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General Education Course in Intuitive Quantum Physics

Michael C. Wittmann

Principal Investigator; University of Maine, Orono

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Final Report for Period: 09/2006 - 08/2007**Submitted on:** 12/05/2007**Principal Investigator:** Wittmann, Michael C.**Award ID:** 0410895**Organization:** University of Maine**Title:**

A General Education Course in Intuitive Quantum Physics

Project Participants**Senior Personnel****Name:** Wittmann, Michael**Worked for more than 160 Hours:** Yes**Contribution to Project:****Post-doc****Graduate Student****Name:** Black, Katrina**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Curriculum adaptation and development. Research work on student understanding of the Schrödinger equation

Name: Feeley, Roger**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Curriculum adaptation and development. Emphasis on new equipment and experiments. Research work on student understanding of probability and probability density. Paper writing.

Name: Morgan, Jeffrey**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Lead developer besides PI. Curriculum adaptation and development. Research on student understanding of quantum tunneling, oversight of entire development process, second-in-charge of entire research, development, and teaching program.

Name: Sayre, Eleanor**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Curriculum adaptation and development. Emphasis on computer programming and development of conceptual tutorials. Team leader at one phase of project. Research work on student understanding of basic ideas in mathematics and physics.

Undergraduate Student**Technician, Programmer****Other Participant****Research Experience for Undergraduates****Organizational Partners****Other Collaborators or Contacts**

The most important test-use collaboration was with Jamie Vesenka of the University of New England. He spent a semester teaching using our IQP materials while on sabbatical at UMaine. During that time, we had regular conversations about the mindset behind the course, the development of ideas within the course, and the role of epistemology and the teaching of the nature of science in a course such as the IQP. In addition, he sat as outside reader on Jeff Morgan's PhD on the development of materials for teaching quantum tunneling and research into student understanding of tunneling. (The defense came just before Prof. Vesenka taught on tunneling, fortuitous and useful timing.)

The most important development-oriented collaboration was with Rachel E. Scherr at the University of Maryland, source of the Learning How to Learn materials. Regular conversations were required as we struggled to understand some of the guiding elements of the work that they are doing at UMaryland, whose spirit we were trying to adopt at UMaine.

Adaptation of materials from the existing Activity-Based Tutorials (of which I was co-developer) required no collaboration! But, the adaptation of materials from the Tutorials in Introductory Physics occurred in collaboration with my UMaine colleague, John R. Thompson (a former post doc at the University of Washington, where the Tutorials in Introductory Physics are developed).

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:

The four students most involved in this project developed major curriculum writing skills. An entire set of materials was created for a full semester's worth of small group learning activities. Students developed 15 tutorials, at 3 hours each; all the associated equipment and materials to go with each tutorial; and developed the pedagogical expertise on how to teach using the materials. Since one round of development and teaching are typically insufficient for good instruction, it is notable that all these students participated in a second (and often third) round of development in which lessons from the previous year were used to modify and adapt the materials, so as to better match student needs in the course. Thus, students were involved in a full cycle of curriculum development, instruction, semi-systematic observation of classroom events, and curriculum modification, all in the interests of creating the best possible course for students.

Outreach Activities:

Outreach activities are measured in several ways, including workshops given at the state and local level, and poster, contributed, and invited presentations which showcase either the curriculum itself or the research that went into developing the curriculum.

Workshops:

1. Building models of probability and probability density, M.C. Wittmann, Twenty-seventh state-wide meeting of high school physics and physical science teachers, Orono ME, 2007 March.
2. Intuitive Quantum Physics, M.C. Wittmann, J.T. Morgan, 134th AAPT National Meeting, Seattle WA, 2007 January
3. Building Models of Probability and Probability Density, J.T. Morgan, K.E. Black, and M.C. Wittmann, Twenty-sixth state-wide meeting of high school physics and physical science teachers, Orono ME, 2006 March.
4. Listening to Students Differently: A Dialog Between Science and Humanities, M.C. Wittmann, Teacher Talk for the Center for Teaching Excellence, University of Maine, 2006 February.

Posters:

1. A Longitudinal Study of Student Learning of Quantum Tunneling, J.T. Morgan, M.C. Wittmann, Physics Education Research Conference, Salt Lake City UT, 2005 August.
2. Nearly Novel Situations, E.C. Sayre and M.C. Wittmann, Physics Education Research Conference, Salt Lake City UT, 2005 August.
3. General Education Students' Understanding of Quantum Wavefunctions, M.C. Wittmann, Physics Education Research Conference, Salt Lake City UT, 2005 August.
4. A Survey to Investigate Student Understanding of Quantum Tunneling, J.T. Morgan, M.C. Wittmann, Physics Education Research Conference, Sacramento CA, 2004 August.

Contributed presentations:

1. Intuitive Quantum Physics, Quantum Without the Mathematics, J.T. Morgan and M.C. Wittmann, Twenty-sixth state-wide meeting of high school physics and physical science teachers, Orono ME, 2006 March.
2. Reshaping Curriculum to Improve Student Understanding of Quantum Tunneling, J.T. Morgan, M.C. Wittmann, 131st AAPT National Meeting, Salt Lake City UT, 2005 August. The Announcer 35(2) 103.
3. General Education Students' Understanding of Bound State Quantum Wavefunctions, M.C. Wittmann, J.T. Morgan, K. Black, and R.P. Springuel, 131st AAPT National Meeting, Salt Lake City UT, 2005 August. The Announcer 35(2) 104.
4. Conceptual Learning in a General Education Quantum Physics Course, M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. The Announcer 34(2) 172.
5. A Survey to Investigate Student Understanding of Quantum Tunneling, J.T. Morgan, M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. The Announcer 34(2) 172.

Invited presentations:

1. Using Learning Theories to Model Students' Conceptual Changes, M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. The Announcer 34(2) 114.
2. Comparing Instructional Modes: One Element of Physics Education Research, M.C. Wittmann, colloquium, College of Education and Human Development, 2006 May.
3. Comparing Curricula to Study Student Learning, M.C. Wittmann, NES joint meeting of the APS and AAPT, Boston MA, 2006 April.

Non-documented outreach activities:

It is important to add that some events aren't easily listed in a set of workshops, posters, and talks. (Please also see the publications listed in another part of this report, for example.) One of the big sources of outreach has been through the annual Maine High School Physics Teachers meeting, run by the University of Maine either by the PI or his colleague, John Thompson. During these meetings, we have ample opportunity to talk about physics with teachers who might then use some of our materials in their classroom. Between 20 and 40 teachers attend this meeting every year.

Another source of outreach is the Maine High School Physics Teachers Collaborative, run with monthly meetings by John Thompson. By request of the teachers, we had a meeting in which our teaching materials for quantum physics were showcased and discussed. The topic arose at many other Collaboratives meetings, as well. Between 5 and 10 teachers attend on a monthly basis, and the PI was heavily involved in these discussions, getting feedback from the teachers on materials used in the classroom, for example.

Finally, we shared our materials during a poster session organized for the Knowles Science Teaching Fellows. During this time, several of the new Knowles Fellows requested information about the materials. The entire package of Intuitive Quantum Physics materials was shared with roughly 60 teachers.

In each case, it is hard to impossible to know the impact that sharing our materials has had.

Journal Publications

Wittmann, Michael C., Morgan, Jeffrey T., and Feeley, Roger E., "Laboratory-Tutorial activities for teaching probability", Physical Review Special Topics Physics Education Research, p. 020104, vol. 2, (2006). Published, 10.1103/PhysRevSTPER.2.020104

Wittmann, Michael C., "Using resource graphs to represent conceptual change", Physical Review Special Topics Physics Education Research, p. 020105, vol. 2, (2006). Published, 10.1103/PhysRevSTPER.2.020105

Wittmann, Michael C., "Lab-Tutorials für den Quantenphysik Unterricht", Praxis der Naturwissenschaften ? Physik, p. 16, vol. 55:4, (2006). Published,

Wittmann, Michael C., Morgan, Jeffrey T., and Bao, Lei, "Addressing student models of energy loss in quantum tunneling", European Journal of Physics, p. 939, vol. 26, (2005). Published,

Morgan, Jeffrey T. and Wittmann, Michael C., "Examining the Evolution of Student Ideas About Quantum Tunneling", AIP Conference Proceedings 818, 2005 Physics Education Research Conference Proceedings, p. 73, vol. 818, (2006). Published,

Morgan, Jeffrey T. and Wittmann, Michael C., "Student Understanding of Tunneling in Quantum Mechanics: Examining Interview and Survey Results for Clues to Student Reasoning", AIP Conference Proceedings 720, 2003 Physics Education Research Conference Proceedings, p. 97, vol. 720, (2004). Published,

Wittmann, Michael C. and Morgan, Jeffrey T., "Understanding Data Analysis from Multiple Viewpoints: An Example from Quantum Tunneling", AIP Conference Proceedings 720, 2003 Physics Education Research Conference Proceedings, p. 3, vol. 720, (2004). Published,

Books or Other One-time Publications

Web/Internet Site

URL(s):

<http://perlnet.umaine.edu/iqp/>

Description:

We have shared this URL with the largest disseminator of web published materials in the physics teaching and PER communities: PER-CENTRAL, which is part of the ComPADRE online National Digital Library.

All materials created under the project have been placed online in printable PDF and editable Word DOC formats, under a Creative Commons 2.5 license allowing derivative products for non-commercial use and requiring attribution. In addition, we have asked that users contact us when using the materials.

We have strived to make a simple web site that can be used by many of the computers struggling to deal with the "modern web." We've used simple coding and very sparse links throughout. The header cells are common across the site, emphasizing student materials, instructor materials, workshop materials that people might want, and research into student learning that might help users. We have found in other projects as well as this one, for example, that teachers often do not need the specific materials but are as interested in the research into student learning that underlies the materials.

Other Specific Products

Contributions

Contributions within Discipline:

As my principal disciplinary field, I use physics education research, including both the teaching of physics and the understanding of how students learn physics. Contributions within the discipline can be measured in three areas: teaching, research, and development.

Teaching:

New curricula for teaching quantum physics have been created in a way that allows high school teachers to use new and proven

teaching methods in a way that matches their students' needs. Also, my own physics department has responded with high praise on the topic of teaching a guided inquiry course on quantum physics to general education, non-science students at UMaine. Materials, especially those on probability and probability density, have been used in other UMaine courses as well as courses at other institutions, for example.

Research:

The discipline of physics education research has, sadly, too few people doing too many different kinds of work in different areas. Nobody else in the field is doing work on student learning of quantum physics at the pre-introductory level. Our findings, whether on student reasoning about tunneling, probability, wave-particle duality, the shape of the wave function, or any other of many topics, extend the work of physics education research to new areas. The research methods we used, including videotaping classroom activities and new types of exam questions, also help extend the discipline.

Development:

It is always encouraging to have new materials developed that can be shared with others. We are part of a growing movement of open source curriculum development. Thus, our contribution to the discipline is to add our voice to those who believe that web publishing with modifiable materials is the best route for sharing information (We can even create enough appropriate publicity among our intended audience, which the large publishing houses sadly often don't give but which can be done independently.)

Contributions to Other Disciplines:

No known contribution has been made, since much of the disseminated information has not received feedback (for example, from publications or workshops) from people in other disciplines. The publication of the European Journal of Physics paper was honored as one of the most read articles of the EJP in its publication year, implying that many physicists read the paper. Thus, the effect could be found outside of the field of physics education research in the field of traditional research physics, as well.

Contributions to Human Resource Development:

Four students were centrally involved in course development as part of this project. This work was described above in the section on Training and Development.

It is notable that two of these students have moved on to prestigious positions in academia. Jeffrey T. Morgan is now assistant professor in physics and in science education at the University of Northern Iowa. Eleanor C. Sayre has taken a post doc position at the Ohio State University. Both Morgan and Sayre received their PhD in physics from the University of Maine, with the work on the IQP project forming a major part of

their skills as they graduated.

The other two students are still graduate students at the University of Maine, working toward a PhD in physics education research. One, Katrina Black, is teaching the IQP course this year as the PI is on sabbatical. Such instruction can have an immense impact on a student's development, but (as we are in the middle of the semester) the effect is as yet unclear.

Contributions to Resources for Research and Education:

Other parts of this report describe the publications, workshops, posters, and presentations related to this project. Also, outreach activities (to the Knowles Science Teaching Foundation, the University of New England, and through publication in Germany to the teachers of an entirely different country) should be highlighted.

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Organizational Partners

Any Book

Any Product

Contributions: To Any Beyond Science and Engineering

Final report: Intuitive Quantum Physics

DUE 0410895: A general education course in Intuitive Quantum Physics

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Participants

Participants

Details are listed in the online forms. The students involved in the project were (in alphabetical order):

Katrina E. Black.
Roger E. Feeley
Jeffrey T. Morgan
Eleanor C. Sayre.

Of these, Jeff Morgan deserves special credit. He was lead developer (beyond the PI) and took a large leadership role in the project at different times. While we were in our largest development phase, he had oversight of all the development teams, while the PI oversaw the process. Metaphorically, he acted as a post doc while still a graduate student.

Organizations

There were no major collaborations with other organizations.

Collaborations

The most important test-use collaboration was with Jamie Vesenka of the University of New England. He spent a semester teaching using our IQP materials while on sabbatical at UMaine. During that time, we had regular conversations about the mindset behind the course, the development of ideas within the course, and the role of epistemology and the teaching of the nature of science in a course such as the IQP. In addition, he sat as outside reader on Jeff Morgan's PhD on the development of materials for teaching quantum tunneling and research into student understanding of tunneling. (The defense came just before Prof. Vesenka taught on tunneling, fortuitous and useful timing.)

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Adaptation of materials from the existing Activity-Based Tutorials (of which I was co-developer) required no collaboration! But, the adaptation of materials from the *Tutorials in Introductory Physics* occurred in collaboration with my UMaine colleague, John R. Thompson (a former post doc at the University of Washington, where the *Tutorials in Introductory Physics* are developed).

Activities and Findings

Project Goals

Our goals when starting this project were to take two leading curricula, the *Activity-Based Tutorials* and the *Tutorials in Introductory Physics*, and adapt them to use in a non-science-major course, such that these generally math-phobic students would learn quantum physics. We later took some teaching innovations from the *Modeling Method* of instruction, as well. We used, as our guiding structure, the University of Maryland *Learning How to Learn* project, in which issues of epistemology (“how do you know what you know?”) determine the topic of learning. Thus, we were to create a series of primarily laboratory activities for instruction 3 hours per week, using a guided inquiry approach, and spending as much time helping students on why they believed their answers as getting them (conceptually) to the answers themselves. Our long term deliverable on the project was to be a complete set of teaching materials which would be freely available to all interested users.

Activities

The project goals were to create a series of research-based curriculum materials appropriate for teaching wave and quantum physics to students who are typically math phobic and are only taking the given course as a required laboratory science course at the University of Maine. The population, colloquially speaking, is not excited to be in the classroom.

The major activities of the project lay in creating a series of laboratory teaching materials (“lab-tutorials”) that could be used in such a setting. These materials were designed to assume that students came in with no background knowledge of wave physics or quantum physics, but very much did have basic ideas which are necessary for learning both topics *and* for misinterpreting observations which would be used to push their thinking forward.

Materials were adapted from the *Activity-Based Tutorials* (Wittmann, Redish, Steinberg, and the University of Maryland Physics Education Research Group) and the *Tutorials in Introductory Physics* (McDermott, Shaffer, and the University of Washington Physics Education Group), as well as the *Modeling Method* (Hestenes, Wells, and Swackhammer, at Arizona State University), all in the mindset of the University of Maryland *Learning How to Learn* project. A central part of our course development was the adaptation of the French & Taylor method of graphical solutions to the Schrödinger Equation to a non-mathematical audience. The course used the Schrödinger Equation in the form:

$$\text{Curv}\psi = -k(TE - PE)\psi$$

Here, the “curviness of the wave function” was the name given to the second spatial derivative of the wave function. The other terms are from the typical Schrödinger equation, written in terms of the constant k (which subsumed all constants related to mass and Planck’s constant) and the total energy of the particle, TE , and the potential energy of the particle-system interaction, PE . Using this method and several “rules” which constrain how you draw a wave function (“no kinks” and “finite area under the curve”), students were able to draw bound state wave functions that had parts that looked sinusoidal or that looked exponential. Several weeks of activities went into teaching them these skills.

Research was carried out on various parts of the course to help us understand which materials were succeeding and which were hopelessly in need of change. In our first draft of materials, many needed changing; by the end, as we worked out kinks in the program, things were better.

The lab-tutorials and instructor materials have been posted online, freely accessible to all interested users and made public under a Creative Commons License modeled on the open source software movement. We use a derivative products, non-commercial, attribution license.

Student Materials

The lab-tutorials developed for the course are shown in Figure 1. Students were also given the pretests and post-tests at appropriate times. These are listed with the instructor materials, in Figure 2.

First-time development of these materials was carried out primarily in teams. Two teams worked in staggered format to create every other week's materials. Jeff Morgan headed one team and Eleanor Sayre the other; the PI was in charge of the whole process and guided each team appropriately, as needed.

The development cycle was as follows. A team would work alone (including with PI assistance) on a lab-tutorial for one week. Early in the second week of development, the tutorial would be viewed by all course developers. Feedback was given. Later in that week, the revised tutorial would be reviewed again, and any changes necessary to best match student needs would be incorporated. The tutorial was finished, and the full development team would review it, this time from the perspective of *facilitating instruction* using these materials. Any last-second changes would be made, though the effort was one of translating pedagogical intent into classroom actions. Lab-tutorials were developed in staggered form, so that one team was always presenting its materials while the other team was working more privately on theirs.

Tutorial: Seeing the same things as other people.....	p. 1
Homework.....	p. 11
Tutorial: Waves passing through.....	p. 13
Homework.....	p. 25
Handout.....	(to be passed out separately)
Tutorial: Analogies connecting light and waves.....	p. 27
Homework.....	p. 39
Handout.....	(to be passed out separately)
Tutorial: Doing impossible things.....	p. 41
Homework.....	p. 51
Tutorial: Probability.....	p. 53
Homework.....	p. 69
Tutorial: Energy.....	p. 73
Homework.....	p. 83
Handout.....	(to be passed out separately)
Tutorial: Energy and probability.....	p. 85
Homework.....	p. 101
Tutorial: Curviness.....	p. 105
Handout.....	p. 125
Homework.....	p. 127
Tutorial: Physically possible wavefunctions.....	p. 129
Homework.....	p. 137
Tutorial: Bound states and more impossible things.....	p. 139
Homework.....	p. 145
Tutorial: Excited States.....	p. 147
Homework.....	p. 163
Tutorial: Modeling Molecules.....	p. 165
Homework.....	p. 175
Tutorial: Tunneling – A quantum mechanical consequence.....	p. 179
Homework.....	p. 191
Handout.....	(to be passed out separately)
Tutorial: Modeling Radioactivity.....	p. 193
Handout.....	(to be passed out separately)

Figure 1: Student Materials, including list of tutorials, handouts, and topics covered. Please see notes for additional detail on sources of adapted materials.

Notes to Figure 1:

- Pages 1-4 are lightly adapted from McDermott, L. C., Shaffer, P. S., & The Physics Education Group at the University of Washington. (2002). *Tutorials in Introductory Physics*. Upper Saddle River, NJ: Prentice Hall.
- Pages 6-9 are lightly adapted from Redish, E. F., Hammer, D., & Elby, A. (2001-2003). *Learning How to Learn Science: Physics for Bioscience Majors*: NSF grant REC008-7519.
- Pages 13-17 are adapted from Wittmann, M. C., Steinberg, R. N., & Redish, E. F. (2004). *Activity- Based Tutorials Volume 1: Introductory Physics*. New York: John Wiley & Sons, Inc.
- Pages 19-21 are adapted from McDermott, L. C., Shaffer, P. S., & The Physics Education Group at the University of Washington. (2002). *Tutorials in Introductory Physics*. Upper Saddle River, NJ: Prentice Hall.
- Page 28 is adapted from McDermott, L. C., Shaffer, P. S., & The Physics Education Group at the University of Washington. (2002). *Tutorials in Introductory Physics*. Upper Saddle River, NJ: Prentice Hall.
- Pages 47-48 refer to a simulation taken from Joffre, M. (2002), *Quantum Mechanics CD*, Berlin Heidelberg: Springer-Verlag, which accompanies Basdevant, J.-L., and Dalibard, J. (2002) *Quantum Mechanics*. Berlin Heidelberg: Springer-Verlag.
- Question B on the pretest to p. 73 is taken from the *Wave Diagnostic Test*, M.C. Wittmann, 1998 (unpublished PhD dissertation, University of Maryland).
- The simulations used on p. 79-80 are taken from the *PhET-Simulations* , located at <http://phet.colorado.edu/web-pages/index.html>.
- The activities on p. 87-96 are designed to be used with *Pasco DataStudio*. They can easily be modified for use with other data acquisition hardware and software.
- The software used on p. 150-153 and on p. 163-164 was developed at the University of Maryland by Rebecca Lippmann Kung and Michael C. Wittmann. It is based on *Physlets*; more information can be found at <http://webphysics.davidson.edu/Applets/Applets.html>.

Instructor Materials

For each of the given tutorials, there are also instructor materials. These are listed in Figure 2.

Tutorial: Seeing the same things as other people.....	Pre-lab and post-lab materials taking from <i>Tutorials in Introductory Physics</i> and not available
Tutorial: Waves passing through.....	Pre-lab and Post-lab
Tutorial: Analogies connecting light and waves.....	Pre-lab and Post-lab
Tutorial: Doing impossible things.....	Pre-lab and Post-lab
Tutorial: Probability	Pre-lab
Tutorial: Energy	Pre-lab
Tutorial: Energy and probability	Pre-lab and Post-lab
	DataStudio files for use ramps, carts, and magnets.....
Tutorial: Curviness.....	Pre-lab and Post-lab
	Drawing tool (for editing circles and transparencies)
Tutorial: Physically possible wavefunctions.....	Pre-lab and Post-lab
Tutorial: Bound states and more impossible things.....	Post-lab
Tutorial: Excited States	Pre-lab
Tutorial: Modeling Molecules.....	Pre-lab
Tutorial: Tunneling – A quantum mechanical consequence.....	Pre-lab
Tutorial: Modeling Radioactivity	Pre-lab and Post-lab
	Graphs for modification.....

Figure 2: Instructor materials for Intuitive Quantum Physics.

The Instructor materials found online include all necessary computer files (but one, which is copyrighted - similar materials can be found easily online) and pdf and Word.doc versions of materials. The largest lack of assistance for outside users, at the moment, are a series of course descriptions which help future users get a foothold on how to use these materials in their own classroom. The descriptions exist and are part of Jeff Morgan's Ph.D. dissertation, but they have not yet been placed online and made a part of the whole package of materials. We plan to address this lack (found only while writing the final report) in the near future. Furthermore, a publication of such a description is planned in appropriate journals, letting us both publicize the materials and give users an easily accessible source of information about the course.

Research activities

In addition to the materials adapted from existing materials (as shown in the Notes to Figure 1) or created at UMaine while using the mindset and framework of the UMaryland *Learning How to Learn* materials, there was also a major effort to carry out research on the types of learning students were participating in and the level of understanding they were attaining.

These findings are listed in other parts of this document, but should be highlighted here. During the course of this project, there were 4 workshops (1 national, 3 statewide) presenting both materials and research findings, 4 posters, 5 contributed talks, and 3 invited talks, all highlighting the different elements of this project. In addition, we published 7 papers, including 2 in the new *Physical Review Special Topics Physics Education Research* and 1 in the *European Journal of Physics*. Furthermore, one paper was published in a German journal that is read by teachers in Germany, much like *The Physics Teacher* is read by teachers in the United States.

The project supported the research and development beyond one Ph.D. dissertation (Jeff Morgan), as well.

Findings

To present all the research findings from our project, as given in our presentations and publications, is far beyond the scope of a final report, and can be supplanted through the publications themselves. Certain findings have not been published, though, and are important for measuring the success of the project.

Class retention

Before the start of the project, the *Descriptive Physics* course at UMaine had been suffering a constant decrease in students enrolled in the course. This was one of the motivations for redesigning the course. By the time the PI took the course over, only 45 to 50 students a semester were enrolling in *Descriptive Physics*. This was down from a high of over 100, and much lower than the possible 80 for which classrooms were designed (the enrollment of 100 had been when other classrooms had been in use). In addition to the low enrollment, there was a very high attrition rate in past versions of the *Descriptive Physics* course. At times, the course ended with under 20 students.

Both problems were addressed by the new course design. First, enrollment rose steadily. From the first year of implementation to the 3rd (and now into the 4th), enrollment rose from the

mid-40s to the mid-70s. Before the semester starts, the course is fully enrolled, with a few students dropping out before the first day of class (as typically happens in university courses as other course openings arise) and enrollments are in the high 70s.

Second, the drop out rate dropped, nearly instantly, from over 50% of enrolled students to less than 5%. For a course with 50 students, only 1 or 2 would drop out, typically for reasons independent of the course and instead for personal reasons that were discussed with the instructor before leaving the course. With the higher enrollment, drop-out rates remained low, under 10%.

We attribute these changes to a mix of effects, though we have no direct evidence for them (such evidence would have required a major sociological study outside the financial constraints of this project). First, students received personal attention in the course of their long lab-tutorial periods, ensuring that concerns could be aired easily during instruction. Second, instruction was completely student-centered, once the outline of topics was presented. The pace of instruction was always adjusted to match the needs of students, such that students could feel that their needs were being met and their learning was of more importance than getting through some set amount of course content. (This last point was often explicitly stated during lecture instruction.) Third, it must be admitted that students worked through the material very slowly. For example, they used no mathematics, and did in 4 weeks what might be covered in 1 week of an introductory physics course that had not just conceptual but also mathematical content. So, students were challenged mentally (many pointed out how hard the course was) but were supported structurally.

Learning the physics

As stated above, it is difficult to summarize all our results in a single document such as this one. We highlight two results, among many, showcasing the conceptual learning and results about attitudes toward physics and the nature of science.

1. Understanding quantum tunneling.

It is hard to overstate how difficult this topic seems to be for students. We made a special effort to make it from wave physics through bound states (with finite square wells whose energy diagrams can be explained through metaphor in the real world) to molecules and quantum tunneling. The idea was specifically to connect to the research work being done on campus by our Laboratory for Surface Science Technology (LASST). Our hope was that students would come away with an appreciation of what kind of scientific research occurs on campus, even if they themselves were in the humanities, for example.

We have found, as summarized in our *European Journal of Physics* article, that students typically use a very material sense of tunneling to discuss both the physics and the mathematics describing tunneling. So, for example, a tunneling particle loses energy because it is passing through a barrier. One student, in an interview, stated “it’s like a snowball passing through a snowbank,” describing that it came out moving slower on the other side. Such energy loss reasoning is prevalent throughout instruction, from our course to sophomore level modern physics students to senior level physics majors taking a course in quantum mechanics. Jeff Morgan, in his Ph.D., investigated how student reasoning about the ideas changed with time, carrying out a longitudinal study of physics majors on this topic. Part of his work included the

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We found that our students, the non-science majors who were afraid of math, were better able to answer questions about tunneling than were the sophomore *and* the senior physics students! Their instruction was not focused on energy loss, but the tools they used in the course, specifically the graphical analysis of wave functions, helped them to better understand the basic physics behind the problem.

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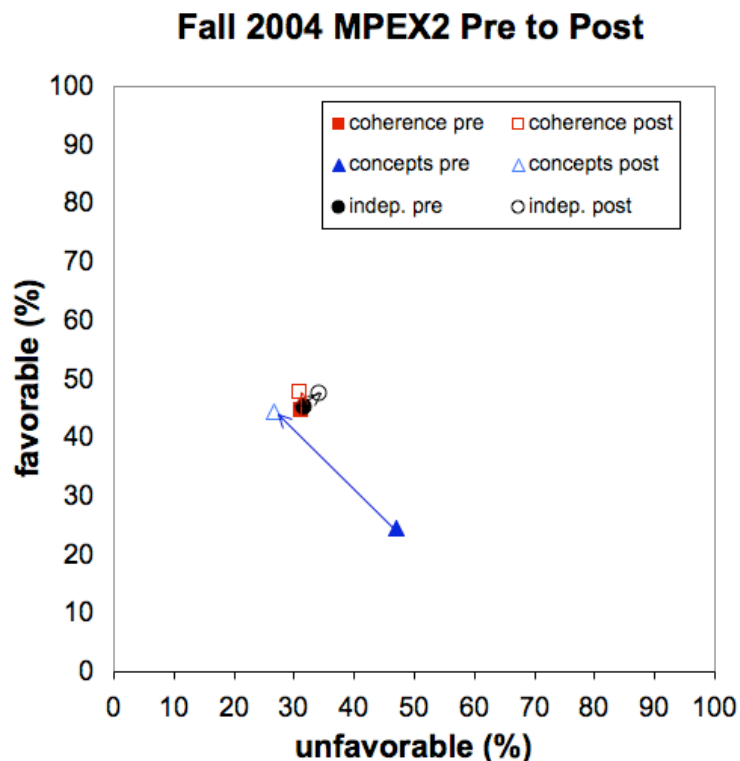


Figure 3: MPEX 2 data from the University of Maine, showing increases in student expectations. Students start with particularly low attitudes about the conceptual basis of physics and improve, unexpected for a course on quantum physics

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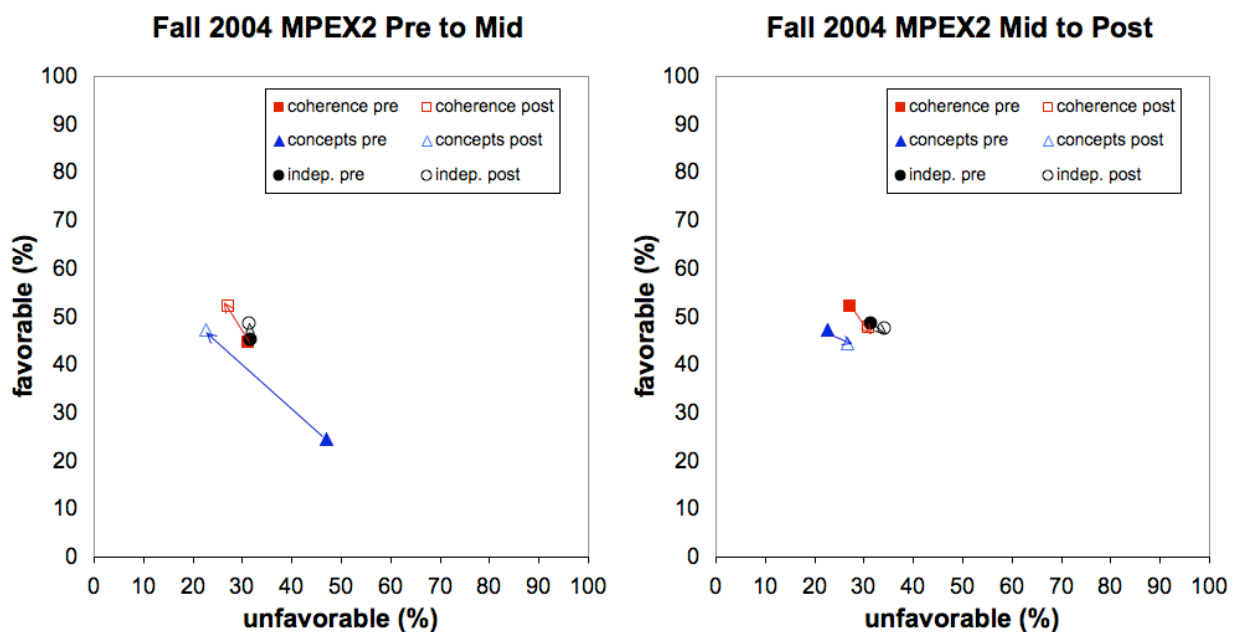


Figure 4: Comparison of MPEX 2 from pre- to midterm instruction and from midterm to post-course instruction. Gains in the concepts cluster happened during instruction on wave physics, while instruction on quantum physics led to minor declines in favorability of scores.

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4. "A Survey to Investigate Student Understanding of Quantum Tunneling," J.T. Morgan, M.C. Wittmann, Physics Education Research Conference, Sacramento CA, 2004 August.

Contributed presentations:

1. "Intuitive Quantum Physics, Quantum Without the Mathematics," J.T. Morgan and M.C. Wittmann, Twenty-sixth state-wide meeting of high school physics and physical science teachers, Orono ME, 2006 March.
2. "Reshaping Curriculum to Improve Student Understanding of Quantum Tunneling," J.T. Morgan, M.C. Wittmann, 131st AAPT National Meeting, Salt Lake City UT, 2005 August. *The Announcer* 35(2) 103.
3. "General Education Students' Understanding of Bound State Quantum Wavefunctions," M.C. Wittmann, J.T. Morgan, K. Black, and R.P. Springuel, 131st AAPT National Meeting, Salt Lake City UT, 2005 August. *The Announcer* 35(2) 104.
4. "Conceptual Learning in a General Education Quantum Physics Course," M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. *The Announcer* 34(2) 172.
5. "A Survey to Investigate Student Understanding of Quantum Tunneling," J.T. Morgan, M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. *The Announcer* 34(2) 172.

Invited presentations:

1. "Using Learning Theories to Model Students' Conceptual Changes," M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. *The Announcer* 34(2) 114.
2. "Comparing Instructional Modes: One Element of Physics Education Research," M.C. Wittmann, colloquium, College of Education and Human Development, 2006 May.
3. "Comparing Curricula to Study Student Learning," M.C. Wittmann, NES joint meeting of the APS and AAPT, Boston MA, 2006 April.

Non-documented outreach activities:

It is important to add that some events aren't easily listed in a set of workshops, posters, and talks. (Please also see the publications listed in another part of this report, for example.) One of the big sources of outreach has been through the annual Maine High School Physics Teachers meeting, run by the University of Maine either by the PI or his colleague, John Thompson. During these meetings, we have ample opportunity to talk about physics with teachers who might then use some of our materials in their classroom. Between 20 and 40 teachers attend this meeting every year.

Another source of outreach is the Maine High School Physics Teachers Collaborative, run with monthly meetings by John Thompson. By request of the teachers, we had a meeting in which our teaching materials for quantum physics were showcased and discussed. The topic arose at many other Collaboratives meetings, as well. Between 5 and 10 teachers attend on a monthly basis, and the PI was heavily involved in these discussions, getting feedback from the teachers on materials used in the classroom, for example.

Finally, we shared our materials during a poster session organized for the Knowles Science Teaching Fellows. During this time, several of the new Knowles Fellows requested information about the materials. The entire package of Intuitive Quantum Physics materials was shared with roughly 60 teachers.

In each case, it is hard to impossible to know the impact that sharing our materials has had.

Publications and Products

These publications are listed in the online system as well as in this location. More information is given here, since some information cannot be shared easily in the online system.

Papers:

1. Wittmann, M.C. (2006) "Using resource graphs to represent conceptual change," *Physical Review Special Topics Physics Education Research* 2, 020105. Available online at <http://prst-per.aps.org/abstract/PRSTPER/v2/i2/e020105>
2. Wittmann, M.C., Morgan, J.T., and Feeley, R.E (2006) "Laboratory-Tutorial activities for teaching probability," *Physical Review Special Topics Physics Education Research* 2, 020104. Available online at <http://prst-per.aps.org/abstract/PRSTPER/v2/i2/e020104>.
3. Morgan, J.T. and Wittmann, M.C. (2006) "Examining the Evolution of Student Ideas About Quantum Tunneling," in P. Heron, L. McCullough, J. Marx (Eds.) *Physics Education Research Conference Proceedings 2005*, AIP Conference Proceedings 818, 73-76.
4. Wittmann, M.C. (2006) "Lab-Tutorials für den Quantenphysik Unterricht," *Praxis der Naturwissenschaften – Physik*, 55:4, 16-21. Available online at <http://www.arxiv.org/abs/physics/0604112>
5. Wittmann, M.C., Morgan, J.T., and Bao, L. (2005) "Addressing student models of energy loss in quantum tunneling," *European Journal of Physics* 26, 939–950. Selected for *European Journal of Physics* 'Highlights of 2005,' for articles which received the highest praise from international referees and the highest number of downloads from the journal's website (announced 2006 Apr 19). Available online at <http://www.arxiv.org/abs/physics/0502053>.
6. Morgan, J.T., Wittmann, M.C., and Thompson, J.R. (2004) "Student Understanding of Tunneling in Quantum Mechanics: Examining Interview and Survey Results for Clues to Student Reasoning," in S. Franklin, K. Cummings, J. Marx (Eds.) *Physics Education Research Conference Proceedings 2003*, AIP Conference Proceedings 720, 97-100.
7. Wittmann, M.C. and Morgan, J.T. (2004) "Understanding Data Analysis from Multiple Viewpoints: An Example from Quantum Tunneling," in S. Franklin, K. Cummings, J. Marx (Eds.) *Physics Education Research Conference Proceedings 2003*, AIP Conference Proceedings 720, 3-6.

Internet Dissemination

Our main Internet presence can be found at <http://perlnet.umaine.edu/iqp/> .

We have shared this URL with the largest disseminator of web published materials in the physics teaching and PER communities: PER-CENTRAL, which is part of the ComPADRE online National Digital Library.

All materials created under the project have been placed online in printable PDF and editable Microsoft Word .doc formats, under a Creative Commons 2.5 license allowing derivative products for non-commercial use and requiring attribution. In addition, we have asked that users contact us when using the materials. We have found that users tell us at meetings that they are using our materials, but do not send us the requested email – as a result, we have no sense of how many are actually using our materials.

We have strived to make a simple web site that can be used by many of the computers struggling to deal with the “modern web.” We've used simple coding and very sparse links throughout. The header cells are common across the site, emphasizing student materials, instructor materials, workshop materials that people might want, and research into student learning that might help users. We have found in other projects as well as this one, for example, that teachers often do not need the specific materials but are as interested in the research into student learning that underlies the materials.

The NSF is acknowledged prominently (just under the page title) on every page of the web site.

Curricular Target(s) of Project

Discipline(s) affected by project:

Physics and “general education” students (those not in science, but required to take a semester-long laboratory-based science course).

Subject(s) affected by project:

Physics.

Title(s) of course(s) affected by project:

PHY 105, Descriptive Physics, University of Maine

Summary description of pedagogical approaches:

The IQP course centers on guided inquiry, small group work, with different levels of class discussion designed to help students build a consensus on newly learned ideas without having the professor simply present ideas and answers to them. The pedagogical approach is consistent with the University of Maryland *Learning How to Learn* approach to teaching.

Students taking the course are required to attend 6 hours of instruction per week. Of these, three hours are in laboratory, three in lecture. The major project work in modifying the course was to affect laboratory instruction. There, students engage in 3 hours of guided inquiry, small group interactive work. We typically used the following instructional methods (though sometimes the order changed slightly):

1. Students begin work in small groups, using guided activity worksheets
2. After a certain period, students prepare to answer and discuss “Board Meeting” questions. They prepare whiteboards with answers to certain questions. Not all students prepare the same questions. (Sometimes lab time started with a board meeting. Typically, there were two board meetings per class.)
3. At an appropriate time (as determined by a teaching assistant dealing with groups working at different paces), the whole class meets for the Board Meeting. Questions are either review of what has been covered in class, prediction of what will come next, or discussions of extensions to previously learned ideas
4. Students return to their small group work.

The role of the course instructor was to facilitate discussion among students and use pointed questions to guide students’ reasoning. Answers were not to be given, but hints for how to help students were occasionally necessary. The mindset of instruction was to help students as they took charge of their own learning.

Lecture time adjusted dynamically to laboratory instruction. The course revolved almost entirely around lab time. Lecture was where larger (full class) discussions on different topics could occur, as students argued with each other about interpretations of the ideas they had learned.

Contributions

Contributions within Discipline

As my principal disciplinary field, I use physics education research, including both the teaching of physics and the understanding of how students learn physics. Contributions within the discipline can be measured in three areas: teaching, research, and development.

Teaching:

New curricula for teaching quantum physics have been created in a way that allows high school teachers to use new and proven teaching methods in a way that matches their students' needs. Also, my own physics department has responded with high praise on the topic of teaching a guided inquiry course on quantum physics to general education, non-science students at UMaine. Materials, especially those on probability and probability density, have been used in other UMaine courses as well as courses at other institutions, for example.

Research:

The discipline of physics education research has, sadly, too few people doing too many different kinds of work in different areas. Nobody else in the field is doing work on student learning of quantum physics at the pre-introductory level. Our findings, whether on student reasoning about tunneling, probability, wave-particle duality, the shape of the wave function, or any other of many topics, extend the work of physics education research to new areas. The research methods we used, including videotaping classroom activities and new types of exam questions, also help extend the discipline.

Development:

It is always encouraging to have new materials developed that can be shared with others. We are part of a growing movement of “open source” curriculum development. Thus, our contribution to the discipline is to add our voice to those who believe that web publishing with modifiable materials is the best route for sharing information (We can even create enough appropriate publicity among our intended audience, which the large publishing houses sadly often don't give but which can be done independently.)

Contributions to Other Disciplines

No known contribution has been made, since much of the disseminated information has not received feedback (for example, from publications or workshops) from people in other disciplines. The publication of the *European Journal of Physics* paper was honored as one of the most read articles of the *EJP* in its publication year, implying that many physicists read the paper. Thus, the effect could be found outside of the field of physics education research in the field of traditional research physics, as well.

Contributions to Human Resource Development

Four students were centrally involved in course development as part of this project. This work

was described above in the section on Training and Development.

It is notable that two of these students have moved on to prestigious positions in academia. Jeffrey T. Morgan is now assistant professor in physics and in science education at the University of Northern Iowa. Eleanor C. Sayre has taken a post doc position at the Ohio State University. Both Morgan and Sayre received their PhD in physics from the University of Maine, with the work on the IQP project forming a major part of their skills as they graduated.

The other two students are still graduate students at the University of Maine, working toward a PhD in physics education research. One, Katrina Black, is teaching the IQP course this year as the PI is on sabbatical. Such instruction can have an immense impact on a students' development, but (as we are in the middle of the semester) the effect is as yet unclear.

Contributions to Resources for Research and Education

Other parts of this report describe the publications, workshops, posters, and presentations related to this project. Also, outreach activities (to the Knowles Science Teaching Foundation, the University of New England, and through publication in Germany to the teachers of an entirely different country) should be highlighted.

Additional Information

Description of Equipment or Instrumentation

1. New teaching laboratory equipment, including ripple tanks, tools for teaching probability, new setups for teaching energy in gravitational systems, and applications of wave interference to everyday situations. These are typically commonly available at other schools, but we had not had them before at UMaine.
2. New applications of software to the classroom, including some homespun tools and some applications of existing tools such as the PhET simulations from the University of Colorado.

Additional Sources of Funding

1. Students were supported in part by teaching assistant funds at the University of Maine.
2. Some RA funding came from "Creation, coordination, and activation of resources for learning undergraduate physics," (co-PIs John R. Thompson and John E. Donovan II), National Science Foundation, REC-0633951, \$662,914, Sep 1, 2006 to Aug 31, 2009.
3. Some RA funding came from "Developing a tutorial approach to enhance student learning of intermediate mechanics," Collaborative proposal with B.S. Ambrose, Grand Valley State University, National Science Foundation DUE-0442388, \$55,503.

Activities and Findings

Project Goals

Our goals when starting this project were to take two leading curricula, the *Activity-Based Tutorials* and the *Tutorials in Introductory Physics*, and adapt them to use in a non-science-major course, such that these generally math-phobic students would learn quantum physics. We later took some teaching innovations from the *Modeling Method* of instruction, as well. We used, as our guiding structure, the University of Maryland *Learning How to Learn* project, in which issues of epistemology ("how do you know what you know?") determine the topic of learning. Thus, we were to create a series of primarily laboratory activities for instruction 3 hours per week, using a guided inquiry approach, and spending as much time helping students on why they believed their answers as getting them (conceptually) to the answers themselves. Our long term deliverable on the project was to be a complete set of teaching materials which would be freely available to all interested users.

Findings

To present all the research findings from our project, as given in our presentations and publications, is far beyond the scope of a final report, and can be supplanted through the publications themselves. Certain findings have not been published, though, and are important for measuring the success of the project.

Class retention

Before the start of the project, the *Descriptive Physics* course at UMaine had been suffering a constant decrease in students enrolled in the course. This was one of the motivations for redesigning the course. By the time the PI took the course over, only 45 to 50 students a semester were enrolling in *Descriptive Physics*. This was down from a high of over 100, and much lower than the possible 80 for which classrooms were designed (the enrollment of 100 had been when other classrooms had been in use). In addition to the low enrollment, there was a very high attrition rate in past versions of the *Descriptive Physics* course. At times, the course ended with under 20 students.

Both problems were addressed by the new course design. First, enrollment rose steadily. From the first year of implementation to the 3rd (and now into the 4th), enrollment rose from the mid-40s to the mid-70s. Before the semester starts, the course is fully enrolled, with a few students dropping out before the first day of class (as typically happens in university courses as other course openings arise) and enrollments are in the high 70s.

Second, the drop out rate dropped, nearly instantly, from over 50% of enrolled students to less than 5%. For a course with 50 students, only 1 or 2 would drop out, typically for reasons independent of the course and instead for personal reasons that were discussed with the instructor before leaving the course. With the higher enrollment, drop-out rates remained low, under 10%.

We attribute these changes to a mix of effects, though we have no direct evidence for them (such evidence would have required a major sociological study outside the financial constraints of this project). First, students received personal attention in the course of their long lab-tutorial

periods, ensuring that concerns could be aired easily during instruction. Second, instruction was completely student-centered, once the outline of topics was presented. The pace of instruction was always adjusted to match the needs of students, such that students could feel that their needs were being met and their learning was of more importance than getting through some set amount of course content. (This last point was often explicitly stated during lecture instruction.) Third, it must be admitted that students worked through the material very slowly. For example, they used no mathematics, and did in 4 weeks what might be covered in 1 week of an introductory physics course that had not just conceptual but also mathematical content. So, students were challenged mentally (many pointed out how hard the course was) but were supported structurally.

Learning the physics

As stated above, it is difficult to summarize all our results in a single document such as this one. We highlight two results, among many, showcasing the conceptual learning and results about attitudes toward physics and the nature of science.

1. Understanding quantum tunneling.

It is hard to overstate how difficult this topic seems to be for students. We made a special effort to make it from wave physics through bound states (with finite square wells whose energy diagrams can be explained through metaphor in the real world) to molecules and quantum tunneling. The idea was specifically to connect to the research work being done on campus by our Laboratory for Surface Science Technology (LASST). Our hope was that students would come away with an appreciation of what kind of scientific research occurs on campus, even if they themselves were in the humanities, for example.

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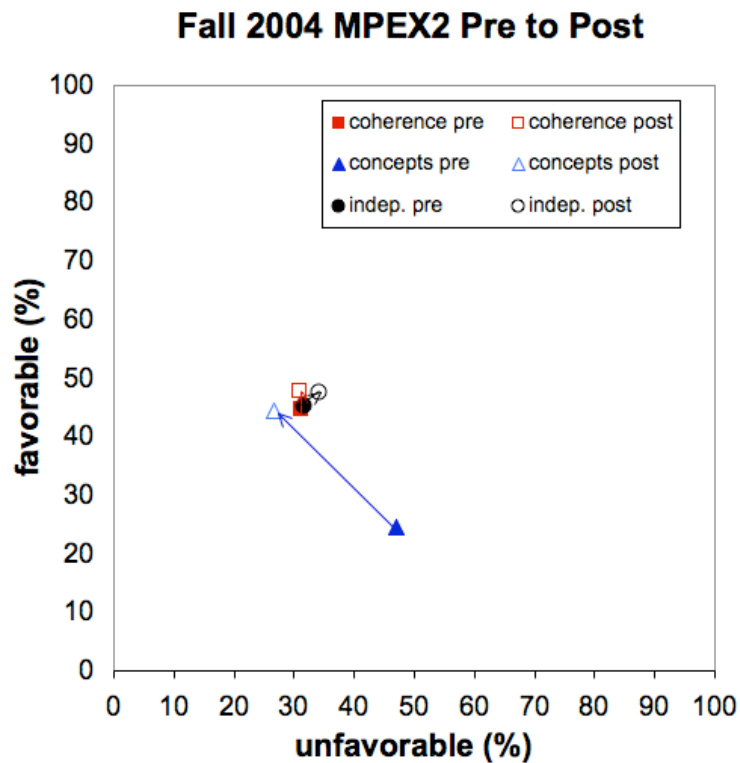


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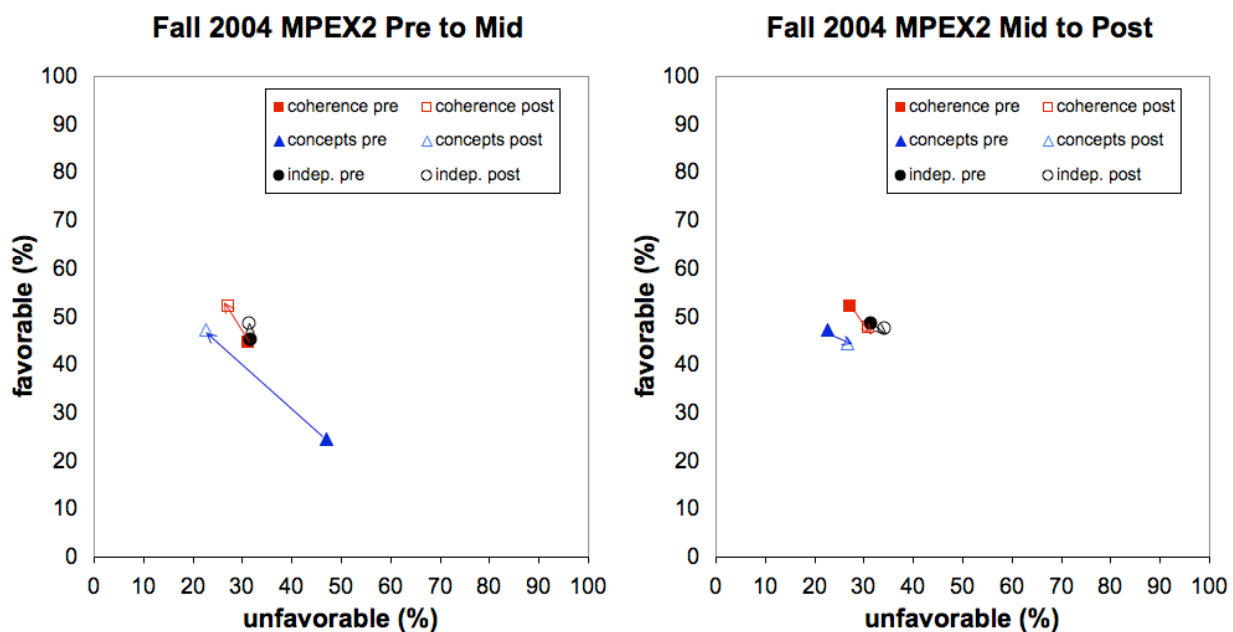


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1. "A Longitudinal Study of Student Learning of Quantum Tunneling," J.T. Morgan, M.C. Wittmann, Physics Education Research Conference, Salt Lake City UT, 2005 August.
2. "Nearly Novel Situations," E.C. Sayre and M.C. Wittmann, Physics Education Research Conference, Salt Lake City UT, 2005 August.
3. "General Education Students' Understanding of Quantum Wavefunctions," M.C. Wittmann, Physics Education Research Conference, Salt Lake City UT, 2005 August.
4. "A Survey to Investigate Student Understanding of Quantum Tunneling," J.T. Morgan, M.C. Wittmann, Physics Education Research Conference, Sacramento CA, 2004 August.

Contributed presentations:

1. "Intuitive Quantum Physics, Quantum Without the Mathematics," J.T. Morgan and M.C. Wittmann, Twenty-sixth state-wide meeting of high school physics and physical science teachers, Orono ME, 2006 March.
2. "Reshaping Curriculum to Improve Student Understanding of Quantum Tunneling," J.T. Morgan, M.C. Wittmann, 131st AAPT National Meeting, Salt Lake City UT, 2005 August. *The Announcer* 35(2) 103.
3. "General Education Students' Understanding of Bound State Quantum Wavefunctions," M.C. Wittmann, J.T. Morgan, K. Black, and R.P. Springuel, 131st AAPT National Meeting, Salt Lake City UT, 2005 August. *The Announcer* 35(2) 104.
4. "Conceptual Learning in a General Education Quantum Physics Course," M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. *The Announcer* 34(2) 172.
5. "A Survey to Investigate Student Understanding of Quantum Tunneling," J.T. Morgan, M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. *The Announcer* 34(2) 172.

Invited presentations:

1. "Using Learning Theories to Model Students' Conceptual Changes," M.C. Wittmann, 129th AAPT National Meeting, Sacramento CA, 2004 August. *The Announcer* 34(2) 114.
2. "Comparing Instructional Modes: One Element of Physics Education Research," M.C. Wittmann, colloquium, College of Education and Human Development, 2006 May.
3. "Comparing Curricula to Study Student Learning," M.C. Wittmann, NES joint meeting of the APS and AAPT, Boston MA, 2006 April.

Non-documented outreach activities:

It is important to add that some events aren't easily listed in a set of workshops, posters, and talks. (Please also see the publications listed in another part of this report, for example.) One of the big sources of outreach has been through the annual Maine High School Physics Teachers meeting, run by the University of Maine either by the PI or his colleague, John Thompson. During these meetings, we have ample opportunity to talk about physics with teachers who might then use some of our materials in their classroom. Between 20 and 40 teachers attend this meeting every year.

Another source of outreach is the Maine High School Physics Teachers Collaborative, run with monthly meetings by John Thompson. By request of the teachers, we had a meeting in which our teaching materials for quantum physics were showcased and discussed. The topic arose at many other Collaboratives meetings, as well. Between 5 and 10 teachers attend on a monthly basis, and the PI was heavily involved in these discussions, getting feedback from the teachers on materials used in the classroom, for example.

Finally, we shared our materials during a poster session organized for the Knowles Science Teaching Fellows. During this time, several of the new Knowles Fellows requested information about the materials. The entire package of Intuitive Quantum Physics materials was shared with roughly 60 teachers.

In each case, it is hard to impossible to know the impact that sharing our materials has had.

Activities and Findings

Project Goals

Our goals when starting this project were to take two leading curricula, the *Activity-Based Tutorials* and the *Tutorials in Introductory Physics*, and adapt them to use in a non-science-major course, such that these generally math-phobic students would learn quantum physics. We later took some teaching innovations from the *Modeling Method* of instruction, as well. We used, as our guiding structure, the University of Maryland *Learning How to Learn* project, in which issues of epistemology (“how do you know what you know?”) determine the topic of learning. Thus, we were to create a series of primarily laboratory activities for instruction 3 hours per week, using a guided inquiry approach, and spending as much time helping students on why they believed their answers as getting them (conceptually) to the answers themselves. Our long term deliverable on the project was to be a complete set of teaching materials which would be freely available to all interested users.

Activities

The project goals were to create a series of research-based curriculum materials appropriate for teaching wave and quantum physics to students who are typically math phobic and are only taking the given course as a required laboratory science course at the University of Maine. The population, colloquially speaking, is not excited to be in the classroom.

The major activities of the project lay in creating a series of laboratory teaching materials (“lab-tutorials”) that could be used in such a setting. These materials were designed to assume that students came in with no background knowledge of wave physics or quantum physics, but very much did have basic ideas which are necessary for learning both topics *and* for misinterpreting observations which would be used to push their thinking forward.

Materials were adapted from the *Activity-Based Tutorials* (Wittmann, Redish, Steinberg, and the University of Maryland Physics Education Research Group) and the *Tutorials in Introductory Physics* (McDermott, Shaffer, and the University of Washington Physics Education Group), as well as the *Modeling Method* (Hestenes, Wells, and Swackhammer, at Arizona State University), all in the mindset of the University of Maryland *Learning How to Learn* project. A central part of our course development was the adaptation of the French & Taylor method of graphical solutions to the Schrödinger Equation to a non-mathematical audience. The course used the Schrödinger Equation in the form:

$$\text{Curv}\psi = -k(TE - PE)\psi$$

Here, the “curviness of the wave function” was the name given to the second spatial derivative of the wave function. The other terms are from the typical Schrödinger equation, written in terms of the constant k (which subsumed all constants related to mass and Planck’s constant) and the total energy of the particle, TE , and the potential energy of the particle-system interaction, PE . Using this method and several “rules” which constrain how you draw a wave function (“no kinks” and “finite area under the curve”), students were able to draw bound state wave functions that had parts that looked sinusoidal or that looked exponential. Several weeks of activities went into teaching them these skills.

Research was carried out on various parts of the course to help us understand which materials were succeeding and which were hopelessly in need of change. In our first draft of materials, many needed changing; by the end, as we worked out kinks in the program, things were better.

The lab-tutorials and instructor materials have been posted online, freely accessible to all interested users and made public under a Creative Commons License modeled on the open source software movement. We use a derivative products, non-commercial, attribution license.

Student Materials

The lab-tutorials developed for the course are shown in Figure 1. Students were also given the pretests and post-tests at appropriate times. These are listed with the instructor materials, in Figure 2.

First-time development of these materials was carried out primarily in teams. Two teams worked in staggered format to create every other week's materials. Jeff Morgan headed one team and Eleanor Sayre the other; the PI was in charge of the whole process and guided each team appropriately, as needed.

The development cycle was as follows. A team would work alone (including with PI assistance) on a lab-tutorial for one week. Early in the second week of development, the tutorial would be viewed by all course developers. Feedback was given. Later in that week, the revised tutorial would be reviewed again, and any changes necessary to best match student needs would be incorporated. The tutorial was finished, and the full development team would review it, this time from the perspective of *facilitating instruction* using these materials. Any last-second changes would be made, though the effort was one of translating pedagogical intent into classroom actions. Lab-tutorials were developed in staggered form, so that one team was always presenting its materials while the other team was working more privately on theirs.

Tutorial: Seeing the same things as other people.....	p. 1
Homework.....	p. 11
Tutorial: Waves passing through.....	p. 13
Homework.....	p. 25
Handout.....	(to be passed out separately)
Tutorial: Analogies connecting light and waves.....	p. 27
Homework.....	p. 39
Handout.....	(to be passed out separately)
Tutorial: Doing impossible things.....	p. 41
Homework.....	p. 51
Tutorial: Probability	p. 53
Homework.....	p. 69
Tutorial: Energy	p. 73
Homework.....	p. 83
Handout.....	(to be passed out separately)
Tutorial: Energy and probability.....	p. 85
Homework.....	p. 101
Tutorial: Curviness.....	p. 105
Handout.....	p. 125
Homework.....	p. 127
Tutorial: Physically possible wavefunctions.....	p. 129
Homework.....	p. 137
Tutorial: Bound states and more impossible things.....	p. 139
Homework.....	p. 145
Tutorial: Excited States	p. 147
Homework.....	p. 163
Tutorial: Modeling Molecules.....	p. 165
Homework.....	p. 175
Tutorial: Tunneling – A quantum mechanical consequence.....	p. 179
Homework.....	p. 191
Handout.....	(to be passed out separately)
Tutorial: Modeling Radioactivity	p. 193
Handout.....	(to be passed out separately)

Figure 1: Student Materials, including list of tutorials, handouts, and topics covered. Please see notes for additional detail on sources of adapted materials.

Notes to Figure 1:

- Pages 1-4 are lightly adapted from McDermott, L. C., Shaffer, P. S., & The Physics Education Group at the University of Washington. (2002). *Tutorials in Introductory Physics*. Upper Saddle River, NJ: Prentice Hall.
- Pages 6-9 are lightly adapted from Redish, E. F., Hammer, D., & Elby, A. (2001-2003). *Learning How to Learn Science: Physics for Bioscience Majors*: NSF grant REC008-7519.
- Pages 13-17 are adapted from Wittmann, M. C., Steinberg, R. N., & Redish, E. F. (2004). *Activity- Based Tutorials Volume 1: Introductory Physics*. New York: John Wiley & Sons, Inc.
- Pages 19-21 are adapted from McDermott, L. C., Shaffer, P. S., & The Physics Education Group at the University of Washington. (2002). *Tutorials in Introductory Physics*. Upper Saddle River, NJ: Prentice Hall.
- Page 28 is adapted from McDermott, L. C., Shaffer, P. S., & The Physics Education Group at the University of Washington. (2002). *Tutorials in Introductory Physics*. Upper Saddle River, NJ: Prentice Hall.
- Pages 47-48 refer to a simulation taken from Joffre, M. (2002), *Quantum Mechanics CD*, Berlin Heidelberg: Springer-Verlag, which accompanies Basdevant, J.-L., and Dalibard, J. (2002) *Quantum Mechanics*. Berlin Heidelberg: Springer-Verlag.
- Question B on the pretest to p. 73 is taken from the *Wave Diagnostic Test*, M.C. Wittmann, 1998 (unpublished PhD dissertation, University of Maryland).
- The simulations used on p. 79-80 are taken from the *PhET-Simulations* , located at <http://phet.colorado.edu/web-pages/index.html>.
- The activities on p. 87-96 are designed to be used with *Pasco DataStudio*. They can easily be modified for use with other data acquisition hardware and software.
- The software used on p. 150-153 and on p. 163-164 was developed at the University of Maryland by Rebecca Lippmann Kung and Michael C. Wittmann. It is based on *Physlets*; more information can be found at <http://webphysics.davidson.edu/Applets/Applets.html>.

Instructor Materials

For each of the given tutorials, there are also instructor materials. These are listed in Figure 2.

Tutorial: Seeing the same things as other people.....	Pre-lab and post-lab materials taking from <i>Tutorials in Introductory Physics</i> and not available
Tutorial: Waves passing through.....	Pre-lab and Post-lab
Tutorial: Analogies connecting light and waves.....	Pre-lab and Post-lab
Tutorial: Doing impossible things.....	Pre-lab and Post-lab
Tutorial: Probability	Pre-lab
Tutorial: Energy	Pre-lab
Tutorial: Energy and probability	Pre-lab and Post-lab
	DataStudio files for use ramps, carts, and magnets.....
Tutorial: Curviness.....	Pre-lab and Post-lab
	Drawing tool (for editing circles and transparencies)
Tutorial: Physically possible wavefunctions.....	Pre-lab and Post-lab
Tutorial: Bound states and more impossible things.....	Post-lab
Tutorial: Excited States	Pre-lab
Tutorial: Modeling Molecules.....	Pre-lab
Tutorial: Tunneling – A quantum mechanical consequence.....	Pre-lab
Tutorial: Modeling Radioactivity	Pre-lab and Post-lab
	Graphs for modification.....

Figure 2: Instructor materials for Intuitive Quantum Physics.

The Instructor materials found online include all necessary computer files (but one, which is copyrighted - similar materials can be found easily online) and pdf and Word.doc versions of materials. The largest lack of assistance for outside users, at the moment, are a series of course descriptions which help future users get a foothold on how to use these materials in their own classroom. The descriptions exist and are part of Jeff Morgan's Ph.D. dissertation, but they have not yet been placed online and made a part of the whole package of materials. We plan to address this lack (found only while writing the final report) in the near future. Furthermore, a publication of such a description is planned in appropriate journals, letting us both publicize the materials and give users an easily accessible source of information about the course.

Research activities

In addition to the materials adapted from existing materials (as shown in the Notes to Figure 1) or created at UMaine while using the mindset and framework of the UMaryland *Learning How to Learn* materials, there was also a major effort to carry out research on the types of learning students were participating in and the level of understanding they were attaining.

These findings are listed in other parts of this document, but should be highlighted here. During the course of this project, there were 4 workshops (1 national, 3 statewide) presenting both materials and research findings, 4 posters, 5 contributed talks, and 3 invited talks, all highlighting the different elements of this project. In addition, we published 7 papers, including 2 in the new *Physical Review Special Topics Physics Education Research* and 1 in the *European Journal of Physics*. Furthermore, one paper was published in a German journal that is read by teachers in Germany, much like *The Physics Teacher* is read by teachers in the United States.

The project supported the research and development beyond one Ph.D. dissertation (Jeff Morgan), as well.