Oersted Lecture 2014: Physics education research and teaching modern Modern Physics

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AWARDS

Oersted Lecture 2014: Physics education research and teaching modern Modern Physics

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Modern Physics has been used as a label for most of physics that was developed since the discovery of X-rays in 1895. Yet, we are teaching students who would not use the label "modern" for anything that happened before about 1995, when they were born. So, are we and our students in worlds that differ by a century? In addition to content, sometimes our students and we have differing views about methods and styles of teaching. A modern course in any topic of physics should include applications of contemporary research in physics education and the learning sciences as well as research and developments in methods of delivering the content. Thus, when we consider teaching Modern Physics, we are challenged with deciding what the content should be, how to adjust for the ever increasing information on how students learn physics, and the constantly changing tools that are available to us for teaching and learning. When we mix all of these together, we can teach modern Modern Physics or maybe teach Modern Physics modernly.
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I. INTRODUCTION

Receiving the Oersted Medal is humbling because of all of the previous recipients who have contributed so much to physics education. I will mention a few of them in this paper. The medal has also caused me to do quite a bit of reflection on my career. I started at Kansas State in 1970 in a two-year temporary appointment that was not related to physics education. I can state rather well when I began to think that my career might be in physics education research (PER), even though the term did not exist then. In 1971 Jackie Spears and I travelled from Manhattan, Kansas to Colorado Springs. At that time I was still in the temporary appointment, but Kansas State's Physics Department was advertising a tenure track position for an Assistant Professor who would specialize in physics education. With that ad as motivation, we talked about physics teaching for most of the trip. I had probably said everything that I knew about physics teaching by the time we got to Salina (100 km from the start of the trip). Jackie had been a high school physics teacher, so she gently kept telling me that most of my ideas about physics education were wrong. But, somehow that conversation gave me the courage to apply for the PER job at Kansas State even though I was not qualified. I was appointed to the position in June 1972 and began to conduct scholarly activities related to physics teaching. During that summer I went to a workshop that was conducted by Bob Fuller. That started a collaboration that continued for 40 years. Today, our PER group is quite different from the one in the early 1970s when I had at most one graduate student. We now have three faculty members, one visiting faculty, and a bunch of graduate students and postdocs. We and the discipline have come a long way.

Some of the seeds of change in PER were planted long ago, many of them by previous Oersted recipients. For example, in her Oersted response in 1973 Melba Phillips stated, "We must learn to be more receptive to responses, more sensitive to viewpoints of those we try to reach."[1] This idea expresses what all of us are trying to do. With the research of the past 30–40 years we have been learning what our students think when they begin their studies of physics, how they process new ideas, and how they make the new ideas fit with what they already know. Then, we try to help them learn physics while enjoying it as well.

This paper is divided into four parts. It will start with some thoughts about physics education research. Those ideas will then be connected to topics in modern physics, and this will be followed by some ideas about modern delivery methods. Lastly, I provide a few concluding thoughts.

In this paper, I will be using the term "modern physics." Physicists tend to use that term to refer to most developments in physics that occurred after approximately 1895. Thus, "modern physics" is not necessarily modern. However, my son, who is a philosopher, tells me that philosophy uses modern philosophy for everything that occurred after about the 17th century. Moreover, I have been doing some posts on my daughter's blog for historical novelists about the history of models of matter.[2] I find that many historians of science label as "modern" anything that comes after Galileo. So I will use "modern physics" in the traditional sense that physicists use it, for developments of the 20th and 21st centuries.

II. A FEW THOUGHTS ABOUT PHYSICS EDUCATION RESEARCH

In response to receiving the 1961 Oersted Medal Francis Sears stated, "the most important thing today is for those in power to recognize that research in teaching is as important as research in physics."[3] To reach this goal has taken a long time, and certainly we are not entirely there yet for all "those in power." However, we are to the point where research in physics education is a respected field within the discipline. In addition to physics education researchers, many physicists would consider themselves consumers of the results of PER. As one of my colleagues said recently, "By itself, physics education research will not make you a good teacher. If you apply it, it will definitely make you a better teacher."

Another smaller group of the physics community regularly reads PER papers but does not actively incorporate the results in their teaching. Unfortunately, there are still a few physicists who see PER as inappropriate for physicists to undertake. However, we are getting close to Francis Sears' goal.

A. Some recent PER reviews

For the PER consumers and readers some recent documents are rather valuable. One is the National Research Council Report *Adapting to a Changing World: Challenges and Opportunities in Undergraduate Physics Education*.[4] It is not a PER report per se, but a report on undergraduate physics education that includes much about PER. A fundamental message is, "While a few physicists may be naturally talented teachers who can reach a broad spectrum of students using instinct alone, most physics faculty can improve their teaching just as they improve other scholarly efforts, by incorporating practices based on scientific evidence." (p. 75)

As the quote from Francis Sears indicates, thoughts about developing a research area such as PER are older than some of us usually think. So is some of the research. A footnote in Eric Rogers' 1969 Oersted talk[5] describes an experiment that looks very similar to an experiment some of us would run today. He found that students could calculate using Newton's Second Law. However, when asked to explain in their own words the meaning of the equation, they had difficulty. His results are not much different than we would expect today in most of the traditionally taught classes.

When Rogers ran his experiment, he probably had no other data with which to compare it. Fortunately, today's situation is quite different. Some recent reviews provide good places to start when looking for results or applications of PER. A valuable reference that does not receive much notice is *A Synthesis of Discipline-Based Education Research in Physics* by Jennifer Docktor and Jose Mestre.[6] This long and rather complete document was commissioned for a committee at the National Academy about four years ago. Its 150 pages provide much detail about the status of PER when it was written. More recently, David Meltzer and Ron Thornton[7] wrote a resource letter on evidence-based active learning instruction. For up-to-date information, the web-based PhysPort[8] is readily available as is a large amount of information on ComPADRE.[9] Even better, the PhysPort Assessment Data Explorer,[10] now in open beta, enables us to actually compare our data with other's data directly and in a way that maintains confidentiality.

B. PER and modern physics

The research in teaching and learning of modern physics is somewhat parallel to that in other topics. There are, however, a few differences. For example, most students will have completed some study of physics before beginning to learn modern topics. Also, everyday experiences are likely to have a smaller influence on understanding of the concepts than they do with classical topics. Thus, a possible classification scheme to focus on research in modern physics could be:

- Students' initial conceptions of various topics
- Students' difficulties in learning various topics (duality, photons, energy, potential energy diagrams, probability, …)
- Transfer of learning from classical to quantum
- Using resources while learning quantum mechanics and other contemporary topics
- Assessment of student understanding.

The use of resources and transfer or learning, in particular, make the situation in quantum physics a little different from classical physics. For example, students seldom come to a modern physics course with a preconceived idea about wave functions. However, they can have difficulty accepting quantum ideas and they can apply their knowledge of classical concepts inappropriately to their study of modern physics. When we look at the history of modern physics, we see our students are not much different than many physicists in the early 20th century.

There are times when we inadvertently facilitate the inappropriate transfer or just make the learning more difficult than it needs to be. Fig. 1 has appeared in many modern physics and quantum mechanics books. What is wrong with using this diagram as an aid to learning quantum mechanics? This question was posed to the audience at the Oersted Lecture and they responded using the online audience participation system Poll Everywhere.[11] Figure 2 shows a word cloud created from those responses.[12]

Today, many physicists immediately recognize the problem. The most common response was "no labels on axes." Indeed, that is a major issue. It is difficult to label the vertical axis because it represents multiple units, both amplitude and energy. Even more troubling, the horizontal line representing the total energy seems to be the horizontal axis for the wave function. Clearly, these types of diagrams can be very confusing for students.

The issue with this diagram is not a new discovery. At an AAPT meeting many years ago I was describing to Edwin Taylor how we had discovered this problem and how to address it. When I finished enthusiastically explaining how we now use two separate graphs, he pointed out to me that he and Tony French had used similar ideas for graphs in their 1978 quantum physics book.[13] They had recognized this issue even though they had done no research. Today many textbooks use separate graphs for the wave function and the energies.

Several researchers have found that diagrams of potential energy by themselves cause some learning difficulties. Wittmann *et al.*[14] and McKagan and Wieman[15] have investigated the difficulties that students have in learning about the relation between these graphs and the motion of small objects. Students talk about the electron needing to climb up the side of the barrier or losing energy as the electrons pass through the barrier. Morgan *et al.*[16] suggest that the type of

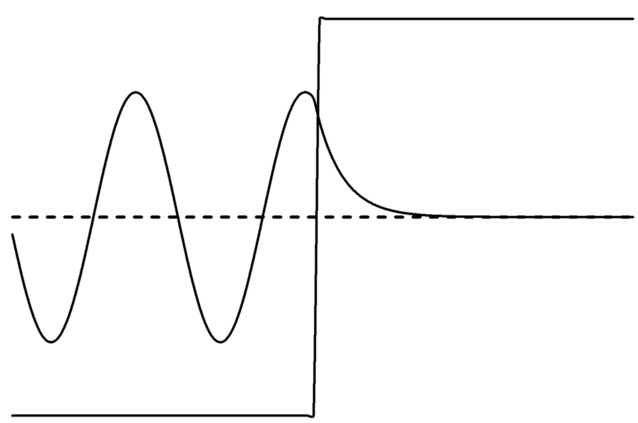

Fig. 1. A diagram that frequently appears in an introduction to quantum mechanics.

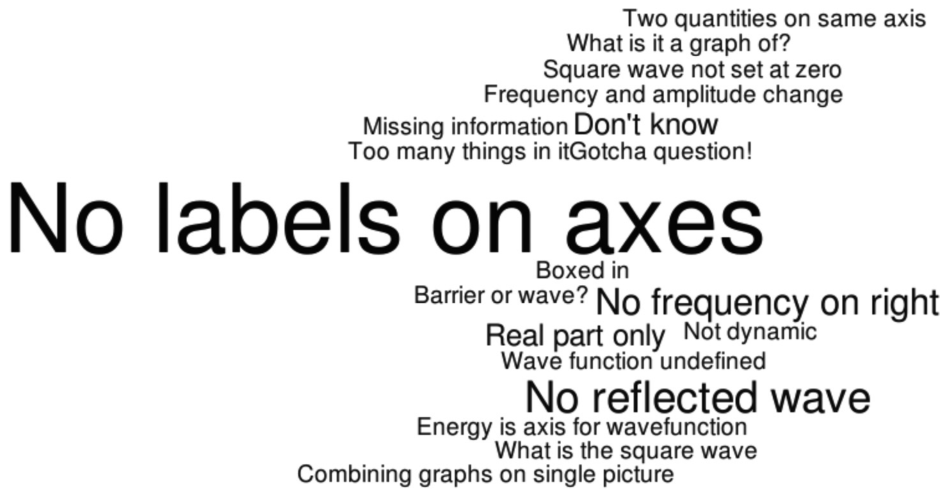

Fig. 2. A word cloud constructed from the responses at my Oersted Lecture. The size of the word is related to the number of responses.

graph in Fig. 1 could contribute to students concluding that the energy of a particle to the right of the barrier (or undergoing tunneling) decreases. After all, an exponentially decreasing curve is shown on the graph and seems to be related to energy. This and similar research has been carefully performed and is very useful when we are teaching quantum physics.

C. PER-based contemporary physics instruction

Many groups have built on the research in the teaching and learning of quantum physics to create instructional materials. Some of the developers of these research-based lessons or curricula have taken the approach that quantum ideas can be taught to students who are casual learners of physics while others have focused on upper-level undergraduate physics majors. For the more casual learners, including high school and college level non-science students, the instruction tends to use little or no mathematics and to emphasize concepts and visualization. Table I shows some of the projects that are primarily for non-science students and could be used in a high school as well as in a university. (The PhET project, of course, covers many areas of science in addition to modern physics.)

For more advanced levels, there are some good pieces of work that can be used and put into various classes (see Table II). I included the last three on this list to indicate that this effort is not just US-based. (Neither Tables I or II are exhaustive, they are just the ones I am most familiar with and use in my teaching and research.)

To conduct research or assessment of learning we need appropriate tools. Fortunately, some useful concept inventories are freely available (see Table III) and can be accessed via PhysPort's assessment page.[31] The entries in Table III are loosely ordered from the most advanced courses down to the most conceptual courses. The *Quantum Physics Conceptual Survey* is included in Ref. 28; the others require a password that you can get from ComPADRE or PhysPort. (In general, PhysPort and the Quantum Exchange on ComPADRE are great resources for more information on research, instructional materials, and assessment in modern physics.)

III. MAKING ROOM FOR MODERN PHYSICS

In his 1998 Oersted Lecture Edwin Taylor stated, "Public hunger for relativity and quantum mechanics is insatiable, and we should use it selectively but shamelessly to attract students, most of whom will not become physics majors, but all of whom can experience 'deep physics.'"[32] The first step in following up on Edwin's idea is to use various informal education techniques about modern topics to entice students to enroll in a physics course. Certainly, books and videos are doing much to help us with this aspect. Unfortunately, in many cases once the students take that first—and possibly only—physics course, they learn very little about the topics that prompted them to take the course. Thus, a natural extension of Edwin's thought is that we should include more Modern Physics in introductory courses than we do now. Of course, what to include and what to omit are difficult issues to address.

In December 2013 Gary White, editor of *The Physics Teacher* (TPT), distributed a survey about this topic. His survey was independent of my Oersted talk but so closely related that I asked to use it. Gary very graciously gave me his results. I asked the same questions of the Oersted Lecture audience so we can compare the two. (I do not pretend that either survey is scientific, but both provide starting points for discussions on this important issue.) To help the audience I provided two definitions. *Modern Physics* is as defined at the

Table I. Some research-based and free Modern Physics materials for non-physics students.

Instructional materials	Source
Visual quantum mechanics	<http://web.phys.ksu.edu/vqm/>
Intuitive quantum mechanics	<http://umaine.edu/per/projects/iqp/>
Physics education technology (PhET)	<http://phet.colorado.edu/>
Contemporary physics education project	<http://cpepweb.org/>

Table II. Some research-based and mostly free Modern Physics materials for undergraduate physics students.

Instructional materials	Source
University of Colorado modern physics	<http://www.colorado.edu/physics/EducationIssues/ModernPhysics/index.html>
Physlet® quantum physics (Ref. 17)	<http://www.compadre.org/quantum/items/detail.cfm?ID=4161>
Quantum interactive learning tutorials (QuILTs) (Ref. 18)	<http://www.phyast.pitt.edu/~cls/quantum/>
Upper-division quantum mechanics (Ref. 19)	<http://www.colorado.edu/physics/EducationIssues/Quantum/>
Paradigms in physics quantum mechanics and quantum measurement courses (Ref. 20)	<http://physics.oregonstate.edu/paradigms/courses>
QuVis: The university of St Andrews quantum mechanics visualisation project (Refs. 21 and 22)	<http://www.st-andrews.ac.uk/physics/quvis/>
Quantum physics online (French & English)	<http://www.quantum-physics.polytechnique.fr/index.html>
Münchener Internetprojekt zur Lehrerfortbildung in Quantenmechanik (milq) (Ref. 23)	<http://homepages.physik.uni-muenchen.de/~milq/>

beginning of this paper (the physics developed since the discoveries of X-rays and the electron). *Introductory course* is the first physics course (or maybe the only course) that a student takes. The questions posed to both the Oersted lecture audience and the TPT readers were:

- What is the most essential topic in modern physics that ought to be in an introductory course?
- To make room for these topics what would you take out of the present course?

A. What should we add to the current "normal" introductory course?

For the Oersted audience the responses were open ended; participants enter a word or phrase into their mobile devices. Figure 3 shows a word cloud of the results. Quantum Mechanics and Special Relativity are by far the dominant topics. Several other topics such as wave-particle duality, the uncertainty principle, and quantization are closely related.

The TPT survey had both an open-ended responses and questions in which respondents could select topics from a list. The open-ended responses are rich with information but difficult to analyze easily. Figure 4 shows the results for the select-from-the-list question (respondents could select as many items as the wished). The results are similar to those displayed in Fig. 3.

The largest difference between the two sets of responses is that photons appear to be rather small in Fig. 3 but represent a large number of responses in Fig. 4. In analyzing these data, we need to keep in mind that for Fig. 3 respondents needed to type into a mobile device whereas the responses represented in Fig. 4 were selected from a list. Given the time constraints and age distribution of the audience at the Oersted talk, the respondents may have decided to be brief rather than struggle with the device in order to give more extended responses.

B. What should we omit?

Figures 5 and 6 show the results for the harder question—what to omit from the present introductory course. Looking first at the results from the Oersted audience we see that thermodynamics and rotational motion received the largest number of responses. If the respondents who said "optics" meant geometrical optics, then that option would also be a large choice. A small but not insignificant number of people entered two words at about the same frequency and that are very telling: "nothing" and "everything."

Comparing the Oersted audience result with the TPT readers is also very telling. First, the results from the two groups are quite similar in that thermodynamics and rotational motion are omissions of choice for many people in both groups. Also interesting is that about 450 TPT readers responded to the question about what to add to the introductory course but only about 10% of those people provided an opinion on what to omit. Perhaps the question was too hard to deal with. The overall conclusion is that we have no consensus on what to omit and there are a reasonable fraction of teachers who believe that we can add more content without omitting any of the current topics that are presently covered. Is that possible? I doubt it, but I cannot give a definitive answer.

C. Issues when we try to change

Those people who felt that we cannot leave out anything from classical physics are in good company. In his Oersted response in 1948 Arnold Sommerfeld said, "The lectures were confined essentially to classical physics, which, as a basis for all modern developments, must never be curtailed."[33]

Table III. Freely available conceptual surveys for quantum mechanics.

Authors	Instrument
E. Cataloglu and R. W. Robinett	Quantum mechanics visualization instrument (Ref. 24)
Homeyra Sadaghiani and Steven Pollock	Quantum mechanics concept assessment (Ref. 25)
Steve Goldhaber and Steven Pollock	Quantum mechanics assessment tool (Ref. 19)
G. Zhu and C. Singh	Quantum mechanics survey (Ref. 26)
Johan Falk	Quantum mechanics concept inventory (Ref. 27)
S. Wuttiprom *et al.*	Quantum physics conceptual survey (Ref. 28)
S. McKagan *et al.*	Quantum mechanics conceptual survey (Refs. 29 and 30)

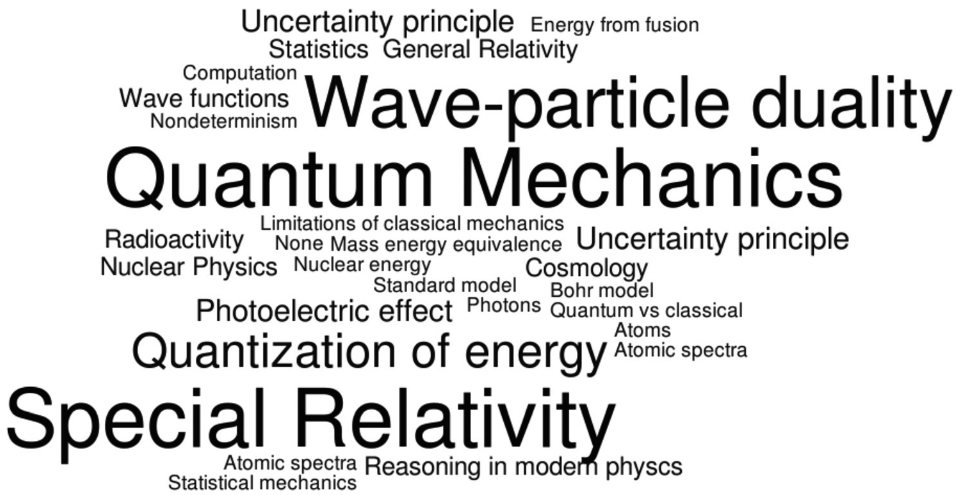

Fig. 3. Oersted audience results: most essential topic in modern physics to teach in an introductory course (75 respondents).

We cannot curtail anything because all of it is important. In his 1973 Oersted response Arnold Arons had a different viewpoint when he said, "In [a] sequence involving models that transcend direct experience, one can get students to follow and examine the evidence that led to our belief in the atomic-molecular structure of matter as well as in a structure of atoms themselves."[34] Arons changes the focus from *what* topics to teach to having students learn *how* we know about contemporary concepts. If we make that change, students can understand the foundation for our models of atomic structure, wave-particle duality, and related concepts. Arons was ahead of his time in many respects. In this case he anticipated the Next Generation Science Standards (NGSS) by about 40 years.[35]

Another approach is to consider how to rearrange topics and to integrate post-classical physics into the flow. We could consider when various contemporary topics could be learned during a course rather than placing all of them at the end.

Many years ago Jackie Spears and I wrote a textbook for a non-science audience in which Chapter 4 was special relativity.[36,37] Everybody except the people who tried it told us that the students would not be able to learn this material so early in the semester. However, we felt that some of special relativity could be learned with just a knowledge of kinematics.

Similarly, Visual Quantum Mechanics, which I discuss in Sec. IV, includes modules that require only conservation of energy as a prerequisite but help students learn about the energy structure of atoms and solids. Perhaps, rather than looking at the situation as adding and subtracting topics, the discussion should be about how to get contemporary topics integrated in the mainstream of physics content.

IV. OUR GROUP'S APPROACH: VISUAL QUANTUM MECHANICS

My colleagues and I have taken Arons' point of view with the Visual Quantum Mechanics[38,39] project in which we created instructional materials for both high school and introductory university students. The effort combined visualizations with real hands-on experiments and other activities so that students can understand not just what physicists say about nature but why physicists think that nature can be modelled in the way we do.

For example, students look at an emission spectrum and then use their knowledge of energy conservation to create an energy model of what must be happening in the atom. From this effort they come to the conclusion that because they see only a few energies of light, the atoms must contain only a few energy levels. Students are asked to build some energy level models using a program that enables them to match the light that would be emitted by their model with the spectrum of hydrogen (see Fig. 7).

Figure 8 shows three models that various students created. In our discussion students are challenged to determine which one is "right." They must do so using only the observation of the visible hydrogen spectrum as data. Based only on that observation, it is very difficult to distinguish between these and a number of other possible energy level models. At this

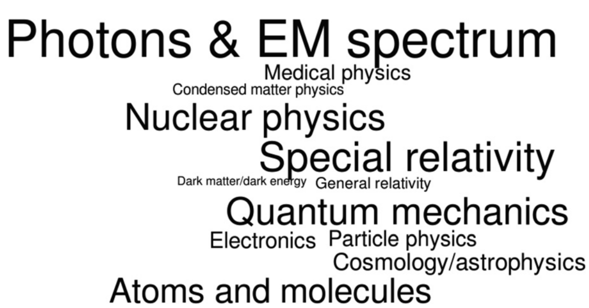

Fig. 4. TPT reader results: most essential topic in modern physics to teach in an introductory course (about 450 respondents listed about 630 topics; the topics listed in the figure were the most common).

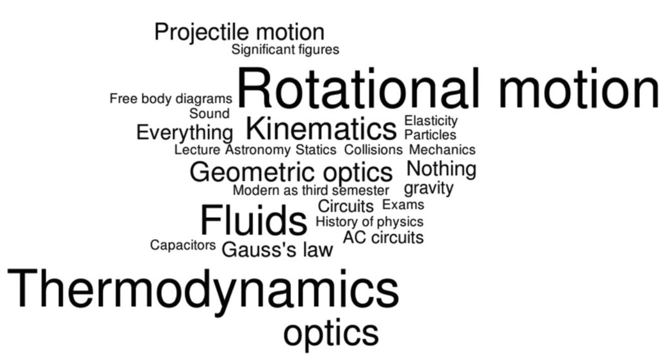

Fig. 5. Oersted audience results: what to omit (76 respondents).

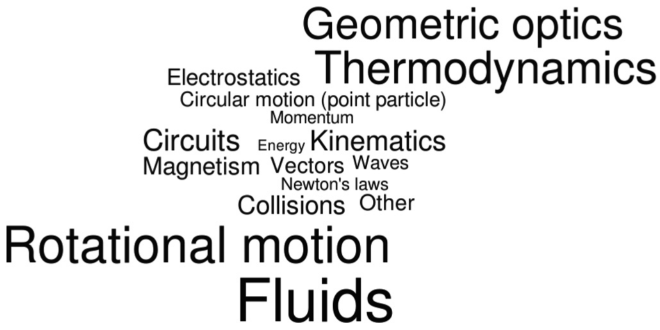

Fig. 6. TPT reader results: what to omit (40 respondents selected about 60 topics).

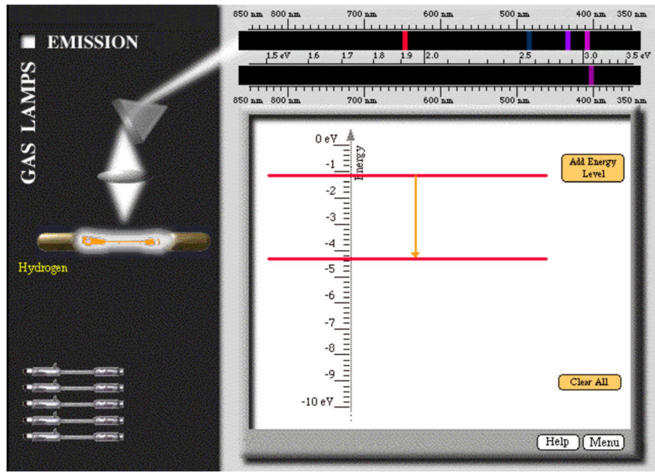

Fig. 7. A screen capture of the Emission module from Spectroscopy Lab Suite. The top spectrum is a simulation of the hydrogen gas spectrum. The second spectrum is the one that would be produced using the energy model in the lower right window.

point the students see that creating a model from limited data is not always easy. Any one of these three models could be correct to explain just this one observation.

To narrow the acceptable choices, we add more information. For example, students are asked what other transitions could occur with each of their models. Frequently, they find some transitions that would result in photon emission outside the visible region. So, the students look at data for the infrared and ultraviolet spectra of hydrogen and eliminate some models. (Unfortunately, direct observation of the IR and UV spectra is not easy with common student apparatus.) This procedure enables the students to eliminate most of the models. With this process students learn a little about how physicists build and refine models of nature.

The students have taken one relatively simple observation—the spectrum of hydrogen—and extracted from it the conclusions that energy levels in the atom are quantized. Thus, as advocated by Arons, they have examined evidence and learned something about the structure of atoms. They have also had a direct experience that shows how models can be incomplete when the amount of evidence is limited.

A. Extending the model

In addition to the energy level model of a gas atom, the students observe the spectra and behavior of several light emitting diodes (LEDs). We ask the students to use as many single energy levels as they need to create a spectrum similar to that of an LED. This process naturally leads to bands of energy to match the bands of light being emitted with gaps between those bands. The students then use a different visualization to manipulate these bands and gaps and see if they can build energy models to match the spectrum of different LEDs. All of the observation and model building is empirical, but it is an opportunity for students to see how they can build energy level models of atoms and of solids from just a little bit of information.

Our materials continue with other visualizations and conceptual activities to help students understand some quantum mechanics and some applications of modern physics to medical imaging.[36] All of our materials are based on research into teaching and learning. Sometimes we use the research from others; sometimes we need to conduct the research ourselves. In all cases, the evidence from studies of teaching and learning forms the foundation for the instruction, which always includes interactive engagement.

Assessments are used to see how much the students learn. My conclusion from these assessments is that much contemporary physics can be taught at a conceptual level to students who have limited mathematics and physics preparation. A sophisticated knowledge of classical concepts is not necessary.

B. Delivering the content

Content and research-based pedagogy are two components of a modern Modern Physics learning-teaching effort. A third is the delivery method. Our group's next step is an exploration of delivering learning about contemporary physics including the hands-on activities to an online, non-science-major audience. I am not considering massive open online courses (MOOCs) yet. Instead I am working toward a course that students enroll in, take seriously, and complete experiments at home with equipment that they build or buy.

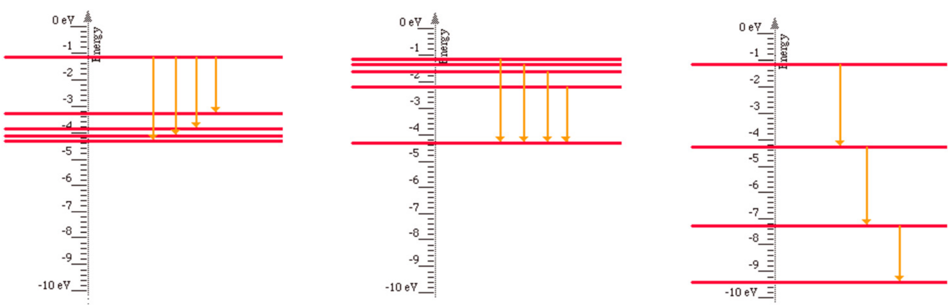

Fig. 8. Some of the energy level models that students have created to explain the hydrogen spectrum.

Additionally, they use interactive visualizations such as those described above to build models.[40]

Simultaneously, they take advantage of the vast amount of information that is available on the Web. Of course, that vast amount of information is mostly unfiltered. As I have been reviewing Web-based materials related to modern physics, I have been quite disappointed. Some people are willing to make videos or Web pages even though they have little knowledge of the topics. Equally disappointing is the pedagogy. Tell them and they will know seems to be the teaching-learning approach of many developers of Web-based instruction. Research tells us this method does not lead to deep learning.

So, one of the issues that I am addressing is how to incorporate something with good content and production values but poor pedagogy into an interactive engagement learning environment. So far, I have not discovered any general principles but I think I have had some success. In our initial comparisons of student learning in the online course with that in previous offerings of the face-to-face course we have found that the level of learning is comparable.[41] However, so far we have had only a few students complete the on-line course so further study is underway.

V. CONCLUSIONS

Research and development on instruction in topics in contemporary physics has been undertaken by many people. Much of the effort so far has been focused on learning of upper-level undergraduates. This work is quite important. We know that students come to these courses with knowledge obtained from everyday life and from previous courses. Additional research on the transfer of those experiences to the study of contemporary topics, which can seem counter intuitive to all of us and even in conflict with classical physics, is needed.

Likewise, more effort needs to be placed on contemporary topics in introductory-level courses, including secondary school physics. Students who take only one physics course need to understand what excites physicists today. Those who plan to continue study in physics deserve to learn about some of this excitement and need to be enticed to continue their studies.

In his Oersted Medal talk Len Jossem said, "Recognizing the need for change is easier than deciding what to do."[42] I think that many of us have recognized the need for change in teaching modern physics. Many people who are mentioned in the paper have undertaken some of the things that need to be done. However, as a group we have much to do in this area. Fortunately, physics education is now a strong community of researchers, developers, and practitioners. Working together we can make changes that will improve the teaching-learning experiences for both students and instructors and in the process include a strong component of modern physics.

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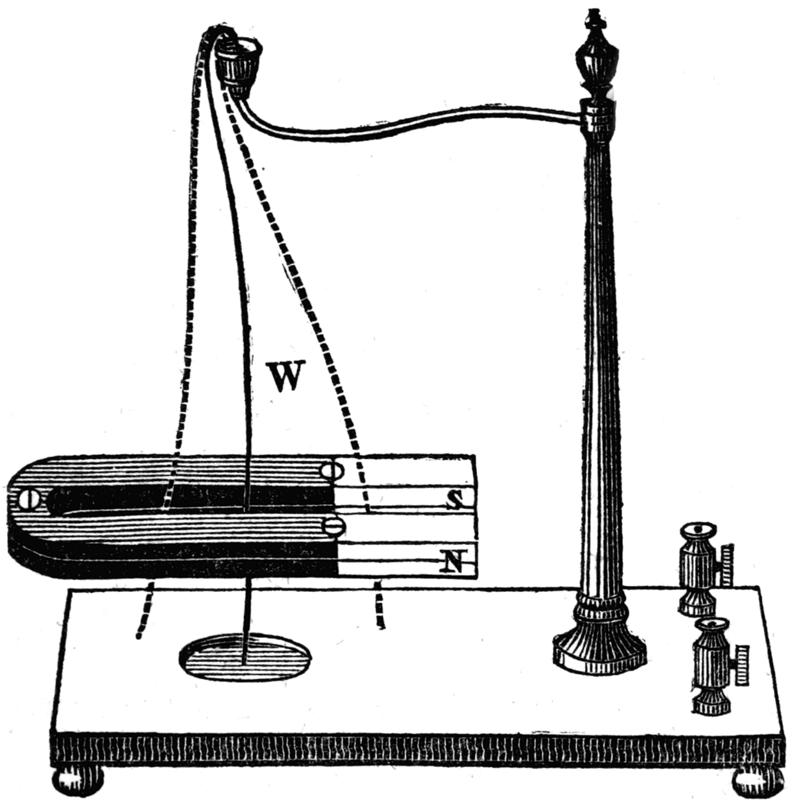

Marsh's Vibrating Wire

In 1821 Michael Faraday discovered that, with the right geometry, the force on a current-carrying wire immersed in a magnetic field can be used to produce motion. One early example of this is James Marsh's Vibrating Wire, first mentioned in an article by Peter Barlow in This picture, from the 1842 edition of Daniel Davis's Manual of Magnetism, shows the lower end of the freely suspended wire dipping into a pool of mercury. Electric current through the wire produced a force on the wire that flipped it out of the mercury. Barlow improved on this by substituting a copper wheel for the copper wire, thus producing continuous motion. The apparatus sold for $1.50 without the magnet, and $5.00 with it. (Notes by Thomas B. Greenslade, Jr., Kenyon College)