CREATING DIGITAL LEARNING OBJECTS TO TEACH ABSTRACT IDEAS IN MODERN PHYSICS AND ASTRONOMY

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ABSTRACT
Teaching modern physics and astronomy poses a daunting array of challenges. Many science curricula contain detailed outcomes and emphases which add to the complexity of this task, and increasingly we are becoming aware of the need to attend overtly to conceptual understanding in students. In this paper we present a discussion of digital resources developed at The King's Centre for Visualization in Science and CRYSTAL-Alberta to enable teachers to meet this challenge. We also argue that effective use of such resources entails a shift in pedagogical emphasis from skill development to teaching that focuses more overtly on evidence based reasoning. Exemplars are provided which demonstrate how teaching to encourage evidence based reasoning can be realized and how the major goals of the curriculum can be met.

KEYWORDS
Applets, Digital Learning Objects, Conceptual Physics, Active Learning, Evidence Based Learning, Nature of Science

INTRODUCTION

Physics teachers face a daunting task. On one hand many curricula have focussed increasing attention on topics in modern physics and astronomy. On the other hand traditional pedagogical practices have been under increasing scrutiny and a call for more active learning is increasingly heard. As well, most science curricula formally acknowledge the need to more overtly attend to the development of "scientific literacy" in students while at the same time demanding the maintenance of existing skills and competencies. There is little wonder that teachers are resistant to change – especially when it pushes them into new frontiers of knowledge.

When introducing topics in modern physics the integration of knowledge and skills is particularly problematic; modern physics by its nature pushes the student beyond the "touch/feel" world of Newtonian physics into a world in which the student (and sometimes the teacher) has little direct intuitive contact. In this paper we will argue that this calls for both the introduction of new tools with which to teach but more significantly a new kind of focus of pedagogy. To do this we will provide an overview of digital learning objects or DLOs (applets and ancillary resources) that have been created over the past three years at The King's Centre for Visualization in Science (KCVS) and the Alberta Centre for Research in Youth Science Teaching and Learning (CRYSTAL Alberta). We will also draw on exemplars from the physics curriculum used in the province of Alberta to illustrate how the DLOs produced by our group are designed to address curricular emphases such as development of scientific attitudes, understanding Nature of Science and the use of evidence in scientific reasoning.

THE NEED TO VISUALIZE – AND WHY SEEING IS NOT ENOUGH

There is a vast literature devoted to identifying problem areas in the learning of modern physics from upper elementary grades to advanced undergraduate levels. A common motif found in the literature is the disconnect between the student's lived reality and the concept(s) being taught. Taber (2005), for example, looks at the barriers encountered by students attempting to understand the concepts of quanta and orbitals. In this analysis Taber works from a constructivist learning theory to develop a typology of learning impediments: deficiency, fragmentation, ontological and pedagogic. In the case of a fragmentation impediment the student is unable to incorporate the concepts being taught within his or her intuitive framework. From a learning theory perspective the knowledge fails to create any linkages within the student's world and will never become robust knowledge. Sadly, Taber offers little in the way of remediation for the problem of fragmentation. If one takes the lessons of learning theory and constructivist teaching (Ausubel 2000) to heart, then the need to develop intuitive scaffolds for students is imperative. The hypothesis invoked herein is that Applets (small, web-delivered computer programs) offer a way to develop these intuitive links. For example, the concept of quantization is introduced explicitly in the Alberta physics curriculum through a series of knowledge outcomes (30-D2.1k-.7k), STS outcomes (30-D2.1,2sts) and skill outcomes (30-D2.1s-.4s). Quantization is a threshold concept (Meyer & Land, 2006, Park & Light, 2009) which is critical for a student to make sense of most of the modern physics ideas that he or she will encounter. Hoeksema (Hoeksema et al.) has also described the use of the particle-in-a-box model as a "pillar" on which a treatment of quantum physics in Dutch schools is built.

Figure 1 illustrates a simple applet designed to introduce the concept of quantization and to root it in prior knowledge – specifically the concept of standing waves (Physics 20 Unit D – mechanical and acoustic resonance).

In this applet the student is able to confine a particle (electron, proton or particle of student-assigned mass) to a 1-dimensional region. This is, of course, the well known particle-in-a-box model which is a staple in a physicist's toolkit. By changing the dimensions of the box the student is able to investigate how energy changes (e.g., E_5-E_1) and to see the corresponding change in the wavefunction (bottom right in the applet) and thus a connection to standing waves. Another threshold concept (probability) is introduced with the accompanying wave-function tool and the generation of discrete spectra (top left) can occur via student-selected transitions between energy levels, E.

Experience and research indicate, however, that seeing is not enough to help develop intuitive hooks for the student. For the visualization to prove effective there is a ternary relationship among visualization, interaction and assessment as illustrated in Figure 2. The student not only interacts with the visualization; there is also interaction with a critical assessment component. The assessment comes via components linked internally to the digital learning objects (e.g., guided lessons and self-assessment) that can be used to provide both formative and summative evaluation. Finally, there is a critical connection between the visualization and assessment. We argue that the effectiveness of a visualization is positively correlated to prior correct knowledge.

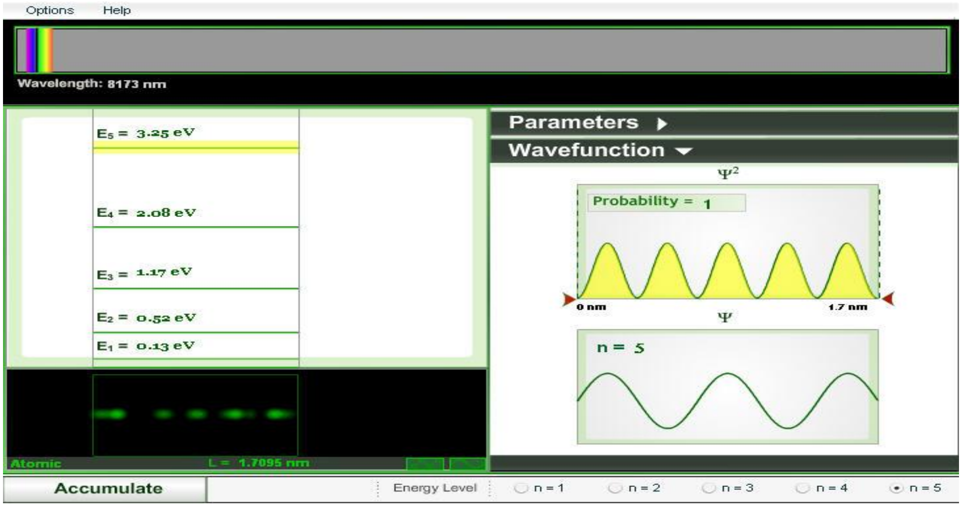

Figure 1. "Particle in a Box" applet which introduces concept of quantization

That is, the more correct the student's understanding, the more effective the visualization. (There is of course an odious flip-side to this – a poorly deployed or designed visualization could deepen a student's misunderstanding! We will address this point later in this paper.) Nurmi and Jaakkola (2006) investigated the effectiveness of digital learning objects as a function of instructional methods employed.

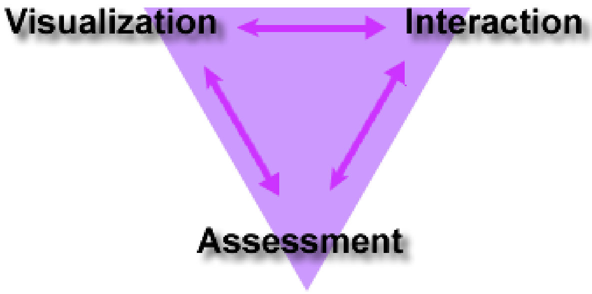

Figure 2. The ternary structure of an effective use of an applet

Encouragingly, they found that students using simulated learning objects (their term which is equivalent to the applets/DLOs described here) to learn about electric circuits showed statistically important gains in mastery of concepts when compared to students using traditional, text resources. This was most pronounced in blended teaching approaches in which simulations and laboratory activities (not just lectures) were combined. We argue that the assessment-visualization bridge illustrated in Figure 2 will play a similar role in enhancing applet effectiveness. The bottom-line in all of this is that visualizations do not speak for themselves – their effectiveness is critically rooted in how they are employed by teachers and students.

EVIDENCE-BASED REASONING

A fundamental question that should be on the lips of students is "how do we know this?". This question should become part of a critical attitude in which students are able to demand and use evidence to create warranted knowledge. For the curricular pillar of attitude to mean anything beyond commonplace then, we argue, an explicit move must be made to nurture this mode of thinking – this habit of mind. To accomplish evidence-based reasoning and, if the ternary relationship shown in Figure 2 is to be effective, then the assessment role becomes critical.

The term assessment is multi-layered and can imply a host of teaching strategies. It is important to stress that regardless of what strategy is being employed, the sub-text is to develop a teaching moment in which the student is asked to critically examine evidence and to create and/or evaluate claims to knowledge. We illustrate a few of these approaches to assessment below.

1. **Teacher-directed questioning** in class where the teacher demonstrates a specific effect and then elicits student responses. This is a common approach used in many active learning settings (Moore, 2003).
   As an example, Figure 3 shows trajectories created by a proton and a muon, travelling with the same velocity perpendicular to a magnetic field of known strength. Many questions can emerge; for example, based upon the evidence gathered:
- how do you know the particles have different charges?
- how do you know which is the more massive particle? (How could you test this and what assumptions would be needed?)

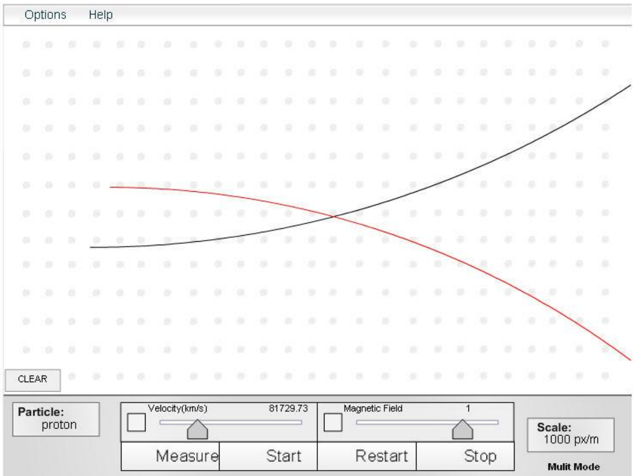

Figure 3. Comparison of muon and proton trajectories

2. **Student self-assessment** in which the student is asked to perform a conceptual or numerical analysis of an event and then assess his or her answer. For example, the student could be asked to use an applet such as the one shown in Figure 3 to investigate (gather evidence about) how the curvature of a trajectory is related to charge, mass, magnetic field and velocity. Because the applet is able to produce an infinite variety of instances very efficiently, the student could be encouraged to identify those parts of a concept that he or she finds problematic – with the objective of guided remediation. The student is not only involved in self-assessment but also is learning how to do science and evaluate claims to knowledge – by manipulating one variable and controlling all other variables.

3. **Creation and analysis of evidence** in which a student uses an applet to investigate a phenomenon in depth. For example, Figure 4 shows a screen capture from the cloud chamber applet. Here the student could be asked to provide evidence that the process of beta decay has a “peculiar” energy signature - beta particles, created via the same decay are not emitted with consistent energies. Having done this, the student could then be asked to explain why this suggests the possibility of an unseen particle in the beta decay process.

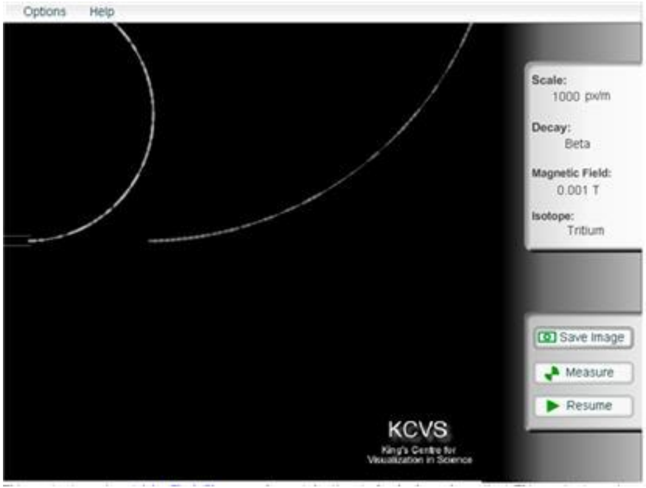

Figure 4. The cloud chamber applet demonstrating tracks produced by a beta decay process

4. **Guided Exploration** in which the student uses digital learning resources to augment teacher instruction. For example, in trying to understand nuclear stability the student can use the applet shown in Figure 5 to work from a well-model for the nucleus to predict when nuclei will decay and by what mode. The applet also includes an extensive data base of decay modes so that the student can evaluate his or her predictions concerning a given nucleus. The particle-in-a-box applet described earlier could also be employed here.

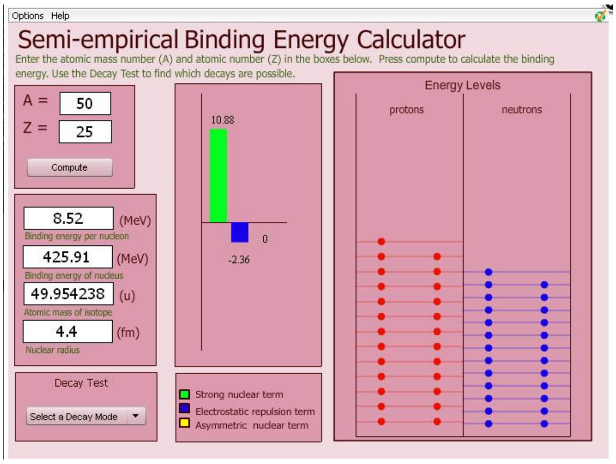

Figure 5. Applet that uses a well-model of the nucleus to teach about nuclear stability

5. **Laboratory instruction** in which the student either augments the use of an actual apparatus or simulates an apparatus to enact an important experiment. Figure 6 shows an example applied to the photoelectric effect. Ideally students would have access to the actual apparatus – gathering evidence to create or test the concept. However, in many examples from topics in Modern Physics, access to such equipment is beyond the scope of most schools.

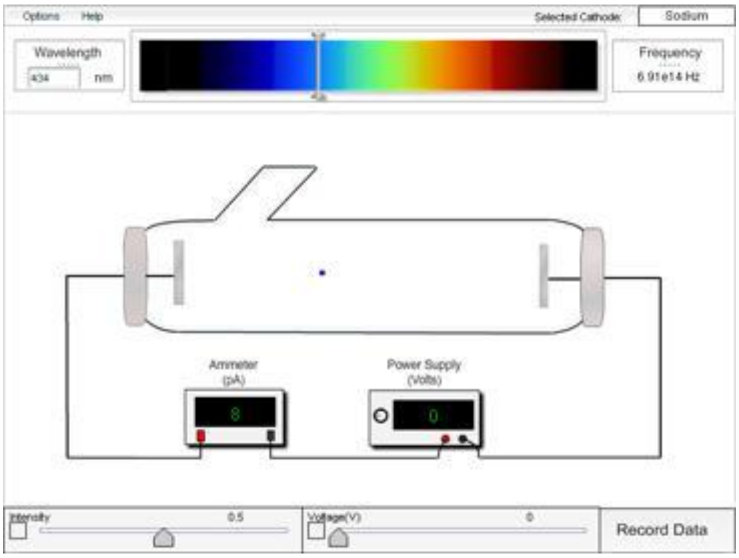

Figure 6. Simulation of the Millikan photoelectric effect experiment.

Many of the applets that we have developed also contain a powerful graphing application with a built-in mathematical parser as well as a facility to collect data and export this to a spreadsheet for additional analysis. This is especially important if we wish to provide students with an opportunity collect data and to engage in meaningful evidence based reasoning.

THE INTEGRATION OF TEACHING RESOURCES WITH APPLETS

For an effective instantiation of the "ternary" usage model described above it is critical that the DLOs include ancillary curricular materials that provide a teaching context as well as support incorporation of individual teacher-constructed lessons. A design feature of all of the applets produced will be a direct linking of applets to teaching materials with the intent that the applet and supporting digital resources become a complete and robust set of teaching/learning/assessment tools. While these resources have been made explicitly for the Alberta curriculum they should be adaptable with a minimum of effort to other curricula.

The attempt is to make the DLOs as "classroom ready" as possible but, since different curricula will have their own unique sets of emphases, it will also be necessary for users to augment or replace the ancillaries with custom designed resources. For example, the Cloud Chamber applet shown in Figure 4 is embedded in a DLO that has a direct link to several classroom ready lessons on Alpha decay and Beta Decay. These have been designed around specific parts of the physics curriculum in the province of Alberta and its curricular emphases (Roberts, 1982). The supporting documents that are comprised by the DLO also include help files and teaching tips or suggestions on how to use the applet effectively in the classroom. All of this is controlled by a "generic" menu item that is linked to an external html file that can be used to organize these resources.

GETTING AT THE NATURE OF SCIENCE THROUGH A RECONSTRUCTION OF CRITICAL HISTORICAL EXPERIMENTS

One of the "deep" goals in teaching physics (any science) is to enable students to appreciate the tentative and dynamic nature of scientific knowledge. Confusion, in the mind of the public, over what constitutes scientific knowing is well documented and poses a real threat to creating a scientifically literate population. To ameliorate this problem the Alberta Science Curriculum, for example identifies, as a specific curricular emphasis, the nature of science. Thus far we have developed 4 extensive, multi-applet Digital Learning Suites that explore The Thomson Experiments (discovery of the electron), The Rutherford Experiments (discovery of nucleus), The Millikan Experiment (discovery of unit of charge) and the Photoelectric Effect. (A similar treatment of Special Relativity is currently in “Beta” vesion and will be released summer 2010.) Each of these suites, in addition to numerous applets, contain either access to the original papers or to adaptations of these papers. They are also designed to simulate the experiments to the point of allowing students to collect data (“evidence”) and try to re-trace the conclusion drawn by past physicists

Figure 7 illustrates this for the Rutherford Experiments. Panels “A” and “B” show the splash screen and main navigation system for the resource. The student can choose to interact with the Thomson “currant bun” model prediction (Panel “C”) , perform a schematic re-enactment of the Geiger-Marsden experiment (Panel “E”) and investigate nuclear scattering (Panel “F”). Also shown is an interactive exploration of a lattice of gold atoms (Panel “D”).

Aside from building an important historical “context” in which to present important ideas, a careful reconstruction of these famous experiments can put the student in the place of acquiring data, evaluating evidence and, through carefully constructed argument formulate conclusions leading to the creation of knowledge.

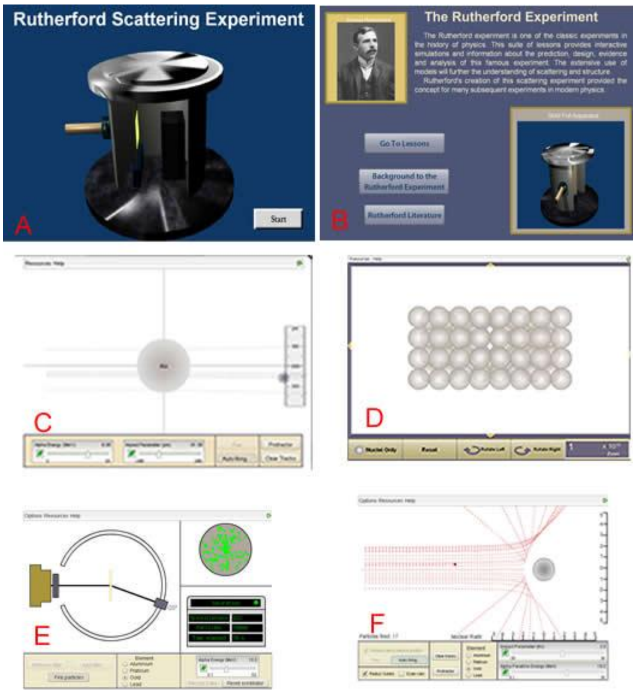

Figure 7. Part of the Digital Learning Suite dealing with Rutherford’s discovery of the nucleus.

To better illustrate the unique integration of teaching resources and applets Figure 8 shows a close-up of the Thomson Experiment applet menu bar with the “Resources” item selected. This opens a drop-down menu with direct links to:

1. **Background** is a brief summary of the history of the experiment and its role in the development of 20th century physics.
2. **Exploration** guides the student through the experiment and how the applet illustrates main ideas in the experiment.
3. **Simulate Experiment** helps the student to design their own experimental test of the charge to mass ratio with some focussing comments as well as links to the CRYSTAL-Alberta web site in which more information on designing experiments is presented.
4. **Links to Literature** provides the student with access to either primary literature or adapted primary literature.

In the case of applets that are not explicitly historical but rather address a specific conceptual goal some of the options are replaced with appropriate links to other ancillary files. What is important to understand, however, is that all of this is facilitated by the applet itself. Built into each applet is a link to external files accessed through an html shell that a user can easily construct. This gives the applets both flexibility and the ability to tailor them to specific user needs.

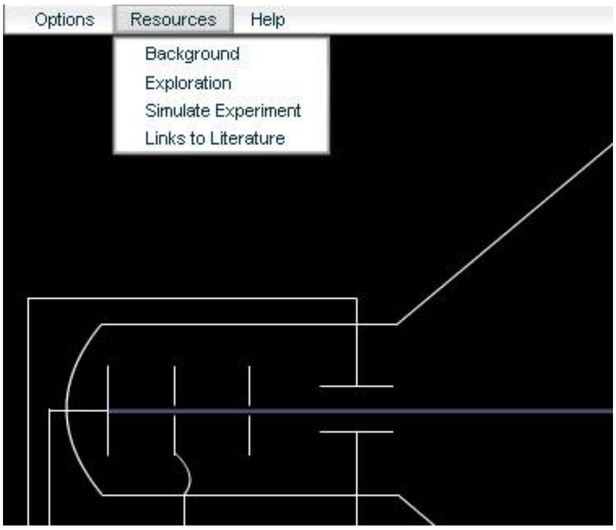

Figure 8. The Resources menu and links which is a common feature of most of these applets

ENCOURAGING CONCEPTUAL THINKING AND ADDRESSING MISCONCEPTIONS

Deliberate and strategic attention to conceptual understanding has and continues to be one of the central driving motives in physics education reform. For more than two decades numerous papers, studies, projects and texts have appeared stressing the importance of overtly dealing with conceptual physics – both as recognition of the role that conceptual understanding plays in developing robust knowledge as well as the persistence of "misconceptions" in the face of teaching. This has led to new approaches to physics pedagogy and refreshing new texts (Moore; Chabay and Sherwood). Although many different technological interventions are used in enacting these more conceptually focused teaching strategies, DLOs are aptly suited to this kind of teaching. Figures 8 and 9 show DLOs designed to address a common misconception in astronomy – the confusion between legitimate Doppler shifts (Figure 8) and cosmological redshifts (Figure 9) that result from a changing scale length and not motion per se.

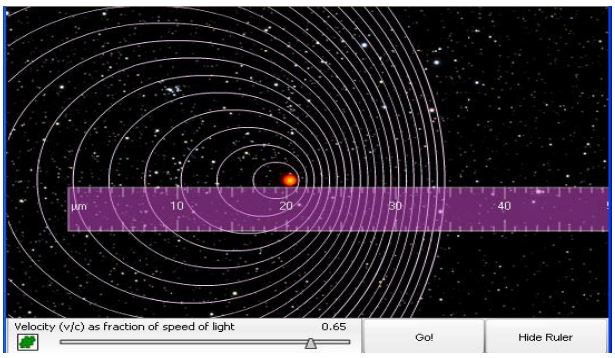

Figure 9. The Doppler Effect

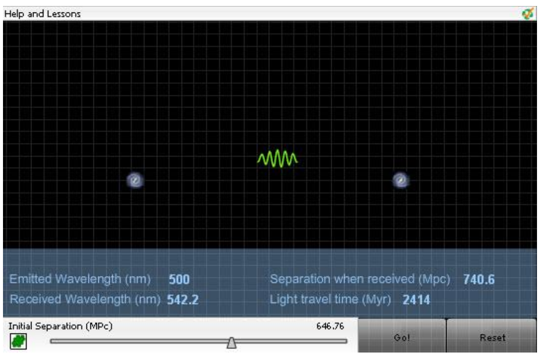

Figure 10. Redshift due to cosmological expansion

In the applet shown in Figure 9 the user can direct the motion of a star and "measure" the wavelength of light from a rest frame and illustrate the Doppler Effect. Figure 10 allows the user to adjust the separation between galaxies and observe the scale-stretching of space as photons from one galaxy travel to the other – thereby illustrating the true origin of the cosmological redshift. Both of these phenomena are difficult to visualize and represent topics aptly suited to demonstration via DLOs.

One advantage of DLOs such as the ones shown above is their flexibility and immediacy of evaluative feedback to the student. They can be used to fit a wide variety of learning/teaching strategies and are tools well suited to the task of nurturing conceptual growth in students.

THE DANGER OF TRIVIALIZATION AND WHY THE TEACHER PLAYS A CRITICAL ROLE

In the 2007 Oersted Medal address, Carl Wieman cautions:

> *"Simulations are very powerful, but not necessarily beneficial. A good simulation can lead to the relatively rapid and very effective learning of difficult subjects. However, if there is something about a simulation that the student interprets differently than is intended, they can effectively learn the wrong idea." (Wieman, 2008)*

The applets described here are not stand-alones, nor are they designed to replace active, engaged and skilled teaching. Indeed, they are designed to equip the teacher to more effectively present difficult ideas. Frequent student assessment and instructional evaluation, however, are critical if we are to avoid the situation described by Wieman. An even more subtle danger inherent in the a-critical use of applets is the danger of trivialization. An example of this (which can come via something as innocuous as a textbook diagram) is the presentation of Kepler's laws of planetary motion and the drawing of elliptical orbits. Students often fail to fully grasp that Kepler had no God's-eye-view – his discoveries of the shape of planetary orbits and the Rudolphine tables represent one of the greatest scientific achievements of his time. Sometimes applets can trivialize great and difficult achievements. Similarly, Figure 6 shows a schematic version of the Millikan photoelectric apparatus. It could give students the impression that the experiment is easy. Such a presentation obscures the great lengths that Millikan had to go to in order to carry out this experiment. Millikan described his apparatus as a "machine shop in a vacuum tube" and it remains a very difficult experiment to perform. To mitigate the danger of trivialization, the digital learning resources which accompany the applets described here contain important information on assumptions and simplifications used.

CONCLUSIONS AND LESSONS LEARNED

In this paper we have introduced the reader to a new set of digital resources devoted to the teaching of modern physics in Alberta high schools and universities. While there is no "shortage" of applets on the web purporting to facilitate learning we have attempted to show that the applet or simulation is only a small part of the entire digital learning object. By way of lessons learned over the past decade and primarily through working with classroom teachers we have adopted the practice of embedding applets within richer contexts. When appropriate these include historical discussions as well as links to primary literature. In other cases there are links to lessons that encourage the student (and teacher) to use the applets and DLOs in deliberate and strategic ways. A critical barrier to the use of even very good applets in the classroom is the lack of integration with the curriculum. Most teachers lack the time and familiarity with the applet to accomplish this. By deliberating creating ancillary resources that address the many different goals one may have for a physics or astronomy lesson we have attempted to make these applets both classroom ready and classroom useful.

Another sub-theme that we have developed is the need to move students toward a more overtly "evidence based reasoning" approach to learning physics. We have provided a typology of 5 different approaches to stimulate evidence based reasoning using the digital resources developed at our centre. A concomitant idea developed in this paper is the need to shift physics pedagogy away from a traditional lecture approach to one which encourages active learning. If teachers are to effectively meet the goals and emphases laid out in today's physics curricula then new resources and more importantly new approaches to pedagogy will need to be employed. We invite teachers to visit The King's Centre for Visualization in Science web site at: http://www.kcvs.ca/

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