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General Education Course in Intuitive Quantum Physics

Michael C. Wittmann
Principal Investigator; University of Maine, Orono

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Submitted on: 12/05/2007
Principal Investigator: Wittmann, Michael C.
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. ôBuilding models of probability and probability density,ö M.C. Wittmann, Twenty-seventh state-wide meeting of high school physics and physical science teachers, Orono ME, 2007 March.
4. ôListening to Students Differently: A Dialog Between Science and Humanities,ö M.C. Wittmann, Teacher Talk for the Center for Teaching Excellence, University of Maine, 2006 February.

Posters:

1. ôA Longitudinal Study of Student Learning of Quantum Tunneling,ö J.T. Morgan, M.C. Wittmann, Physics Education Research Conference, Salt Lake City UT, 2005 August.
3. ôGeneral Education StudentsÆ Understanding of Quantum Wavefunctions,ö M.C. Wittmann, Physics Education Research Conference, Salt Lake City UT, 2005 August.

Contributed presentations:

1. ôIntuitive Quantum Physics, Quantum Without the Mathematics,ö J.T. Morgan and M.C. Wittmann, Twenty-sixth state-wide meeting of high school physics and physical science teachers, Orono ME, 2006 March.
Invited presentations:


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


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 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:**

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**Categories for which nothing is reported:**
Organizational Partners
Any Book
Any Product
Contributions: To Any Beyond Science and Engineering
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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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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.
<table>
<thead>
<tr>
<th>Tutorial</th>
<th>Homework</th>
<th>DUE-0410895: A general education course in Intuitive Quantum Physics.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeing the same things as other people</td>
<td>p. 1</td>
<td>p. 6 of 21</td>
</tr>
<tr>
<td>Waves passing through</td>
<td>p. 11</td>
<td></td>
</tr>
<tr>
<td>Analogies connecting light and waves</td>
<td>p. 27</td>
<td></td>
</tr>
<tr>
<td>Doing impossible things</td>
<td>p. 41</td>
<td></td>
</tr>
<tr>
<td>Probability</td>
<td>p. 53</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>p. 73</td>
<td></td>
</tr>
<tr>
<td>Energy and probability</td>
<td>p. 85</td>
<td></td>
</tr>
<tr>
<td>Curviness</td>
<td>p. 105</td>
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<tr>
<td>Physically possible wavefunctions</td>
<td>p. 127</td>
<td></td>
</tr>
<tr>
<td>Bound states and more impossible things</td>
<td>p. 129</td>
<td></td>
</tr>
<tr>
<td>Excited States</td>
<td>p. 147</td>
<td></td>
</tr>
<tr>
<td>Modeling Molecules</td>
<td>p. 163</td>
<td></td>
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<tr>
<td>Tunneling – A quantum mechanical consequence</td>
<td>p. 179</td>
<td></td>
</tr>
<tr>
<td>Modeling Radioactivity</td>
<td>p. 193</td>
<td></td>
</tr>
</tbody>
</table>

**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:


• 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.

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

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
creation of a survey which could be used to investigate student understanding of tunneling. This
survey is included as part of his Ph.D.

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.

2. Student attitudes toward the course.

We report on data from 2004 to illustrate one of the major findings of the development of the
Intuitive Quantum Physics course. These are consistent with subsequent results, but showing
only one semester helps us control variables better and give a more coherent story.

We used the Maryland Physics Expectations Survey (in modified format, not yet published) to
measure student attitudes and expectations toward learning the course. Previous results had
shown that students taking physics courses with a lecture and laboratory component, even
using reform methods, typically show a movement toward less favorable attitudes. Such results
are typically shown in “favorable/unfavorable” plots (see Redish et al., American Journal of
Physics, 66 p.2, 1998 for more details). In such a plot (shown with data from our course in
Figure 3), the upper left corner shows the prevalence of favorable responses on the MPEX2,
and the lower right corner the prevalence of unfavorable responses. In addition to a general
“deterioration” in expectations during instruction, Redish and collaborators found that
expectations about physics got worse when quantum physics was the subject of instruction.
Thus, our hopes for improvement of expectations in the Intuitive Quantum Physics course were
relatively low. Both the format (lecture and lab) as well as the course content (wave and then
quantum physics) were problematic.

As shown in Figure 3, students started the course with among the least favorable and most
unfavorable attitudes (note that these are two dimensions on the test, not necessarily related to
each other due to the existence of neutral responses on the MPEX2) on the “concepts cluster”
that we had ever measured. This concepts cluster measures how much students believe that
physics contains a conceptual basis. These students came in thinking that physics consisted of
facts to memorize, not conceptual ideas to understand and build with. They came in with low
favorability scores toward their own independence in being able to learn the material as well as
low favorability scores toward a sense of coherence of the physics (that it all fits together into a
single picture).

Again, our prediction had been that attitudes would become less favorable during instruction.
For example, quantum physics is a topic that contains (in the example of wave-particle duality
and many others) a fundamental sense of incoherence. To learn coherence in such a setting
sets a high bar for students. Also, students confronted with difficult ideas would most likely rely
heavily on the instructor (or teaching assistant) in order to succeed in the course.

We found, to our surprise, that student expectations improved or barely changed during the
course. The largest leap came in the concepts cluster. Students moved very far in the favorable
direction, if still arriving at a point that showed barely favorable scores overall. In the coherence
and independence clusters, there were only very small changes.

DUE-0410895: A general education course in Intuitive Quantum Physics.
To investigate the situation further, we made use of data taken during the middle of the semester. Typically, the MPEX 2 is given at the start and end of the semester. We gave it once during the course, as well. The time of this mid-term assessment is important: it came just before the end of the unit on waves, meaning it preceded students’ studies of wave-particle duality. This midterm period MPEX was given, therefore, before all instruction in quantum physics. Results are shown in Figure 4.

We find that the large improvements in student attitudes toward physics (and science) occurred during instruction on wave physics. Students immersed in a course with an unexpected format (student centered discussion based on observations, rather than fact-based lecturing based on accepted physics models) had large changes in their expectations, in only a short period. After students began to talk about quantum physics (first with wave-particle duality, then after an excursion into energy and probability, with bound states and tunneling), expectations did become less favorable with time. But, these changes were very small compared to those measured by Redish et al. in their previous work, and much smaller than the previous improvements in the concepts cluster.
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.

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.

Posters:


Contributed presentations:


Invited presentations:

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:

Review Special Topics Physics Education Research 2, 020105. Available online at
http://prst-per.aps.org/abstract/PRSTPER/v2/i2/e020105
teaching probability,” Physical Review Special Topics Physics Education Research 2,
Quantum Tunneling,” in P. Heron, L. McCullough, J. Marx (Eds.) Physics Education
physics/0604112
5. Wittmann, M.C., Morgan, J.T., and Bao, L. (2005) “Addressing student models of energy
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
0502053.
Tunneling in Quantum Mechanics: Examining Interview and Survey Results for Clues to
Student Reasoning,” in S. Franklin, K. Cummings, J. Marx (Eds.) Physics Education
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.

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 creation of a survey which could be used to investigate student understanding of tunneling. This survey is included as part of his Ph.D.

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.

2. Student attitudes toward the course.
We report on data from 2004 to illustrate one of the major findings of the development of the *Intuitive Quantum Physics* course. These are consistent with subsequent results, but showing only one semester helps us control variables better and give a more coherent story.

We used the *Maryland Physics Expectations Survey* (in modified format, not yet published) to measure student attitudes and expectations toward learning the course. Previous results had shown that students taking physics courses with a lecture and laboratory component, *even using reform methods*, typically show a movement toward less favorable attitudes. Such results are typically shown in “favorable/unfavorable” plots (see Redish et al., *American Journal of Physics*, 66 p.2, 1998 for more details). In such a plot (shown with data from our course in Figure 3), the upper left corner shows the prevalence of favorable responses on the MPEX2, and the lower right corner the prevalence of unfavorable responses. In addition to a general “deterioration” in expectations during instruction, Redish and collaborators found that expectations about physics got *worse* when quantum physics was the subject of instruction. Thus, our hopes for improvement of expectations in the *Intuitive Quantum Physics* course were relatively low. Both the format (lecture and lab) as well as the course content (wave and then quantum physics) were problematic.

As shown in Figure 3, students started the course with among the least favorable and most unfavorable attitudes (note that these are two dimensions on the test, not necessarily related to each other due to the existence of neutral responses on the MPEX2) on the “concepts cluster” that we had ever measured. This concepts cluster measures how much students believe that physics contains a conceptual basis. These students came in thinking that physics consisted of facts to memorize, not conceptual ideas to understand and build with. They came in with low favorability scores toward their own independence in being able to learn the material as well as low favorability scores toward a sense of coherence of the physics (that it all fits together into a single picture).

Again, our prediction had been that attitudes would become less favorable during instruction. For example, quantum physics is a topic that contains (in the example of wave-particle duality and many others) a fundamental sense of incoherence. To learn coherence in such a setting sets a high bar for students. Also, students confronted with difficult ideas would most likely rely heavily on the instructor (or teaching assistant) in order to succeed in the course.

We found, to our surprise, that student expectations improved or barely changed during the course. The largest leap came in the concepts cluster. Students moved very far in the favorable direction, if still arriving at a point that showed barely favorable scores overall. In the coherence and independence clusters, there were only very small changes.
Students start with particularly low attitudes about the conceptual basis of physics and improve, unexpected for a course on quantum physics.

To investigate the situation further, we made use of data taken during the middle of the semester. Typically, the MPEX 2 is given at the start and end of the semester. We gave it once during the course, as well. The time of this mid-term assessment is important: it came just before the end of the unit on waves, meaning it preceded students’ studies of wave-particle duality. This midterm period MPEX was given, therefore, before all instruction in quantum physics. Results are shown in Figure 4.

We find that the large improvements in student attitudes toward physics (and science) occurred during instruction on wave physics. Students immersed in a course with an unexpected format (student centered discussion based on observations, rather than fact-based lecturing based on accepted physics models) had large changes in their expectations, in only a short period. After students began to talk about quantum physics (first with wave-particle duality, then after an excursion into energy and probability, with bound states and tunneling), expectations did become less favorable with time. But, these changes were very small compared to those measured by Redish et al. in their previous work, and much smaller than the previous improvements in the concepts cluster.

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.
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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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.
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:


- 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.

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

*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.

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