Teaching for Understanding in Modern Physics:

What does it look like and how might we get there?

Written in partial fulfillment of the requirements of I&L 3448
At the University of Pittsburgh
Fall 2004

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Investigating Understanding (Preliminary Essay)

There is a difficulty in pinpointing precisely what "understanding" means. We bring it to the forefront of our classrooms, expect it of our students, and even test for it. Unfortunately, it is tough to know exactly what it is we are trying to achieve. Is it sufficient to denote understanding of a concept as a passing score on a multiple-choice test that stresses terminology, memorization, and pattern matching? Or, do we expect that a student who understands a scientific concept to be able to stand in a room with a certain apparatus and be able to apply that concept flawlessly? Ultimately, understanding cannot be a discrete term: it is a vague term that has a range of meanings. It is my goal in this paper to try to elucidate what scientific understanding means in the context of undergraduate physics student education.

A study was done by Chi and Feltovich[1] that involved asking people with varying levels of education in physics to group introductory level problems that were written on index cards by their similarities. The study showed that novices tended to group physics problems with similar surface features, while experts (in their words "only physicists") were able to detect the "deep structure," that is, the underlying physics law required, of the problems. This seems to give us a hint about what understanding means: someone with scientific understanding is able to identify problems (and by extension, situations) with the true scientific principles that underlie them. This permits them to adapt their understanding from one situation to another, so that when presented with a new situation, an expert should be able to determine a solution.

The question of who can be considered an expert is not so easily answered, however. It may be clear that a typical freshman physics major does not have a full understanding of basic physical phenomena; it may be equally as obvious that the tenured physics professor teaching the freshman class does have this understanding. However, the transition in terms of understanding between one to the other over, say, ten years is not clearly marked. When the school year begins and the professor takes on the responsibility of teaching the students, he most likely wants his students to leave the class with a sense of "understanding." Perhaps he expects that the students should be able to solve standard textbook problems, identify logical conclusions from Newton's Laws, and apply the concept of energy conservation to a wide range of situations. There are many ways he might go about accomplishing this, and though some seem to be more successful than others, they are all attempts to accomplish his goal. He then attempts to gauge the amount of understanding the students achieve by giving exams. However, a student who achieves good grades on these exams cannot yet be called an "expert." Expertise does not come from a certain amount of formal education or a certain amount of classwork; expertise comes with the ability to think like a scientist. Introductory science classes would benefit strongly from teaching how to make that transition in addition to simply pushing specific content knowledge.

Unfortunately, we are left with the question of what is means to "think like a scientist." Some favorable characteristics of a student who is actively working towards this understanding are as follows (from Redish, Steinberg, and Saul[2]). The student takes responsibility for construction of her own understanding, stresses the ability to know and apply the underlying ideas and concepts, believes that physics needs to be considered connected and consistent, believes ideas in physics are appropriate to apply to a variety of real-world phenomena, and considers mathematics nothing more than a convenient way of representing physical phenomena. Hopefully a student who wears those glasses everyday will eventually see physics in that light.

It is not an immediate transition, however. Even the brightest students struggle with certain facets of the subject matter at one time or another. Understanding does not imply the ability to know the answer to every problem immediately, however. For example, consider a project done by Singh[3]. She asked twenty professors and a number of students to answer a non-traditional problem from an introductory physics textbook. The professors, when interviewed, all failed to solve the problem in the allotted time; however, they were following a scientifically sound approach that would have eventually led them to the correct answer, with the correct physical reasoning. The students who answered the question correctly failed to provide that correct physical reasoning, instead citing incorrect conclusions from surface features (the popular case where two wrongs give the correct solution, but for the wrong reasons). Even though the professors weren't able to give the correct answer immediately, they are still considered to be experts; the important focus is on the approach and procedure when faced with a novel situation. The ability to detect understanding on hour-long multiple choice exams is therefore highly suspect, and care must be used in trying to ascertain who does and does not understand both the overarching science and the specific concepts involved.

It may be helpful to look briefly at a specific example from modern physics, to attempt to point out what it means to understand a specific concept. Modern physics is especially interesting because it comes at a time in the students' progression through coursework where she finally is beginning to understand the simple classical view of physics, in terms of particles and trajectories. In the midst of this, the student is suddenly confronted with situations that are truly mind-boggling. One of these is the concept of matter having a specific wavelength. We can go over the simple equation in class: $\lambda = h/p$, and we can ask the students to do problems such as finding the wavelength of an electron or a tennis ball. However, the result of this calculation is unlikely to have much meaning to the student, unless the student is able to comprehend what this wavelength actually implies. An acceptable amount of understanding would be found in a student explanation of how we can observe diffraction patterns from electrons but not tennis balls due to their momenta and therefore their wavelengths; however, it is not immediately clear how to go about teaching that in a non-authoritarian way. Ascertaining this amount of understanding through evaluative methods is no less of a challenge. Nonetheless, that simple bit of understanding is an example of a concept that needs to be mastered in order to become a true expert in physics.

Hopefully, some insight has been given towards a preliminary meaning of scientific understanding, at least as it is applied to undergraduate physics education.

Referneces:

1. Chi, Feltovich. "Categorization and Representation of Physics Problems by Experts and Novices." Cognitive Sci. 5:121-52, 1981.
2. Redish, Steinberg, and Saul. "The Distribution and Change of Student Expectations in Introductory Physics." AIP Conf. Proc. No. 399. AIP Woodbury, NY, 1997.
3. Singh. "When Physical Intuition Fails." Am. J. Phys, 70(11), 1103-1109, 2002.

Analysis of a Typical Modern Physics Curriculum

Modern Physics for scientists and engineers by Stephen Thornton and Andrew Rex serves as a foundation for a one- or two- semester course in Modern Physics. When used with the following suggested materials: an instructor solution manual, website, and a resource CD-ROM which includes text figures for classroom lectures, this book presumes to encompass all required references for designing a sophomore-level course in modern physics. An instructor could reasonably take his or her notes from the book and perform lectures from those notes with a strong internal logic that should ultimately impart a strong introduction to twentieth-century frontier work in physics. Taking this premise as understood, I will investigate the strengths and weaknesses of this textbook as a curriculum with regards to its assumed and explicit goals, education models, and methods.

An Overview: Textbook Structure

One of the most obvious and explicit assumptions the text makes is that students have already taken a full-year course in introductory calculus-based physics. Implied is the belief that they fully absorbed and understood the material presented in that class. In fact, much of the text is based upon analogies to simpler classical systems that students have hopefully understood. However, making an analogy between quantum mechanics and light waves is only successful if the physics of light waves is previously known. An example of this phenomenon will be addressed later.

The textbook touts a “featured strength:” the broad selection of end-of chapter problems and questions. Many of the problems are located under section headings, presumably to help the students link certain problem types to the appropriate topics. Some, including specially marked “challenge” problems are then listed in a “general problems” section, probably so the students can make a transition to problems removed from any topic heading, or perhaps crossing between topics.

The next feature of the text is an abundance of “Special Topics” boxes that present both breakthrough technological advances based on the science and historical descriptions of scientists at work. These boxes serve to hold the interest of the students and instructors and also hope to link them to real-world experiences. They also support the overall structure of the text, which is largely historical and follows a fairly standard course. It sets the stage, then progresses through special relativity to quantum theory. After providing necessary statistical physics, it then goes on to look at the theory behind current major fields of research in physics: solid state, particle, and general relativity/cosmology. This is internally consistent and has a strong logic to it; much of what is done in one chapter depends on work previously explored.

Additionally, the text shows “photographs of physicists at work and of original apparatus [to] help to enliven and humanize the material.” Ideally, this should cue the thought to students that this formula of “theory, experiment, improved theory” that is used throughout the textbook (because that’s how science tends to progress, with experiment and theory evolving with each other) is more than an abstract notion. In reality, it happens in the upper floors of our buildings even as they’re sitting in the classroom. Since the course in modern physics is actually an introduction to contemporary work, these photographs and discussions should help the students identify with the reality of the science beyond established laws.

Overall, the implied philosophy in the text is that the subject matter is best learned individually by reading the text carefully and working through many of the problems at the end of the chapter, is based on experiments, and can be linked to prior knowledge obtained by the students in prior courses and in their everyday lives. There is a definite effort to help the students build a conceptual framework for the material in this course. However, since there is also a strong echo of the belief that simply pouring knowledge into the students will give them understanding, the textbook falls short of having a constructivist feel to it. Additionally, some of the analogies that the text creates are weak, appeal only to experts, or are simply misleading. An example will be presented later.

Finally, the book is intended largely as an introduction to the modern physics world. It is assumed that physics students will revisit the materials in the book over and over again in more depth, and as such one of the implications is that it is more important to expose the student to as much material as possible than to spend much time enforcing the learning of anything in particular. Unfortunately, these “inch deep and mile wide” approaches sometimes fail to reach the mark on both accounts.

A Closer Look: The Quantum Theory

I now turn my attention to the sixth chapter in the book, which is about quantum theory. This chapter should be taught after the midpoint of the first semester of the course. Grounding itself in the conclusions in the previous three chapters, this chapter first reveals the actual quantum theory that it had been leading up to for much of the book. It begins with an interesting quote from R. H. Fowler that serves as a double-edged sword: "Anyone at present in this room has a finite chance of leaving it without opening the door – or, of course, without being thrown out the window." An expert, upon reading, would see it as a witty, if oversimplified observation; however, a novice would likely be intrigued – which is good – and misled – which is bad. It sets a dangerous precedent that the book continues to follow throughout the chapter.

The implicit goals of the chapter can be summed up as follows. After studying the unit, the student should have a basic working understanding of the quantum theory: its origins, basis, and uses. Namely, he or she should understand that microscopic measurements are probabilistic, they should see how the uncertainty principles plays out in the quantum world, and they should be able to predict and explain particle decay. Additionally, he or she should understand three basic, yet durable models: the infinite square well, the finite square well, and the harmonic oscillator; also, the student should be able to identify when approximations to those models are valid and useful.

That is clearly a lofty goal, and the book spends a fair part of the previous three chapters setting the foundation for the quantum theory. It spends time exploring the experiments that led to the quantum model, developing the structure of the atom, and explaining the wave/particle duality. Unfortunately, the transition to the formal quantum theory, and especially the Schrödinger equation, is not obvious. The sixth chapter simply begins by writing down the wave equation. After some comments about the characteristics about the wave function and some derivations, the book goes on to relate classical and quantum mechanics by claiming that, just like wave optics is more fundamental than ray optics, quantum mechanics is more fundamental than Newtonian mechanics. This is an insightful observation, but many students at this level have not been exposed to optics in sufficient detail to appreciate the digression. However, these analogies to optics are theoretically very productive, because there are very clear demonstrations that can be done in optics to show phenomena, whereas in quantum mechanics, one can be hard-pressed to find demonstrations. Therefore, rather than claiming that these are superfluous attempts to relate knowledge, they can be employed by an instructor who takes sufficient time to develop the students' knowledge to the point where they can be appreciated.

The textbook also frequently employs detailed derivations and examples to try to illustrate how a certain concept or equation naturally lends itself to being understood a certain way. When used as a reference, these can be excellent tools for developing mathematical techniques and for seeing the usefulness of certain equations or theories. Unfortunately, the lack of support for the student's metacognition is likely to leave him or her struggling when faced with a similar problem. If he or she hasn't been trained how to think about problem-solving, then it is unlikely he or she will be able to simply do it without resorting to "equation-hunting." This is exceptionally relevant in this chapter, since the quantum theory is guaranteed to be a topic that the student knows very little about. The student must not only understand how the concepts link to one another and to the classical physics that he or she already knows, but the student must also be able to reason and learn the material for himself or herself. Part of the real trick with quantum theory is that even the best analogies to classical physics are bound to fail at some point because the quantum world is so very different from the classical, macroscopic world students are used to.

Quantum mechanics is an exceedingly abstract subject, and this only complicates the difficulty of the student and instructor. A few "laboratory-type" experiences exist, and there are numerous computer resources available that would help guide an instructor in presenting a more hands-on approach to understanding quantum mechanics. Unfortunately, these resources still need a good instructor to explain how what the student is doing or seeing on the screen relates to the quantum world. The students' prior conceptions are likely to muddle interpretations that are given, especially ones that draw out somewhat flawed comparisons to the classical world, such as one that appears in the following section of the book and will be described in more detail.

A Detailed Investigation: Barriers and Tunneling

The final section of the unit on quantum theory deals specifically with the conceptually difficult topic of tunneling – the process which explains nuclear decay, among other things.

In typical fashion, the book explains a derivation for finding the probability that a certain particle will be transmitted through a "potential barrier" (which is, of itself an abstract term that students are likely to misinterpret). The text also includes a few diagrams showing transmission and reflection and the exponential decay of the wave function in the "barrier region." The explanation seems rather esoteric and abstract, and the authors of the book were likely aware of this. They explicitly explain alpha particle decay (with which the student is assumed to have some familiarity) and they devote two full pages to a "Special Topics" segment on scanning probe microscopes. Additionally, to help build connections with student understanding, they go on to create another questionable analogy, again comparing a quantum mechanical event to an optical one.

When light is sent through an air gap between two prisms, the light acts as a potential barrier for the light to cross. As that gap is made wider, the intensity of the light that goes from one prism to the other is decreased. This corresponds to a decrease in the transmission probability, and therefore fewer photons are able to cross the gap. It is a fairly good analogy on the surface as again it relates an unobservable and abstract concept in terms of something that can be shown to students in the laboratory. Unfortunately, it has a huge flaw.

An expert is likely to perceive the example as it was intended, but a novice may relate it to a change in *energy* of the transmitted light. Because it is a macroscopic quantity – light amplitude – that is being observed, the student is likely to relate that to energy by the simple relation that when you increase the power to a light bulb, it becomes brighter! Therefore, a student might see the example and say "aha! As the gap widens, the probability of the light making it across the gap decreases, as does the energy of the emitted light."

When the student looks back in the text to verify or disprove this, he or she will find no mention of it whatsoever! Particles are given an amount of energy at the beginning of the problem ("… a particle with kinetic energy E approaches the step function…"), and it is not made clear that its energy remains constant when it is transmitted or reflected. Worse still, an instructor is not likely to notice this difficulty immediately and may be surprised when students fail to demonstrate comprehending of the phenomenon.

As was said before, the analogies to light can be effective, but the instructor must be mindful that they show the effects on an ensemble of identically prepared systems and amplitudes, whereas most quantum mechanics problems deal with single particles and probabilities. It is a subtle but vital difference. Presenting the example to the students while challenging them to explain what would happen in the single-photon limit might be beneficial.

Conclusion

While deeply rich in content, the curriculum as extracted from this textbook often falls short of its goal to prepare the students for understanding twentieth-century phenomena. It presents many examples and explanations, with an eye on historical developments and linking with students' present models. However, some of the analogies require detailed work from instructors to insure the appropriate interpretation from the students. Additionally, the sheer breadth of the textbook discourages detailed units that may include computer-based explorations and/or laboratory experiences. Instructors will be hard-pressed to push through all material in this text within the course of a year, even if they don't focus on the students' understanding. Unfortunately, because the text by its nature tends to focus on content rather than understanding, the vital aspects of metacognition and linkage may simply never occur.

Uncertainty: A "Big Idea" in the Modern Physics Curriculum

The uncertainty principle is one of the most fundamental concepts that students must learn in a modern physics course. In classical physics, particles follow trajectories; that is, given a certain initial position and momentum along with information about the forces that are acting on the particle, it is in principle possible to find the position and momentum of the particle at all later times. In other words, the particle has a definite location in phase space; it is merely the task of the scientist to measure it or calculate it. However, quantum mechanics brings a radically new way of understanding the world.

The uncertainty principle states, in one of its many forms, that we cannot simultaneously know the position and momentum of a particle. This lack of knowledge is not a result of poor equipment or inability to perform mathematical analysis. Rather, it is intrinsic in the world around us. "[The Heisenberg uncertainty principle] is a consequence of the de Broglie wavelength of matter (Thornton and Rex 177)." The uncertainty principle isn't visible in everyday life because it represents a quantitatively small effect. When large numbers of particles interact, the laws of probability take over. Actual position and momentum give way to expectation values; the odds of observing a macroscopic object like a baseball not following the classical trajectory are so absurd that it is not a surprise that we never see it. One of the great challenges in any modern physics curriculum is allowing the students to come to terms with this apparent dichotomy and resolve it in a meaningful way: they must understand its significance in the microscopic world without discarding their previous training and knowledge about the macroscopic world.

A “big idea” is a concept that has enduring value beyond the classroom, resides at the heart of the discipline, requires “uncoverage,” and offers potential for engaging students (Wiggins & McTighe 26). Here, “uncoverage” refers to the unveiling of aspects and subtleties, usually by engaging students in activities that elucidate those aspects of the topic which are especially important. This “big idea” can then be used to help create generative topics or questions. These generative topics are central to the domain because they provide a foundation for work within the discipline and represent and influence the discipline as a whole. Additionally, generative topics are accessible and interesting to students, interesting to the teacher, and easily linked to students’ previous experiences. Perhaps most importantly, generative topics have a “bottomless quality, in that inquiry into the topic leads to deeper questions (Wiske 65).” Emphasizing a focus on the big idea and the generative topics that follow from it allows the teacher to help the students form meaningful understandings that can then have value beyond the classroom.

The concept of uncertainty is a “big idea” in the modern physics curriculum. One helpful aspect of the concept of uncertainty is that it is counterintuitive to the students and therefore likely to hold their interest. Additionally, it is central to the transition from a classical picture of the world to a quantum picture. Furthermore, it lends itself readily to generative questions such as “how can we explain the classical world in terms of the quantum world?” and “how does uncertainty have any noticeable affect in everyday life?” In answering these questions, students would uncover more interesting topics such as probability and tunneling, which have subtleties and plenty of room for further investigation.

A quick survey of a modern physics textbook (Thornton & Rex) reveals that the uncertainty principle is explicitly mentioned in a number of places. Besides being initially defined, it appears in discussions of harmonic oscillator potentials, statistics, and stimulated emission. It is also implicit in many discussions, such as in tunneling. Clearly, therefore, the uncertainty principle has long been regarded as central to quantum mechanics. The challenge that now exists is in making uncertainty more apparent throughout the curriculum without trivializing it. This can be done through the use of benchmark instructions (Hunt & Minstrell 58) and emphasized through performance tasks (Wiske 72).

Benchmark instructions are memorable lessons that are used as reference in later discussions. A benchmark instruction includes a well-posed question, a class discussion, and a demonstration that reveals the physics involved. Each of the three steps is important. A demonstration without the question and discussion is likely to be misinterpreted by the students or completely ignored; without cognitive dissonance arising, the students are unlikely to understand its significance and may simply file the results away without allowing them to affect their thinking. Similarly, a discussion without a question is going to be directionless, and a discussion without a concluding demonstration is going to leave students without resolution in their musings. That lack of resolution will likely frustrate and confuse the students. Finally, a question without discussion and demonstration will barely have an effect on the students. Even if the question is posed as a preliminary quiz to which the students then receive solutions, the correct answer may simply be memorized without regards to the reasoning behind it.

Therefore, while the question/discussion/demonstration approach is very time consuming, each of the three segments is integral to the success of benchmark instructions.

Unfortunately, one of the great difficulties that a teacher of quantum mechanics faces is finding demonstrations that are appropriate. Besides showing bubble chamber prints, there is no good way of showing pair production. Showing the decay of a single nucleus is impossible, and even showing diffraction and interference patterns can prove to be a great challenge in a large class. Many of the great challenges to the uncertainty principle in specific were brought to the forefront by Gendanken (thought) experiments involving particle transmission through slits. Discussing these with a class would be incredibly helpful in allowing the students to gain insight not only into the meaning of the uncertainty principle but also as to how challenges within the discipline of physics are raised and ultimately resolved. Unfortunately, there is no culminating demonstration that could clearly show which viewpoint was correct. Rather, these disputes were solved with very detailed and careful analyses that are likely to be lost on introductory students.

Finding a demonstration that is successful then becomes an important focus for the teacher. One suggestion for a benchmark lesson would be to discuss two different aspects of Young's double-slit experiment (which involved sending a laser beam through a double slit and observing the pattern formed on a screen): "what pattern will be formed?" and, "if we repeat the experiment, will we always observe the same exact placement of dots on the screen?" When a computer simulation is run, we can limit the number of photons that hit the screen. In that case, we can observe about 300 hits, where the pattern is just beginning to emerge. We can then save that result and run it again. When students look at the two patterns, they will see that their basic structure is the same but that the exact placement of the dots varies slightly. This is a suggestion that due to the uncertainty principle, the old belief that two experiments set up exactly the same will yield exactly the same results must be re-examined. Furthermore, it can serve as a benchmark to reconsider again and again, for example, when electron interference is considered. Young's double-slit experiment has long been thought to be important, and it is likely that students in a Modern Physics course have already heard of it. However, by explicitly taking the time to talk about it – particularly with the added dimension of the uncertainty principle in mind – it will serve the students more strongly.

Measuring students' understanding should not be neglected. Performance tasks are valuable as assessment tools, and they should be connected to the big ideas and the benchmark instruction. Wiske describes three levels of performance and assessment: messing about, guided inquiry, and culminating performances. The first two are difficult to expand within the modern physics curriculum. Some of the great experiments in the early twentieth century are readily available and accessible – such as calculating the charge to mass ratio of the electron, Millikan's oil drop experiment, and the photoelectric effect. However, not only are these difficult to translate from laboratory experiments into meaningful performance experiences, they are also likely to have much of their value with regards to the advancement of the discipline of physics stripped away. In other words, these experiments were so great in the history of physics largely because they were novel. Presenting these laboratory experiments to students as natural and obvious is doing a disservice to the physics discipline at large. Great care should be taken to allow the students to either develop for themselves or in some way come to appreciate the need for these experiments, rather than simply presenting them "matter-of-factly."

The culminating performances can be arranged more simply in the form of written or oral quizzes or examinations at the end of each unit. Each performance should require the students to examine and apply their knowledge to a novel situation, linking it specifically to the benchmark instruction and to the big idea. Continuing with the double-slit example, a performance task that the students should be able to perform is to ask them to draw or explain what would happen if one of the slits were covered with a piece of tape. Even if they've never seen a diffraction pattern from a single slit, they should be able to reason that the dots won't merely cast a shadow of the slit or produce half of the double-slit interference pattern. A follow-up question can then remind the students of uncertainty by asking either whether a repeated performance by the same apparatus will yield exactly the same placement of hits or whether the student would be able to predict where a certain photon (say, the tenth one) ended up in the pattern.

Using uncertainty as a "big idea" in the presentation of a modern physics curriculum would require an incredible effort on the part of the instructor, as this requires more than simply brining it up again and again in the text or lecture. It requires a shift of focus for the class as a whole from learning about "a neat and clean knowledge" which simply needs to be memorized and used as directed (Wiggins & McTighe 26). The students must come to learn that the development of quantum mechanics in particular was fraught with controversy, questioning of assumptions, and apparent contradictions that needed (and some which still need to be) resolved. They must understand that the uncertainty principle, something that is simply not encountered in classical physics, is central to the progression of quantum mechanics and to the world we perceive as a whole – although its manifestations are strikingly subtle. Most importantly, the students must realize that physics doesn't proceed neatly in a linear fashion with "right" and "wrong" theories. Rather, there are always competing theories with experimentation as the sole determination of which theory is superior. Investigating something as fundamentally counterintuitive as the uncertainty principle provides an excellent base for allowing students to create those sorts of necessary understandings.

References:

Thornton and Rex, Modern Physics for Scientists and Engineers. Brooks/Cole 2002.

Wiggins & McTighe, Understanding by Design. Upper Saddle River, NJ: Merrill Prentice Hall 2001.

Wiske, M. S. (Ed.), Teaching for Understanding: Linking Research with Practice. San Francisco: Jossey-Bass 1998.

Hunt & Minstrell, "A cognitive approach to the teaching of physics." In K. McGilly (Ed.), Classroom lessons: Integrating cognitive theory. Cambridge: MIT Press 1994.

Assessing Understanding of Uncertainty in a Modern Physics Curriculum

Assessing understanding of any subject poses a considerable challenge for an educator. Assessment and task design must be matched so that an assessment of a student's performance in the task neither underestimates nor overestimates the student's understanding. Assessment must address not only what the student has "on tap" in the form of knowledge and skills, but also a deeper, truer understanding of the subject, addressing the different aspects of the student's understanding independently. Assessment must be continuous and consider the student's education in terms of a progression rather than a set of discrete, uncorrelated examinations or performances. With these seemingly overwhelming constraints, the challenge before any educator is apparent. In the realm of modern physics, the challenge is no less striking. How can one assess understanding of the big idea of "uncertainty" in a modern physics course?

Assessment and Task Design in Modern Physics

We must first make the assumption at this point that traditional examinations that stress memory and rote procedure do little to draw out student performances of understanding. Unfortunately, this means that task design plays a crucial role in assessment and that the two must evolve together when designing a course. If only a simple rubric were required to evaluate a traditional examination, our job as evaluators would be easy; however, a course designed with an eye on assessment must necessarily require more than just rubrics and examinations (though these may play a vital role).

Tasks must be designed to address the following two questions, according to Wiggins and McTighe (67): “Where should we look to find hallmarks of understanding?” and “What should we look for in determining and distinguishing degrees of understanding?” Because task design should follow after those two questions have been addressed, designing appropriate tasks for a modern physics course will not be explicitly addressed here. Rather, a method for assessing understanding in that course will now be explored with task design always implicit.

To simplify the problem, consider a “big idea” in modern physics, the uncertainty principle. Following a course in modern physics, we expect that the student knows the following many things with regards to the uncertainty principle. If we take, for now, the Teaching for Understanding (TfU) model, we are looking for knowledge, methods, purposes, and forms. Examples of knowledge such as: “subatomic particles do not follow trajectories,” “two complementary properties of a subatomic particle can’t be simultaneously known (such as position and momentum),” “we can’t simultaneously observe particle-like and wavelike properties of an electron,” and “we cannot predict the exact location of an electron fired through an aperture” are all “obvious” manifestations of the uncertainty principle; experts would claim that those statements are equivalent. Understanding their relationship is simply a deeper level of the knowledge aspect of understanding. We should also expect students to understand beyond the knowledge dimension. They should understand the process involved in nuclear decay, why certain materials decay more quickly than others, and how we can use that as a source of energy (purposes dimension), how our quantum observations relate to classical observations (methods dimension), and how our models in physics have continued to evolve because of the uncertainty principle (forms dimension).

The first question to be addressed is “where should we look?” A traditional written examination may in fact access the knowledge aspect of understanding in an acceptable way. Suitable prompts may be provided for a student to answer conceptual questions or solve uncertainty principle problems such as finding the product of the uncertainty in position and uncertainty in momentum for some toy scenario. Unfortunately, even in these situations one must be careful not to simply ask for recall; some new analysis must be required to elicit understanding performances. Interacting with the students and observing student interactions with others may prove to be an advantageous way to probe for all four aspects of understanding. Obviously, this question leads into task design. We must construct tasks in modern physics that explicitly look for the examples of understanding mentioned above.

The second question seems much more directly relevant to assessment. How can we make distinctions between different levels of understanding? Both Teaching for Understanding and Understanding by Design encourage assessing each aspect or facet independently of the others. Within each dimension, both establish a general rubric to establish four (in the case of TfU) or five (in the case of UbyD) levels of sophistication to differentiate levels of understanding. These rubrics are intentionally broad, yet they draw specific distinctions between the levels. In assessing a student’s work, then, they classify aspects as “sophisticated” or “at the apprentice level.” However, in the TfU assessment examples, it was clear that statements like “at the apprentice level, with novice tendencies” became common, and the discrete stages became muddled. Perhaps their intention is not to provide discrete stages after all, but to simply provide milestones on a continuum. If that is the case, then the continuum should be exposed; we need to make distinctions where possible, but often such distinctions aren't possible. Perhaps, at least in fields such as intermediate and advanced physics, we should make an effort to assess each aspect of a student's performance on a continuum with error bars, if possible. This is an idea that will be left temporarily while another issue is addressed.

Whenever we are able to make distinctions, we should do so. A student who is able to list the statements associated with a basic knowledge understanding of the uncertainty principle but who is unable to know that they are manifestations of the same statement has clearly not built a level of sophistication equal to a student who does realize the relationship. Simply asking someone what the uncertainty principle means on a written examination is unlikely to help the assessor make the distinction; the response will probably be a textbook or lecture-based definition. We can begin to make progress by asking students to list four manifestations of the uncertainty principle. This might yield the responses we are looking for, if the question hasn't been explicitly mentioned in the textbook or in lecture. We can also ask for the explicit links between them; for example, we could ask the students to explain the statement "particles don't follow trajectories" in terms of our lack of simultaneous knowledge of momentum and position. As is becoming more and more apparent, our line of questioning would likely be student-specific; personal interaction (or, to a lesser extent, computer-based quizzes) would probably be more suitable than written quizzes or exams for finding some of the finer intricacies of understanding.

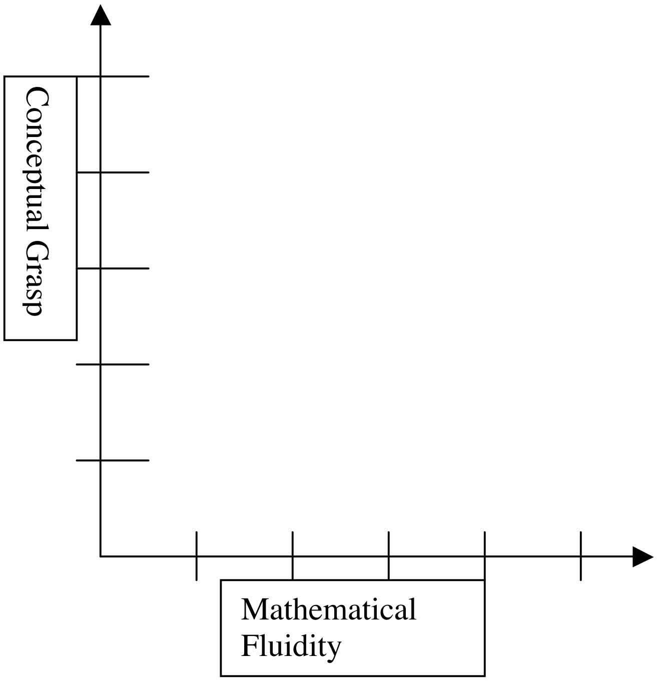
This is not to say that written exercises are meaningless; properly constructed homework and exams with problems of varying complexity have great value in physics courses. Learning the procedures and the language of mathematics in describing and solving physics problems is vital. When dealing with the uncertainty principle, knowing how to work with wavefunctions in the context of Schrödinger's wave equation to calculate probabilities and uncertainties can be very neatly assessed through homework, quizzes, and examinations. Rubrics can be designed to help assess an aspect of understanding through these written performances. However, solely relying on them is problematic, as it overlooks those aspects of understanding that can only be seen through interaction with the students.

Assessing Understanding of Modern Physics

Teaching for Understanding encourages assessment of four independent aspects of understanding; Understanding by Design encourages assessment of six independent facets. While either approach is probably very beneficial, it is somewhat more complicated than what I hope to achieve here with regards to the understanding of the uncertainty principle in modern physics.

Consider two dimensions: conceptual grasp and mathematical fluidity. I claim that they are independent: one who has a solid conceptual grasp of the physics involved may still have difficulty solving problems, while someone who has good mathematical fluidity may have difficulty interpreting the results. Unfortunately, at this point, the independence of the two variables needs to be taken on faith. More research could be done to establish this.

Now, because the dimensions are independent, we can draw the axes perpendicularly to define a plane, as shown below:



The grid should be left infinite; for all intents and purposes, the student's understanding of something can always improve. However, certain benchmarks can be put on the grid. These can be similar to TfU or UbyD milestones if desired. I prefer the UbyD rubric and will present a similar one for each of the two dimensions for the case of understanding the uncertainty principle in modern physics (see appendix). A single assessment may not reveal information about both aspects. Even if it does, the assessment may not be able to gauge both dimensions with the same resolution. In that case, error bars may need to be introduced. These would have the added affect in a modern physics class of allowing the students to get a first-hand disciplinary experience that again reinforces the role that probability (and thereby, the uncertainty principle) plays in life.

Additionally, there is the opportunity to realize the statement in TbyU (79) that "averaging one's initial versus one's final understanding of a complex idea would be a questionable measurement." The points that are plotted on the grid, corresponding to the assessments of a student's performances, can be viewed as a whole. The assessor can then view the best-fit line through the points (possibly giving later points a greater weight than earlier ones) to give additional information as to where the student's understanding seems to be trending. Any mapping of final grades from this method to the typical linear letter-grade scale would then need to be discussed in conference with the student. It is unclear that a simple claim that "most of the student's assessment points seem to lie above the $y = 5 - x$ line" or "the student is trending above the $y = 2/x$ curve" would have much immediate, legitimate value. Rather, the combination of the trendline and actual locations of the student's points should be discussion points for a semester-end meeting with the student.

The student should be receiving updates to his grid whenever possible, so that he or she is able to make scientific analyses of it throughout the semester; in a sophomore-level course on physics, coming to terms with concepts such as "outlying points," "statistical analysis," and "margin of error" should be encouraged. Additionally, a student to whom the grid method is not novel should be encouraged to keep his own throughout the course and compare it with the educators. The student's ability to coherently argue for the accuracy of the grid would encourage metacognition and a deeper appreciation for the techniques of science. Accordingly, the educator should spend a significant amount of effort explaining the grid technique, making it visible – and aligned with the equally visible big idea and course goals – in the course from the onset.

One other advantage of the grid is the ability to plot every student in the class on the grid to get a feel for the degree to which the two dimensions are correlated. If they are completely uncorrelated, as has been implicitly assumed in simple examination scoring, the students' performances should all fall on a 45-degree line (the y = x line). If, however, there is no correlation, the students' performances should look more like a scatter plot. I expect there should be some correlation; however, note that correlation doesn't necessarily imply dependence of one on the other. If the degree of correlation is too strong for the educator's tastes, he or she can then adjust the rubric to reduce that correlation in future courses.

Unfortunately, the grid method produces some challenges to implementation. Its success depends on a class suitably large so that good distributions of points can arrive for each assessment, but small enough that each student can discuss his progress with the educator at least once during the semester and once at the end of the semester. Additionally, the types of assessment required go beyond the "larger-class friendly" multiple choice or even problem-based exams.

Also, the grid method is not very easily transferred outside of intermediate to advanced science courses. It would likely work in all advanced physics courses designed for understanding with "big ideas" and tasks appropriately designed; it would also survive in intermediate chemistry or other disciplines where data analysis is central to disciplinary practice. Using it for a history class, however, would likely result in disaster. The students must appreciate the disciplinary relationship to accept being assessed in such a bizarre way. If they see it as an unnecessary complication, it would likely serve only to appear as a gap between the student and educator.

Continuous Assessment in Modern Physics

A necessary consideration in the grid method of assessment is that the student be continually assessed to varying degrees. While the point has been made previously for written examinations, these may only provide a few points that are strong for determining mathematical fluidity while being weak for determining conceptual grasp. Therefore, more performances are needed to both adequately assess conceptual grasp and provide a more continual flow of assessment, rather than forcing a few discrete points to describe the student's understanding over the course of the semester.

Written 10-15 minute quizzes and individual homework assignments, given once a week, could provide weak data points for both mathematical fluidity and conceptual grasp. Simple or complex group tasks, ranging from 15 minutes to multiple hours in length, can provide either weak or strong points for conceptual grasp. Discussions between students and assessors could also help provide points. Precise tasks should be designed around the big idea: the Uncertainty Principle, in this case. Those tasks should elicit tasks that act as a lens to focus the students' understanding in the eye of the assessor.

Particular attention should be paid to questions that students raise; these give a deep indication as to the student's current understanding. Understanding by Design (79) treats this as "insight." While insight is difficult to perceive and evaluate, it should play a significant role in identifying the level of a student's understanding.

As previously mentioned, the student should receive regular updates to the assessment grid he or she receives. Biweekly updates should suffice, if the educator is conscientious enough to update each one at least weekly. The student should help with this task by periodically being explicitly told to self-assess a performance. Additionally, the student should be encouraged to challenge any assessment he or she feels does not adequately represent his knowledge (after considering the error bars, of course).

Continuous assessment, while vital to the success of any meaningful approach to assessment, is the most difficult and time-consuming aspect of a curriculum designed for understanding. The educator must make a dedicated commitment to seeing it through to completion. Otherwise, a few points on a grid will have no more meaning that a few numbers to be summed and averaged.

Overall, the grid method for assessing a modern physics class should be effective. It would likely require a large amount of time and dedication by the instructor, both in implementation and in upkeep. However, those investments are likely to result in a richer assessment for the students, as it not only provides a measurement of two independent variables that is subject to change over time, but it also gives them a formative introduction to the disciplinary data analysis found in physics. Research is needed to determine whether this approach to assessment will yield pleasing results, and only in a curriculum that is specifically designed to incorporate meaningful tasks and a big idea ("uncertainty") is it likely to succeed.

Appendix: Rubrics for Assessment of Understanding of Uncertainty

Mathematical Fluidity (akin to Application in UbyD or Forms/Methods in TfU):

Tier 0: The student is unable to recognize symbols such as psi and has no familiarity with any of the mathematical procedures needed to solve problems concerning the uncertainty principle in any respect whatsoever.

Tier 1: The student recognizes relevant physical symbols, equations, and algorithms. Student is able to follow the logic of a worked problem but is unable to perform operations such as normalization of wavefunctions without substantial coaching.

Tier 2: The student is able to repeat certain algorithmic procedures with minor coaching. Student can normalize wavefunctions readily and find expectation values $<x>$, $<x^2>$, $<p>$, and $<p^2>$ (and hence, $\sigma_x\sigma_y$) with some coaching.

Tier 3: The student can solve algorithmic problems and prove the uncertainty principle for a simple and familiar system by using $\sigma_x\sigma_y$ with no coaching. The student is able to deduce approximate wavefunction solutions for the Schrödinger Equation with minor coaching. Student is able to solve barrier problems with heavy coaching.

Tier 4: The student can deduce approximate wavefunctions for novel (but similar) systems and use this wavefunction to solve for the uncertainty condition without coaching. Student can use mathematical reasoning to support conceptual arguments (regardless of the validity of the claim). Students are able to solve barrier-type problems with little or no coaching.

Tier 5: The student is able to fully analyze a system using the appropriate mathematical forms and procedures. The student is able to coherently explain and describe the uncertainty principle with mathematics and is able to show different mathematical manifestations of the uncertainty principle in very novel contexts (such as in the "chunking" description of phase space), possibly employing some coaching.

Conceptual Grasp (Explanation/Interpretation - UbyD or Knowledge/Purposes - TfU):

Tier 0: The student is unable to define the Heisenberg Uncertainty Principle and has no familiarity with any differences whatsoever between the quantum and classical descriptions of the world.

Tier 1: The student is able to provide superficial descriptions of quantum mechanics and is able to define the uncertainty principle in some generic way. The student makes no identification that he or she sees the role the uncertainty principle plays in life and is unable to do little more than repeat what he or she has read or been told.

Tier 2: The student is able to present multiple definitions of the uncertainty principle, but only when prompted in specific contexts. The student does not recognize these manifestations as equivalent. The student begins to provide vague implications of quantum physics and may even provide some isolated insights into support for the quantum theory. The student has yet to form a consistent theory for himself (or herself) and is still largely accepting of the theory based on authority.

Tier 3: The student is able to see manifestations of the uncertainty principle as equivalent if prompted and coached. The student is able to see some historical value in developing an understanding of the quantum theory. He or she can point to many different implications of the uncertainty principle but has not yet reconciled the abstract and "unreal" quantum description of the world with the classical description of the world.

The student begins to be able to tell a story of quantum mechanics, but many facts are unsupported and some claims invalid.

Tier 4: The student is able to make smooth transitions between manifestations of the uncertainty principle to support arguments. The student sees the classical picture of the world as an approximation of the quantum picture of the world and is able to explain the development and role of the quantum theory is a mostly-consistent historical (or equivalently attractive) manner. The student should confusion at (and begin inquiring meaningfully about) apparent paradoxes in the theory.

Tier 5: The student has taken ownership of quantum theory and is able to defend its value and role very consistently. The student, with coaching, is able to use quantum-mechanical language and descriptions to formulate rich and satisfying perspectives on novel ideas that may or may not be directly related to quantum mechanics. The student also appreciates and inquires meaningfully about the conflicts, paradoxes, and non-mainstream theories (that is, beyond the Copenhagen Interpretation) in the development of the quantum theory.

References:

Thornton and Rex, Modern Physics for Scientists and Engineers. Brooks/Cole 2002.
Wiggins & McTighe, Understanding by Design. Upper Saddle River, NJ: Merrill Prentice Hall 2001.
Wiske, M. S. (Ed.), Teaching for Understanding: Linking Research with Practice. San Francisco: Jossey-Bass 1998.

Understanding and Task Design in Modern Physics

(Concluding Essay)

Why Understanding?

Jean Paul Sartre wrote, in *Existentialism and Human Emotions*, that "Man is nothing else than his plan; he exists only to the extent that he fulfills himself; he is therefore nothing else than the ensemble of his acts, nothing else than his life." This is a strong claim, that a person is nothing more than the sum of his or her actions. In structure and implications, it is similar to the claim that David Perkins makes in *Teaching for Understanding* that understanding is performance. If nothing else, this has a pragmatic ring to it: how can we assess someone's understanding if that understanding is not a performance that we can observe?

Perkins further claims that, "knowledge, skill, and understanding are stock in the trade of understanding." Knowledge and skills he refers to as information and routines "on tap." Understanding, however, is more subtle: it "is the ability to think and act flexibly about what one knows." (TfU 1998 p.40) If the student is not thinking or acting in a manner that forces a flexible application of what he or she knows and is able to do "by rote," then understanding is not being addressed in any way. The implication is that understanding then increases your stock knowledge and skills so that one who has previously demonstrated one level of understanding should be able to show a deeper level of understanding in the future. These understandings then have a profound effect on life: being able to swerve away from danger while riding a bicycle or being able to rewire one's house both are understanding performances. It is additionally unlikely that either of these two challenges could be overcome merely by reading about them in books or hearing about them in a lecture. Instead, someone needs to practice riding a bike or apprentice with an electrician: these require understanding performances of ever-increasing difficulty. In our courses, then, we should require performances of understanding from our students that reach beyond simple knowledge and skill.

Understanding by Design gives us six facets of understanding to look for. When understanding something, a student should be able to explain, interpret, apply, show perspective, empathize, and reflect self-knowledge. The first three aspects of understanding are more easily sought out in a classroom than the latter: a student should be able to provide thorough and justifiable accounts of phenomena, tell meaningful stories and make the phenomena personal, and effectively use and adapt his or her knowledge in various contexts (UbyD 2001 p.44). These three are relatively easy to observe, since an instructor can explicitly ask for a demonstration that requires an explanation, application, or interpretation of the knowledge and skills that he or she should have obtained in the classroom. Note, of course, that just because a question or task could be designed in principle does not mean that it is trivial to do so.

The remaining three facets are much more difficult to deal with in a classroom setting because they require the student to be fully aware that he or she is alone responsible for constructing his or her own understanding. While this is true of all of the facets, a student who is intent on playing "the assessment game" might be able to do what the instructor is asking without really internalizing the material. However, the final three facets require the student to change as a result of what he or she has learned. Specifically, a student is "able to see and hear points of view through critical eyes and ears," "find value in what others might find odd, alien, or implausible," and perceive one's own prejudices and mental habits that "both shape and impede [one's] own understanding." (UbyD 2001 p.44) These understandings occur in the classroom in very subtle ways: a steady, careful observation of a student between the beginning and the end of the course should reveal whether he or she truly exhibits perspective, empathy, and self-knowledge. Unfortunately, there is no simple way to "test" for these facets. The best way to observe them is to form dialogues and relationships with the students that allow for them to reveal the extent to which they are internalizing the subject matter. However, in a class with hundreds of students, this is not a likely reality.

If the goal of a course is to provide a framework within which a student may construct his or her own understandings through a cycle of tasks, the instructor's role is beyond that of merely the purveyor of knowledge. The instructor becomes task designer, mentor, guide, and assessor. This is not a simple role; however, a course framed with a goal of understanding is destined to be much more effective for making a positive impact in the intellectual growth of any student.

In science, shooting for understanding is no different than any other field. We must look at not only scientific knowledge, but also what it means to think like a scientist: what questions to ask, how to look for answers, what assumptions one can and should make. Exposing students to disciplinary context through experiments, professional papers, and true laboratory experiments, in addition to the expected scientific content, is necessary. Further, instructors and courses should challenge students to deeply engage in the discipline – beyond simply memorizing terminology or solutions to toy problems.

Why Modern Physics?

When Einstein published his paper on Special Relativity in 1905, the public reacted more than ever before from a scientific work. This is because his interpretation of the world – a constant speed of light in any inertial reference frame, leading to relativistic addition – was so radically different from the model that Isaac Newton proposed, where a universal time and reference frame existed. Through the end of the nineteenth century, scientists had tacitly assumed this absolute time and space, though they failed to realize that no one really bothered to define these terms in any meaningful way. Thus, what Einstein did was reveal that the "Emperor had no clothes." It was as if someone had "dumped a bucket of cold water over the human race, and physicists were not the only ones to get wet." (Baker 1970 p.114)

The reason why this was such a shock revolved around the nature of the physicists' explanations of the world. The explanations they had been using weren't adequate: they were often using terms that had no meaning or relevance. What followed was an explosion of scientific work in the early part of the twentieth century that sought to make more of an effort to define terms meaningfully. In effect, it was more than just *where* physicists were looking for explanations of their lives but also *how* they were looking.

What is usually classified as "Modern Physics" is the subject matter that was discovered in that extraordinarily fruitful 30 years. However, it ought to be more than that. A course entitled "Modern Physics" should also deal with this incredible shift in the discipline of physics, not only for historical interest but also because a similar shift should be occurring in the students as they begin their training as scientists. Students should commence learning how to ask meaningful questions about the nature of the physical world, where to pursue answers to those questions, and how to justify their claims with appropriate data. The implied assumption here is that all students taking a course about "modern physics" will eventually become scientists – maybe not in career, but at least in their perceptions of the world. This is not an unreasonable assumption; a course on modern physics is not taken en masse by university students; it is a class reserved for those majoring in science or engineering.

Relativity and Quantum Mechanics were two very different fields that sprang up in the fruitful early 20th century, and students should study each one carefully within a Modern Physics course. For the purposes of this portfolio, however, I have focused exclusively on introductory quantum mechanics: its content and its importance as a paradigm shift. The continuous, orderly model that Newton designed has been replaced with a discrete, probabilistic one. Nonetheless, Newton's observations were sufficient for much of our daily life. The deep dichotomy and meaning implied here needs to be investigated by students as they force themselves to understand the continuing struggle physicists endure. It is overly ambitious to expect students to see this issue and resolve it within a semester course that is also partially devoted to a similar issue regarding relativity; a course would be considered a success if it empowers the students to "merely" internalize the problem. Since a Modern Physics course comes relatively early in a student's college career, it should merely serve to entice the student; there is plenty of time for resolution in more rigorous courses.

Unfortunately, "traditional" Modern Physics courses fail on this account. Here, I am defining a "traditional" course as one that uses a textbook such as Thornton and Rex for supplying reference and homework problems, lectures that primarily reference the textbook, "cookbook" laboratory experiences that reproduce famous experimental data collection such as Millikan's Oil Drop or Einstein's Photoelectric Effect, and essentially no engaged discussion about the consequences that any of these discoveries had on the discipline of physics. For more information regarding this claim, see the paper included in this portfolio, "Analysis of a Typical Modern Physics Curriculum."

Applying Understanding to Task Design in Modern Physics

In a traditional course, lectures occur for three hours a week, and the students are usually ill-prepared to receive them. Numerous studies have exposed the failures of this approach in introductory physics courses, both in terms of the students' lack of improvement on standardized tests and in terms of causing significant shifts in true understanding (see, for example, Halloun & Hestenes 1985). It is not unreasonable to assume that Modern Physics courses also fall short on both of these claims; however, it must be noted that the analogy to introductory physics breaks down at some point along a physics major's coursework. At some point, physics students are able to perform just fine and understand material from "only lecture" – although this generally applies exclusively to the very small percentage of students who survive the introductory coursework and who have a deep personal commitment to learning the content and discipline of physics. I claim, without supporting data, that the Modern Physics course, a sophomore level class, is still a place where such an analogy with introductory physics is apt.

The concern here is not that lecture is uncalled for. Rather, the challenge is to know when it is "time to tell:" the students will only internalize and use lecture in their mental construction if they feel they have a *reason* to know (Carpenter and Lehrer 1999). One effective way of bringing students into feeling that they have a reason to know is to employ benchmark instructions (Hunt & Minstrell 1994), as I investigated somewhat in the paper "Uncertainty: A Big Idea in the Modern Physics Curriculum," included in this portfolio.

When introducing quantum mechanics, a challenge that faces instructors is that there are no clean experiments or demonstrations that can engage the students and cause them the cognitive dissonance that they need to work on their mental constructions in any meaningful way. Quantum physics applies to the world of the very small and is thus very abstract; we simply cannot show a trapped electron in a deep potential well tunneling into the barrier region. However, in this age of increasing computer simulations, we are more able than ever to model some events such as photoelectric effects, light diffraction and interference, and particle – wave duality of electrons (see, for example, Kansas State University's *Visual Quantum Mechanics* project). Used properly, these demonstrations might be able to fill the role that simpler classroom demonstrations fill in introductory courses. Students should use these sorts of programs to the point where they recognize an "irresolvable" problem between the quantum and the classical models. At this point, discussion amongst the students and with the professor (and often, lecture) is needed to resolve those issues, thus allowing the students to form mental models of the situation so that they can demonstrate understanding when faced with similar situations.

There is no magic formula for giving students understanding – in fact, it is *impossible* to give students understanding. Understanding is not a "thing" to be given; it is a performance (Perkins, in TfU 1998). Students are ultimately responsible for their own understanding; it is the role of the instructor to guide the students by having a deep knowledge of content, discipline, and appropriate teaching practices. The best instructors have a good mix of each of those so that he or she can anticipate students' struggles and provide scaffolding as appropriate to guide their growth (Carpenter and Lehrer 1999). Instructors should not get distraught when students struggle; it is only through those struggles that we ever actually learn. This is a significant shift from the belief that the students enter the classroom with an empty brain to be filled, and that the instructor is the authority figure carrying the bucket. "Cognitive Apprenticeship" models, such as the ones described by Collins, Brown, and Newman (1989) seem to hold much promise for achieving this goal. They claim that there is too little attention paid to experts' processes: the emphasis in too many classes is on formulaic methods, textbook problems, and low-level skills developed in isolation. However, because cognitive and meta-cognitive strategies and procedures are more central than low-level subskills or abstract concepts or facts, they call for instructors to "model, coach, and fade." They also encourage student reflection and "many masters" since no one individual is able to demonstrate the knowledge or skill within a domain.

One way understanding has been modeled to students is through short sessions where the students would challenge a math teacher with a problem and observe his thinking processes as he described aloud what he was doing as he attempted to solve the problem (Schoenfeld 1983, 1985, in Collins, Brown, & Newman, 1989). Because students typically only see instructors answer questions or solve problems to which the answers are already known, they do not often see the complex procedures that experts employ to demonstrate understanding. Making such procedures transparent would certainly be helpful in a modern physics context; understanding how quantum mechanics plays out in a given situation may not be immediately apparent to either the students or the instructor.

The challenge with a cognitive apprenticeship is that instructors should be careful about what they intend their students to learn. We should want the students to gain knowledge and insight so that they can "create understanding performances." For example, we would want a student in a modern physics classroom to be able to explain how quantum mechanical tunneling can supply a source of energy; this is preferable to the student being able to solve a toy "tunneling" problem and not understand the results of his or her mathematics.

One valuable resource we have that can help us achieve this end is a wealth of papers from the scientists themselves who were engaged in the studies during the early 20th century. Bohr and Einstein, for example, wrote competing papers back and forth about the uncertainty principle. These papers were very deep, and introductory students may not fully appreciate them, but they should be able to still gain some useful insight into the discipline of physics, with proper guidance from the instructor. These papers often set up *Gendanken* experiments – thought experiments – which can not be set up and tested like the traditional demonstrations in introductory courses. These experiments are nonetheless a vital part of physical inquiry: logical reasoning alone is often enough to dispel arguments. Students in a modern physics course should be exposed to this, perhaps by giving them Bohr's original paper and Einstein's rebuttal and allowing students to discuss them. The discussion is vital; a professor simply explaining the (very subtle) errors in Einstein's argument is likely to have no effect on the students. However, if the papers are seen in the context of two colleagues passionately debating in hopes to better understand the world, the students may leave the class with more than an appreciation of "who was right." In this particular case, just because Einstein's argument was wrong, we should not neglect his paper. Instead, we should realize the role he played in challenging and deepening our model as it stands today. That criticism and intensity plays a significant role in physics in the modern era. The students should appreciate the difference between modern scientific challenges and the non-scientific challenges in the early development of science (say, in the Copernican era).

Throughout task design in a modern physics course, assessment plays an integral and vital role. A detailed look at the importance of assessment can be found in the paper "Assessing Understanding of Uncertainty in a Modern Physics Curriculum" within this portfolio. While its suggestions for assessment in a modern physics course may have been ambitious and unlikely to succeed precisely as written, it should be clear that continuous assessment of differing degrees of meaningful understanding performances is necessary to both encourage students to pursue deep understanding and helpful in gauging how well they are accomplishing that goal. More discussion can be found in the aforementioned paper.

In summary of the comments raised within this section, a successfully designed modern physics course should involve many aspects. It should focus on two major areas: relativity and introductory quantum mechanics. Each of those sections should be developed in terms of finding unsatisfactory results in “traditional” models, such as classical mechanics being unable to predict or explain nuclear reactions. The students should investigate these major points through the use of computer simulations, readings of expert papers, and classroom discussion. Lectures should be used carefully and only when adequately prepared for. The instructor should serve as guide, resident expert, assessor, and mentor to the students. Finally, the students must “buy into” the course and claim responsibility for their own understanding; to this end, the appropriate classroom dynamic must be created and sustained.

A rough example of a unit introducing the uncertainty principle might include a class discussion about certainty in classical physics, a demonstration or exploration into “uncertain” events such as die-rolling and computer simulations of atomic decay or photons hitting a screen after going through an aperture. These guided inquiries would then be followed by another class discussion recalling the conclusions reached in the first class discussion and the results from the inquiry. Following this might be a few lectures about uncertainty, a reading of Bohr’s and Einstein’s papers, and another class-wide discussion about what role these papers play. Another lecture or two might follow this; homework problems and small quizzes of one form or another may be scattered intermittently. Finally, a unit-covering project, such as a discussion paper or oral or written exam should be the culminating experience. All of these steps should be held within the context of developing the course’s “Big Idea” (see “Uncertainty: A Big Idea in the Modern Physics Curriculum,” included in this portfolio). Notice that such a unit is bound to take weeks to perform; hence, only a few such units would be possible within the semester allotted to the class. Nonetheless, this depth in a few areas should prepare students for doing physics better than any of the numerous "inch deep and mile wide" courses presently offered.

Obviously, many of the suggestions raised in this paper (and throughout this portfolio) regarding improving and renovating instruction with regards to modern physics and introductory quantum mechanics are rough and without experimental support. However, they are well grounded in previous research and should provide a good framework for future investigations into such issues. Future research is needed to determine precisely how effective any specific units are at achieving the desired level of understanding, and hopefully this research will someday be done. Ideally, a course on modern physics should act as a springboard for student interest in physics and as a foundation for more involved future coursework and scientific research. This would be a worthwhile and pleasing shift from its current role as an abstract and confusing course that disenchants and weeds out many prospective scientists.

References:

Baker, A. *Modern Physics and Antiphysics*. Addison-Wesley. 1970.

Carpenter & Lehrer. "Teaching and learning mathematics with understanding." In E. Fennema & T. R. Romberg (Eds.), *Mathematics classrooms that promote understanding* (pp. 19-32). Mahwah, NJ: Lawrence Erlbaum Associates. 1999.

Collins, Brown, and Newman. "Cognitive Apprenticeship: Teaching the Crafts of Reading, Writing, and Math." In L. Resnick (Ed.) *Knowing, Learning, and Instruction* (pp. 453-494). Hillsdale, NJ. 1989.

Halloun & Hestenes. "The initial knowledge state of college physics students." Am J Physics 53 (11) November 1985. 1043-1048.

Hunt & Minstrell. A cognitive approach to the teaching of physics. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory*. Cambridge: MIT Press. 1994.

Thornton and Rex, Modern Physics for Scientists and Engineers. Brooks/Cole 2002.

Wiggins & McTighe, Understanding by Design. Upper Saddle River, NJ: Merrill Prentice Hall 2001.

Wiske, M. S. (Ed.), Teaching for Understanding: Linking Research with Practice. San Francisco: Jossey-Bass 1998.