id need to look it up and make a more solid plan.

CO: Lemme ask for something a little closer to home, for the Introductory Nuclear and Particle, what types of material would you like the students to enter that class withfrom QM?

DR. BLUE: For Introduction to Nuclear and Particle Physics, basic QM like Schrodingers equation and some knowledge with the Dirac equation. Those would be very important, especially the second part when we discuss particle physics. Unfortunately when I gave the courses a couple of years agoyear and a half agoseveral of the students dropped out after the first couple of lectures because I basing knowledge of good knowledge of the Schrodinger equation then the second part with Dirac equations kind of surprised the students. So that preparation SO for my course I am teaching nuclear AND particle Physics, the time is very, very limited and I need to take a lot of effort on the part of the students if they dont understand QM.

Okay.

DR. Blue: Although, I should say that my course is mostly an introduction, so I dont go deep into the math associated with the [???]. However, if you wanted to teach, for example Quantum Field Theory (QFT), that would require really a strong knowledge of both Schrodinger and Dirac Equations, gamma matrices and That would probably be a course geared towards graduate students as opposed to undergrads. In my school, I took QFT. The first time I took the course was as an undergraduate, but I was senior. Its a tough course. Yeah.

CO: Okayumjust two more questions. Do you Youve been saying two more questions for the past hour. The last physics related question was if the students are learning the Schrodinger equation and a small amount of perturbation theory and the Dirac equation, what knowledge do you think they would keep with them a year later, assuming some will go to graduate school and some will not?

DR. BLUE: Understanding of how things work at a microscopic levelbut general understanding. And of course, like any other science, you forget most of it, but as soon as you face that knowledge again, refreshing that knowledge would be much quicker. I dont expect them to remember everything, but if they see some similar to Schrodinger Equation or Dirac Equation and you talk about it for a little bit, its gonna come back hopefully.

CO: Finally, Ive been talking with some of the instructors about how to evaluate students knowledgethis is sort of generalI was wondering what do you think the best way to evaluate a students knowledge of material is?

DR. BLUE: I think...you meanof Quantum Mechanics Of course, the only part we can substantively students is doing written exams, but I think also maybe near the end of the semester associated with each exam, if there is not so many students, and the instructor doesnt have a heavy load of teaching, half an hour discussion with every student about some of the basic understanding would be great, but unfortunately due to the limitations and having a heavy load, having a half-hour with every student becomes an impossibility is very difficult. But I think its very good to have some kind of oral exam or oral part of some discussion with the student. I agree. But usually when I teach, this course especially, for example, Introduction to particle and nuclear, I make it some kind of a part of the class. Some kind of a discussion and see how [?DISTINGUISH or THINK?] But this all depends on the number of students you have.

CO: Okay, well, thank you very much. I appreciate your time.

FOLLOW UP ON 4/3/2013

CO: One of the things that is, is how you evaluate how faculty instructors evaluate students who are senior-level students

DR. BLUE: Students who are senior level students

CO: Yes students were taking the 4000 level courses how they are evaluated I was wondering if I could ask you about several different types of evaluation and you tell me if you think they are appropriate wire why not

DR. BLUE: Okay I thought you were going to ask me how I evaluate my students

CO: Well then I imagine that will come out while where while I'm asking so for example multiple-choice questions do you think that those are appropriate for students at the senior level courses

DR. BLUE: No

CO: Any particular reason why you are against using them explicitly could you say why

DR. BLUE: Why am I against why would you not use multiple-choice questions? Because they actually it's about understanding of the process or understanding of a particular problem and yes or no answers it's not the best choice in fact if I get the help that I need I don't think a multiple-choice question is even good for freshman courses it's just for freshman courses there is an anonymous amount of grading to and it helped to do that so if I had a greater I would actually not use multiple-choice questions

CO: So in the most practical sense

DR. BLUE: For me, evaluation...the question you should ask yourself why do we evaluate? what are we trying to do when we evaluate? Yes We are not trying just to see who's good and whos bad. Were trying to differentiate between who understood and who did not you know understanding is in degrees it is not black-and-white, zero or 1, and that's what multiple-choice gives you and for senior students... for even graduate students, understanding is more involved. Understanding more complicated processes and it becomes even harder to just judge by zero or one and that's why I don't prefer multiple-choice.

CO: So short written responses would be another type of evaluation obviously I understand that time is a big constraint for everyone instructing but in an ideal situation would having short answer type of questions being more helpful

DR. BLUE: I imagine it depends on the subject I think for example I teach nuclear physics in the classroom teaching now has two parts nuclear physics and particle physics I mentioned particle some questions in particle physics some parts of the subject conservation laws and it's violations so short answer is good if it violates if it does not violate and why the short answer is sufficient however if I want to ask a student to give them the special problem asked them to go through the decays gamma and beta invented to case and explain why it's more extended explanation it takes more than just a short question it's also it's not like my exams of both some some questions or require short answer just like my works some questions need more details going to see how deep their understanding is so there's question with very quick short answer and then there's a question that you need to explain more

CO: So the next type of problem would be... the next question would be the traditional problem that you would solve, like you mentioned going to decay processes. Um...do you use those by themselves exclusively? You mentioned that you have those type questions and short answer questions, are they ever together Yeah produce a result and explain the result.

DR. BLUE: Yes. Of course . Explaining is the most important part, because like I told you, it depends... we do the exams...to me the exams are a necessary evil. I see. I don't see a more efficient way, because the problem is you would like to have a ideal world and trust all students to just go. Everybody do their own homework and do their work... and that would be nice. Sometimes when theyre in a higher graduate-level, you can give them take home exams. Thats an ideal case.

DR. BLUE: The problem is that you don't always see, I see in fact in some of the homeworks I see some students copy exactly what other students do. Sometimes they just make this mistake, the other students make a mistake and they make the exact same mistake. Transcribe the mistake. That actually forces us to do in-class exam. Okay? And that's just sort of the nature of the practical world [Not an ideal world.] So the point of the exam comes to differentiate who understood, who did not and what kind of level understanding we have. I'm assuming that I did all I could to teach the students, and I want to, you know, differentiate between them based on their effort and their achievement. Achievement in the form of understanding and that's why, to me, multiple choice questions are not for our field. Of course But like I said freshman course ,I teach to Corse i year and 1111 and 1112 120 students in the class if I make a first second and third and final that's for exams you know for 500 papers to grade just

CO: I understand it's logistics make it very difficult that makes it impossible

DR. BLUE: In many schools for example, UNIVERSITY, where they have actually a grader with the faculty and many people don't actually do multiple choice.

CO: I've seen systems like that that worked nicely but to keep moving some courses do presentations in class presentations.

DR. BLUE: Un huh. I have in my class, actually, I require every student to select a project, for example in nuclear physics, its a particular device to use to study, and I asked them it's a two. Part one is 5 to 10 minute short presentation and also a two to three page paper written about it. Excellent. and that's actually a lot of benefits. See how they can, give them a chance to go explore on their own, and see what they can accomplish. Of course presentations, once you graduate it can be one should graduate it can be a way of communicating your information and what you want to say so it's a career skill gap

CO: Now do you think that works the same I know its nuclear physics you can sort of broad survey of some different topics some of the other courses though like the fundamental classical mechanics, quantum mechanics, and E&M...do you think the doing presentations in those classes would be the same applicable the same way.

DR. BLUE: No, I don't think so. These classes are less than an hour, early in years I assume. So it's like first second third year so so they are early in their training anyways I don't think there...

CO: The last type of valuation that I discussed with other faculty is like an oral exam do you think that is applicable in anyway at the senior level?

DR. BLUE: The problem is the problem with oral exam is that they are very intimidating and you know... all of us as humans we have different personalities and different responses to pressure especially face-to-face. I took a course general relativity with faculty and that course was 90% of the evaluation was based on a 15 minute quiz before each class. And you know some people do very well because they dont care and they are not intimidated by anybody and some people theyre shy and they tend not to do as well and the class is becoming all about passing this quiz. So the concentration of class might even be affected. So I personally don't like it, if I see a student always interrupting the class and making smart remarks, I might ask him a question directly and see...

CO: But conversations happen in the classroom something like that? Yeah, we always talk to each other..even today we had discussed several things. But students come to me but some students feel little bit shy and they come ask me after class. Okay that makes sense.

CO: In the same idea in the same sort of vein of presentation skills being important I think that sometimes oral communication skills are also important as well

DR. BLUE Well I mean there's a difference between oral exams and oral communication. okay it's a completely different thing oral communication is very necessary thing you need to communicate with your students, because many things you can actually read it over and over again for the students could read it and not understand that's with the role of the teacher is. but oral exams I don't like to have in my class

CO: okay that makes sense

DR. BLUE: But it's mostly due to the reaction the students would have

CO: yes it's in fact the message the whole focus or trend in teaching and I'm sorry I just wanted check to make sure I wrote down some questions so I don't have to keep bothering you laughter

CO: How much would you say you discuss the course content with other faculty members is a conversation that happens a lot in our department

DR. BLUE: It depends on the course for example how many faculty know much about COURSE here to that are here to discuss with them just so it depends on the course that you're teaching for example when we taught freshman courses be used to have a meeting with all the faculty who teach freshman courses and discuss the content and move towards changing the content so yes if you're teaching like this class not so many people know about it

CO: A handful.

DR. BLUE: I don't want to say handful only show show yeah it would be the GROUP OF US definitely and that's why it is it's kind of depends okay but the content is if it's a courses, and then basic the basic requirement it's important to communicate discuss faculty and see what the point of view are. So maybe like the upper level courses the core the quantum being in the class yes yes it's necessary for any faculty teaching a course to discuss with others but I'm hoping that the court topics that must be discussed have already been discussed over and over again and settled on so if you come up the new course then someone in the department reacts but

CO: For those core type courses to keep trying to call mechanics because part of my research is learning trying to determine what the preparations for the students have a best to be in the classroom from the purpose of the class general speaking on mechanics in general not just here shouldn't be more mathematical foundation for graduate school should be focusing on conceptual things that are strange or should be coming

DR. BLUE: I don't know why he should be one of the other I'm not both it should be both when I teach if I've a chance to teach I would actually stress on the map but every time you too man you need to explain what's the point of doing it and will convert salt reach affect both can help each other into making a complete picture in someone's but of course I think I'm just finishing the highest priority

CO: Understanding both is crucial

DR. BLUE: But understanding the physics is the highest priority is a physics class if I have to sacrifice some math to give more time to the physics point I would I would do that

CO: Part of what I'm interested in saying is what is the man that these people need so that you can say okay or talk about for a series and I'll be okay and Babettes March onwards one already use a Fourier series to do in physics so that's

Dr. BLUE: But I think you know first course one mechanic does not require such complicated high level of that at least when I took my undergraduate course I took want One and met medical physics one at the same time by the time I'm ready for quantum mechanics to I already have a good background I also took partial differential equations at the same time so I'm already catching up with that that actually gives a chance to the teacher to stress more spend more time on the physics which should be a more private higher priority but sometimes amount is very very important you need to reach some

CO: Yes sometimes the maths we used to communicate what's going on so I understand you took your undergraduate coursework abrazo correct

DR. BLUE: Yeah but when I took undergraduate physics the set up is a little different in the first year the first semester I took physics one chemistry one biology one calculus one the second semester I took physics to calculus to bounce you to chemistry that's the first year then after that. I took classical mechanics one quantum one and mathematical physics one and waves and bright vibrations and ordinary differential equations and so so by the time I reached the third year I took most of the basic courses that sounds Strong foundation yes it's top but when I seen the US is a lot of focus on other stuff having a well-rounded education the problem is to lose a lot of your of what you're studying I understand and that's a big problem I see

A.6 Dr. Indigo

CO: So to get the ball rolling, I kind of like to ask you about your experience in Quantum Mechanics (QM) at the undergraduate level. So I'll tell me about where and when you took QM as an undergrad.

DR. INDIGO: Okay I took QM in the grad in... probably 1982. I graduated in with my bachelors degree in 83, so Im not sure exactly sure, but I took a two semester QM sequence at the for physics majors two three-credit-hour classes or whatever... in my senior year, I think, or spanning my junior to senior year 82 or 83...

CO: Okay do you specifically remember any topics that found particularly difficult?

DR. INDIGO: I don't think I remember well enough what happened in that class to really say that much. No problem. I remember was very difficult. The way that instructor taught it was that the exams were incredibly long and difficult and there was no way anyone to get through them and it was heavily curved. So I remember it was shocking... I think it was in my junior year I was shocked because I never been the class was taught like that. So the first exam I scored like 45/135, and I thought my physics career was over. I mean, I didn't know what my score was but I knew walking out of exam I thought my career was over and I was thinking about what it would like to be driving a truck or the other job options I had as to where my next career move was. And I didn't talk to a lot of the other physics majors, I had other friends, so it was a week later when I got the exam found out the average was a 45 and I learned that you have to approach the test very differently than what I was used to, because there's no way you'll ever ever get through so you skip the problems you don't know and you move to the problems that you do that you can do... and do fast. I learned strategy in that class and got A's in two semesters, the professor wrote me letters of recommendation and all this kind of stuff, because I did very well in this class. Once I learn the rules, which were not like any rules I never seen before. So, that was my biggest memory of this class I cannot remember we did or didn't do

CO: That's fascinating because I had the same experience my junior year in electricity and magnetism (E&M). I got a 32/100 on an exam, I started crying in class for the first time in my life. I never received a score like that. The professor showed us the distribution of grades and said I'm very disappointed. and I was shocked because the 32 I got was on the high-end of the bell curve... so I had a similar experience

CO: The courses you took before QM... was QM sort of the last course she took as an undergrad or...

DR. INDIGO: It was towards the end. It was... There was a three semester engineering style sequence intro.r of physics that covered some modern physics but there was a junior level of modern physics course and QM was two semesters at the senior level. I believe all the physics majors took the first semester and only those on the graduate school track took the second semester.

CO: Now classical and E&M... were those in sequence beforehand, or were those courses at the same time as QM?

DR. INDIGO: At least the way I took, them I don't remember how rigid it was for other people but they had a two semester sequence of both Classical Mechanics (CM) and E&M, and I think it was a similar arrangement as to who took what and I took him I took one of them... they weren't both before QM. They weren't sequenced like that, but I took at least one of them...I think probably... I can't remember which one and one of them kind of at the same time.

CO: We are going to jump to evaluation. I'm basically just going to mention a handful of different evaluation type questions and my interest is how appropriate do you think that those types of questions are for an upper division class like QM. So starting sort of at one end of the spectrum with multiple-choice questions, how do you think are they applicable for senior-level courses or are they not applicable...what do you think?

DR. INDIGO: I think they could be used in a very narrow range of situations. If you had an emphasis on some vocabulary or very basic ideas that you wanted to make sure they got, then if they knew that was coming on a test in a multiple-choice form, then they might do that. But generally, I almost always...I would want them not just to be identifying an answer, but explaining it in some fashion. So I tend not to use that those at all although, I would agree there are some circumstances where it's appropriate to use that.

CO: Okay that leads into the next type of question...would be like short answer...two or three sentences something brief...

DR. INDIGO: Yeah, and I think that is very appropriate. Especially for testing kind of a basic concept. Having them have the ability to recognize with the appropriate physics...or the appropriate rule or concept to be applying there and explaining in a short answer how they got there... why they got there, why that's appropriate one. So that's mainly getting at... that short of an answer, you're getting a something that's probably more the basic concept. It shouldnt be something with a lot of suddenly to it.

CO: So, do you think that there are situations where it's appropriate to have, like, an essay question on the physics test? Yeah, absolutely.

DR. INDIGO: I use them all the time in modern physics, and with the emphasis that they need to be able to not just get right answers, but explain their answers and to do that. Have that expectation that they're going to do orally, and in writing, and they're going to practice that because that's also part of the skills of being a scientist. Is that being able to not just... I mean you could just have all the ideas... I tell them you can have all the right answers you want, but if you can't explain to somebody where you got the answers, no one's going to nobody's going to pay any attention to you. Yeah, that makes perfect sense.

CO: That being said, written problems... those are kind of the bread and butter for your standard upper-division course. Yeah. Do you have any particular thoughts about when those are most appropriate, or how they best to be used?

DR. INDIGO: Certainly those appropriate. Certainly you want them to be able to...apply, pick the right, understand which concept, which idea they're trying to apply and mathematically how you put that in the right form to actually crank through and get to answers and evaluate those answers. So the problem kind of covers the whole range of what you need to do and that's why we rely on them so much, I think. What you missed sometimes with just that, especially if you don't require them to explain and justify as they are doing it, is that you have no way to discern the earlier steps, because there're some things that come right up front about identifying what's the type with the right concept to use and whether they understand the concept or not. And they can approach those by more memorization, so if you don't compliment it then they... the students will tend to fall back to a more comfortable memorization pattern and pattern recognition and not, you cannot discern necessarily, whether they know...first of all you encourage them to go the wrong direction in how they approach the problem. Then when you look at the problem you can't necessarily tell, if you haven't asked them to demonstrate certain steps in there because you're giving them a straight textbook...well they are producing a straight textbook kind of solution mathematically this is how you get from A to B.

CO: So, really what you are looking for is almost sort of like a mathematical mechanics of the problem with having, having appropriate steps motivated by physics concepts?

DR. INDIGO: Something in the problem at least to justify steps and I encourage them to use words or that problems are complemented by conceptual questions. Written questions...either essay or short answer longer answer, so that the focus of the student on the students understand that what they're looking not just to be able to crunch numbers mathematical answers but they have to understand and explain concepts, so that they approach it in the right way. There's nothing wrong with the problems, if the butt they can be approached in the wrong way, if all problems are straight problems and don't have any balance to them. Sure.

CO: So as I moved sort of towards the more non-traditional end of the spectrum here, a lot of junior-level courses do things like presentations. Do you think student presentations are the kind of thing that can be appropriate at the senior-level, for classes like QM?

DR. INDIGO: I think probably less so in QM. than in lots of other courses in a more advanced topical class that students can dive a little deeper into some aspect of, probably works better for presentations. QM being mostly, well it could work in QM if you say theyre going to dive into things that you would not normally covered in class, some kind of quantum entanglement or or quantum computers or applications how QM applies to different areas, but... I don't know. I'm kind of ambivalent as to what the best way, or if it would be worth spending your time in that kind of class. It seems like you with a different class. The focus of QM is those concepts and the mathematical applications of them, and you concentrate so much on standard problems to build a foundation. The students would certainly be interested in those kinds of things and there are areas where you can make that work,but what probably works better in a more survey class where but anyway...Where you are addressing multiple topics? Yeah.

CO: The final sort of evaluation idea is something like an oral examination. Sort of a one on one conversation between the instructor and the student. Do you think that type of evaluation could be acceptable for an upper-division courses?

DR. INDIGO: Absolutely. I think it should be our expectation that the students can communicate the ideas. Hopefully in class there is discussion and students do have to do that with each other, and with the instructor, or a group discussion... class discussion. I know informal evaluation that there's a lot of of that students asked questions whether it be one-on-one or in a group setting you really get an idea of what they are whether they are understanding or not and having to communicate the ideas requires a deeper level of understanding often than doing a good number of the kind of problems. So I think we do evaluation that way, although we are doing more of an informal evaluation that helps us understand where individuals in the class are. So there's no reason why you could not be used in a more formal evaluation, especially useful well I think... it's useful for both formative and summative kinds of assessments because it does it gives the instructor and awful lot more information than any written test could. Sure. It gives you a deeper sense, as a summative assessment , it gives you a deeper sense of how, how deeply the student has understood the material. Sure. So, I don't see any reason why we couldn't do that. I think most of the time it's really practical considerations that keep us from doing it. If you have 10 in the class that's one thing if you have 30 that's another. Sure. Absolutely.

CO: Just out of curiosity, do you think that's the type of thing that would be...that you could do throughout the semester or would it be more better at the end of the semester, as a capstone activity?

DR. INDIGO: What it does when you do that, is it changes the learning outcomes of what you're looking for. Most QM classes and most upper-division physics courses...most physics courses probably, overall do not emphasize oral communication being able to talk about the ideas. They expect everybody to be able to think about them, and maybe write about them but not such an emphasis on actually talking about it. Which...professionally, we put a high value on that, because we attend conferences, we do more of that than we do writing papers. So it's more prominent and we have group meetings and collaborations, so oral communication usually important and yet we don't emphasize it that much in the classes. So what was the question again?

CO: Do you think it would be better to do that type of assessment throughout the semester and have a short meeting or would it be better as a capstone activity at the end of the semester?

DR. INDIGO: So the answer I was trying to get to is that it depends on the goal. If you redefine the learning outcomes, especially in the context of this is what professionals do, this is what it means to be a physicist. Then students actually take to that pretty well, as long as... so if you if you're going to use it at the end especially as a final exam you need to have that kind of assessment all the way through the semester. Not just once at the end. The other way to go, if you are going to use it a little, I would say you would want to do it earlier in the semester where you're using it as a more formative assessment, where you are understanding where the students are...at an early enough stage that you can adjust the class or adjust...work with individual students, in order to make sure that they're going to really get out of the class what you want them to get. Yeah. Excellent.

CO: So, you to sum up this whole topic is if you could describe for me, if you were the person who was conducting this this QM course, or a QM course in general, tell me what you think would be the ideal evaluation technique throughout the semester and maybe what the most practical method would... be in your opinion.

DR. INDIGO: I think the most practical is always... usually the classes are small enough that tests and homeworks can be graded. They can be...they don't have to be just mathematical answers that you you can put in their conceptual questions that and make it manageable to be at actual able to teach that kind of class because you're not grading 50 of them. So, but definitely if you... both for the students and for the instructor, if you're going to have the oral kinds of evaluation somehow you're going to have to back off on some kind of other evaluation. So that can be a tough balance, I haven't thought through it enough to know what I would do less of in order to make space for that, because as I said, I think the best way, as anything when you're teaching, is if if you're going to have something as part of your class it needs to be a big enough part and consistent enough part that students can get use to kind of what it is, what the goal is, it has to be consistent we done, and they have to see it as integral to what we are all about in that class and so that is kind of a big step. Okay.

CO: One last question that just came to me. You know, if this was the type of thing that would replace a final exam in a three-hour timeslot, that would probably imply that you have a short amount of time to talk with each student, maybe 15 or 20 minutes. Do you think that the amount of time would be acceptable to gage someone's understanding, or do you think you probably you would need more time...just out of curiosity.

DR. INDIGO: Well it depends on what you're trying to gauge in there. If you say it's a final exam equivalent if you're trying to replace the final exam, then that 15 minutes and you're not going to do that. What you so you could, so what are you trying to accomplish with that? You could you could have them actually prepare and doing oral presentation to be prepared to talk about the particular topic and then you're really looking for their ability to master one thing, which they know about ahead of time. There is another way to go which is just an oral exam in which you discuss a range of things trying to replace the final exam, in that short a period of time you've got to talk about several things because maybe you hit the one thing that they are not very strong in and if it's really going to be a fair assessment you have to talk about a range of things... and I would be, that short of an assessment to replace a final exam I would say, I would be very leery of sure so that's one of the difficulties there. That makes sense.

CO: Okay. Now I'm going to jump to physics preparation. Okay. So, before a student enters a QM class, what types of physics content do you think that they should be familiar with...and I realize that in order to get to, to register for QM, our students have to taken Modern I [PHYS 3401] and they have to have to taken the math requirements. Are there a handful of ideas that are absolutely crucial to making QM learnable?

DR. INDIGO: Certainly, Schrodinger's Equation (SE) is the main part of it. It's a differential equation with multiple variables, so they have to have been exposed to that. They should have done that in their Calculus three, their multivariate calculus [MATH 2215], and then some of them will have taken PDEs [MATH 4265] (PDEs), so at a graduate level, you're looking for somebody who actually have done PDEs. Becasue that's what you're actually looking at. At QM, an undergraduate class, ideally you would really like to be at that point, but that is a high-level. At some schools you can maybe accomplish that, but most, you can't get them to that high of a math level before they take QM. So that limits kind of what they can do, but... so what they need to be able to do is understand enough about multivariate calculus to be able to understand how to take that and turn it into some single variable differential equation that you can solve and to at least be able to follow that, and to be able to apply that kind of procedure under the circumstances you are asking them to. So you're right there on the edge of their mathematical abilities, so what you're trying to do for them, to really be able to understand QM because you are starting point is a multivariable differential equation. Yeah. Definitely. So to understand the concept around that...the QM class as opposed to a modern physics class you are on the mathematical end of things. Yes. So, you're trying to establish both foundations at the same time. The other piece of it and what I found teaching modern physics class, is that coming into that, they are not very familiar with things like distribution functions. They are more ...some of which are quite abstract. For instance, one of the things you do early on in modern physics class is black body radiation...Plancks Law, and you have equations which have variables which are like spectral density. So intensity per wavelength range, in units like Watts per meter to the fourth, or Watts per meter cubed per nanometer, and those are very strange and abstract kind of ideas, and they're not used to working with these density functions. Which can be functions of several variables, right? Usually at one time you are saying, for instance, fixing temperature and looking at it as a function of wavelength and you plot it is a function of wavelength around a fixed temperature, but it is a rather... there always a rather abstract quantities, and they're not used to that. They're not used to it if they maybe understand a calculus but they need to do...

DR. INDIGO: [Ringing phone] Excuse me a second I'm just going to turn this down.

CO: Okay. I was going to say if you need to take that I can shut things down

DR. INDIGO: So they... so it's really their ability to... the modern physics take their mathematics and actually understand how it relates to physical quantities in this more abstract kind of physical quantities and then to be able to think and recognize the graphics as having a physical connection and by the time you get to QM... full QM, now you're talking a very abstract ideas. You jumped past some of the little bit more concrete examples like that and you've got gone to a distribution function, a wave function that is a probability distribution function that is complex and that is not observable. So it's quite an abstract thing and if they haven't really got those developed those tools to deal with distribution function in general to relate these... mathematics to a little bit more concrete physical ideas that having the mental fluidity to be able to think about what these equations stand for when they got wave-functions in them is really hard. So I think it's kind of more of an abstract critical thinking kind of skills that are bigger hurdles in a lot of cases than the pure mathematics. Of course they have to be well-rounded again in differential and integral calculus sure of course

CO: That being said, do you think that some of the other upper division courses would add to that sort of critical thinking creative problem solving ability. The ability to tie the mathematical to something more concrete?

DR. INDIGO: I think all of the classes do that, to some extent. Probably E&M more. There's quite there could be quite a lot of mathematical skills in Statistical and Thermal Physics (S&T) and differential Calculus and some partial differential stuff, but probably CM is the most concrete. it's not the most mathematical, but you would use...in all of those you might use the same type of distribution functions and so and mass distribution charge distribution kind of stuff that is beyond simple stuff you do at the introductory level. So they all could add to the skill level that they need going to QM.

CO: That makes sense. So, if there was a... could you rank by importance the courses you think that they should see before they reach QM?

DR. INDIGO: Well ideally, QM is a higher level class I think for those reasons than CM and E&M, but in practice you can't really do that most of the time. In my program at Illinois, there were a number of tracks with a lot of undergraduates, so they could separate people and have a graduate school bound track that was...they had actually three different undergraduate bachelor's degrees a BA, two different BSs. One more grad-school track and one not necessarily. So, even then you can't sequence it totally with that... to rank the rank By physics content. The physics that you would get out of a certain course is the most important for QM. Well, the modern physics is the one that leads directly to it and that's why it is prerequisite... it's absolutely necessary. Then the others which arent prerequisites now, in preference would probably be... I would rank E&M slightly higher than CM for our students, both of those two classes and not near the as much S&T.

CO: Is there any motivation behind what E&M in second CM?

DR. INDIGO: I think there is much more natural analogies between fields and the abstract concepts of fields and wave-functions. So that's my...and it's kind of a progression. In my mind ideally, you would to CM, more concrete, but highly mathematical level at that point. Then youd do E&M now youre moving to something more abstract, and has a different nature because its a vector quantity that you are dealing with... and then you move to QM which youre dealing with a quantity that is not a vector quantity, its a complex quantity and is not directly measurable and so the level of abstraction is moving up as you go through there. That makes perfect sense. Yeah, it's just not real practical ...and practical and ideal are obviously two different things. So I understand completely. That's just the way it is.

CO: You mentioned modern physics and that you're the instructor for modern I. What are your goals for the students that are leaving modern I, in terms of content?

DR. INDIGO: The most important is the conceptual understanding of quantum ideas of wave particle duality, Schrodinger's equation, so I emphasize things like being able to draw a plausible wave function for a particular situation. Things that where the skills they will need if they go on to QM and actually calculate an exact solution for something that is beyond what you doing modern physics to be able to recognize or when presented with a solution be able to her recognize if that is plausible and the last kind of step of evaluation that they have skills to do that... so both and I guess the other big... Conceptual understanding of those core ideas of QM up to the hydrogen atom so Schrodinger's Equation, the hydrogen atom, one dimensional, three-dimensional, cartesian and spherical...but you start with wave particle duality and it's done in a very historical kind of way so the other big piece we are trying to get is that you're learning those concepts but you're also learning about these concepts which are very strange but you're also learning about how you get to the strange ideas. So for me and modern physics, the big goal which isn't there in any of the other classes really, is how science works and so that kind of that's one reason why you have maybe a lot lower goals mathematically of where you want to get them as far as calculationally, because you're getting more the big ideas of science, scientific progress, evaluating models, and that these, all are models, how you compare and it's how they compare to something you can actually observe or measure determines whether they're good models or not. When you, when they don't work, what you do. So if those two big ideas science works and then in the particular context here these radical ideas came about including relativity, which is in there...although we don't have time for as much relativity as I would like and might like to actually move it to another class because we really don't have time to cover in the depth that we need too, but those core ideas of QM and that's the good context because they are wild and wacky ideas that you would not adopt if you could choose the world... the rules of the world operates by Yes. and so why would we adopt these kinds of rules and that's why it becomes a really good lens and when you get to QM. Full QM that's not really true goal it's really now this is the way the world works so let's take this equation and let's see mathematically how can we apply this to situations and really see in the mathematical complexity what it leads to.

CO: Sure that makes sense so you basically your goal for modern physics is to lay a lot of the groundwork in terms of the conceptual and also some more of these critical thinking ideas that are geared towards actual scientific reasoning, I guess sort of. I kind of want to jump math know that we talked a little bit about ordinary differential equations are there any particular kind type of tools you can think of that would be really really fundamental to studying QM I know there are a couple options handful of obvious Yeah. Yeah

DR. INDIGO: I think I said for just partial differentials having a good idea of what that is... because understanding, exposure to that, at least enough to be able just to see you understand it and manipulating equation where you can do some kind of separation of variables. To see and get to real solutions to problems. So otherwise, I think it's mainly just strong calculus skills and then it's not really mathematical it's it isn't the ideas of what these quantities are distribution functions or other kinds of functions and being able to connect the physical world with the mathematical equations. I don't know, I guess I don't know I'm not so familiar with the exact how advanced of the mathematical problems they end up doing in QM class so I don't know what the highest so answer question I don't know what's the highest level math they need. A better answer of where I think they need to be to go to the next step beyond modern physics the things that would hold them up to them from going further. So for instance in, modern physics what you do we should take problems and you you don't ever solve Schrodinger's Equation, you should have solutions and hope that they could understand how they got there as opposed to a QM class we actually expected them to be a looking at themselves.

CO: So that being said, if we were to perform the same kind of ranking exercise for ideas in physics... it seems to me that what you're saying is that PDEs would be high on that list. Specifically the ability to deal with separation of variables, so that they can create, they can see where the one-dimensional schrodinger equation comes from as something that is time independent.

DR. INDIGO: Yeah. you are we don't require them to take PDEs, but we're leading them right up to the edge of it, because they have ordinary differential equations [MATH 3260] (ODEs). They've had multivariate calculus and now you are presenting them with PDE and so in essence you're teaching them some PDEs, although you're not teaching them the mathematical course here are all the techniques you can apply. Youve got the foundation now to at least understand and be of start to apply them to situations we can lead you to, that this is the right kind of technique. So you need the same preparation you would need going into a PDEs equations class, because you're right there on the edge, and you teach them a little on the way. I would think that if somebody didn't take PDEs and came out of the QM class would find PDEs easier, and the other way around... I hope. There are things that you can't talk about [with]

Schrodinger's Equation without engaging the ideas of PDEs.

CO: Okay, so sort of all the mathematics that builds up to that point is what is really key. Okay. Excellent. I'm going to go through a handful of topical questions that are related to QM content and that's really about it. So if you were... how would you believe a student would respond to when asked what an atom looks like ?

CO: How would they respond to that what? I should be explicit the students that are entering the QM, so they have taken all the coursework prerequisite up to that point, how do you believe they would respond to the question what does an atom look like?

DR. INDIGO: I think they would think of the nucleus as kind of a hard sphere, or whatever a popcorn ball...sometimes that's how I describe it in my class. Some kind of the protons and neutrons, because you don't really get into the quantum mechanical nature of the nucleus in that class, and then hopefully they would think of the...an electron cloud as an...Electron cloud of some kind in orbitals, but they probably in their minds are somewhere between a Bohr model and a quantum mechanical because quantum mechanical model and thinking of them as orbitals and wave-particles and standing waves around there is something that they know and have learned that they're unfamiliar and uncomfortable with at that point still. Then they probably fall back thinking of it more like particles. Okay. Excellent

CO: That being said, how do you feel about using the Bohr model as a teaching tool at that level as well, sort of between modern and QM?

DR. INDIGO: It's hard to...it's a teaching tool...in some sense it is counterproductive to be putting forward a classical model, that that works in some way. Although it has some big holes in it. It works and then replacing it with something that doesn't look very much like an all at all in that sense. I mean they're not orbiting so and but but you kind of have to have a way to get there you can jump right into orbitals and so comparing with some of the classical features even that they had angular momentum, orbitals is really kind of hard to see the angular momentum, especially in a standing wave...and historically, you've got to go there, because so in the modern class you kind of have through the Bohr model with an understanding that they can get real comfortable with that, and uncomfortable with the real QM description and so you give them that Bohr model and they'll be reluctant to let go of it. Sure, I don't want to call it a necessary evil, but it is a necessary step, and a little bit of a dangerous one. Ok. But it is also... one of the things you learned along the way as far as historical or the process of science is how to adopt a model that has some really good features even though you know it has some holes, and you might know right away that there are some holes... somethings that there're some features that we cant explain. Bohr had no idea why is there a ground state. There was no reason for that until you get to DeBroglie.

CO: In your class, do you explicitly highlight these ideas? I think in PER this would be more considered hidden curriculum material.

DR. INDIGO: What do you mean these ideas?

CO: I mean the idea the scientific rationale behind the ideas that you are presenting. This idea of the motivation why you choose this model, acknowledging the fact that the model is, in fact, only a model.

DR. INDIGO: Absolutely, we go through and say here's the idea as it's presented and there are couple cases which we talk about ideas that didn't work... and that kind of were not adopted were kind of put out there and not adopted. We do investigate ideas of what is the reason for this, what is the problem, why do you need new theory, and how does this match up with what we're looking for. So yeah that's a big emphasis in the class is being able to evaluate the model and how do you do that. Excellent...cool.

CO: How comfortable you think the students that are about to enter QM would be with Heisenberg's uncertainty principle (HUP)?

DR. INDIGO: They know the ideas but they don't yeah they are very sure of what they mean. The... for instance that it causes uncertainty, but I don't know that they...it's hard to get them to develop that idea of what that means. Measurement uncertainty and how that's connected this wave-particle nature so it's a very complicated thing to get a real handle on, and I don't think they're very good... I think they.. or for instance how when you put it in the energy time domain, nuclear lifetime stuff, they have a very hard time grasping the fact that a short lifetime means an uncertainty in the energy state. There's no they don't see a logical connection. So they understand enough to go in and calculate it, but they they can use the equation but they haven't really taken in the meaning of it, so I think that's where they are they're struggling. It's like a lot of the QM, they're just rather unfamiliar ideas, so there's no reason to expect that... there's every reason to expect that they'll be a will to mathematically manipulate them long before they are to a point of really understanding what those things mean, because they are, from our macroscopic perspective, non-physical effects... theyre thing that they cannot experience directly. We need to expect that and to say that they're still recognizing, going to QM at that stage where they may have gotten pretty good at manipulating these things mathematically, but yet they haven't fully understood that...and if we just have mathematics in the QM class, we can bring them a step further maybe, but you may leave behind their conceptual understanding. Sure.

CO: And my understanding, generally speaking, is that the QM focus is less conceptual and more having them fundamental mathematical tools to move onto the next level so it definitely... I think the modern physics courses one of those key points where conceptual comes into play. That being said, we already talked about wave-functions, how comfortable do you think the students are both conceptually and mathematically by the time they're approaching the QM course?

DR. INDIGO: Well, yeah. I think they've learned to do some mathematical things and emphasize perhaps being able to draw plausible wave-functions, at least the real parts, but connecting those real and complex parts and understanding why there is a complex part in there and what it means...dealing with things that are the time part of it, which we don't do very much of. So there's a lot of elements of it then and you're just trying to get them to the beginning of it and dealing with the simplest wave-functions, the real parts without the time in in, so and that actually is hard...that means they don't always see the oscillating part of it so so it's standing wave characteristics of it. When when you're looking at the special wave-functions, hard to keep connected when they haven't made that connection it's hard to spend the time always showing them that over and over again they need to see. Its a very complex thing, even a ground state of the harmonic oscillator you add in the time part, you at in like one of the simulations and it's a complicated kind of thing. So they haven't really taken on all that. Hopefully they are getting kind of some understanding of the ground rules and then what that means, what kind of solutions you can get,and what the physical consequences of that are that's kind of where they are I think just the basic idea of okay this is what wave-functions are like this is the kind of effects that you get, but don't ask me anything too far beyond that.

CO: Do you think that they get a lot of exposure in regards to whether ...are they talking about the... interpretation of what the wave function is... I think that question is do you think that they are sort of understanding what the meaning of a wave-functions when what is trying to describe? I think mathematically it's not tremendously difficult with the appropriate training, but I think conceptually what a wave-function is and where it is and those types of questions are making people want to shy away from...

DR. INDIGO: And you jump back and forth between, for instance, its a probability distribution, so if your measurement that localizes it, whats the probability of you finding it? But if you're not doing a measurement and you looking orbital or some wave-function... that is the whole thing. The particles the whole thing and its not in one place and its a standing wave and all that. So, I don't think they're taking in that kind of an understanding of the wave-function. When you get to the hydrogen atom and you're trying to talk about these orbitals, they will quickly fall back to particle language. Sure. So they are not ready to take on a wave-particle or wave at that point really...at that point its a wave...understanding of how to talk about it...and that leads into operators. You have enough time...you don't spend enough time in the modern... just to do some simple expectation values for position X,X squared p sub-X, p sub-X squared, that's about it, but kinetic energy and those kinds of things and to see that there is information in that wave-function thing. That tells us about the different physical quantities, but how that is there or what that... I don't know if I fully capture the depth of that. Yeah that's definitely a tough thing to deal with. I try to tell them that is a full description of the particle. Everything there is to know about the particle is in that wave-function and it is the mathematical description as best we understand it and I say that many many times, but I see it bounce off their foreheads. Gotcha. I understand that.

CO: Do you ever mention the Hamiltonian operator over the course of the class that sort of the...

DR. INDIGO: It's in the table when we do operators and they can see how...the things that we are using, we are calculating, are connected to the Hamiltonian, in the simplest case. I show it and mention it and talk about it and then say that you'll see this a lot more when you get to QM. So they get about five minutes on it.

CO: Okay...um.. am so the last topical thing wave-particle duality. I think we've sort of danced around this, but the students are about to enter this QM course having taken modern, how mature do you think that development of that idea is?

DR. INDIGO: Oh it is not all. it's not at all. They are thinking in particle terms, theyre able to apply the mathematics of waves, they aren't real comfortable with waves, so I think they're understanding of waves lacks to begin and that means they're not all that comfortable describing things in terms of waves. So I mean I go back and teach 2211 and 2212 wave stuff before we get into this, because I know they're coming in without a real firm understanding or ability to think about waves or you've got again mathematically when they learn waves they've got a function of position and time and they are not all that clear with that or have to think about that or manipulate it. So a lot of times they have big holes going back there. Were building up from that point to go forward. So, I think they're not comfortable with waves and so when the getto wave-particles they think they...theyre choosing. Yes. They're thinking of it is particles, and at times they're applying wave mechanics because they know they have to.

CO: Sure, that makes sense...Gotcha and I was going to ask about the Pauli Exclusion Principle (PEP). Is that addressed in the modern physics class?

DR. INDIGO: It is and its... both in terms of when you get to the hydrogen atom of the fact that you have two electrons that spin...and you introduce spin and that we see that that's the reason why historically there two electrons per orbital because of the spin and you have to have different quantum numbers talk about symmetric and anti-symmetric and that is not treated enough depth and a lot of quantum numbers, so they get the general idea but they have to have the sense of what quantum numbers are I don't think most time Im able to get them understanding why they have different quantum numbers so they understand the PEP as a rule. That makes sense.

CO: So okay, two more quick questions. I was going to ask how often do you talk about course content with other faculty members within the context of everyday conversations?

DR. INDIGO: With a few people we talk quite often. You know always talking about what went well, usually what didn't go well or what they didn't understand as well as you had hoped they would...why it may not have with a few colleagues mostly the lecturers, or others were maybe a little more engaged in thinking about pedagogy and what is a better way to teach it. bouncing ideas off..coming up with things from The Physics Teacher or other places like those. So, I think I have regular conversations with a few people

CO: Are those conversations more geared towards introductory courses?

DR. INDIGO: Well, no. I mean, if I'm teaching modern then I'm moaning can complaining about how students didn't understand something and that I had a great example and it didn't work. So we talk a whole range of stuff. Okay. Excellent. Good to hear.

CO: The last question is if you could offer one piece of advice to a student who is about to enter QM what would that piece of advice be?

DR. INDIGO: I'm well that's a good question that's a hard question. Yeah...I guess I would suggest to think about it conceptually. Think about what things mean and try to keep your balance and not just focus on mathematics because I know that's probably my tendency as well and often a perceived mathematical difficulty is sometimes a conceptual difficulty.

Appendix B: Student Transcripts

B.1 Adam

CO: If you encountered somebody in an elevator, and you had to give them a quick rundown and they said Well, whats Quantum Mechanics(QM)? What would you tell them QM is...like the short answer?

ADAM: The interaction between subatomic particles on a very small scale. Okay. Thats what I think it is.

CO: I assume that youve taken Modern Physics, correct?

ADAM: Yeah, one and two. [PHYS3401 and PHYS3402] Is that the new Advanced Lab? No, Ive taken that as well. [PHYS 3300] Sorry, Im woefully ignorant when it comes to the undergrad[uate] curriculum, so humor me.

CO: So, what topics do you think youll be covering this coming semester in QM?

ADAM: Definitley a lot more wave equations, and probably learning about the different forces and different particles. Okay. Its like a very broad thing, I dont know exactly what were going to be doing with it.

CO: Is this information based on folks youve spoken to in the department? Have you had a conversation with the instructor?

ADAM: No, I really dont know anything about QM [the course] to be honest, because Ive never really looked into it. Ive just kinda been like Thats beyond my understanding right now.

CO: You mentioned going back to the lab. If youre comfortable talking about it, would you mind telling me what you do? Experimentally?

ADAM: Just mathematical models of leach hearts with Will. I just do simulations on the computer change things and see what happens. Okay, cool.

CO: So, in the Modern course, what types of topics did you cover when you took modern...I guess Modern [Physics] I?

ADAM: Lets see. Relativity, blackbody, just definitely wave and particle interaction, and duality, I dont really remember everything that was covered...it was like a year ago, but I know Id be familiar with it if I saw the...list of things So if someone gave you a square-well potential...Oh yeah. Well potential. its hard to list off everything. Modern II was a little but more recent...

CO: If you dont mind me asking, because I had no idea what was going on...what was that course like?

ADAM: It was more specific things. I think Modern [Physics] I was more general and that lead into Modern [Physics] II which was more specific. Things like Solid State and... was it topic-focused with the research that goes on here or was it...? Yeah, like superconductivity, solid state, energy differences between molecules. Who taught... Dr. Mani.

CO: Lemme ask you this...what do you remember about wave functions?

ADAM: Schroedingers Equation (SE)...and...Do you remember generally what it looks like?

I couldnt write it from memory, but I can understand that we simplify it a little bit to make it easier to compute, but it's not the full...expression? Yeah. thats like the most

I remember from it...its kinda complex. Gotcha.

CO: Can you tell me what SE describes...kinda sort of?

ADAM: Um...I guess like...the way the wave moves. Thats the best way I can put it...but Im not positive though. Im just curious. The whole entire electromagnetic field kind of confuses me as well. Im also excited to take E&M [PHYS 4700] this semester. So, itll hopefully give me a better description of what is actually moving and that an electromagnetic wave being propagated through space. I think having the two together will probably be helpful.

CO: Did you guys ever normalize a wave function? When you were taking the introductory course? Yeah. can you describe to me what that means when you normalize it?

ADAM: Where you are setting the left side equal to one and solving for a specific portion.

CO: So, mathematically thats absolutely correct...can you tell me what it means when you set that side equal to one?

ADAM: I dont recall, specifically. I dunno, I feel like I have an idea, but i dont know if its right or not. Ill tell you what...Ill let you know if it is right.l Does it have anything to do with...like...scaling it?

CO: In a sense. Normalization of a wave function, when you set that side equal to one, what you are doing is say...Ill tell you what let me come back to this. Okay. I just wanna ask a few more things about wave functions. Um...the dimensions of a wave function, would you be able to tell me what they are?

ADAM: Um...space and time. Sure...that works Theres frequency and all the wave characteristics.

CO: Okay, do you know how its related to the probability density?

ADAM: Kind of...I know what a probability density is, and I know that... The odds of finding that object in a given place. Yeah. I remember all that...and the different wells and the probability density relates to the well. The weird phenomenon where you can find it outside of the well, which is not possible, but it is possible...confusing.[Laughter]

CO: So basically when you have the wavefunction squared set equal to one, what you are sayin is that the the wave function, Psi, that Psi squared is equal to one...when you integrate over all space, Oh, yeah. it has to be there. means that theres 100

ADAM: Thats what it is...thats what you mean by Normalizing. I remember that, I just...Hopefully this will help get the juices flowing for next week. Definitely.

CO: If I said the wave function is equal to zero, how would you interpret that? If I said that Psi of x and t is equal to zero?

ADAM: Then the particle is not there. It cant be there.

CO: Can you tell me what you know about Heisenberg's Uncertainty Principle (HUP)?

ADAM: Um...Its the relation between velocity and position, where the more you know about one, the less you know about the other. Okay.

CO: do you have any kind of background on where that came from?

ADAM: Um...based on how we measure the particles. Obviously because we have to indirectly measure each particle. Either we are shooting a photon off it and measuring where it when and how much energy it has afterwards or...I dont really know how they...which one is used for which, but thats what Im familiar with. One of them is trying to find velocity and the other is trying to find position and you cant find both by one single experiment.

CO: You mentioned Wave-Particle Duality (WPD). What can yo tell me about that topic. What does it apply to first.

ADAM: The number one thing thing people think of when you say WPD is electrons because thats the biggest studied one that I know of.. in my own studies. When you are detecting it, it behaves like a particle and when you are observing its interactions it behaves like a wave...based on the double-slit diffraction test.

CO: So, if you have an object that is emitting electrons and it interacts with that double slit somehow, right? There are two different situations, right? What has to happen for that double slit to provide a diffraction pattern?

ADAM: The electron has to go through both slits at the same time. Unless its just going through one and theres some other force were not aware of that is going through both slits.Either we dont know the whole picture or its going through both.

CO: This may seem silly, but it makes sense...do you believe that its possible to send information faster than the speed of light?

ADAM: Yes. Can you explain what your reasoning is? Um... only based on the one think that I didnte really read it...about quantum entanglement. Two particles that are lionked can...the way I understood it when I read it was.If you measure one, then the other one will take the opposite path... er... features. I didnt really understand it, but Im familiar with Quantum Entanglement That would destroy all of physics, but I like to believe that stuff is possible until proven wrong. Sure, that makes sense.

CO: Along the same vein, when you are dealing with an object, it has both a particle and a wave nature...thats what this whole duality sort of tells us. the way you understand it. Does the particle have wave features where it exists, or how would you explain it to someone who is starting off ...coming up behind you in the physics program?

ADAM: I think that it is more like a wave than a particle, cause I feel like all the particles interact as a wave when they are not being observed, that we are changing something about their behavior when we observe them. Is [the wave] it localized or does it exist in all space? or the immediate region? thats something...Thats a tough question. Im just curious where you stand on it. I dunno. I feel like if everything was in infinite wave, then it would be a very cluttered universe. I think that they have to have some length.

CO: Are you familiar with the Pauli Exclusion Principle (PEP)?

ADAM: Yeah. How in depth? I just remember using it in computations. Its kind of like the HUP, but different just describing anotehr aspect of waves. I dont quite remember exactly what it was.

Pauli Exclusion...I remember the name exactly I have a feeling if I mentioned it, it would click. Yeah, probably.

CO: In chemistry its used a lot to fill atomic or molecular orbitals where you can't have two Oh, Yeah... electrons in the same of the same spn in the same state. Oh, Okay. Yeah, I know that rule. I just dont connect the... connect the name with the principle? Yeah, like if you asked me what this person did...I dunno, but if you ask me to describe how to do something I can do it. Then you say thats that person;s think, Id be like Oh! Completely off topic, do you think...what do you think about the idea of historically contextualizing a lot of the stuff that happens in Physics? Like, if there was a history of Physics class, would you sign up for that?

ADAM: Yeah. because thats what most courses do. You know, our course plan kinematics, physics I & II, and all that classical stuff, and newtonian physics. Then you move up to modern physics, youre already doing the history of physics, in the classes that you are being taught. you go into Modern, and they are like Thats all classical stuff that we taught you for two years...er...semesters You need to think this way now. Well, it would have been good to know that while youre learning that... to keep that in mind. Because this is circa 1800, this is how it progressed up to the 1900s. Its very important also because... to give credit to who made those advancements. I dont think people get enough credit in the actual courses Do you have a favorite Physicist? Um... I dont have a favorite one , I more or less just respect everybody for their own thing, because there are so many different topics.

CO: Okay, Im going to shift now towards your preparation for the class. What kind of math do you think the instructor is going to expect from you for QM? In terms of courses or topics, things like Well definitely need to be able to integrate.

ADAM: Yeah. Derivatives and integrals and possibly...differential equations. Other than that, thats as far as Ive gone, so hopefully they wont require anything else. heh. Yeah. But I did hear that for E&M that vector calculus [MATH 4258] was pretty important, and I skipped a math class last semester to take one more physics class last semester to help get some requirements out of the way. Gotcha. But I didnt take

Vector last semester so hopefully its not too heavy on that. Im not too worried about it.

CO: Do you think thats what the instructor will probably expect? Differential Equations, and integration and...Yeah Is there something you think will be the most helpful...something you want to go back and brush up on...one mathematical tool or something?

ADAM: Just the wave equations again cause I feel like that will be the heaviest part of the course. Then manipulating them, normalizing and...working with those equations and trying to remember the tricks that were involved. I think the tricks are the hardest part, because you get stuck at certain places and then you dont remember how to manipulate it in the way that simplifies it. Remembering all those tricks is the most important, because everything else is pretty straightforward. You do this then you do this then you do this

CO: Im gonna go through a couple topics, like math topics, and get your feedback on how confident you feel you are in them...if youve seen them, if not whatever...Ordinary Differntial Equations [ODEs] is the first one I have on my list. Have you taken a course here [GSU] that deals with ODEs [MATH 3260]? Yeah. How do they treat them? Was the presentation similar to what youve seen in other classes. Did the physics and the math follow the same suit? Yeah.

ADAM: Yeah. There was definitely points in the class where I was like Oh, cool Im doing this else where. or this directly relates. Its almost seems like it starts out all spread out, but then it comes up to a point where things start combining to help each other and across different areas.

CO: I know its asking a lot, but do you remember any of the topics where you were likeOh, wow! Ive seen this in other classes this makes perfect sense Are there any specific topics you can remember that were like that ?

ADAM: No, I just remember having that feeling where it just connects and youre like This is awesome.

CO: Have you taken Linear Algebra [MATH 3435] here? No. Have you worked with matrices at all?

ADAM: Yeah, a little bit, in Physics II E&M [PHYS 2212]... Oh, and in Differential Equations. So, in dealing with finding the determinant of a matrix, would you say you know what that is...do you think you could do that.. Dont ask me to do it right now. I wont. I know what a determinant is and I know how to find it? Id have to read up and refresh my memory a little bit, but I know.. Just need to go back...okay.

CO: The same thing towards ODEs, how comfortable do you feel with that material?

ADAM: Pretty comfortable, especially now that I have been working in the lab, because we only work with Differential Equations, so hes been having us read all this.. Do you deal with specific solutions to DIfferential Equations or just in general? I feel like we just mainly use trajectories as the solutions. We don't really explicitly find the solutions. We have our system that we evolve over time and see what happens so its more like a geometrical approach I guess than a strictly mathematical solution approach...which I like because you make the computer do all the work. That is always pleasant.

CO: Have you ever taken any Partial Differential Equations course [MATH 4265] here?

ADAM: No, but Im signed up this semester. So, itll be kind of dual. So hopefully, if there is any partial stuff...I know partial you are integrating and deriving from one specific variable out of all the variables, so thatll be the focus of that. Okay. Thats what I remember, but I think we did some of that in ODEs.

CO: Have you seem Fourier Series (FS)?

ADAM: Its just like taking the wave equation and breaking it down into its successive parts...added together.

CO: Did you see that in a specific class or...?

ADAM: Maybe. I dont remember exactly...Probably if I did it was Modern [Physics] I...no, my work in the lab talk more about FS. Its just the most recent thing I've done...

CO: Have you done fourier transforms in the past...you know integrating with respect ot one variable, then integrating with respect to a different variable.

ADAM: Um...Im not sure. I feel like I might have, but thats a bit hazier than...

CO: I ask the question because in QM, you can Fourier transform from real three-space to momentum-space and that is a valuable capability. Its one of those tools that may come in handy in the next semester.

ADAM: Hint. Hint. [laughter] I figure at the very least all the stuff were talking about will give you some ideas... Its already given me a bit of a refresher.

CO: I have two more things on this list. Integration and Calculus is the next thing. Honestly, how comfortable are you being given a function and integrating int?

ADAM: Pretty comfortable. As long as its not such a special case that I dont remember how to evaluate it. I feel pretty comfortable over most cases. I usually have to look up trigonomic [sic] functions. but if somebody said Oh, you need to use a trig. substitution you would know what they meant? I feel like I have...can do that.

CO: And the last thing on the list here is being able to deal with Trigonometry...How confident would you say you feel dealing with Trig. on a regular basis?

ADAM: I think it would be fine. In terms of the basics? Basics I know pretty strongly, but switching in and out of equations... So, in terms of identities... like the half-angle theorem? Oh, yeah. Those are good.

CO: Is that the kind of think you could come up with from the basics? From memory? You know could you build it from, prove it? like sine squared plus cosine squared equals one? Can you get there from that?

ADAM: Manipulate it...yeah, I can do that....but I dont have to do that very often, so it would be something Id have to refresh on. I know Ive done it in the past so why not be able to do it now?

CO: Sure. If you were the instructor for QM, what type of math background would you expect of the people coming into the class.

ADAM: Um... I guess everything weve talked about really, but as instructor, Im sure Id have a much more exact list of requirements that I believed was important. Its hard to look at it from an instructors point of view, because Ive never been an instructor. Im assuming it would be more than the students knowledge [?it has?].

CO: Let me rephrase the question, are there physics topics or classes that you think are gonna really help you as you...when you take QM...in terms of background information or exposure to formulas?

ADAM: Yeah, probably the Modern Classes [PHYS 3401 and 3402] probably the most prepared ...of the classes that I have taken. Other than that I havent gotten any background, like Differential Equations and that.

CO: You mentioned that you are taking E&M this semester. Have you taken Classical Mechanics (CM)?

ADAM: No. Im taking Classical Mechanics my last semester. Gotcha.

CO: Where do you think your greatest strength lies in terms of physics topics? Is there something you feel really comfortable with...more than other topics.

ADAM: Topic-wise? I feel Im very good at understanding most topics. If I dont understand it, it bothers me and I go til I figure it out...so probably pretty common between physicists...its what drives us.

CO: Do you have a preference in term of...do you feel like you are better in E&M or Kinematics?

ADAM: I guess if you look at it from what I enjoy doing, Sure. I enjoy electricity and magnetism because I find it more interesting. If that plays a role into how well I do in it then yeah. It probably affects it a little bit. I guess Thermodynamics [PHYS] it was interesting, but the way the teacher taught it, it was hard to do it. So, thats still a weakness for me. because that class didnt really.. I feel like it was being taught a little bit over our head and not being connected as well.

CO: So, in terms of the other topics, CM, E&M, and Modern Physics, Do you feel like you are on even ground with three? Do you think you are stronger in one? I think everything is interesting. Thats fantastic. Thats the kind of student you want to produce.

ADAM: I dont ever go to a subject and just like trash it, like This sucks, I dont care about this. I known that its easy to have a strength or find one most interesting. I think the kind of relate a lot to each other, because the foundation is math, and math is pretty easy for me to understand.

CO: Have you ever dealt with a Lagrangian or a Hamiltonian? When I throw those around Maybe in electricity [PHYS 3500]. do you know...Okay.

ADAM: Cause I took an electronics course Ahhh. So, I dont know if we did anything in there, but I feel like some of those concepts might have been in there, but Im not positive...Im not as familiar with those. No problem.

CO: I was just curious to know how you familiar you were the Hamiltonian and how it was used.

ADAM: I think it goes back to what I said earlier. The name kind of is wishy-washy, but if you show me the actual mathematics, Ill be like Oh yeah. Ive done that before. If I have.

CO: In E&M [the topic], youve seen the wave equation? Would you say you feel pretty comfortable working with those?

ADAM: Yeah.

CO: In terms of Modern Physics, that course is supposed to set up the groundwork for QM, do you feel like in terms of doing simple problems, like a square well, you could handle that? Yeah. What about the historical background and motivation for QM...Little bit hazier. Do you feel like you got some of that out of Modern? Like, We saw this experiment happen and CM could not predict it.

ADAM: Modern I was more geared towards who did what, and what caused what, and progression. Then modern II was, obviously I had two different instructors, so they taught it differently. It was more focused on math and doing problems all the time instead of learning history. It really depends on how the teacher teaches.

CO: If you could pick the way that you are evaluated in QM, what do you think would be the best way to be evaluated on that material?

ADAM: Well, on like a test, I guess you kinda have to have tests. Because how else would you know. The best way to do it, even though it kinda stresses some people out to the point where they forget about other stuff...is having other assignments in there too, like homework. I like being able to do stuff and have as much time as I want to get familiar with the topic, but then also get that grade based on effort. You know I think effort should definitely be considered. The test are time limited test your knowledge and how fast you can do it. I think they are both important.

CO: I have a short list of different ways to evaluate students. I want you to give me an idea of what you think of them as I go through the list. First thing I have here is like short answer questions. Like one or two sentences answers to questions that would deal with QM.

ADAM: I like those alot, cause thats more if you know what's going on. Some people can just do the math, and are just good enough at math where they can work out the right answer without really knowing what is going on. In a perfect world, youd have this sort of holistic evaluation where youd determine if someone just knows the math or really understands what is going on...its something were trying to get towards.

Or like asking So, what does this answer mean for the system? and everyone is like Uhhhhh...Dammit.

CO: What do you think about class presentations?

ADAM: I think they are important because in any science field, youre going to have to be giving presentations, and that's a weakness of mine. I really havent had to do that. I was like Oh, science. So I wont have to write papers and talk in front of people or do any of that, but then as you progress you realize that science is all-encompassing of all skills. You have to be able to write, read, present, communicate, do math, and logic. Its very difficult to do any kind of experimental science in a vacuum by yourself. Yeah, without having to prove to anybody that what you are doing is pretty valid.

CO: You mentioned kind of written problems that you have to solve mathematically. What do you think about ...typically in a physics class that is the only way you are evaluated.

ADAM: Yeah. it shows the importance of math in physics. Which, its the basis of what we do and how we prove things, but on a test having only math problems is kind of...mentally tolling. By the end of the test, you start making mistakes that you wouldnt normally make. And form me at least, Im a little bit slower at working through stuff, because I enjoy taking my time and if I rush I make more mistakes. Im the same way. So, if I'm rushed on a test, then I dont do as well on the math part, but if Im explaining how things are...like in my Modern I class, Dr. Thoms would have us explain ...have short answer and math questions. So that was a really good encompassing thing. So, you thought his tests were really strong? I thought his test were really, really good. I hate multiple choice (MC), it sucks, its confusing, because it requires you to read about it more and think about picking the right answer instead or recalling from memory what the right answer is. I feel if you can recall it from memory its a little stronger. And when you're making MC questions the teacher is always like Im giving them the answer in this...so they word the question differently than they would have. Sometimes it makes it more confusing, to find out what they really want...are asking of you. Sometimes you read it three times and you still don't even know what they are trying to ask...just because they feel like they have to do that because theyre giving you the answer.

CO: Another evaluation thing I have here is one-on-one conversations with the instructor. What do you think about that as a means of evaluation?

ADAM: You mean like an oral test? Kinda...for example DESCRIBE ORAL EXAM IN SPANISH COURSE Its definitely very important for a language class, but again. You still are going to have to converse and be able to convey ideas with other physicists in a physics research job. So, definitely think itd be a new interesting twist on being tested in physics and math, because typically people dont think that would be a valid way. Maybe the first time do it youd be nervous, but implemented at a younger age, then it would be pretty...I think that would be a good thing.

CO: So if that was the evaluation for QM, how would you feel about that?

ADAM: I would feel nervous at first. but it would motivate me to know what Im talking about, because if Im going to go talk to the person whos been standing up there teaching, I dont want to give the impression that I wasnt listening and you know...daydreaming in class, not trying and kind of not make myself sound like I dont care. That would be very interesting to see how that would work out. I would support as many different ways of testing as you can. Because all students arent as good at different things. Maybe multiple oral presentations would be better, because the first one, you know...youd probably start off rocky, but by the time you get to the fifth one, its more relaxed and just tell me what you think this is...Hmmm...I never thought of that. More short ones would probably be better...if the instructor has enough time. I like homework and presentations, and tst are alright. I think testa are my least favorite because there is so much emphasis and weight put on that one test that if you mess that up, then your whole grade is ...you know.

CO: Let me ask you this...if you could choose between having equally spaced out homework assignments all through the semester and a single final exam, or the same homework schedule spaced out, and a midterm and a final. Would you choose one final at the end or the midterm and the final situation?

ADAM: I would choose more test, because thats again, a lot of weight on one test and people mess up...Its natural. Especially when they're being tested. You go take the test, and then you mess up one thing and look at it and youre so disappointed in yourself, that you will not make that mistake again. You know what I mean? Definitely

When I took Differential Equations the teacher had three tests and a final and your grade...if you got an A on the three tests then you didnt have to take the final...which is reasonable. I had like a B, then he said that if you show that you went back and you knew the knowledge that you previously missed on the final ...that you increased what you knew, then the final would be weighted more that the rest of tests, which I also believe is a good way to do things. Because the whole point of the class is to learn, not to punish you for messing up on the first test. Cause I know I got a C, a B, and then an A, and on the final I got an A, so then I got an A in the class. Excellent So, it didnt hurt me too much that I got a C on that first test, because they didnt do any homework in that class, so it was all tests.

CO: Is there anything youd like to convey to me about QM that we havent covered yet? Do you have any topics...is there anything you are hoping to see in the class?

ADAM: Um...I really am excited to take the class, because I dont know anything about it really. I know that theres particles and theyre doing stuff, and different particles hold the different forces [?inside matter?] and they behave like waves and particles and there a bunch of energy flowing around.

CO: Oh, thats something I was going to ask you...if you were to describe anatom to somebody, how would you describe it...in terms of the components, how is is built?

ADAM: Like a densely packed center where the mass is, and every picture is of little balls stuck together but I feel like that...its not a rigid system...as rigid as those pictures convey. the cloud of electrons around it. The most interesting part of the atom to me is that most of it is empty space, or considered to be empty space, which is valid for a lot of the experiments that have been done. I cant understand...the forces must me so strong to have none of that be expressed in larger physical objects...you know, just start passing through stuff.

CO: I think...yeah...I think youll really enjoy QM

ADAM: Probably, Im taking it as an elective. So, are you a physics major? Its not necessarily required in the standard program.But youre a physics major taking QM? Yeah.

CO: Do you have a concentrations within Physics?

ADAM: Yeah. I was doing Biophysics, but Ive been taking biology and chemistry classes. I was originally pre-Med. I had a conversation with a few instructors and they were like Oh, well physics is like what gives people the understanding for all the other science topics. Well, if Im gonna fully understand everything I might as well start at the bottom and work my way up.

CO: Do you hope that theres anything in this class thats related to work you are doing in the lab? Do you think thats a possibility?

ADAM: Um...I dunno. Theyre pretty big biological systems. So, it might not be pertinent. I dont think so...maybe though in E&M because Im also very interested in electronics and technology. Im doing the research because I enjoy it, but its also an internship thing, where Im seeing how much I like research and that area of science. There are so many to pick from, you just need to start jumping in and see if you like it.

CO: Do you know anything about the guy whos teaching QM this semester?

ADAM: No. A lot of people like to look up their professors and stuff before and get the easy professors, but theres only one class offered in physics classes so I just sign up...half the time the instructor isnt even listed and when you are signing up for the class because itll just say staff or something and itll show up later.

CO: Okay, last question, because I have a vested interest in QM, are you planning on taking any other courses related to QM in the department, like Nuclear and Particle?

ADAM: Um...maybe. Im almost done, this is my senior year, so I have twenty-seven hours left to compete, so...next semester Ill be taking like whatever I have left I guess. Classical Mechanics I know I have to take, and then other than that I have 4 elective hours. Im going to try to do some directed readings from the lab and just work in the lab and try to get hours for that instead of taking more classes.

CO: When you finish your Bachelors Degree, are you planning on sticking around in academia...are you planning on getting a higher degree or ...?

ADAM: Possibly, my plan right now is to go out and try to get more experience to try to see what exactly I want to do. Okay. Ive done the research all summer, so I know what thats like now, but I cant make a decision if I dont know what other stuff is like. So, you are looking at industry and things like that? Yeah. I definitely enjoy learning, but I believe that you can learn on your own. Sure. So I dont have to be in school for the rest of my life. [snicker.]

B.2 Bill

CO: Okay, let me start with some of these topical questions. If you were to have to give someone a elevator, or a two-minute response to What is Quantum Mechanics (QM)? How would you respond to that question?

BILL: Id probably say that its the study of atomic particles. I guess that would be the simplest way. Bear in mind, there are no right or wrong answers...were just interested in what you have to say. Id say its the study of things that are smaller than were used to dealing with. Sure.

CO: What do you expect to learn this coming semester in 4810?

BILL: Oooh...I expect to learn...I just expect to be able to apply all the mathematics Ive been learning, Im actually not a physics major...Im just a math major. I only ever took physics courses because I wanted to take quantum [PHYS 4810] just before Im done with my undergraduate just cause I thought itd be cool and everyone talks about it like its magic, so I should learn it. Heh...definitely.

CO: So, you not real familiar with...do have any expectations of the topics you are going to cover in that class.

BILL: I know like um...Im just more familiar with the math, the Hilbert spaces and stuff. How to calculate inner products and stuff. Im expecting to apply that is a more physical manner, but I mean... I dunno about specific topics. Like uncertainty or something like that? Yeah. I mean... I already learned all that stuff, so Im not really learning an[???] unknown.

CO: Maybe a better way to do this is to jump into your physics prep...so you've taken Modern Physics? Yeah. One and two. And theres the Advanced Lab...have you taken that as well?

BILL: Yeah, I took the Advanced Lab. Okay...cool.

CO: What about Classical Mechanics (CM) [PHYS 4600] and E&M [PHYS 4700]?

BILL: Nope. I took Stat. and Therm (S&T). [PHYS 3850] and then Im not going to be able to take E&M or CM before I graduate. Okay.

CO: So, in Modern Physics, could you tell me what kind of stuff you covered in Modern Physics?

BILL: Yeah. We started with kinda going into...we learned about inner products and how to calculate probabilities and how to normalize wave functions and such. Went over various tpes of wave functions like particles in boxes and one dimensional wave functions. I imagine that 4810 is going to be way harder than that, but I guess thats [???]

CO: Okay, did you guys talk about some of the historical aspects, what brought everybody to QM?

BILL: Id say that was actually the majority of what we focused on in Modern Physics I...was the history behind it and to a certain extent, Modern Physics II as well. Id say Modern Physics II helped very much too, because we had to do a research project and one of the projects was on quantum computers... and that kinda helped me understand the kinds of bra and ket notation. Which I think was probably the most helpful, because I learned how to manipulate matrices because I took Linear I and II [MATH 3445 & 4435]. So, I know how to do all that I just didn't know how to translate it into the language of QM. I think doing that particular project helped in Modern II

CO: So you took Linear Algebra I before you took Modern II, is that correct?

BILL: I took Intro to Linear Algebra when I took...the same semester I took Modern I and then I took Linear Algebra when I took Modern II. Gotcha. It seems that those would go together really well. Yeah. definitely worked well.

CO: So, you took all the Moderns and the Advanced Lab, is there a part of physics where you feel like you are the strongest?Are you most comfortable with a certain topic within physics?

BILL: I only took S&T. I feel like I was really comfortable with that. I feel like I was a little more comfortable. I got a B+...so did a lot of people I dont know what the average grade was. Sure. Who knows.

CO: What did they cover in S&T?

BILL: Just like...um...Gibbs Cannonological [sic] Distribution and Bose-Einstein Condensate, how to calculate ensembles of particles and then...Maxwells identities the differential identities...how they are all related and how to calculate things with the methods of Jacobians and stuff.

CO: How would you rate your grounding in each of these three topics. So, like in CM how would you rate you grounding? Do you think its something you dont have a problem with wyo ld you be nervous?

BILL: Id be a little nervous if I wanted to take the Physics GRE, because those two classes are not an option for me if I am going to graduate on time anymore. Id say E&M seems pretty basic. I can understand the math behind it really well, thats kinda like ninety percent of the work...so.

And as far as CM, I think the calculus invariance...I didnt take that class, I know about what that is, how its supposed to make it a lot easier, but just never having taken the class...Im never gonna get that information.

CO: Have you ever heard of a Hamiltonian?

BILL: Yeah. The operator? Yeah.

CO: Could you give me a definition of it?

BILL: The Hamiltonian is the .. I think I might be wrong on this, but dont you just put it in between the conjugate of the wave function, like when you take the inner product you just put the Hamiltonian in the middle. That is definitely the Hamiltonian Operator And its like different if you are doing it in momentum space its like dp over h bar squared.

CO: So you seem pretty conversant with some of this. Have you been preparing for QM or are you just working off what you know from Modern?

BILL: Yeah...no. I thought I was gonna prepare for QM, but Im just kinda going off what...I mean, Ive been kinda preparing. I always try to stay one step ahead of my classes, but I didnt get the QM book til much later...a lot of this is from Modern though. Okay...Excellent.

CO: So, CM you havent had, E&M you havent had, but Modern youve taken here, with Linear Algebra...Awesome. What kind of physics background do you think expects of you? Do you think he expects you to have taken all these classes or some of them, or....

BILL: You know. It just kinda occurred to me as were doing this interview, that theres gonna be problems that are most likely going to be solved classically in class...with CM and Im probably gonna be at a disadvantage because I didnt take CM, but yeah. I guess I didnt think Id have to take those classes first. As far as the math goes, I think Ill have an advantage that much cause

CO: Sure, but what do you think the...if you put yourself in the professors position, what do you think they would expect of students coming in?

BILL: Well, I guess from his point of view, I would expect that they knew CM, E&M, cause thats pretty important when you are trying to figure out the [?Matches?] and stuff.

CO: Sorry, Im not trying to freak you out...No no, Im not freaked out. In terms of your math prep, youve taken linear algebra, so youve dealt with matrices and determinants and... how comfortable would you say you are finding eigenvalues and stuff like that?

BILL: Oh. Pfft. [Gestures Okay hand signal] Okay. No sweat. I got that down pat.

CO: In terms of differential equations, what courses have you taken? ODE? PDE?

BILL: Im in PDE now...I mean ODE. That was the majority of what I did on my own during the summer. When I wasnt taking classes, was I taught myself the stuff from PDE. Excellent. I think that will benefit you greatly.

CO: In terms of integration and trigonometry...the basics, you feel pretty comfortable with your background in that?

BILL: Yeah, I got that.

CO: When I say trig...I mean coming up with the double and half angle identities from Yeah, I got that down. [Laughter] Where would you say your greatest strength lies in mathematics? Is there one particular place where you think you really shine.

BILL: Doing proofs. Proving things. Cause thats something that as a math student that has been drilled into my head. I can imagine.

CO: What is your familiarity with Fourier Series? Is it something youve seen before...worked with?

BILL: Ive never used them, but i mean it seems pretty simple. You move from a ...like just a transformation of the spaces to make something that is very erratically oscillating into something that is more manageable.

CO: Sure, yeah. Let me ask you this. What kind of mathematics background do you think the instructor will expect of you?

BILL: Um...Im expecting him to at least want us to have taken partial Differential Equations, and thats why I kinda studied that. PDEs and kinda flipping through some quantum books before I know that a lot of the stuff that is important is in Linear. Okay. Like about vector spaces.

CO: So, Linear and PDEs? Yeah. Okay. Are those the two big ones that stick out in your mind? Yeah, definitely. Do you think...you say youve been flipping through books...so you have some exposure to what QM is? Yeah Is there stuff youve seen in the text that youre pretty confident youll see in the class?

BILL: Yeah. Definitely. Could you name any of those things that you think you are gonna see? Yeah, I guess I could. I know Im gonna see a lot of inner products, and some outer products, which are the inner products ugly cousin...um. but like potential wells, right? Odds are good hes gonna make you look at potential wells. Do you think theres any other specific QM topics you are gonna hit on? ....I would say that one think we would probably hit on would be the [Heisenbergs] Uncertainty Principle (HEP). I understand how you get that how you use the operators...kind of like an inner product of the standard deviation then multiply the two to get the HEP.

CO: Okay, so that being said, if somebody asked you what an atom looks like, how would you respond to that?

BILL: Id say that it was an incredibly dense, tiny neutron [sic] with an electron cloud around it Okay. with the electron spinning with angular momentum... in two directions at times.[Rolls Eyes]

CO: Excellent okay. What can you tell me about wave functions? Have you heard someone throw around the term wave function? Yeah definitely. What is the wave function?

BILL: A wave function is like... a WAVE function, in a more general sense, the function that describes an oscillating wave Yes. ...in QM, it's usually standing waves and electron travels around in the electron cloud, but really represents the probability of the particle be at that particular location whether you're measuring... the wave function in quantum physics, is the wave of probability that's around a particle that measures the probability of finding it close to observable, measurable quantity. Okay, yeah.

CO: So I'm just gonna start rapid firing questions here... if I asked you what the dimensions were of a given wave function would you be able to tell me what the dimensions are? The dimensions? yeah.

BILL: Yeah, I guess. Are we talking about the bases of the space? I mean if I gave you the wave function of electron, just a free electron in free space, that wave function as the dimensionality associated with it. Yeah, I know. you, for instance, you can have like wave function describing a particle in one dimension or two or three or possibly more.

CO: If you have a one-dimensional wave function, off the top your head, could you say the units for the one-dimensional wave function or something like right now?

BILL: Yeah yeah I could probably do that Okay, if you feel inclined to show me... I'm just wondering if off the top your head you knew the dimensions of the wave function. You know, if you are measuring distance it was measured in meters. Yeah... I mean, I don't think I can do that it. It makes sense ...but it's the kind of thing you have to sit down and go to work through. Yeah, if I saw the equation I could look at the parts ideally, because there's radial and... more

CO: You mentioned normalizing when functions earlier are you familiar with the method for how to do that? Yes.

BILL: Do you want me to say? Yes, sure... if you're going to normalize a wave function, how would you do it? You take the indefinite integral with the conjugate of the function times the function... well okay, that's in my complex Hilbert space that has the polynomial basis or function basis. there's also other basis for the space so you take.Well considering it's it's... The complex conjugate of the vector time the vector then the integral of all that is equal to one. So whatever that indefinite integral equals, divide one by it then multiple by that function and it will also be normalized. Yeah that's exactly right. Thank you.

CO: Are there any requirements that you know for a wave function to exist in free space?

BILL: No. I dont know that. Is there an answer to that?

CO: One of things that were interested in seeing is if people can talk about continuity of, continuity of the function. Well, yeah obviously. That it exists everywhere. Hold on one second...

STOP/START RECORDING FOR INTERRUPTION

BILL: Wait, so it would need to like... if it was a one-dimensional wave function it would need to be continuous everywhere, even if it was an infinite potential well?

CO: Well for an infinite potential for a well you would... yes it needs to be continuous everywhere...er, at the interfaces...at the boundaries... exactly. Where the boundaries are. thats the type of thing were thinking about here.

CO: If I told you that the wave function is equal to zero, how would you interpret that?

BILL: The wave function equals zero? I would say that I would say that it was at a boundary of potential. okay.

CO: Thats fine...and for some of these questions, I have no idea is an acceptable answer. It's just sort of some topical stuff we're trying to get some peoples perspective on.

BILL: Is that the right answer?

CO: It's more of a representation of what you think equation means that anything else. I mean... you can read more than one way. One way to look at it is like you said this complex conjugate of that particle...the integral of that function being equal to one, is sort of the object existing somewhere in the space that you are measuring. If that was set equal to zero, obviously that particle would not existent in the space that you are measuring.

CO: Can you tell me what you know about HEP?

BILL: Yeah Shoot. This is one thing, I wish I could go back to that question about things expected to learn, because I want to learn more about this. Because I'm a little curious to why... cause youve go the change in X times the change in momentum is less than or equal to H-bar over two. So I kind of have a real ignorant idea of what this means... something about the moment space not being the same as the position so they have this natural distinction. It's one of the things I want to learn.

CO: Sure, that youre taking the class.

BILL: And then of course there's like other things that have to do with uncertainty, like um... I forget all them, but.

CO: It's not just momentum and space. Yes it's also like some other ones that I forget. Energy and time is a big one. Yeah. Okay, let me ask you this... this is kind of a deeper question, do you know why HEP exists? because said because the moment of space and real three-space and they don't quite jive but...

BILL: Isn't it just like a mathematical fact...That's definitely one would look at it. They have to be that way because, its like the standard deviation of the two operators... the first Hamiltonian of space taken I dont know if its alright to say, like, the inner product with that. Like you put that in there, so you have X in the brackets minus X squared the brackets both of those squared... square root of that. Then multiply that by the momentum...varaince and that's where it comes from mathematically. I imagine that it's like the variant between those two distinct spaces. That's my best guess no one's ever really been able to fully explain it to me.

CO: Theres sort of different deep scientific way of looking at why does this exist and there's also that rigorous mathematical perspective as to why it exists, too. So there's more than one way to look at that.

CO: When you talk about particle-wave duality, what can you tell me about wave-particle duality?

BILL: Oh, Well. That's an easy one. Particles are both waves and particles. Okay. I know that there's been some crude experiments done where people use and electron microscopes and look at hoels and observe kinda waviness inside there, but I'm not sure if it's ever been observed. Doesn't only apply to electrons or... No, we all have a DeBroglie wavelength...were just too big to notice it exists.

CO: So, the standard sort of situation is that you have an electronic gun firing at a double slit. If somebody asked you what the possible outcomes that could happen there could you describe for them?

BILL: Yeah, well probably... well because of particle wave duality there will both be a diffraction pattern but if you look at the other way, there will be a particle shoot through one or the other... because the electrons hate us. [Laughter]

CO: They are strange things. You should ask the instructor about quantum entanglement or spooky action at a distance as it is called. Sometimes they come up with some very interesting names for these things. Have you heard of the Pauli Exclusion Principle (PEP)?

BILL: Yeah I have. In what capacity? I forget it's kind of slipped my memory.

CO: Let me try to jog, jog your memory because usually PEP comes into play in chemistry when you're filling electron orbitals. You have to ensure that...Oh yeah!

BILL: Okay, yeah. I'm sorry two Fermions cannot occupy the same state. I don't know why...

CO: Yeah it's okay. There are a lot of times when... they don't focus on teaching us the names of these guys. they just make sure you have the idea and then move on. So I can understand, don't sweat it. This is another one where I want to ask do you know why that exists that way?

BILL: Why... It's two fermions that cant right? Correct. Because bosons will condensate. Two fermions cant occupy the same state because they're spins are ... if theres two fermions in the same state, their spins would interact and they would cease to be fermions Okay. I think... Is that right?

CO: Ill tell you what, we'll go into it after this... let me just... I'm in the home stretch here, but I'm when you observe something the wave function that describes the possible outcomes collapses into one observable. There are folks who say that allows people to send messages faster than the speed of light. What do you think about that?

BILL: Originally, I thought that that was kind of nutty, but I also think now that, there, it might be true. Wasn't there some sort of thought experiment by Einstein... the kind of the Eisenstein Rosen experiment where they thought about information traveling faster than the speed of light and they kind of like demonstrated that is true or something...I don't know

CO: I need to go back and look at that...to be perfectly honest with you.

BILL: It's like a famous presentation...a famous thought experiment by Einstein and I think that maybe true...I don't know. Okay.

CO: Okay this last section, I just like to talk to you about how you're evaluated and this is sort of in general and all of your classes. If you could choose...Let me go through this, Im going to mention some different ways of being evaluated on your knowledge, and let me know what you think about them as we go. So let's start with multiple-choice questions, are you cool with them? opposed to them?

BILL: I'm cool with them. [Smiles] Well honestly... if you took an upper-division course like this somebody gave you a multiple-choice exam... No I wouldnt like it. Is there any reason specifically? I just expect like... it's just not what I'm expecting if I was if I to get this far in physics and I got a multiple-choice thing, Id be like Oh, I could just guess this. So I don't know, maybe it's just me.

CO: Sure, thats fine. What about like short answer type questions, like one or two sentence short answers about QM?

BILL: I guess things are alright... I expect there to be some of those because we did a lot of them in modern physics, but I'm not sure.

CO: Then there is the traditional written problem. Yeah, that's what I expect. That's what you expect...I know other upper-division courses do like, class presentations. Have you ever been in that situation?

BILL: Yeah we did them in modern two, and I learned a lot. So, good experience overall? Yeah I liked that a lot. It was a good experience, but that was also because I chose to punish myself and pick the topic that was as hard as possible on the list of topics. I mean it was rewarding because I decided to do this one, but some of the topics were on Quasar's and stuff and it just would've been kind of simple, but the one I had to do was really tough and helped me figure out the language of bras.. er bras and kets are.

CO: Excellent. Last one, there folks who do like one on one conversations with...like you go schedule time with the instructor and talk to them about what you learned in the course. What you think about doing that?

BILL: Oh, I think that would be great. Yeah? Even though...yeah I think that would be great Have you ever had the situation happen? No, but it sounds cool, though.

CO: I've only experienced this myself in the language course and what you do is you would every semester go see the instructor instead of scheduling a three hour exam they break it up into amount of bunch of 15 minute intervals and you can talk for 15 minutes [EXPLAIN SPANISH CLASS FORMAT].

BILL: Yeah, I mean that, thats a good thing. Especially if you want to go into science. Being able to articulate things in like scientific jargon is really important.

CO: Sure, having gone through all that, If you, if you could choose the way you were evaluated from any combination of the stuff we talked about, what would you prefer? Talking and written exams... traditional problems. Okay. I think I'll be really good combination.

CO: Is there anything that you're excited about?

BILL: I'm excited about learning I am excited to learn about the HEP. I really want to figure out what the difference between momentum space is and space space is...position space.

B.3 Clark

CO: Okay I'm just going to get started the way this is going to what I'm going to ask you about our sort of some topics within quantum mechanics (QM) and then about your physics prep... what the courses you've taken to get to this point, and then the math courses and then talk a little bit about evaluation. Okay. Actually so I might flip that around...just because I think will help the conversation. Yeah. So, starting with evaluation, basically I'd like to ask you about a couple different types of evaluation and you give me your impression of how useful you think they are, starting with with, like multiple-choice questions.

CLARK: Okay. How useful multiple-choice questions are? Yeah In what terms? Of understanding the material?

CO: In terms of how good do you think it is at evaluating what you know. Especially, specifically in QM.

CLARK: I think it's proper. You can use it to evaluate how much someone knows but at the same time, it only shows...with class like physics. Normally, a lot of times, you have to solve issues or solve the situation, basically...I don't want to say problem, but it's a problem. So I'm figuring out the situation and I don't think a multiple-choice question can necessarily do that for you. So you don't really get to solve the situation as a physicist. Sure. I think that multiple-choice questions...I mean, they're adequate. I think they are good especially if you use them for a quiz to help reboot memory on certain things, like terminology. So they're good for terminology and other stuff like that, but asked her when you're solving for situations then they're not as useful... but....I do find usefulness throughout the with the class. Okay. Perfect answer.

CO: What about like short answer written answer type questions?

CLARK: Short answers...um...I believe short answers would be good. I mean, I think they would work well. Part of me feels that is just they're just like a brief summary, you're just giving a brief summary. So it's not necessarily...I don't know, I'd rather...I like short answers because they're easy to answer for grade purposes...minus the grade idea, I think you should be able to give more detail and more in depth. So short answers for an overview...if you are asking me to give an overview...

CO: Sure I see. And a lot of this I'm thinking about in the context of, like, if you saw this on exam in the class you are taking, would you think Well, this is a good way to check, test my knowledge? or not.

CLARK: Yeah. That's what I mean. I don't necessarily believe it's the best way to test your knowledge...maybe to test my knowledge to give me a summary to describe what was going on. That's the best way, but a classic QM, I know there's more in depth on the details of what's going on at the quantum level, and I don't over short answer is necessarily the best to get the detailed description of what's going on.

CO: What about like traditional written problems the kind of stuff you have to solve... Mathematically? Exactly.

CLARK: I believe that those are...um...though don't like them because they are too cumbersome...sometimes. They're perfect for the class, though. They help to be able to understand what's going on on the quantum level. So, I mean, those type of answers...er...questions give more in-depth detail. It helps you to figure out what's going on, because you're doing more than just solving. Youre actually trying to figure out what's going on, really. I think what would be good too is if you could relate those numbers to actually what's happening. So being able to show the mathematical aspect which solved also has a meaning in real life.

CO: So, maybe like a combination of different types of...

CLARK: Yeah, if you have a combination of both by showing what exactly this numbers describing or if it was always, like if we do the mathematical sense and always give a description of how the mathematical relates to the real world, then that would help to better understand quantum, definitely

CO: I know some classes do like presentations at the end of the semester. What do you think about that in the context of QM?

CLARK: Well I'm just using the knowledge that I know about QM, since QM is a good class...it's always recommended for grad school. So I believe that those presentations are useful, because if you're going to grad school, especially if youre going to get your Ph.D. and do research. That's exactly what you're going to be doing. As far as... that I really do I think are useful. Especially to be creative, you can be more creative with that, and design the presentation in a manner that you see fit and how you want to present it. So I mean it's useful and I think we've actually gained a lot of knowledge on it. So part of me thinks that it's...I don't necessarily as important within the class aspects. I believe that they serve a purpose, especially for grad school and can be fun and creative. You can make it fun and creative, but another part of me is still just figuring... I don't know...if it still is important for the class. Especially people who are just taking a class to be interested in it or don't want to go to grad school after it or don't want to actually do any research. Sure. That makes sense.

CO: Okay so the last thing is sort of the other extreme. There are some courses, very rarely in physics, where you do one-on-one conversations with the instructor. I know Ive done this in language courses where you would schedule, instead of giving you three hour exam block, they chop it into 15 minute chunks and everyone comes in and talks to the instructor for 15 minutes. Do you think that that kind of evaluation would be appropriate or helpful in QM?

CLARK: Absolutely. Absolutely. I think that by having that one-on-one conversation with the professor, it gives the opportunity for the student to be able to clarify anything they don't understand. Because I think, especially during office hours, a lot of misunderstandings would be figured out during office hours when you talk to the professor in the class.

CO: Even - What if this was like an evaluation, like you're going to go in and talk to Dr. so-and-so and you sit down with the instructor and he says Well what did you learn this semester?

CLARK: I think that it would still be important, because it helps the professor to get an insight on the way understanding how the person thinks. Because each person has a different way of thinking, so they now understand the material the same way, so it allows the professor actually look at person and see how they are interpreting material or what they're hearing or saying. To me, it really allows you to build like conversation between the professor and student so that they can actually better understand...to better be on the same page and understand the material. I mean I would love that so much better if professors did that because they would actually understand how the student thinks the students understand the professor. I think that grades would actually improve dramatically.

CO: I think, I think that's kind, of kind of part of what I want to do here. So I'm glad you feel that way. That's excellent, so that's all I have based on evaluation stuff, thank you. I'm going to jump into talking about physics. So you've taken modern physics here? Correct. Have you taken one and two? Ive take in modern physics one not two. Okay. Have you taken the advanced lab?

CLARK: I've taken advanced physics lab, yes. Okay, cool.

CO: Have you taken classical mechanics(CM)? No, I have not taken CM or... E&M? E&M...and I'm doing that this semester So you're taking him in conjunction with quantum? Yes in like 30 minutes. Gotcha...I guess we need to make sure things get squared away.

CO: So in terms of modern physics, do you think it prepared you adequately... the best way to ask this is... what material do you remember best from modern physics? What did you get out of it the most? If asked you what Modern Physics was about, what would you say out of it

CLARK: Had to explain that to someone recently, because I have residents that I asked their science majors and they're talking about all the Physics courses. Modern physics to be honest, all the mathematical portion Im just gonna be honest I really don't remember too much about it, but I gained a better understanding of how the quantum world works. So kind of the build up and history of finding out electron and all the history leading up to our current model of how we believe the quantum world works. So that's what I mostly out of it. Even though I really, to be honest, the specific understanding of how everything works. I have a general understanding and abroad overview of how everything worked.

CO: It might be that if you saw something that would jog your memory from it you can say Oh yeah, I remember seeing that in modern.

CLARK: Yeah, I can probably remember seeing something, like maybe if I see the wave equation Id be like Yeah, I remember looking at that before. But to be honest, Id have to practice so much more maybe I have to practice more problems for I actually...

CO: Well, that's that's how the expert mind is supposed to be. You have this familiarity and you know where to find an answer when you need it.

CLARK: I know what area to look into. Nobody knows the answer to everything, so I understand completely.

CO: You haven't taken CM. Have you ever someone talk about the Hamiltonian? No, I have not. How about the LaGrangian?

CLARK: I've heard people talk about it, but I don't know what it refers to, to be honest.

CO: That's fine. No problem, and have you seen the wave equation in the past?

CLARK: Yes, Ive seen it in the past and even like modern physics class I've seen the wave equation before. Okay excellent.

CO: Is there... we kind of look at physics in terms of classical, E&M and quantum and maybe stat. Have you taken stat here? I haven't yet, Im taking it next semester. Okay, Cool. Would you say that there is an area that you feel most comfortable in?

CLARK: Is there an area...Ummm and no I don't feel comfortable in any area is an acceptable answer I understand to be honest too I feel comfortable in any area... no not quite [Laughter] but I'm not going to deter myself to any area so Im still gonna try my best at it, but do I feel that I'm necessarily prepared? No, I think have a lot of studying a lot of still things I just don't quite understand yet and I mean that comes with still just try to figure out things in physics and still maybe some questions I should have asked that I haven't asked. So there's still a lot of things that has to be figured out.

CO: Let me ask you this, what do you think the instructor expects you to have seen before you come into the class?

CLARK: In quantum? I feel like the instructor expects me to know like... pretty much everything. It's impossible to know everything about the quantum world and I'm gonna come in and be like Well, in reality I don't know everything about the quantum world...well I guess we need to start all over from scratch. [Laughter] Time take the drawing board black a few notches. Yeah I just feel like they expect... it's going to be expected that we know like...We have to know so much this really just comes from speaking to other students who've actually taken the class and they're just like You have to make sure that you know this, know this, know this, know this, you're going to go over this within the first week and then that's it, and you know when you hear stuff like that youre like I have no idea even if someone says that from this class I'm like No not at all. [Laughter] So I'm expecting that sometimes you feel you have to know so much already coming to class. That's why it seems, like, it's really intimidating in a way and at the same time... the same time...well...I understand.

CO: What is your math background like? Have you taken ordinary differential equations(ODEs)?

CLARK: Yes I've taken ODEs and vector calculus as well.

CO: Have you taken linear algebra yet?

CLARK: And linear algebra, though linear algebra was tough.

CO: Of those classes, which one do you think you felt the best about?

CLARK: Vector calculus, actually. That's actually the one I did the best in, and to be honest, it's one of the ones, even though I don't remember everything about the class, I still found it more interesting from all my other classes I'm taking. Okay. So actually, that's actually the class I grasp more material than the other classes, because to me, ODEs was just... it was alright, but Did you take it pretty recently? Yeah. I took it last semester, Spring semester, but it wasn't as interesting, in my opinion, but vector calculus for me was more interesting. Concept-wise was... thats why when I am taking E & M, I'm thinking it should be, shouldn't be as bad.

CO: So in terms of matrices, working with matrices, would you say you feel pretty comfortable with like finding determinants and things like that? Do you think you could if you had to?

CLARK: I could, probably could, if I had to. I'm not gonna say that itll be like [Snap fingers]. I'm not gonna ask you to get up and on the board to do the right here. Yeah, exactly you see we can come back tomorrow. We will see how things go...

CO: Have you taken PDE's here? I am going to be taking that class this semester. So you're taking okay PDEs this semester, cool. Have you ever seen a Fourier series?

CLARK: No ,not I can recall. I've heard of people actually Fourier transforms in the SPS kind of actually writing them out but I've never actually paid attention to it because I just never found it at the time so that maybe maybe it wasn't as relevant and actually I had to be focusing on something else at the time so...[Laughter].

CO: I've got to ask this. So how do you feel that your ability to integrate into deal with trigonometry?

CLARK: Trigonometry, I feel comfortable actually, to be honest, trigonometry...I don't remember all the trig functions, but to be honest trigonometry doesn't... it used to phase me like in Calc two be used to phase me a lot. Now trigonometry is not that bad, integrating is not either I feel so much more comfortable actually. After taking vector calculus, it doesn't bother me as much, the integrating, as much. So integrating is not as bad, integrating, derivatives, all that is not as bad. Its just when I apply the physics to [something] [Laughter]. Well, we'll see.

CO: Of all the stuff we talked about, what do you think do you think the instructor... what do you think he's a value the most out of these kinds of topics in terms of what things you should know for QM?

CLARK: What he's going to value the most? Probably, the best part I feel like the mathematics Is, is there specific stuff within the math? I'm not sure I'm not entirely sure, because I'm not entirely sure what kind of mathematics goes into solving for QM... solving the quantum level. I believe it's a lot of Integration, because I know that a lot of integration was used in modern physics to get to the equations we use for the formula of light. So I just believe really a lot of integration, a lot of derivatives...Expect to be [something] but I hope this... that I hope the professor will be willing to go to the material explain it with clarity, so that everyone can actually understand. We'll see how that works Or that I hope that a whole bunch of students will bombard professor with questions until he explains with clarity. [Laughter].

CO: When in doubt, dont be afraid to go to the instructor. Thats something that took me so long to learn myself. I would strongly recommend go ask questions to put you in front of the instructor don't get to know you as a person...

CLARK: Actually I think my new tactic is asking as many questions in classes as possible if I dont understand. In the past I was like I don't want to interrupt class at the same time, I don't want to fall behind, so...

CO: Okay that's pretty much it for the background. Im gonna ask you some of stuff about quantum mechanics. I have no idea is a perfectly acceptable answer. I'm just trying to gage where you stand. Yeah. Where everyone stands. So somebody asked you while you're taking elevator, What is QM? what kind of answer would you give them...Like somebody asked you Hey, what's QM? Could come up with a short answer?

CLARK: Yeah the understanding of the microscopic level that we cannot see, nor interact with... well no, that we cannot see, but we interact with everyday on a daily basis.

CO: What kind of, what do you think of the big topics are going to cover in this course in the coming semester?

CLARK: Maybe wave particle duality? I feel like that's going to be part of it, but a lot of it dealing with the atom...Different particles themselves, quarks, spin, like proton and I'm kind of going into understanding the inside of particles and also just like to tell how different atoms interact on the quantum level.

CO: Speaking of atoms, if somebody asked you what looks like, how would you describe it?

CLARK: How would I describe an atom? I would say... okay, it has a proton and a very tense core...it has protons and neutrons inside depending on what type of element it is and...Ummm...very very far away I guess atom was the size of a pea, at least 14 km away... You would see this giant cloud which we called electronic cloud electrons of the zooming around acting both as a wave and a particle. So [Laughter] the electronic itself would be like a cloud you wouldn't see particle, it would be a cloud just covering the entire surface around the dense nucleus. That is incredibly thorough. That is exactly how Id describe an atom.

CO: Have you ever heard of the Pauli Exclusion Principle(PEP)? I have heard of it, I do not remember it or recall it. Let me jog your memory, the PEP is used a lot in chemistry, when you're filling out electron orbitals and making sure that there are not two electrons of the same Spin in the same state. More familiar?

CLARK: Yes, that is very familiar. I remember learning about that. Did you ever encounter why that exists in your previous studies? Ummm...we did talk about it. I don't necessarily remember why electrons can... it has something to do well... I'm sure I don't know. we'll see what happens when you put two up spins together... what they do, to be honest, I no idea exactly why that is. You know and I guess theres a mathematical reason, but I think that's one of the kind examples that we may have went into and I just can't remember that as well. I kind of don't know, I just knew the two electrons couldnt exist in the same state, name-wise, it went out the window.

CO: That's okay. I think a lot of people, a lot of instructors don't emphasize who the person is. Theyre always focusing on the mathematics so that's understandable. How about Heisenberg's Uncertainty Principle(HUP)? That's out the window too. I have heard of it, but I don't remember what like, what it is.

CO: Not being able to know the position and momentum of an object at the same time with perfect precision?

CLARK: That sounds a little bit familiar, but I couldn't actually say where Ive heard it from.

CO: You mentioned wave particle duality (WPD) learning about that. You know, the standard situation is having electron or a photon gun shooting at a double slit... Yeah. Are you familiar with what the two types of results you can have in that situation are?

CLARK: You can have it coming out as a particle or as a wave. Which ever one you if you try to detect the particle, you'll see it as a particle, trying to detect a wave, youll see it as a wave. But I still dont understand why. I think that's the question, why? Why when you detect one way comes out this and when you get another it comes out that.

CO: I think that borders on the philosophical. You're familiar with what happens if you have to wave, if you are in fact looking for a wave, what youll see on the other side of the slit? You're familiar with that, right?

CLARK: You're looking for a wave the kind of dark, light, dark, light, it's a pattern for diffraction pattern. Yes, I do remember that correctly doing the experiments in physics two [2212] with a laser beam and double slit okay.

CO: The last thing I wanted to ask you about, how familiar are you with wave functions?

CLARK: That sounds familiar... I remember differential equations going over wave functions. So I remember actually... it's not like in differential equations that actually clarified some of the many questions of the mathematical part of the wave function, like me to understand it much better where comes from but I wont necessarily in detail, won't be able I won't remember exactly how to derive the wave function but I...

CO: Do you remember what it describes?

CLARK: The wave function... I remember it when Youre going to go over this in painstaking detail over the next couple of weeks so don't feel bad about it I remember it described the we were talking about in advance physics and modern physics. The wave function describing the I remember, described it because when you had to his imaginary number in the imaginary number two to south the real number and it's like two different waves going in phases crossing the real and imaginary plane and they cancel each other and it becomes... It's okay I'm trying to picture I'm just thinking about what you're saying that's all Well I remember in ODEs I remember it overlapped because that way function function that we went over in modern is just want to describe a certain situation and then there are other situations of when waves when you overdamping and underdamping.

CO: When you've picture a wave function, the picture something that's spread out over space or localized or in the area in your mind? How do you picture it?

CLARK: It's everywhere existing spread out in all space like a wave.

CO: I think they talk about normalizing wave functions in modern physics is that right? Do you remember parts?

CLARK: Sorry I just talking about it...I remember John understood it. He said, You have to normalize it. I turned around and I was like Okay, John. [Laughter]

CO: So what the wave function is, is a tough thing?

CLARK: Yeah exactly, I guess so. To my mind I have an idea of what the wave function will look like. Its Psi and, I remember Psi and Psi-star and they cancel out each other and create a real plane...or its two imaginaries that create a real plane.Yeah, there we go...and it turns into a negative number. I remember learning about that. I remember thinking Gosh, mathematically, this is really easy. [Laughter] Yeah, and I do remember we did apply the differential equations because that was one property of the wave functions, so...

CO: Alright this is kind of out there, but did you remember what the units are for wave function? Did you ever talk about the dimensions of a wave function? We did, but I know that in ODEs it didn't matter as much we are just solving for that mathematical property and with modern, I just... unit-wise. I don't remember. Okay. To be honest even when I solve for it in modern, I was thinking solve for the answers, but the unit-wise, I dunno. I didnt really understand what the units...

CO: So last thing Im interested in is, if somebody gave you a wave function and said Psi of x is equal to zero. What would that...what is your initial reaction to that. how would you interpret that? So, the wave function is equal to zero.

CLARK: The two imaginary waves cancel each other out to equal zero? [Laughter] Okay I just curious. People hear that and they think different things. Psi of x equal to zero, yeah, I just...I would think I forgot what it means, I remember it means maybe its something with odd or even wave functions. I know it goes along something like that. I dont necessarily remember exactly.

CO: Is there anything you're excited about seeing this coming semester particularly? People? People... okay. what a material in QM is everything youre dreading seeing? All the long functions? okay. [Laughter] honesty...okay.

CLARK: I just hope that the teachers thorough and understanding and definitely willing to communicate with the students.

B.4 Doris

CO: Alright I'm interested in starting off with some questions about a evaluations. Basically, I'm wondering what your thoughts are on different kinds of ways of evaluating what you know. So for example, if you saw this type of question in Quantum Mechanics [PHYS 4810] (QM), how effective do you think it would be. So like, if you had multiple-choice questions on an exam, how do you feel about that in QM?

DORIS: A multiple-choice question in QM? Or in general. What do you think about dealing with multiple-choice questions? and this is the in the sense of evaluating my knowledge? Well I do not think that multiple-choice questions are very good at evaluating what I know. I definitely like them sometimes, because they make tests easier and I have a better chance of getting the answer right, but yeah. Definitely in physics, it can be... if I were a teacher I would not do it.

CO: What about short written answers?

DORIS: Short written answers? I guess would depend on the question. Really. I was thinking sort of mostly in QM type situations.

CO: Yeah. Um...How about traditional written problems? That's the kind of thing that most people deal with in QM and that's sort of I guess what you would expect from this course. Yes, so basically where you have like a numerical answer at the end. Now if you had a short written answer that ask you to explain the numerical answer or explain how you got to the numerical answer... do you think that would help or hinder? You know?

DORIS: It might hinder my score a bit, but I think it would be... I think that would be helpful...better evaluate A better evaluation tool maybe? Yeah, because and I'm not sure how much you could actually do when you get to the upper level physics like this... plug and chug kind of stuff you really do have to have an understanding but just knowing that you're going to have to give a little extra explanation might be enough incentive to study and understand what the formulas and things better.

CO: Sure. That makes sense and I know of some of these upper-division courses do like class presentations at the end of the semester.

DORIS: Yeah. We did that in Modern [Physics] II [PHYS 3402] (MPII).

CO: Do you think that kind of thing would be applicable in QM? Like if you did something similar?

DORIS: Yeah, I actually think that would be really good. I enjoyed the MPII and I think a lot of alone I think of a lot of things in MPI and MPII being this QM in there, but it's just touching upon it pretty lightly and um...Yeah, I really enjoyed the presentations. Cool. So I thought that was a great...

CO: There's one other thing I've been talking about with people it's having one-on-one conversations with the instructor. Um...now usually I've seen this in the context of something like a language class. Where you schedule... instead of having a three hour exam you schedule a 20 minute blocks and the instructor an you have a conversation and you demonstrate your command of that language. Do you think that's the kind of thing that could be translated to a physics class? Where you go if you went and saw the instructor for 20 minutes or something and said...he said Well, what did you learn this semester?

DORIS: And this would be for a grade? It would be evaluated for a great. Yeah. I would say I don't think that that would be effective. Okay. Probably because I don't, I think it's, maybe would take bias out of the equation and intimidation Sure. That definitely might be a factor. Yeah, and especially... some of I think the physics professors, there is definite people they don't like in the class and you can be aware of that and I wouldn't want that to affect someone's score...you know, having a written exam you can challenge and looked over is very important. I can see that being beneficial for other departments, but I think...I think it would be a definite intimidation factor that would There's always a power dynamic between the instructor and student, definitely. Yeah, definitely. There's a lot of that in physics. So instructors can be very intimidating when you talk one-on-one with them.

CO: That took me forever to get over. [Laughter] Okay, so the other things I want to talk about basically are your physics prep. up to this point in the program and your math prep. up to this point in the program. Okay. and I just ask and I'll just asked you a couple of conceptual questions what you think right now at the moment. Oh okay. So in terms of you mentioned you took MPII, so I assume you took Modern [Physics] I [PHYS 3401] (MPI) and wanted to have you taken Classical Mechanics [PHYS] (CM)?

DORIS: I have not. I was...I had to drop it, unfortunately.

CO: And E and M [PHYS 4700] (E&M)?

DORIS: I'm taking that now.

CO: Did you take the advanced lab?

DORIS: I did. Cool.

CO: So you do you feel like you have a pretty strong background in terms of the modern physics?

DORIS: Yeah, I think that especially MPII, because Dr. Mani made it really hard. So we had to study like crazy for those tests. So I feel...I don't really know... about the time I get to QM and realize that Oh no I didn't learn as much about modern as I should have.

CO: The whole idea behind taking the classes that you're learning the material there too. Exactly. And one of the things I think is important for everyone in the program to realize is that you don't become an expert over the course of a of a one semester. It takes repetition and time and exposure.

DORIS: Exactly and MPI and MPII where that overview.

CO: That's why at the grad[uate] level you see QM three times.

DORIS: Right. That's understandable.

CO: Do you feel like like you have a strong suit in terms of modern or E&M or CM? Is there something you're more comfortable with and the others?

DORIS: Let's see. Well two of those I cant really speak for, because I haven't taken them, but So out of the three you're probably most comfortable with the modern material. Just because I haven't taken the other two. Have you ever heard of a LaGrangian? Yes. That's cool. Have you ever heard of a Hamiltonian? Yes. Awesome. Do you know to Hamiltonian is? No.

CO: Okay. Thats not bad. You definitely ...the Hamiltonian is key to Schroedingers Equation (SE) because it's a part of the potential that you're using in the SE. So it's definitely one of those key things.

DORIS: I think we brushed upon it in MPI maybe and I but I can't remember what it is.

CO: So, what do you think the professor is going to expect you have under your belt when you come in to QM?

DORIS: Probably...I'm thinking just the MPI and MPII.

CO: In terms of math, I've had some math classes too. Yeah. Do you think that there is a particular math that he's probably going to expect you have seen?

DORIS: I'm thinking probably...up to Partial Differential Equations [MATH] (PDEs) maybe, but I'm taking it at the same time.

CO: So you are taking PDEs right now? Right. Have you taken ordinary differential equations [] (ODEs) already? Yes. Cool. Do you feel pretty good about what you saw in there?

DORIS: Yeah. I made an A that class.

CO: Way to be. Have you taken Linear Algebra [MATH]?

DORIS: No I haven't I will take Intro. to Linear my last semester here. That's how it worked out.

CO: Hopefully what you see in QM will will help ease the transition into linear then. There's the little bit of that dealing with matrices and determinants and stuff like that.

DORIS: Yeah I hope that I'm not going to meet intro to linear for anything because it's an optional class.

CO: I think it's something that's been recommended by a couple of the faculty...for that exposure to working with matrices but have you seen Fourier series or Fourier transform?

DORIS: Yeah I've seen the Fourier series we did a little bit of that electronics [PHYS 3500].

CO: Awesome have you taken Stat and Therm [] (S&T)? No. Okay, no big deal and I'm obligated to ask this, but how do you feel about your ability to integrate and deal with trigonometry?

DORIS: Oh I feel good about that. Trig. identities? Trig. identities...Yeah does need a review. I always need to review those because I forget.

CO: Well the beautiful thing is once you've seen them once you've it always say I need to go back and refresh my memory...so that's fine, but I know that this course focuses on your ability to integrate by hand and that's one of the thing the instructor sort of pushes that you guys can do this. It's not beyond your capabilities so that's something that is...that the instructor values

DORIS: Well I think that that's good, because pushing to have stronger integration skills is key. It's kind of a big deal. I remember thinking it was a pain in the neck, so I sympathize. Integrals can be a pain in the neck, but the more that you know the more that you learn...the better I think you are.

CO: Okay, if you had to give somebody a quick answer or how would you describe QM in general?

DORIS: Quick answer for QM...I guess feel like a lot of what QM is going to deal with is like wave properties, matter waves basically Schrodinger's equation things like that. Stuff we brushed upon in MPII and potential wells and things like that and just really going into depth into that that's sort of what I expect from this course I'm not sure along the lines of whether or not I'm right about that.

CO: I know I can tell you that right now you'll see potential wells and you'll see perturbation theory at the very end of the semester Okay. and that sort of plays into some of this working with matrices, I know the instructor touches on spinnors...spin matrices and you'll deal with some radial wave functions, like for example, if you were dealing with a hydrogen atom or something like that. RIght. That kind of material is going to be in there closer to the end of the semester.

DORIS: Okay well maybe I should do a little... dabble in some matrices beforehand that's actually good advice.

CO: That's one of the reasons why I was hoping to get a bunch of people to come here and talk about these topics get sort of either motivate or help bridge the gap in some stuff that people might need to check out, so you guys can be awesomely prepared.

DORIS: I heard that quantum is really hard class, but if you work but getting an A is feasible, if you work hard. That's what Matt has told me.

CO: The trick in my mind is...I've asked all the faculty what they think, If they could give students one piece of advice what would it be? And move most of them are in agreement that is pretty much you should work every single day, and don't let it get too far out ahead of you or else you'll have this towering edifice of stuff you dont know. That's good advice pretty much for anything. Yes that something that applies everything.

CO: I'm just gonna ask you a handful topical questions here. In terms of conceptual stuff and then that's it. If you had to describe an atom to someone, how would you describe what an atom is?

DORIS: [Laughter] Probably a bunch of empty space. [Laughter] I would describe an atom as a...having a nucleus of particles protons and neutrons brought us a positive charge orbiting in quotation marks... are electrons much smaller electrons with the negative charge and I would probably emphasize the fact that it's very unlikely that they're actually orbiting around in little circles. We really have don't know quite what's happening we have a bunch of sort of probability distributions of where they can be found and I would also emphasize the fact that...this is one really interesting fact that I learned um... the amount of space that's in between that is so vast I watched the video and the example was if you had a tennis ball representing the nucleus the electron would be like a kilometer away. That's wild. I didnt even know that Just to put it in perspective. Because everybody tends to have this really weird view of atoms...that they're all these little hard balls and they're rotating perfectly nice little ...Planetary model. Yeah it is a planetary model.

CO: I've got to ask you that we've functions okay do you feel comfortable do you know what a wave function is?

DORIS: Yeah but I feel like that is definitely uncomfortable spot ...YOu know...because when you're going over that modern wanted to it's so weird. It's definitely a very weird phenomenon in the first place, that's fine. Did you do you guys deal with normalization when you were dealing with them in MPI? Yes, so basically it's making the probability to one. Yeah... cool.

CO: You wouldn't happen to know off the top of your head what kind of dimensions a wave function has do you? What kind of dimensions a wave function has? Yeah, like the units of a wave function, for example, the units of a wave function.

DORIS: let's see... maybe I'm trying to think if a wave function is more about the...that's interesting, because then you have to you multiply the wave function by its complex conjugate to get the probability... so then that does not have unit....So what's the unit of a wave function? I don't really know, I can't tell you that my head. It's honestly a really tough question... it's a... It's been awhile since I've even dealt with the wave functions.

CO: To be honest with you I had to go look it up myself. What's the answer? It has to do with the dimensionality the wave function but for one of us away function you have it's N over two dimensions of length...so if you have a three dimensional wave function youve got six...hold on...wait... I screwed myself up and I'm recording it on tape...

DORIS: That's okay. You can come back to me later on it.

CO: Its one of these things that nobody really discusses in the course, and when someone asks you you're taking aback and I had to go look it up because we never cover that when I took QM and I've taken four QM courses. I took one in undergrad and three here. That is a bunch. I just want to ask you about a few other things. Are you familiar with Heisenberg's Uncertainty Principle (HUP) of

DORIS: Yes that ones really fuzzy but it's basically you can't know the position and the velocity at the same time. That's right. You can know it perfectly...you wouldnt happen to know it also applies to other properties also plus other properties? Oh um... it does and I forget that...Energy and time?

DORIS: Oh yeah, we didn't really cover that though much that's fine. It was basically the position law. Do we get to go to over that in QM? Yes, youll go over that an exceptional detail. Id love to clear up those...

CO: It's really interesting, and I believe youll actually ...theres actually a derivation and its relatively straightforward in terms of derivations. So, its kind of a nice one. Have you heard of the Pauli Exclusion Principle (PEP)?

DORIS: Yes, the PEP is basically talking about electrons and energy states and how many you can have.

CO: Exactly. You can have two in the same state you can't have two in the same state the same spin. Right...Exactly. If somebody asked you why that is, would you have an an answer for them?

DORIS: No, I would not...um... I would have some sort of convoluted after about wave functions overlapping, but I dont understand why...That's not an unreasonable start. I have a feeling that people to going be here soon. I love how you're always just this one thing and I will be done.

CO: I did that with one of the other faculty and they called me out on it. Oh shoot...Do you wanna pause and move somewhere else? Were okay I just want to ask you about particle-wave duality. I assume...did you have exposure to that in MPI?

DORIS: Yeah, a little bit... Everybody always talks about the standard double slit experiment and what the results are, right? We both did it both with light and electrons. That was the main example of that.

CO: Cool...did you guys see the results... Did you guys fully explore the duality principle that way?

DORIS: No, I think we just brushed on it lightly. Did you get a diffraction pattern when you did the double slit? Yeah but we saw those things, saw a video of that. So, it was basically making it known that everything has that wave particle duality.

CO: Gotcha, Okay. Well, Um...is there anything you're excited about seeing in QM? Stuff you're looking forward to?

DORIS: Um...I don't know if I would say I was excited...I am excited, but I'm excited about going into more depth on something Ive already studied in MPI and MPI that Ive had some some questions about and I think of a little bit intimidated, but I think everybody is...That's the topic. I hear that it's a pretty hard class, but I feel confident that I'll come out of it being... learning a lot.

CO: Do you think that it will play into any...I know you work on campus with one of the researchers here Yeah. Dr. Mani Do you think that will play into the work that you do?

DORIS: Yeah it should definitely, because I'm working with graphene. So there's like all these crazy electronic properties of graphene that I cant understand yet, because I don't have the background. So hopefully this will add to your understanding. Yes I might stay with condensed matter as I try going to grad school and of course going to be very helpful with that.

B.5 Eric

CO: Alright and away we go. I'd like to start off asking you questions about evaluation, so I'm going to ask you about different types of evaluation and how you think, whether you think it would work or whether you think you would like it... in the quantum mechanics (QM) class. Okay. So for example, the first thing I would ask you about is multiple choice questions. If you had a multiple-choice exam or midterm in QM, would you think that's appropriate? Do you think that's a good way to evaluate your knowledge of the topic?

ERIC: No I'm not a big fan of standardized tests or multiple-choice tests. Purely because there's just, there's ways to get around really studying the material. You can learn how to basically beat the test. The answer is already there, you don't really have to...sometimes you don't even have to come up with it yourself. I guess it also depends on how it's formatted and who made it, but my from a general standpoint, no. I don't think that that would be appropriate.

CO: Excellent, What about, then there are sort of traditional written problems, things that you normally would see, like a math problem. Do you think that's probably do you think that's more or less appropriate for the class or...

ERIC: Yeah. So, I'm not sure. I'm not sure, this is kind of getting into my preconceptions of what quantum is. A test that would have math problems where you have to solve... like you'd be given a word problem or something and you have to solve that problem mathematically. Yes. I think that's far more appropriate. Also, I think also it might be useful to have some sort of writing down as well, because That was the next thing I was gonna ask you about. Yeah, okay. That's fine. I would test... you could be tested on both the math portion and the conceptual. So some people may not be a strong in math, but if you get concepts... but in QM, I think it was important for my ideas, it's a little different and I think you have to understand the math of it.

CO: I think there is a bit of it that's what actually woven together...it's a little more woven together the concepts in the mathematics are not quite as separate as they are maybe at the introductory level, but you mentioned sort of short answers combined with word problems do you think the short answer type questions by themselves are appropriate...is it is a way to evaluate you?

ERIC: Yeah, I think that in the right context...I mean there are some problems you just need to know the math and have the tools to do it, but if it's something like trying to get your... trying to understand what your ideas are about a certain concept of the class. I think that a written or a word problem would be fine.

CO: I know some of the upper-division classes do like a class presentation at the end of the semester. What do you think about seeing something like that In QM? Yeah.

ERIC: I'm not sure. I think my idea is that it's not...I don't know. I'd be all for it, I guess, if there was enough substance there that I could intelligently talk about quantum, but my idea is that it's an introductory quantum class. I'm not going to learn as much as I would in, like grad school so I'm not gonna have a better idea of what I'm talking about so... I'd be okay with it okay as long as the professor understand that.

CO: Yeah, know who your audience is, right? Right. And the last thing is, what would you think about having, as part of your evaluation in the class, like a one on one conversation with the instructor?

ERIC: I think that's a good way to do things, because I think when you talk to instructors... instructors a lot of times can really pick up on where students aren't as comfortable, because... like I know from personal experience talking to people on doing it myself, that we dodge certain concepts... and from my experience professors are very good at picking up on that. When they do, they can start probing in that area and see really what you don't understand. So I think that that's fine. Excellent.

CO: Okay, I'm going to move to talking about your physics background. Okay. Now I assume you've taken modern... the modern courses here? Yes. So, youve taken modern one and modern two? Yes. Cool. Have you taking the advanced physics lab? Yes. Awesome. Okay, so that's sort of everything modern physics all in those courses, right? Yeah. Have you taken CM? Yes. Cool. Have you take electricity and magnetism (E&M)? Currently taking it. So, you're taking it together with QM? Yes. From CM, are you familiar with what the Hamiltonian is?

ERIC: From CM, no I'm not, but I have done a little bit of side research over the summer and I understand a little bit about it. Okay cool. So you know sort of what a Hamiltonian is? Sort of... Well, what, sort, of is it?

ERIC: Well, I understand that it describes the total energy of the system and I used to know exactly what it looks like, but I don't, but I understand that it's just driving the energy. That is a good step in the right direction. Okay.

CO: So is there a topic and physics were you think you have greater strength? Do you feel like you're better in CM or more familiar with it than you are in some of the modern stuff?

ERIC: I would think that. I like modern stuff a lot more, like I really like talking about in modern. When we started going over the solid-state section and when doping and these free electrons in semiconductors that's my favorite part. I think that's because what I want to get interested in and then just kind of hit home. Cool.

CO: So you just, you're hoping to move to grad school after you finish the program here? Yes.

CO: Let me ask you this, what do you think the instructor expects you to have seen in terms of physics before you get into the classroom?

ERIC: Okay, so this is kind of a bad question for me. Okay, why is it bad question? Because you've interviewed him and I am involved in the process so I've heard what you... I know what he expects. [Laughter] Yes so that is kind of but...

CO: Can you remember before a time before we had the conversation where you might have... let me ask you this, was there anything that you heard from the interview that was surprising to you?

ERIC: Yeah, so I wouldn't have known to really go over the the Hamiltonian and even know that it was going to be in there prior to that. I know that I expected a lot of linear algebra. Sure. That's why I took the Linear course, I didn't do too well but I understand a little bit of it. I expected to see a lot of stuff from modern one where it was like normalizing wave functions. Yeah. I'm expecting to see some of the potential well stuff, things like that.

CO: all that makes perfect sense. Okay, so you mentioned some of your math background have you taken the ODEs? Yes. Cool. Do you feel pretty confident about the material you got out of that course?

ERIC: In the course I it was extremely easy it was like...

CO: Now when you say it was extremely easy, do you mean that you have command over the topic or was the course material really easy?

ERIC: The course material was easy. I don't have command over the topic. I feel that I have the, I could be good with it pretty quick refresher. I was going to the concepts during the course are not that hard for me to pick up quickly. I think the first test I was struggling that night and I open the book and look stuff up and got 111 on the first test something while I mean I can't do that in other classes, it was purely just that class the teacher wasn't too great so don't feel like I got a lot out of the class. I know there's a lot of things or I expect that there's a lot of things in quantum two to be things that I don't remember that I haven't covered in the new algebra in quantum

CO: So you mentioned that youre taking linear algebra. Doing with the basics of matrices like finding determinants of things like that you feel pretty comfortable with that? Yeah. the processes of working with matrices aren't hard it's the end I mean you can eventually just gets into doing computer work anyway for really good ones but it's the theory understanding really what's going on when you're working with these when you're actually doing and that's something that I think is really important for yeah with the determinant actually yeah and it's like what these things mean going between different what is it Artu our four different transformation what's actually going on that classes very focused on theory and stuff like that and I didn't pick up on that as well I'm not good at that type of math and that I think is a big part of that something that I'm expecting to see in quantum because when you're really popping out and maybe will help reinforces ideas yeah I hope so

CO: Have you taken PDE's no I'm taking it right now okay cool

CO: I'm obligated to ask this but how do you feel about your strength with integration and dealing with trigonometry?

ERIC: Trigonometry I'm fine Integracion it's really easy to get caught in a really big journal and lose place and stuff like that I mean I think it's fun I think I would rather do harder inter-girls that are still doable and do long complex multiple channel derivatives or something short

CO: And from what I know about the course it's sort of there's always a way to simplify or reduce a lot of the equations as you see I think in my experience dealing with this type of material once you know some of the tricks that are used to reduce those functions it makes the integration much more palatable in that sort of I've seen a lot of folks get lost in the Integracion I understand

ERIC: Yeah I've seen a diagram that goes over all physics problems it's basically like to do some transformations integration then go back or do according to change or something yeah there's some truth in that

CO: So you kind of mentioned the type of physics that you think the instructor will expect from you approaching the question the same way was there any math topics that you know kind of surprised you and you said oh wow I might need to go back and brush up on on on that... When you talked about yes when I talked about the prep

not not really I think I saw a little bit of it seems to me like MDs anything that he wanted you to know little bit of PT's in there as well and I was like well I guess I just learned relearn those as I go but no just primarily part of what I know about this course is that I talk to my brother about it too he's taking it at Georgia Tech he's a math major now. He talks to me about how what kind of things it focuses on and stuff like that okay cool I think his class was a little bit more in depth it's good that you have exposure though that's really helpful it's helped me throughout my physics career I wouldn't have the grades that I did without him to help

CO: It's good that you have a brother that's technically adept I'm the oldest of our family so I I've never had that opportunity both my brothers are like science no thank you so be it back to the prep stuff I'm really just would ask you for a couple of questions what you think wanted mechanics is going to be in some conceptual stuff and then we will be done if you had to give somebody a short answer of what QM is what would you tell them I sort of a two minute elevator answer an elevator pitch yet?

ERIC: I mean the first thing that pops into my head is like a wave particle duality the uncertainty principle on I don't know that's kind of a hard question I don't think the thing is I'm the type of guy who doesn't like to really talk about things that I don't know fully understand so with quantum I mean I don't know I don't really understand that well so I don't want to be like hey this is what it is but if I would've just given answer

CO: Well if somebody if one of the 2211 students asked you what should I expect to see coming down the pipeline....

ERIC: Yeah well I tell them probably Eutsy a lot of so going into quantum you probably start seeing just a guess...

CO: When I'm saying what is QM I don't mean what is the course you're going to take me what is the topic QM

ERIC: Well I guess it's I know that's kind of a hard question to ask I guess okay that's fine no problem.

CO: Are there particular topics that you've already addressed this question but other hand. Thanks you think you're pretty confident you'll see in the next couple months?

ERIC: Yeah I'll I think I'll start getting pretty good at normalization I think just some different integration techniques with kind of specific integrals adult with them before I think I wanted to do them better I will learn hopefully a lot more about a lot of times when I learn that medical. I learned through physics so hopefully I'll strengthen my linear algebra skills in minority and PDE skills along the way sure but yeah I think that's what I'm really expecting

CO: Awesome in terms of some topical conceptual stuff if you imagine the uncertainty principle what do you know about the uncertainty principle?

ERIC: that I don't really understand it still. I understand that there is like it's like it's really weird and I talk to people about this before it's like the more you understand the more you measure something about a particle or something the less you can know about another aspect of it him and it's one of the hardest things I've had to grasp I didn't understand it Mottern I didn't understand in modern too but what I've been told is that the more you work with it the more you see that this thing isn't like the uncertainty isn't something abstract and theoretical it's actually something inherently physical about particles and stuff like that sure so I'm kind of hoping I get a little more bit more backing on that sure

CO: Have you are you familiar with the PEP yes cool it's if somebody asked you why it exists would you have an answer for them?

ERIC: Not like a good fundamental answer I could tell them what it is short but no I don't think I know because I think that when I don't know I guess I'll talk this goes off the track a little bit but like off the record no I mean like so saying I don't understand is a perfectly acceptable answer yeah I understand what it is I don't understand where comes from or how works okay that's perfectly acceptable

CO: Same thing with particle wave duality you mentioned it what kind of exposure have you had to dealing with the duality?

ERIC: Just in modern one actually in modern two didn't actually we didn't really deal as much with it we dealt with the two Broseley I can't say his name yeah I think it's to Berkeley or my English butchering of that name can talk about that later but we talked about the Debro the wavelength the double slit experiment and stuff like that

CO: Did you I don't know if you guys actually do these experiments have you physically seen it or have you watch videos of it or...

ERIC: Some videos mostly we did the basic one in 20 to 12 but that's not saying it's not demonstrating the same thing okay

CO: Okay the last thing is what do you know about wave functions?

ERIC: I know that it describes the my idea of it is that it is a probability function so it describes the weight itself is like a probability wave or that's how I understand it okay that describes the basically the probability of finding something like an electron in a particular space or something like that but yeah I don't know

CO: So when you think about it do you think of it as like a localized way packet or something that is sort of in space everywhere or localized okay cool and you mentioned that you didn't globalization in modern do you feel like that's the kind of thing you can pick up again pretty quickly yeah I think so I think it'll come back it's all just doing the work so once I start doing the work and welcome back

CO: Hopeful hopefully this whole conversation will sort of help jog your memory and maybe it made me realize yeah little bit it made me realize I need to relook at a couple of other things if it's any of us

CO: So I guess from the last thing is do you have any idea of what the dimensions are of away function like the units would you would use with it and this is just sort of off-the-wall know okay I just have been asking people if they know what the units are avoid function is there anything you're excited or interested to see coming up in this semester?

ERIC: Yeah I'm kind of excited to see him like I said earlier a lot of the math topics and a lot of the physical concepts and really reinforcing a lot of these things I understand that it's like a pretty difficult course understand that wow that's a weird sentence but yeah I think it's going to be pretty interesting and I think it's very it's important understanding a lot of other every other physical basically

CO: quantum mechanics is really interesting kind of crossroads for a bunch of different topics I see that I just asked one question I came into my head do you know that if there's an undergraduate solid-state course offered here?

ERIC: I know thats something I would be interested in I would take it in a heartbeat if it existed that would be awesome it's been awhile since I saw the undergraduate schedule maybe we can push tonight of course exist I guarantee you there's a handful of people that would be interested in that and teaching it definitely

B.6 Faye

CO: Okay. So basically what I'm interested in learning is, from you today is your opinions about how prepared you think you are to take quantum mechanics (QM) and your opinions about different types of like evaluation of your knowledge and how you feel your preparation for the class.

FAYE: I have no idea what quantum Okay we'll get there. If you want to give me a quick rundown of what quantum entails, I could could let you know. I'm just laying out where Id like to go with this when we get to it I'll explain things. Oh, okay.

CO: Let me start with the evaluation stuff because that's really straightforward. If you were taking a class, specifically like an upper division physics class, like QM...I'm wondering how good of a tool do you think each of these would be for evaluating how much you've learned, starting with multiple-choice questions. Do you think multiple-choice questions are appropriate for like an upper division course physics course?

FAYE: No. Any particular reason why? It's too easy. You know, if you don't know the answer there is still a possibility that you'll get it right. Sure.

CO: And the sort of the traditional method is with, like written problems... Yeah, show your work and youll get credit. So that seems way more appropriate? Yes.

CO: Okay. What about short answer type questions?

FAYE: Yeah, I even like to see more of those, because that way you do... actually being tested on your conceptual knowledge instead of just can you solve the problem.

CO: So maybe even combining like a written problem with the short answer kind of thing would be interesting. okay. One of the other things I've seen done in the upper division courses here is like class presentations were at the end of the semester everybody will give ten minute spiel about a part of the class or some topic in that field. Do you think that type of thing would be appropriate or interesting for quantum mechanics?

FAYE: For quantum? Sure there's plenty of...I guess. I'm not 100% familiar with QM just yet but I'm sure there's plenty of interesting topics to dive into that we wouldn't have time to get into during the class. So having those kind of presentations, because we had them in modern two, really you got to learn more in depthly [sic] about a subject that you may not have gotten to by just taking the class without it.

CO: Do you feel like you got something out of other people giving those presentations, too?

FAYE: Yeah. Definitely.

CO: The last thing is something that I don't really see in physics a lot, but the idea of like a one-on-one conversation with the instructor, like to be scheduled 20 minutes to talk to the instructor about what will you covered during the semester. Do you think that would be a fair way to evaluate your knowledge?

FAYE: Well, I don't know. I've never heard of that.

CO: Well, if you sat down with an instructor and they said...Tell me everything you know? Well, what do you think was the most important thing you learned this semester? and then from there sort of having a conversation with them. Starting from that point, do you think that would be fair or good idea or maybe not appropriate or...

FAYE: Fair, as in, like you're being graded on it? Yes. Oh! I don't know. If you structured it with guidelines or an outline where you could prepare for it, maybe if it was structured, then yeah...but just like Hey, just talk to me. That's sort of nerve-racking. No doubt. That could be pretty stressful....but if it was structured, yeah. I don't see why not.

CO: I interesting, good to know. So that's pretty much it on evaluation type stuff do you think would you like to see any combination of those things in QM or is that is there something you definitely would not want to see in QM?

FAYE: In a combination...I wouldn't suggest all of it, because that's quite a load. Definitely the short answer along with the written problems, presentations not a bad idea...I'd say either presentation or talk with the teacher Both sounds pretty harrowing. Yes

CO: You mentioned that you took modern two...so I assume you've taken modern one and modern two Yeah. Have you taken the advanced lab as well? MmHm. Cool. So how comfortable do you feel with this sort of body of modern physics knowledge?

FAYE: Um...well. Modern was...the whole point of it was that you got a little bit of everything. So in a broad scheme of things, I feel fairly comfortable.

CO: So you feel like you have that broad knowledge base?

FAYE: Yeah. Ive been introduced to the whole book, light, energy...then it was kind of nuclear and particle towards the end. We didn't have a whole lot of time on that, but it definitely, definitely was introduced to it.

CO: Cool. Did you guys cover square well potentials MmHm. Yeah. Awesome. Have you taken classical mechanics (CM)? Yes. Are you familiar with what a Hamiltonian is?

FAYE: I'm sure he talked about it ...And sort of is an acceptable answer. I know he talked about it. I didn't do so well in CM.

CO: Did he talk about the LaGrangians?

FAYE: Yes.

CO: In at least some depth? Yeah. Okay, did you get that same kind of depth about Hamiltonians or was it...

FAYE: I definitely remember the LaGrangians better than Hamiltonians, Okay. Sure. but

The name is familiar but you can't quite place it? Yeah.

CO: Okay. No problem. Have you taken E and M (E&M)?

FAYE: I'm in it right now.

CO: So...um...Do you think that you have an area of one of those classes where you fair the best? You said that you seem kind of shaky in CM.

FAYE: Yeah, CM wasn't my brightest point. But... I did much better in modern and the advanced lab.

CO: Okay. Cool, and not just in terms of grades, but he felt better about the material? [Nods] In terms of your physics background type stuff, what do you expect that the instructor will be looking for in QM? Do you think there's any specific topics that he's going to really wish you have covered before you enter the class?

FAYE: Um...I think... we are just talking about it... it's very important take partial differential equations (PDEs) along with it. So I think he's going to want us to know fourier...Yeah, Okay. That's more of the math side though... He's gonna want us to be very up-to-date with our math. Which I took vector [calculus], but I'm not taking PDEs.

CO:Have you taken ODE's already? Differential Equations? Yes Okay. Cool. Do you feel pretty good about dealing with differential equations?

FAYE: Oh yeah, the math is good. I'm good on the math. Have you taken linear algebra yet? I wasn't required to, so I did not.

CO: Okay not a big deal. I know that is one of those things that I think pops up towards the end of the semester. Yeah... but that's one of the reasons why I'm having, trying to have these conversations with people. It sort of helps people coming contact with what they feel good about what they don't feel good about. What? Linear algebra? ...just in general. I know I've asked a handful people about the Hamiltonian and oh well they say I don't I don't know what that is but it's probably in my best interest to find out, to check it out. Right. So I'm hoping that this is more than just me getting information from you but also you getting a little information from me as well.

CO: In terms of...we were talking about math and what you think the professor is going to expect in terms of math. Do you...I'm gonna go back to physics, do you think there's any physics that he really was hoping that you've already covered? Obviously there's going be some stuff...

FAYE: Yeah I guess like a slight introduction from modern [physics].

CO: Sure, so mostly focused on the modern? Yeah. How comfortable do you feel in terms of the math you talking ordinary differential equations and you're taking PDEs right now. Did you say that?

FAYE: I'm not taking PDE's right now I don't have to take them. You said most people take PDEs. Yes most people take PDEs along with quantum and that's supposed to be helpful...

CO: That's a reasonable statement. Yeah. And you haven't taken linear algebra...you, I'm obligated to ask everybody this, how do you feel about your ability to integrate and deal with trigonometry?

FAYE: I'm fairly good with that. Pretty confident? Yeah, I would not have gotten this far. [Laughter]

CO: One of the instructors actually said something to that effect as well. [Laughter] Some of it is like, I know not everybody knows the double angle and half angle theorems, but I definitely can use them. if you need it to you probably could get to them from some other source. I know that one of the things the course focuses on is being able to do the integration yourself. In terms of the way the instructor runs quantum mechanics, a lot of it is you can do these integrals it's not a job for Wolfram Alpha. So he is focused on that. Okay. Integracion is one of those things where you know the tricks it can be very straightforward. If you know how to reduce the function you're working with to something that is more palatable, it's a lot easier. You mentioned Fourier series are you familiar with Fourier series? Have you seen them?

FAYE: Fairly familiar. We covered them in CM and we cover them in my electronics lab. So you have some exposure to them. Some exposure.

CO: Cool. I know that the Fourier transform is a big deal in QM. When you are taking something in real space and flipping to momentum space or vice versa. So that's kind of something that is used in the course. Is there a mathematics area that you feel the strongest in? Like I can definitely use this all the time.

FAYE: geometry algebra calculus How broad?

CO: I guess you mentioned that integration is no sweat and trigonometry you have got down... an ordinary differential equations. We talked about ordinary differential equations and the other stuff do you feel pretty good about your ability using what you learned in that class?

FAYE: I think so. Yeah. I hope so.

CO: That's pretty much it first a lot of the prep questions. I just would like to ask you some conceptual stuff about QM and bear in mind that this is, some of these questions are... theyre intentionally tough. If you are like I have no idea what you're talking about, that's a perfectly acceptable answer.

FAYE: Okay.

CO: If somebody asked you to describe like what the field of QM is to them, could you give them an elevator pitch of what QM is... just like a two-minute answer?

FAYE: Like I said, I haven't taken the class, but the little that I know is that...

CO: But you've taken modern so so you've seen some QM.

FAYE: Yeah. It's like...it's like the science small things...and small things, how they interact together, how they're structured, how they move...the forces involved within small things.

CO: Okay, but I'm not grading you on any of this. Are there a handful topics you know youre going to cover in the class that's coming up..Are there topics that you know you're going to see in QM, or are you really just coming in having no idea what you're going to see?

FAYE: No idea.

CO: That's exciting [Laughter] it will be an adventure for you. If you were to describe what an atom looks like somebody, how would you do that?

FAYE: Um...very small. Okay and the structure? Small ball in the middle with little things going around that you're not able to see...you can't see any of it anyway but, you know.

CO: Are you familiar with Heisenberg's Uncertainty Principle (HEP)? Yes. How familiar?

FAYE: We covered in modern...covered in chemistry.

CO: In chemistry and modern, you guys talk about position and momentum...and how they cant be known with exact precision, right? [Nods] Do you know any of the other properties that obey the uncertainty principle? Besides position and momentum? Yes...um...mass? I know that energy and time are another two properties that obey HEP. You cant know the energy and the timescale that energy is occurring over perfectly, so that's one of those things I just figured I'd ask everybody. Are you familiar with the Pauli Exclusion Principle (PEP)?

FAYE: Yeah Do you know what it is? I don't think I can give you a verbatim definition, but...

CO: If I jog your memory and set it has to do with the spin of electrons, does that kind of help? Do you know what I'm talking about? You know that you can't have to the same electrons in the same spin state that's the PEP. If somebody asked you why that is the case, would you have an answer for them?

FAYE: Why they can't spin in the same direction? Yeah. Why can't they have the same spin and occupy the same state? You know...I don't know. why.

CO: Okay not a big deal. How much exposure have you had to particle wave duality have you seen it? In I assume you saw in modern courses, right? Did you guys ever do a physical experiment that demonstrates it?

FAYE: Wave duality? He talked about a lot of it. I can't remember if we did a physical one, but we talked about...I assume you are talking about the slits.

CO: Yeah. The standard fare is the double slit experiment where...

FAYE: I can't remember if he actually did one in class, but he did go over several different experiments with us. Okay, no problem. I'm sure he did, I don't know.

CO: If I asked you what objects it applies to could you tell me? What objects? What does particle wave duality apply to?

FAYE: Light? I don't quite understand the question...

CO: Is it just photons? Is it just electrons? Is it...

FAYE: Oh! I guess... I don't think we talk about anything other than those. Okay. Like alpha particles.

CO: Yeah everything. The fact of the matter is everything has a DeBroglie wavelength. The standard, standard fare in the modern class is to have a car and you figure out the cars wavelength and the electron and you see what they are....

FAYE: Something like that. Yeah, I think we just talked about electrons and photons.

CO: Yeah, that's fine. The last thing I'm in ask you about is wave functions. Okay. Are you familiar with wave functions a bit when I say the word wave function do you know what I mean?

FAYE: Like the equation? Yeah. Not that I can remember the equation, but we did talk about it. The Schrodinger equation? Yeah

CO: But if I asked you what it described, could you tell me what it describes?

FAYE: The wave function?

CO: Yeah, and like I said I don't know is a perfectly acceptable answer

FAYE: The wave function describes... I don't know... the wave? [Laughter]

CO: Don't sweat it...it's interesting it's one of these things ...people have different interpretations about QM. The interpretation of QM dictates how you look at what a wave function is. A lot of people sort of you it as it's just this mathematical construct that we use to describe the probability of interaction or the probability of locating a particle.

FAYE: Oh yeah. That's right.

CO: But there's other folks who say Oh the wave functions a real part of it's a physical thing that exists in these wave functions interact with other ways and that's how you have things happen at the quantum scale. So it's a little bit of a question of interpretation and I'm just curious. Did you guys did you ever normalize wave functions in the modern classes?

FAYE: See...most of this is from modern one, which I took a year ago. I don't know if you normal... Yes we did normalize them.

CO: Is it the kind of thing that if you looked up looked into it you probably could figure it out again?

FAYE: Yeah. I wish I had looked over by Modern notes before I came...

CO: Don't worry. This is not a test.

FAYE: When we normalized them I forget...Is that when we multiplied by the complex conjugate? Yes, that's correct. Yeah and said equal to one. Yeah we did that.

CO: There you go see. This is the kind of thing it's... it's returning. Oncet you ask me enough questions I don't know, I'll start I'll start ..Ill remember at least one. Well as long as it jogs your memory for the course coming up, you'll be good.

FAYE: Is all of this in QM?

CO: I want to say yes it is but I don't know how much of this... a lot of these questions are little more conceptual than what I think is addressed in the course. So it's a little bit...because this is like modern one and... really what I'm trying to get with... my research is I'm trying to figure out what people think and what people expect before they take QM. So it's kind of like interface between modern physics and QM, as you transition between the two classes where people stand how prepared to they think they are and based on what I learned from his interviews with students and faculty is there a way to help people become better prepared before they get to QM. So I'm not necessarily I mean. I'm not interested so much in what's going on in the QM classroom, I'm more interested in are you guys prepared to jump into that and start dealing with QM. Okay.

CO: So I'm not gonna do like if I want to do another set of interviews at the end of semester I don't know if that's gonna be in the works. Really well this is before taking the class document what you thinking right now because the moment you went five thirty rolls around he's going to jump straight into the modern physics background sort of a quick refresher. You think about it we function is it something that is localized like a particle or the something that spread out over all space?

FAYE: I want to say more localized I think it could be applied over all space. Most of the problems we addressed are localized, I like to think.

CO: Now when the wave function collapses, you have a single value that you measure. There are folks who say that that wave function collapsing allows for faster than light information travel does that make sense to you? Do you believe that you can send information faster than light?

FAYE: No, I haven't heard that theory.

CO: It's something that's out there. I was going to ask you if you know the dimensions of a wave function like what the units would be, but that's not an easy question?

FAYE: Well you said earlier that is to define the probability, so maybe time and the distribution?

CO: When you're dealing with the time-dependent...Schrodinger Equation, the Hamiltonian is in there because it's the second derivative of the potential then usually multiply in a term for the time Component...but youll see that in a few days. Is there anything that you're really really interested to see in quantum mechanics coming up position one topic I hope they really cover this

FAYE: I don't know I really just don't know anything about quantum. Apparently I know a lot more than I think I did... because apparently a lot of it has to do with something I've already learned Well that's confidence building. Yeah at least I'm not going in empty headed but I really do need to refresh.

B.7 Greg

CO: Alright, let me get started with the evaluation material, because I think it's the most straightforward. If you were taking an upper division course, like quantum mechanics (QM), just tell me really quickly how you'd feel about each of these kind of questions being on a test starting with multiple choice.

GREG: Okay.What do you think, appropriate not appropriate... Good enough to evaluate? I don't think it would be the only option... I would think that would be sort of conceptual type questions would be multiple-choice Okay...Yeah. No problem.

CO: What about something like a short answer short written answer?

GREG: Yeah that's fine.

CO: And obviously there's the sort of traditional word problem that you would do mathematically...

GREG: Yeah, I would think the bulk would be more of those type of questions, then you would have the short answer response type of questions for concepts. Sure.

CO: Something they do in the other upper division courses are like, presentations at the, at the end of the semester. Where you get like a 10 minute spiel in front of a crowd. What do you think about that in terms of using that in QM class do you think that would be appropriate do you think it would be helpful?

GREG: I think it could be helpful to help you verbalize and make sure you are, can communicate concepts to others. That's always helpful. okay

CO: And finally, how would you feel about having like a one on one conversation with the instructor That would be great. and having that be evaluated for your knowledge?

GREG: Hmmm...that's more like a... kind of a graduate qualifier type of thing. Sure. Um...I would say if there was...I think it would be interesting. Yeah.

CO: Maybe if it were structured a little bit? Yeah, if it was clear what was going to be expected. Sure. Okay. Let me ask you about your physics preparation. Okay. have you been in the program at Georgia State University? No, I'm a post-bac.

CO: Oh, okay. Cool. So, I have got a masters in mechanical engineering from Georgia Tech. Oh wow so you are going to be very different from my other interviews...very cool. Yeah, I am that outlier. [Laughter.]

CO: Well all the qualitative stuff outliers are beautiful or wonderful so that is no problem, it's exciting, but... let me ask you real quickly did you take a Stat & Therm course I took that last semester. Okay, have you taken classical mechanics?

GREG: No. Well, mechanical engineering, I've had a lot of mechanics classes. Are you familiar with using LaGrangians or Hamiltonians? Not, not completely. That's kind of one thing that is lacking in the mechanics program. Yeah, that's a little theoretical so I understand. I've done things with the virtual work. I don't know how Lagrangian that is. okay I'm not familiar with it so I'll have to look it up. [Laughter.].

CO: Have you taken electricity and magnetism(E&M)? I am taking it. Okay, are you taking it here in conjunction...Yes. Okay, that's good. Have you had like a modern physics background?

GREG: I have watched all modern physics lectures provided by Case Western on iTunes to prepare [Laughter.] So financially, I was like, and sequentially, there wasn't really an opportunity for me to take that. So I thought I'll just watch them.

CO: That's one way to prep definitely. Okay, let me go straight into Math. Okay Hold on... I have to slow down here. Just out of curiosity, as a student, what do you believe the instructor is going to expect from you in terms of physics knowledge coming into this course?

GREG: I think he's going to expect some basic understanding of QM and probably a general understanding of differential equations and things like that.

CO: When you say a general understanding of QM are there specific things in QM you are thinking about? t's a pretty because that's a broad topic.

GREG: Yeah. Maybe yeah the like of the have an idea of what the uncertainty principle is or... maybe you have seen the wave function before. Things like that. If you are familiar with sort of the historical context that brought QM to light.

CO: Absolutely. okay perfect. In terms of your math prep, have you taken a differential equations course yeah okay

GREG: I took it a long time ago [Laughter]. and I took partial differential equations(PDEs) course for part of my masters degree excellent.

CO: Have you taken something like linear algebra? I don't know how tech structures things so you'll have to enlighten me. yeah

GREG: It's I could have taken a linear algebra class, but I didn't. I took some things where we dealt with matrices and eigenfunctions and things like that, but I don't have a rigorously linear algebra... But you have the fact that you have the vocabulary to talk about matrices determinants and I can functions eigenvalues that is a good sign That's a good start? great yeah I think so. That was one class I was wondering about whether or not I should take before I got into grad school I'm sure

CO: Are you familiar with Fourier series? Yes. Yes. That was a big part of PDE's. Okay...and I'm obligated to ask this, but how do you feel about your ability to integrate my hand and deal with trigonometry? Do you feel pretty comfortable with that? Yeah that's fine. I've tutored it a lot so... Wow. Excellent. That really helps in my opinion.

CO: Do you think out of the math that you have seen are there particular topics that you think will be really important to taking this QM class?

GREG: Maybe this probably, probably differential equations, maybe some PDEs too. Like it would be like breaking them up into independent and... sure system of equations something like that. yeah definitely

CO: Well that's most of what I have about background information okay we are growth going through this at break neck speed. Great. [Laughter.] I'm going to ask you some conceptual stuff about QM just to sort of get a feel for what you think and that will pretty much be the majority of it. Alright. So, if somebody asked you what QM was, on the street, just could you give them a sort of brief, simple answer about what the topic is about?

GREG: I would say...very simply that or maybe just to an undergrad student who is just starting out I would say you know it's all about energies and what is allowed, and what is not it is saying that for a given set of situations some energies can happen in some energies can't and there's also the redefinition of the photon. Sure. so that its energy has a wave length associated with it. Okay, excellent. Is that good? [Laughter]

CO: I think this is a little bit redundant but are there any specific topics you feel like you're definitely going to see as you come through this course like a set of greatest hits or something?

GREG: Yeah I'm interested... I really like the concepts of everything like the tunneling and particle in a box. I think it would be interesting to go further into the 3-D kind of stuff, and see what lies past the atom... just a hydrogen atom. Sure. I don't know if that is going to be the undergraduate level that's kind of what we are trying to figure out. and maybe like matter interactions things like that.

CO: Excellent. If somebody asked you what atom looks like how would you describe when atom is?

GREG: [Laughter.] What century are we in I guess the modern century? You and I are talking. It's 2012. Alright, so I would say the atom is fuzzy and there's no definite position of everything. There's just probabilities of where you can expect to find the atom and from that you get sort of this cloud and...What about its structure a little bit more It depends on how many electrons how many protons you have in there if you just got one and its in its ground state is gonna look spherical. Once you start getting into items like carbon you're going to have P orbitals, more exotic. Yeah. That are going to kind of look like 3-D crosses things like that.

CO: You mentioned a Hiesenburgs Uncertainty Principle (HUP). Yeah. How much do you think you know about HUP?

GREG: Well, how much does anyone know [Laughter]. It says that as you figure out some of the particles position, there's a limit to how well you can know the momentum which is greater than equal to H-bar over two. So that's sort of the limit, I guess. Some practical circumstances you won't really hit H-bar over two.

CO: Have you ever seen anyone show you a derivation of it, or why it exists? it's from a gaussian sort of idea, where you have... it's a wave and if you have an even wave do you know the k-value which is related to momentum. If you have something that is more of a Gaussian type peak, you don't have the as well defined of a k-value for a particular wavelength, but you know right you have a better idea of what the position is. Yeah okay it's coming from the Fourier series?

CO: I was going to ask you briefly with the Paul exclusion principle? Yes. do you know why that exists? it's from experiment right? yeah that's pretty much exactly it because it's a principle it's not in the math we had to add it in. Yeah it's just an absurd experimental fact of nature.

CO: How much do you know about wave functions do you know what wave function is trying to convey?

GREG: Sort of... what it's trying to convey or what it is... okay In terms of QMor just... Yes. The wave function you have to square to find probability. yes correct it is a complex function otherwise it also has to be normalized yeah right so that you integrated from Minus to positive infinity and it's got to equal one yeah that's right.

CO: Okay are you familiar with what the dimensions are or what the units are for wave function...when you're using a wave function have you ever address that?

GREG: Like the electron volt or... yeah what the units are for the actual wave function. like what it's dimensionality is. Energy? yeah that's what I'm looking for I'm trying to think of...Wwe tlakted about the Pauli exclusion principle, we talk about wave particle duality... actually no, we have not. Okay, I assume you're familiar with wave particle duality yeah in what capacity have you seen it? I know you haven't taken modern here so right but you have seen it through what you bought and we're watching yes

GREG: From what I gather is, we found out that light behaves as a particle that led to Broglie to say well light can be a particle and wave can matter be the same thing and he did it with the electron showed the diffraction pattern, but from what understand it's not that he shot one electron and got a diffraction pattern, he shot a bunch of electrons and it ended formed a diffraction pattern. Is that correct? Yeah.

CO: Depending on what you're looking for... if you create an experiment that looks for a particle you'll find particle. If you create an experiment that looks for wave, you'll find a wave. That experimental design component is inherent in the property yeah I'm interested in the [Laughter.] it's definitely one of those it's very interesting. I like QM, one of the reasons why I'm doing this research is that it plays tricks on your classical intuition or sensibilities and I think that's very cool.

CO: That's really the extent of what I have basically this is officially the fastest I've ever done this. Awesome. I was going to ask if you, there are folks who say that wave function collapses wave function will collapse to its value when it's measured. Some people by saying by virtue of that, you can send information faster than the speed of light because of the wave function occupies all space. I was going to ask you if you buy that based on what I told you right now?

GREG: Well, based on what I followed the physics community, it seems like there's something that just recently they sent a photo 200 something kilometers it was like the information was there, but big they couldn't retrieve it until the speed of light came. I don't really understand what that means. So, it might be hesitant maybe. Sure.

CO: Is there anything you are excited about seeing the semester I know you mentioned wave particle duality. Are there any other topics you're really hoping to cover?

GREG: Yeah I got really interested I don't know very much about quantum information kind of stuff, but it seems like that's a really hot topic now and it's something that I would be interested in getting at least a framework to understand. Sure.

CO: Do you have intentions of taking this information and going into sort of a business environment or an academic environment for...

GREG: I do want to eventually be a professor that's my goal. So grad school someday, I'm applying for grad school right now. Excellent. Applying to Georgia Tech and I'll see if I get in, if I don't get it, then Ill apply to other programs next year.

Appendix C: Faculty Interview Schedule

1. Introduction:
    a. (establish rapport) My name is ____________ and I am part of the Physics Education Research group at Georgia State University. I'll be recording this interview because I do not want to miss any of your comments.
    b. (define purpose) I'd like to speak with you today about your opinions on what undergraduate students should be learning in a Modern Physics/Quantum Mechanics course.
    c. (explain motivation) As a community we need to define our expectations for undergraduate understanding of Quantum Mechanics. Being able to describe instructor and student goals for a course is important to offer a quality education
    d. (give timeline) This interview should take less than an hour.

2. Interview Body:(*ask for clarification when necessary [i.e."Can you go into greater detail on _______."])
    a. Incoming Students
        i. What do you think undergraduate students know about Quantum Mechanics before the Quantum Mechanics course?
        ii. Topical Questions
            1. How do you think a student would respond when asked what an atom looks like before taking the course?
            2. What do you think students understand about Heisenberg Uncertainty Principle before taking the course?
            3. How do you think a student would describe Particle-Wave Duality before taking the course?
            4. Would students understand that the Pauli exclusion principle does not create a force?
            5. Could students describe the dimensions of a wave function?
            6. Why do you teach the Bohr model?
    b. Mathematics Expectations
        i. What is your general impression of the students grounding in mathematics prior to taking your course?
        ii. What mathematical tools do you think are most important to learning the material in your class?
        iii. What are the top three mathematics courses you would like students to have taken before entering your class and why?
    c. Physics Expectations
        i. What type of Physics background do you expect of students entering the Quantum Mechanics course?
            1. What Physics courses would you like students to have taken before entering your class?
        ii. What is your general impression of the students grounding in Classical Mechanics prior to taking your course?
    d. Course Material

i. Can you describe your experience in undergraduate Quantum Mechanics.
ii. What do you think the goals should be in teaching a Quantum Mechanics course?
iii. What do you think the student expects to learn in the course?
iv. After the course is over, what do you expect a undergraduate student understand?
v. If you encountered that student one year later, what information would you expect them to have retained?
vi. What are your impressions of what students have gained from taking the Modern Physics course?

3. Closing
    a. If you could offer student one piece of advice about learning Quantum Mechanics, what would it be?
    b. How would you evaluate your students understanding of course material? [ideally and practically]
    c. Is there any other information that you would like to add?
    d. Thank you for your participation in this research.

Appendix D: Student Interview Schedule

1. Introduction:
    a. (establish rapport) My name is ____________ and I am part of the Physics Education Research group at Georgia State University. I'll be recording this interview because I do not want to miss any of your comments.
    b. (define purpose) I'd like to speak with you today about your opinions on what you expect to be learning in Quantum Mechanics.
    c. (explain motivation) Understanding the students goals for a course often helps determine the outcome of what you will learn in a course. I hope that we can use this information to understand how prepared students feel for this Quantum Mechanics course and better understand what students think is important to get out of a Quantum Mechanics course.
    d. (give timeline) This interview should take less than an hour.
    e. (explain confidentiality) I just wanted to remind you that all of your responses will be kept confidential and anonymized responses will only be shared with research team members.

2. Interview Body:(*ask for clarification when necessary [i.e."Can you go into greater detail on _______."])
    a. Incoming Students
        i. What do you think Quantum Mechanics is?
        ii. What do you think you will learn about in Quantum Mechanics?
        iii. Topical Questions
            1. What does an atom look like?
            2. What can you tell me about wave-functions?
                a. what are its dimensions?
                b. What does it describe?
                c. probability density (time dependence)?
                d. What are its requirements?
                e. Can you normalize it?
            3. What does it mean if I said $\Psi(x)=0$?
            4. Can you describe Heisenberg's Uncertainty Principle? Why does it exist?
            5. What is Particle-Wave Duality?
                a. What to what objects does it apply?
                b. What happens when you observe an electron traveling through a double-slit?
            6. What is the Pauli Exclusion Principle? Why does it exist?
            7. Does collapsing a wave function allow us to send information faster than light?
    b. Instructor Expectations
        i. Mathematics
            1. What kind of mathematical tools do you think the instructor expects of students entering the Quantum Mechanics course

        2. What mathematical tools do you think will be most important to learning the material in your Quantum Mechanics class?
        3. What classes did you learn these mathematical tools
        4. How comfortable are you with the following:
            a. Ordinary Differential Equations
            b. Matrices or Linear Algebra
            c. Partial Differential Equations
            d. Fourier Series
            e. Integration/Calculus
            f. Trigonometry
    ii. Physics
        1. What type of Physics background do you think the instructor expects of students entering the Quantum Mechanics course?
        2. In which topic in Physics do you think your greatest strength lies?
        3. What physics classes have you taken that you think will help you with Quantum Mechanics?
        4. How would you rate your grounding in the following:
            a. Classical Mechanics
            b. Electricity & Magnetism
            c. Modern Physics

3. Evaluation
    a. If you could chose the way you were evaluated in Quantum Mechanics, what do you think would be the most effective?
    b. How comfortable would you be with the following:
        i. Short Answers
        ii. Class Presentations
        iii. One-on-One conversations
        iv. Written Problems
4. Closing
    a. Is there any other information that you would like to add?
    b. Thank you for your participation in this research.

Appendix E: Student Survey Questions

1. Please rank the following Physics concepts from most important (1) to least important (10) or not applicable for undergraduate students preparing to take PHYS 4810 (Quantum Mechanics).
   - Experimental Motivation for Quantum Physics
   - Wave Mechanics
   - The Lagrangian
   - The Hamiltonian
   - Maxwell's Equations
   - Special Relativity
   - Superposition Principle
   - Interpretation of the Wavefunction
   - Central Forces
   - Idealizations/Generalizations/Assumptions
2. Please explain the motivation for your number one choice above.
3. Please explain the motivation for your number two choice above.
4. Please explain the motivation for your number three choice above.
5. Please rank the following Mathematics skills from most important (1) to least important (15) or not applicable for undergraduate students preparing to take PHYS 4810 (Quantum Mechanics).
   - Solutions by Series

- Ordinary Differential Equations
- Partial Differential Equations
- Integration without Tables
- Trigonometric Identities
- Vector Calculus
- Linear Algebra
- Greens Function
- Eigenvalues & Eigenfunctions
- Hermite Polynomials
- Legendre Polynomials
- Bessel Functions
- Fourier Analysis
- Dirac Delta Function
- Complex Analysis

6. Please explain the motivation for your number one choice above.

7. Please explain the motivation for your number two choice above.

8. Please explain the motivation for your number three choice above.

9. Please select what topics you believe should be addressed in PHYS 4810 (Quantum Mechanics) and to what degree. Note: Not Applicable is defined as a topic that has no bearing on the students understanding of quantum mechanics. Prerequisite is defined as having a student be "familiar" or have "mastered" the topic in a course taken before the QMC. Introduced is defined as having knowledge of

vocabulary and being able to use equations associated with a topic. Familiar is defined as knowledge of a topic that is greater than only vocabulary and definitions, and involves manipulating equations and explaining results. Mastery is defined as having in-depth knowledge of a topic including its conceptual and mathematical origins. Beyond Scope is defined as a topic that should expect to be "familiar" or "mastered" in a course taken after the QMC.

- Angular Momentum
- Dirac Equation
- Experimental Origins
- Fermi's Golden Rule
- Harmonic Oscillators
- Matrix Mechanics
- Operators and Eigenfunctions
- Particle-Wave Duality
- Postulates of Quantum Mechanics
- Potential Well Problem
- Quantum Measurement
- Reflection and Transmission
- Scattering Theory
- Schrödinger's Equation in a Magnetic Field
- Spherical Schrödinger's Equation
- Spinors

- Systems of Identical Particles
- Time-Dependent Perturbation Theory
- Time-Independent Perturbation Theory
- Uncertainty Principle
- Wave Mechanics
- Other: Please Specify

10. If you could offer one piece of advice to an undergraduate student preparing to learn Quantum Mechanics, what would that advice be?

11. Would you consider the following evaluation techniques appropriate for an Upper-Division course, such as Quantum Mechanics? Please tell us why or why not considering a practical and ideal scenario.

    - Multiple Choice Question
    - Short Answer Question
    - Writen Math Problem
    - Student Presentation
    - Oral Examination

Appendix F: Quantum Mechanics Concept Survey

Quantum Mechanics Conceptual Survey

Version 2.0

April 15, 2008

Your performance on this exam will not affect your grade. Your professor will not see your individual score on this exam, only the aggregate scores of the class as a whole.

Note that some questions may deal with topics that have not been explicitly covered in your class. Don't worry about this; just do your best to figure out the answer based on what you know.

Mark all answers on your bubble sheet.

Be sure to fill in your name and identification number on the bubble sheet.

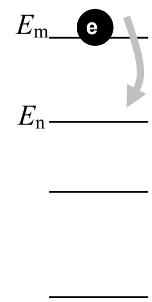
Please answer all questions, and mark only one answer per question.

Your answers should reflect what you personally think.

Plan to finish the 12 questions in 20 minutes.

Thank you!

1. The diagram at right shows the electronic energy levels in an atom with an electron at energy level E_m. When this electron moves from energy level E_m to E_n, light is emitted. The greater the energy difference between the electronic energy levels E_m and E_n …

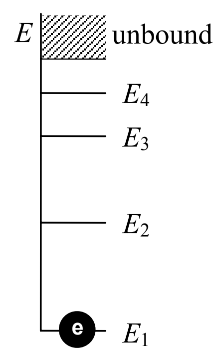


   A. …the more photons emitted.
   B. …the brighter (higher intensity) the light emitted.
   C. …the longer the wavelength (the more red) of the light emitted.
   D. …the shorter the wavelength (the more blue) of the light emitted.
   E. More than one of the above answers is correct.

2. The electron in a hydrogen atom is in its ground state. You measure the distance of the electron from the nucleus. What will be the result of this measurement?

   A. You will measure the distance to be the Bohr radius.
   B. You could measure any distance between zero and infinity with equal probability.
   C. You are most likely to measure the distance to be the Bohr radius, but there is a range of other distances that you could possibly measure.
   D. There is an equal probability of finding the electron at any distance within a range from a little bit less than the Bohr radius to a little bit more than the Bohr radius.

3. An electron in an atom has the energy level diagram at right. The electron is in its lowest energy state, as shown in the diagram. What is the lowest energy photon that it can absorb?



   A. It can absorb a photon of any arbitrarily small energy.
   B. E_1
   C. E_2
   D. $E_2 - E_1$
   E. $E_4 - E_3$

4. True or False: In the absence of external forces, electrons move along sinusoidal paths.

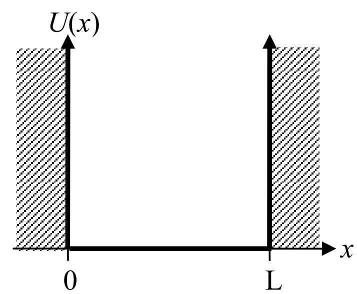
   A. True
   B. False

5. You see an electron and a neutron moving by you at the <u>same speed</u>. How do their wavelengths λ compare?

   A. $\lambda_{neutron} > \lambda_{electron}$
   B. $\lambda_{neutron} < \lambda_{electron}$
   C. $\lambda_{neutron} = \lambda_{electron}$

6. Consider an electron with the potential energy

$$U(x) = \begin{cases} 0 & 0 < x < L \\ \infty & x < 0 \quad or \quad x > L \end{cases}.$$



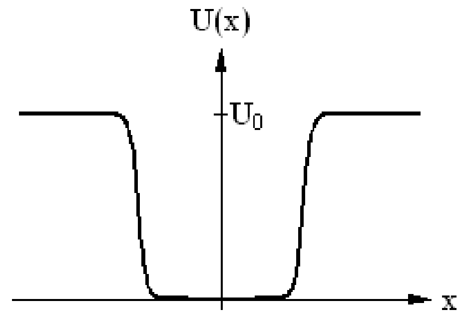
   This potential energy function, plotted at right, is often referred to as an infinite square well or a rigid box. Your electron is in the lowest energy state of this potential energy, with a wave function $\psi(x) = \psi_1(x)$ and a corresponding energy E_1. Suppose you first measure the position of this electron very precisely, without destroying the electron. *After* measuring the position, you measure the *energy* of the same electron. Which of the following statements describes the result of this energy measurement?

   A. The value that you measure will be E_1.
   B. The value that you measure could possibly be E_1.
   C. The value that you measure will *not* be E_1.

7. The total energy of an electron after it tunnels through a potential energy barrier is…

   A. …greater than its energy before tunneling.
   B. …equal to its energy before tunneling.
   C. …less than its energy before tunneling.

For questions 8-9, consider a particle with the one-dimensional potential energy function plotted at right and total energy *E*. The value of potential energy remains the same as x → +∞ or x → –∞.



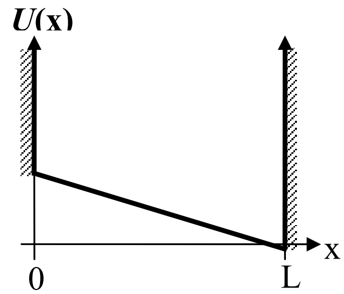
8. Are there any allowed values of the particle's total energy *E* with $E < U_0$, and if so, are all values allowed, or only a discrete set of energy values?

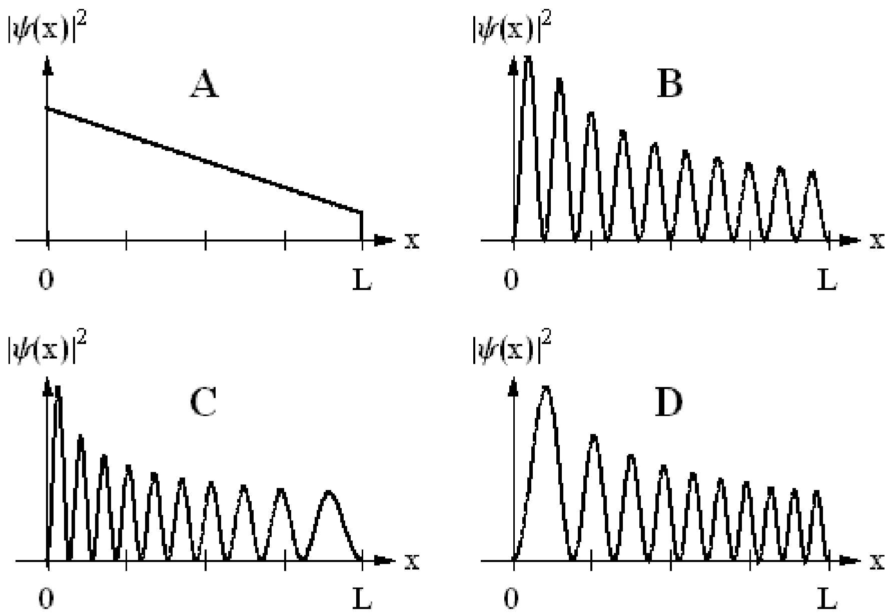
   A. There are no allowed values of energy in this range.
   B. Only certain discrete values of energy in this range are allowed.
   C. All values of energy in this range are allowed.

9. Are there any allowed values of the particle's total energy *E* with $E > U_0$, and if so, are all values allowed, or only a discrete set of energy values?

   A. There are no allowed values of energy in this range.
   B. Only certain discrete values of energy in this range are allowed.
   C. All values of energy in this range are allowed.

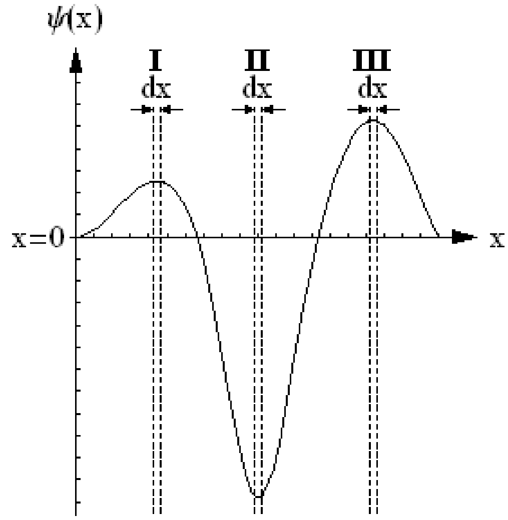
10. The figure at right shows a potential energy function $U(x)$, where the potential energy is infinite if x is less than 0 or greater than L, and has a slanted bottom in between 0 and L, so that the potential well is deeper on the right than on the left. Which of the plots of $|\psi(x)|^2$ vs. x is most likely to correspond to a stationary state of this potential well?





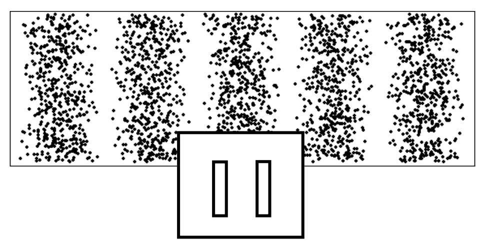
E. More than one of these is a possible stationary state.

11. The plot at right shows a snapshot of the spatial part of a one-dimensional wave function for a particle, ψ(x), versus x. ψ(x) is purely real. The labels, I, II, and III, indicate regions in which measurements of the position of the particle can be made. Order the probabilities, P, of finding the particle in regions I, II, and III, from biggest to smallest.



A. P(III) > P(I) > P(II)
B. P(II) > P(I) > P(III)
C. P(III) > P(II) > P(I)
D. P(I) > P(II) > P(III)
E. P(II) > P(III) > P(I)

12. You shoot a beam of photons through a pair of slits at a screen. The beam is so weak that the photons arrive at the screen one at a time, but eventually they build up an interference pattern, as shown in the picture at right. What can you say about which slit any particular photon went through?



A. Each photon went through either the left slit or the right slit. If we had a good enough detector, we could determine which one without changing the interference pattern.
B. Each photon went through either the left slit or the right slit, but it is fundamentally impossible to determine which one.
C. Each photon went through both slits. If we had a good enough detector, we could measure a photon in both places at once.
D. Each photon went through both slits. If we had a good enough detector, we could measure a photon going through one slit or the other, but this would destroy the interference pattern.
E. It is impossible to determine whether the photon went through one slit or both.