
AC 2011-1904: NSF CCLI: AN APPLIED QUANTUM MECHANICS COURSE ALIGNED WITH THE ELECTRICAL AND COMPUTER ENGINEERING CURRICULUM

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NSF CCLI: An Applied Quantum Mechanics Course Aligned With the Electrical and Computer Engineering Curriculum

Introduction

An Applied Quantum Mechanics (AQM) course was designed and developed for undergraduate Electrical and Computer Engineering (ECE) students at the junior level at The University of Texas at El Paso (UTEP) and was offered to ECE students in place of a Modern Physics course taught by the Physics department. The course was designed to be aligned with the ECE curriculum and stimulating and relevant from the students' perspective. An alignment in the course material was constructed between the Electromagnetic Field course and the Electronic Devices course, the latter being the course that follows the AQM course in the curriculum sequence. The course was designed based on discussions in the literature pertaining to (1) the order the material is introduced, (2) fundamental topics and (3) documented misconceptions.¹⁻⁴ Active learning is a vital component throughout the course and is used to reinforce the learning outcomes for the course. Visualization based on animations, simulations and modeling are used to provide students the opportunity to explore fundamental quantum mechanical concepts in an introductory or applied fashion through a weekly workshop linked to the course lectures. The course was designed to improve the student learning experience with activities that promote improved cognitive and affective behaviors. The evaluation plan consists of 4 assessment tools and will (1) focus on the conceptualization and measures of cognitive functions among ECE students who participate in data collection for the project; (2) examine the impact of the new course on student performance measures, self-assessed learning gains and attitudes, and learning outcomes; and (3) will pin point student misconceptions and student knowledge.

The Applied Quantum Mechanics course was developed during the Fall 2009 semester as a result of an NSF-CCLI grant and was offered to ECE students at UTEP during the Spring and Fall 2010 semesters. A total of 58 students completed the course during this time and 56 of these students participated in the evaluation activities. An estimated enrollment of 35-40 ECE students are expected to enroll for the AQM course during the Spring 2011 semester.

The project's four key objectives are as follows:

1. Improve the cognitive understanding of fundamental quantum mechanics concepts.
2. Improve the affective behavior of students associated with the learning experience of quantum mechanics and motivate them to take senior level Fields and Devices courses.
3. Increase the success, retention and graduation rates of ECE undergraduate students.
4. Increase the number and diversity of students enrolling in Fields and Devices concentration courses, especially female ECE students.

The assessment tools were used to measure the student response to the course in order to improve the students' cognitive understanding, their learning experience, success, and interest in the topic, all of which are tied to the project objectives. Active learning, the use of visual resources and the applied nature of the course are key mechanisms that constitute the course design and learning environment.

Background

The results of a literature review associated with the teaching and learning of quantum mechanics helped to identify critical issues that were addressed when designing the course material for the AQM course at UTEP. Discussions related to (1) the course structure, (2) common misconceptions, (3) the development of concept inventories, and (4) novel teaching tools are prevalent in the literature and their role in the course design was instrumental. A modification of the teaching model described by Jones is used to introduce Quantum Mechanical concepts to Electrical Engineering students in a logical vs. historical sequence where wave theory and the electron's wave-like behavior lead to the derivation of Schrödinger's equation.¹ Classical vs. quantum concepts are clarified throughout the course in order to avoid confusion and common misconceptions as identified by Müller, including a better understanding of photons and the probabilistic nature of electrons.² Several studies that focus on the teaching of Quantum Mechanics also stress the importance of distinguishing between classical and quantum thinking, and this was included in several course themes in order to clear up misconceptions.^{2,3,5} Müller illustrates the use of a Spiral model to teach quantum mechanics, and a conscious effort was made to organize course materials to follow this model (Fig. 1).² Roedel emphasizes the importance of the study of wave theory within the ECE curriculum (electrons and photons exhibit wave behavior and Maxwell's wave equations are used to describe electromagnetic waves), and a brief introduction to waves and wave equations is included in this course.⁶ Bao and Baily discuss the importance of concepts related to probability and probability density in teaching quantum mechanics.^{3,5} In particular, Baily and Finkelstein mention that few students have "the ability to distinguish between classical uncertainty and the uncertainty that is inherent to quantum systems".³ An effort was made to emphasize this concept in the design of the applied course. Finally, there are several sources that mention the importance of applications and/or case studies when attempting to teach quantum mechanical ideas to undergraduate Electrical Engineering students.⁷⁻⁹ The applied role for this course is in the demonstration of fundamental quantum mechanical ideas and how they relate to the physics of electronic devices.

Course Design

Wave mechanics is introduced early in the course and tied to examples of the wave-particle duality of both electrons and photons and the interaction between them. The combination of wave mechanics and the probabilistic nature of the electron are presented prior to a simple example of the derivation of Schrodinger's equation. The meaning of probability density is described in terms of the double-slit experiment as described by Müller and Miller.^{2,10} Schrodinger's time independent equation is used to solve or model simple applied quantum mechanical problems associated with lasers, quantum dots, resonant tunneling diodes and tunneling probabilities.

The AQM course is designed to include the following:

- 1) Alignment of wave behavior, fundamental quantum theory and electric field theory between 3 courses within the ECE curriculum.
- 2) Spiral teaching model.
- 3) Peer led team learning (PLTL) model.
- 4) Daily one-minute essays.

- 5) Daily active learning activities.
- 6) Use of computer simulations and software tools in a workshop.
- 7) Development of a course web page with online resources.
- 8) Development of a concept inventory.

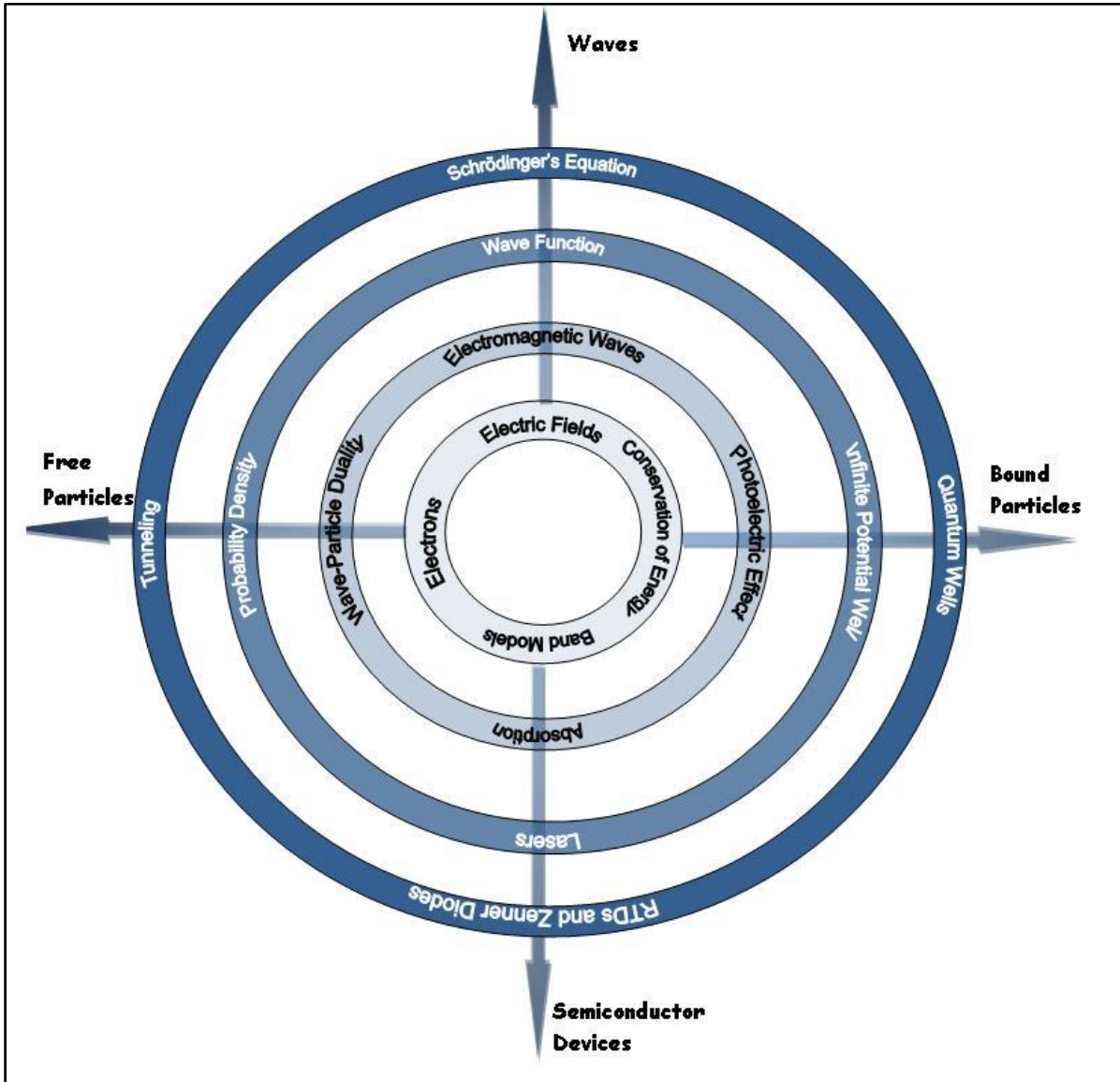


Figure 1: Spiral Model used to connect ideas and teach the AQM course at UTEP

Items 1 (course alignment) and 6 (visual aids) are intended to help students see the relevance of the material to their course of study and to increase their interest in the course material. Items 2 (spiral teaching model), 3 (PLTL model) and 5 (active learning) are aimed at improving the road to comprehensive knowledge in this area as the course progresses, and to improve the learning experience. Item 4 (one-minute essays) provides immediate feedback from students on a daily basis and this is used to develop a database of “frequently asked questions” (FAQs) for the

course webpage associated with the corresponding section. Item 7 (course web page) is intended to provide students with electronic resources that are easily accessible and for future dissemination of course materials. Item 8 (concept inventory) is an ongoing activity that establishes a set of critical concepts students should master in order to form a strong background for future ECE courses in this area, such as the Electronic Devices course, the Advanced Devices course, and graduate level nanotechnology courses.

Select topics from items 1-8 are expanded upon in the sections outlined below and include (1) the alignment of course material and spiral teaching model; (2) peer led team learning; (3) workshops, computer simulations and software tools; and (4) online resources.

1. Alignment of Course Material and Spiral Teaching Model

The Applied Quantum Mechanics course is divided into four parts/areas:

- Part I Electrons and Semiconductors
- Part II Electromagnetic Waves
- Part III Schrödinger Equations and Quantum Applications
- Part IV Advanced Applications of Schrödinger Equations: Quantum Dots, Tunneling, Zener Diodes, Resonant Tunneling Diodes

Within these four areas, themes associated with (1) Waves, (2) Free Particles, (3) Bound Particles and (4) Semiconductor Devices are emphasized. Fig. 1 illustrates the connection between the four overall areas and these four themes. In addition, the workshops give the students an opportunity to explore the concepts learned in class by modeling classical waves, simulating and modeling wave packets, deriving equations for the movement of an electron through an oscilloscope, designing a laser, simulating a quantum dot, and simulating a resonant tunneling diode. The workshops are aligned with the lectures and emphasize (1) the difference between models describing classical waves vs. those for wave packets; (2) the variables affecting the motion of an electron traveling through an electric field; (3) the use of models for photons and electron energies to predict electron-photon interactions in a semiconductor material; (4) the use of Schrodinger's time independent equation to model a confined electron and how that can be used to design a laser fabricated with thin film technology; (5) the use of Schrodinger's equation to model a free electron and how this model can be used to predict wave behavior (Ex. wave interference) and quantum behavior (Ex. tunneling through a barrier). The applied nature is an important component of the applied quantum mechanics course, and the students taking this course during the Spring and Fall 2010 semesters reported that they found this course relevant to their major and that the applied quantum mechanics course would help them in future engineering courses.

2. Peer Led Team Learning

Peer leaders are an integral part of the course dynamics. Peer leaders are chosen based on their performance in the course and based on a demonstration of genuine interest in quantum mechanics. They interact with students during each lecture, providing assistance with class activities and problem solving sessions. They administer a set of 11 workshops that are each

linked to the lectures from the prior week. During weekly meetings with the instructor, peer leaders review and discuss the workshop for the following week and provide feedback and recommendations pertaining to the lecture and workshop from the previous week. Peer leaders also provide the instructor with periodic updates on student progress. The peer leaders have been described by students as helping them learn the course material.

3. Workshops, Computer Simulations and Software Tools

Two hour workshops are designed to provide students with an opportunity to apply knowledge and critical concepts learned during the previous week's lecture. Visual resources such as animations are used as learning tools; modeling and problem solving are used to reinforce concepts; and simulations are used to apply quantum concepts to the operation of electronic devices. Table 1 includes a list of each workshop, the objective for each workshop, and the alignment of the workshop with the lecture course material. The effect of the peer leader experience on the peer leaders themselves has also been documented to be a positive one by Varma-Nelson et al. who reported that "the experience can be a transforming one; not only do they gain a better understanding of the subject, they also become partners with faculty in implementing, documenting, and disseminating".¹¹

Table 1: List of Workshops.

Workshop Description	Type of Workshop	Objective	Alignment with lecture
Double-Slit Experiment	Animation	Explore the particle duality nature of electrons	Wave nature of electrons
Oscilloscope	Derivation and Modeling	Examine the effect of an electric field on the motion of an electron.	Coulomb's Law and relationship between potential, potential energy and kinetic energy of an electron.
Energy Bands in Semiconductors	Modeling and Calculations	Model the carrier concentration in Si as a function of doping	Energy bands, carrier concentration and degenerate semiconductors.
PN Junction	Simulation	Simulation of PN junction energy band diagram and electric field as a function of temperature.	Energy band diagrams of n- and p-type semiconductors and PN junctions
Electromagnetic Wave Parameters	Calculations	Examine the regions of electromagnetic spectrum in terms of wavelength and frequency and relate to the relativistic behavior of electrons.	Particle and wave properties of electrons for classical and relativistic values.
X-Ray Diffraction	Modeling and Calculations	Examine the electron energy required to produce X-rays, X-ray wavelengths and the Bragg condition.	Electron energy-wavelength relationship and interaction of photons and electrons.

Photoelectric Effect	Simulation	Examine the effect of photon intensity and photon energy on the kinetic energy of ejected electrons.	Photoelectric effect, electron photon interaction, relativistic electron velocity calculations.
Wave Packets	Simulation, Calculations and Modeling	Examine how wave packets are formed by the addition of waves and the resulting interference between them.	Wave interference, Fourier Series, Fourier Integral and uncertainty principle
Lasers	Calculations and Derivation	Apply solution to Schrödinger's equation for infinite potential well to determine particle confinement in a laser and Examine energy quantization as a function of well length.	PN Junctions with forward bias, stimulated emission, degenerate semiconductors, Schrödinger equation and particle confinement.
Quantum Dots	Simulation and Calculations	Examine 3-D wave functions, quantized energy values and energy transitions or absorption values for different size Quantum Dots.	Schrödinger equation, infinite potential well example, probability density and normalization condition.
Double Barrier Resonant Tunneling Diode (RTD)	Simulation	Examine the peak bias, peak current and ground state as a function of quantum well width for double barrier RTD.	Schrödinger equation, finite potential well, forward biased PN junctions, degenerate semiconductors, and tunneling.

In preparation for each workshop, students are given a Readiness Assessment Quiz (RAQ) during the first 10-20 minutes of each workshop. Quizzes are graded in class, discussed with group members, and the correct answers are reviewed by the peer leader with some class discussion.

As the student progresses through the lecture and workshops, they work homework problems and model or simulate (1) waves, (2) photoelectric effect and electron relativistic/non-relativistic velocity, (3) biasing of semiconductor junctions, (4) lasers, (5) 3-D quantum dots and (6) resonant tunneling diodes (RTDs), etc. In order to understand the last workshop pertaining to RTDs, students need to comprehend several advanced ideas simultaneously. The RTD involves forward biasing of PN junctions, which results in band bending, this aligns the Fermi level of a degenerately doped semiconductor with the quantized energy level between a double barrier which results in 100% tunneling (see Fig. 2 for illustration of these processes).

4. Online Resources

The software SoftChalk is being used to develop the webpage that will be used to disseminate the course design and materials. The website files will then be uploaded to the nanoHUB.org

website for further dissemination. The course website is organized into mini-lectures and includes course notes, power point slides, useful links, homework problems and “frequently asked questions” (FAQs) links taken from the one-minute essays. Fig. 3 includes examples of screen shots of the web page for Section 2.4 on Probability and Section 1.1 on Conservation of Energy.

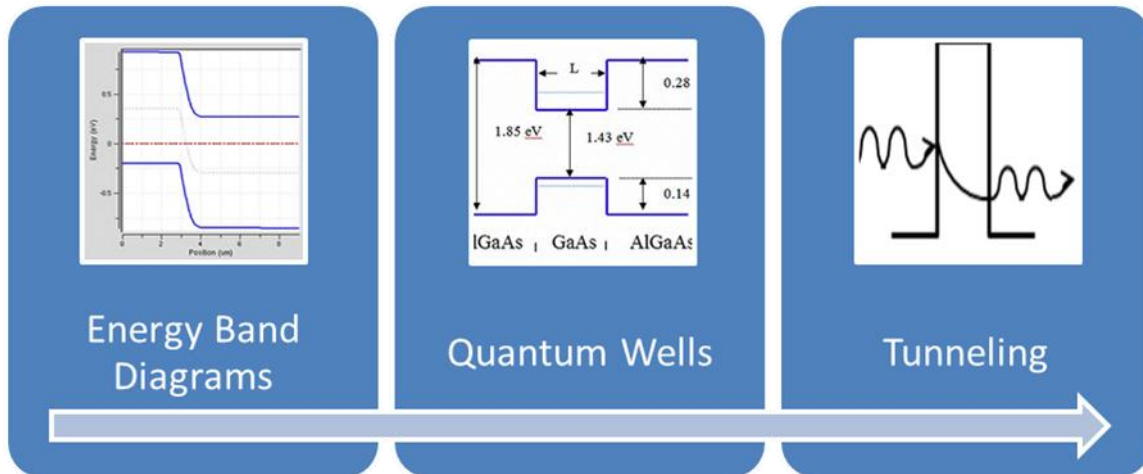


Figure 2: Illustration of key concepts for understanding of the double barrier resonant tunneling diode (RTD) as covered in a series of lectures and workshops.

Evaluation Tools

The evaluation tools used to evaluate the course and monitor the project are described in Table 2 and include (1) How I Work Inventory (HIWI) Tool adapted from H.F. O’Neil and J. Abedi, (2) Work Preference Inventory (WPI) Tool developed by T.M. Amabile, (3) a modified Self-Assessed Learning Gains (SALG) Tool, and (4) a Concept Inventory Tool (tools 3 and 4 are specifically designed for the Applied Quantum Mechanics Course and developed as a result of this project).¹²⁻¹⁴

Cognitive understanding was assessed using the SALG tool and the AQM Concept Inventory Tool (the concept inventory tool is still in the development stage and results using this tool are not reported here). Affective behaviors were evaluated based on the WPI and HIWI tools. As an end of project analysis, the results from the WPI and HIWI tools will be used to test the notion of a Performance Commitment Pathway (PCP) in which motivation and self-regulation of behavior combine to influence achievement.

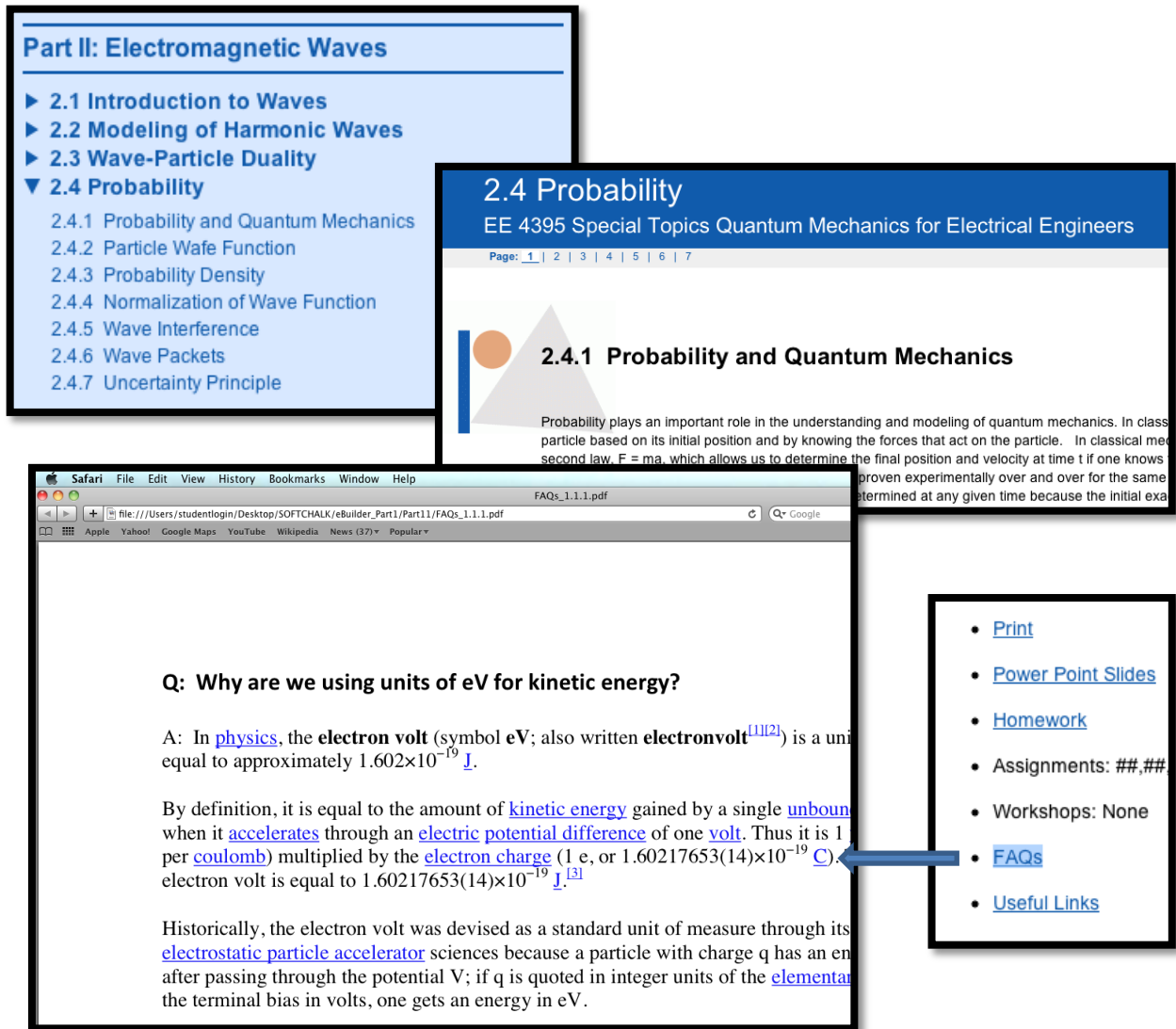


Figure 3: Screen shots from AQM course website showing course sections, course notes, frequently asked questions (FAQs) and links included in each section (Ex. Sections 2.4 and 2.1).

Table 2: Summary of Evaluation Tools.

Evaluation Tool	Description of Tool/ Usefulness of Tool
How I Work Inventory (HIWI)	<ol style="list-style-type: none"> 1. A measure of self-regulation of learning (cognitive strategies, self-checking/planning, confidence, effort, interest, understanding). 2. Will be used to increase the level of interest and confidence and to adjust the level of challenging material for students at the low and high ends.
Work Preference Inventory (WPI)	<ol style="list-style-type: none"> 1. A measure of intrinsic and extrinsic motivation. 2. Will be used when making comparisons between groups.

Self Assessed Learning Gains (SALG)	<ol style="list-style-type: none"> 1. A measure of learning gains, reactions, attitudes, learning activities and resources. 2. Will be used to make adjustments to course in terms of course resources, activities and content.
Focus Groups	<ol style="list-style-type: none"> 1. A measure of learning gains, reactions, attitudes, learning activities and resources. 2. Will be used to make adjustments to course in terms of course resources, activities and content.
Concept Inventory (CI)	<ol style="list-style-type: none"> 1. A measure of concept knowledge and misconceptions. 2. Will be used to make adjustments to course content and material presentation.

Results and Discussion

The results based on the “How I Work Inventory” and “Work Preference Inventory” tools indicate that there is self-reported evidence that most of the students have the motivation and self-regulation habits to contribute to success in accomplishing course and program goals. Also, there is indirect evidence that the initial course design is reasonably well adapted to individual differences.

The percent of student responses at the high end of the scale for the HIWI after the course was taught in the Spring 2010 semester were: cognitive strategy items (85.7%); self-checking and planning items (85.4%); confidence in work in class (72.3%); effort (89.5%); and understanding course material (74.3%). The effect of the course, based on this data alone, is also found in high agreement with the course as increasing their interest (75%), helping them with other courses they will take (80%), and confidence in doing all class activities (84%, if one leaves out confidence in one’s own ability in relation to class average – 39%). This suggests that most students have strong work habits and adaptation to the course as designed, based on self-reports. However, with roughly 10% to 25% of the students reporting at the low end of the variables, course adaptation is required for students at the low end of self-regulation. Also, it suggests an opportunity challenge for students at the high end.

The group of students from the Spring 2010 semester that responded to the WPI on intrinsic and extrinsic motivation, reported being strongly motivated for work driven by intrinsic challenge (60% of item ratings at higher levels), intrinsic enjoyment of the work itself (84% of item ratings at higher levels), and extrinsic motivation such as getting good grades or awards and being aware of that motivation (68% of item ratings at the higher levels). However students reported much less motivation for work being based on extrinsic recognition by others or doing better than others (48% of item ratings at higher levels). For extrinsic recognition, 61% fell in the middle part of the scale. Student reports suggest that they are mostly highly motivated by both grades and intrinsic enjoyment of and challenge in the work itself. However, with up to 40% of the ratings of items at the low end of the scale adaptation is again needed for motivation of these students and opportunity challenges might be taken for students at the high end.

Data from the modified “Self Assessed Learning Gains” survey is presented here for both the Spring and Fall 2010 semesters. Items that were emphasized by the students as helping them

learn the course material include (1) workshops, (2) group discussions, (3) visual resources and (4) peer leaders. The workshops were designed to help the students apply concepts that were introduced in the lecture and practiced through problem solving, modeling or using computer simulations and were rated critical or highly important by 76% of students enrolled in the Spring 2010 semester and by 83% of the students from the Fall 2010 semester. Table 3 includes data pertaining to 3 workshops in which computer simulations of electronic devices were used to help students comprehend the role of quantum mechanics in device physics. The computer simulations consisted of resources available through the NSF Network for Computational Nanotechnology (NCN) supported nanoHUB.org website. The students were asked to rate the workshops and their contribution to their learning of the course material. Table 3 includes the percentage of students that rated the workshops as “critical” or of “high importance” to their learning for the Spring and Fall 2010 semesters.

Table 3: Percent of students reporting the nanoHUB simulations as “critical” or of “high importance”.

Workshop	Spring 2010 N=34-35	Fall 2010 N=20-21
PN Junctions	80%	100%
Quantum Dots	80%	90%
Resonant Tunneling Diodes	88%	80%

The students in the applied quantum mechanics course were also asked to report on the impact the nanoHUB computer simulation workshops had in increasing their interest in quantum mechanics and semiconductor devices. Table 4 includes the percent of students that “strongly agree” or “agree” that the workshops had a positive influence on their interest.

Table 4: Percent of students reporting that the nanoHUB simulations increased their interest in quantum mechanics and semiconductor devices (responded “Strongly Agree” or “Agree” with this statement).

Workshop	Spring 2010 N=36	Fall 2010 N=20-21
PN Junctions	67	76
Quantum Dots	56	67
Resonant Tunneling Diodes	61	70

In addition, 71% of the students in Spring 2010 (N=34) and 86% of the students in Fall 2010 (N=21) reported that they felt more confident about their understanding of quantum mechanics and semiconductor devices as a result of using the nanoHUB simulation tools (PN Junctions, Quantum Dots, and Resonant Tunneling Diode).

Group discussions were rated as excellent or good by 86% of the students from the Spring 2010 semester and by 100% of the students from the Fall 2010 semester. The usefulness of the group discussions was mentioned by the students that took the course in the Spring 2010 semester and an effort was made to include at least one group activity during every lecture during the Fall 2010 course. Visual resources were rated excellent or good by 83% of the Spring 2010 students and 81% of the Fall 2010 students. Assistance from the peer leaders was rated as excellent or

good by 73% of students from the Spring 2010 semester and by 81% of students from the Fall 2010 semester.

Another component of this project is to examine the time gap between student enrollment in Quantum Mechanics and Electronic Devices (in number of semesters). The Electronic Devices course is the course that follows the Applied Quantum Mechanics course in the “Fields and Devices” curriculum sequence. Based on student enrollment data, 38% of students from the Spring 2010 AQM course (N=37) enrolled in Electronic Devices during the Summer 2010 or Fall 2010 semesters, and an additional 30% enrolled in Electronic Devices during the Spring 2011 semester. For the Fall 2010 students (N=21), 48% of students enrolled in Electronic Devices during the Spring 2011 semester. Therefore, the time gap for the Spring 2010 students was zero semesters for 38% of students and one semester for 30% of the students. Likewise, the time gap for the Fall 2010 students was zero semesters for 48% of the students. By comparison, the average time lapse between student enrollment in the previous Modern Physics course and the Electronic Devices course was 3.4 semesters based on data from Fall 2003 - Fall 2007 (N=457).

Conclusion

Most of the students that enrolled in the AQM course during the Spring and Fall 2010 semesters found discussions between students in a group and the use of visual resources as being very useful to them. However, a significant number of students (~20%) did not see these activities as useful for learning (Spring 2010). It is therefore important to improve the strategies that are used to enhance student participation within their groups. Emphasis on teamwork and team building activities should occur throughout the semester in order to improve student attitudes and participation. Peer leader involvement during the lecture is believed to be an important role for the success of students, and this relationship carries over to the workshop which is developed by the instructor but lead by the peer leaders. The majority of students reported that the AQM course would help them in future Electrical Engineering courses and that their interest in quantum mechanics improved as a result of the course.

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