Report and Recommendations on Multimedia Materials for Teaching and Learning Quantum Physics

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Abstract

An international collaboration of physicists, affiliated with Multimedia Physics for Teaching and Learning (MPTL) and MERLOT, performed a survey and review of multimedia-based learning materials for quantum physics and quantum mechanics. The review process was based on more than a decade of experience with similar topical learning material reviews. A total of approximately 250 items were considered for review and eight were recommended by the reviewers. These are described in this report. Observations about quantum learning resources and multimedia tools are included.

Keywords

Quantum Physics, Multimedia, Learning Resources

Introduction

For more than a decade a group of physicists affiliated with the Multimedia Physics for Teaching and Learning (MPTL) workshops has performed an annual review of the state-of-the-art in multimedia-based teaching and learning resources. Each year this working group selects a physics topic, searches for freely available, interactive learning resources, and performs a structured review on the best of these materials. Details of this process have been published in previous reports [MPTL 2014, Dębowska 2013], including the ongoing collaboration with the MERLOT Physics Editorial Board [MERLOT 2014].

The topic of the 2014 MPTL review effort was Quantum Mechanics and Quantum Physics. This was the first topic considered by the MPTL group in 2002 during the original development of the review process. Quantum resources were also reviewed in 2008, making this the first subject to be reviewed a third time. This highlighting of quantum physics is due, in part, to the high level of interest of students in the topic coupled with the non-intuitive and graphical nature of the subject. Quantum physics is a natural application of multimedia simulations and tutorials.

Over the years a number of research groups have been involved in the development of visualizations and interactive simulations of quantum systems meant to aid in learning, and in education research on best practices of use of these materials. For example, Zollman and collaborators at Kansas State University developed and tested a series of tutorials for the

introduction of quantum concepts in introductory physics [Zollman 2002]. This paper also provides an excellent summary of previous efforts in using multimedia for topics in quantum mechanics. Singh and co-workers started with research on student conceptions in quantum mechanics to develop a series of tutorials similar to those developed for introductory physics and other physics topics. These Quantum Interactive Learning Tutorials (QuILTs) take advantage of a number of interactive simulations on concepts in quantum physics [Singh 2008]. The PhET group at the University of Colorado has performed extensive research and development work on the use of simulations for teaching quantum physics [McKagan 2008]. Their work has indicated the importance of game-like, open-ended environments for student-centered learning, the benefits of making real world connections to help develop mental models, and the need to carefully frame the simulation to avoid reinforcing student misunderstanding. This research work is of great benefit in the evaluation of multimedia resources by the MPTL working group.

Resource Discovery and Selection

As has been described in previous reports, the first step in the review process is to collect available learning materials. For this year's review, materials were gathered from the 2002 and 2008 review lists, from digital library collections ComPADRE [ComPADRE 2014] and MERLOT/Quantum [MERLOT 2014], from other collections on the web such as Didattica [Didattica 2014] and Multimedia Physik [Multimedia Physik 2014], general web searches, and searches of the traditional literature.

The result of the discovery process was a list of 250 items that included both collections of multiple learning objects, simulations, and tutorials and single resources developed to address a specific topic. A preliminary review of this list resulted in 32 items being selected for full reviews. These were mostly collections of materials covering multiple topics in quantum. This preliminary selection was based on the MPTL review rubric [Dębowska 2013] and experiences with past reviews. Materials that were not freely available, did not make significant use of multimedia, or did not have an English version available were not included in the final review. The restriction to English materials is necessary to assure that multiple reviewers were available to evaluate each item or collection.

The Appendix provides a list of materials that either received full reviews or were considered to be good quality and of potential use to teachers and students, although not suitable for review.

The result of this year's discovery and selection process was a somewhat larger collection of materials. In 2008, 110 items or resource collections were found and 23 received full reviews. The 2002 review had much fewer items because of the exploratory nature of this first attempt at the review process.

Review Process

Each of the items selected for full reviews was considered by two or three reviewers. Materials were rated with the MPTL review rubric with an overall score and scores in the categories: Motivation and Purpose, Content, and Method. Reviews were completed using the ComPADRE peer reviewing tools that allow reviews to be entered and archived for later use. Reviews were

collected and compared, with those receiving high scores from all reviewers considered "Recommended" by the review process.

Review Results

Of the 32 items receiving full reviews, eight received "Excellent" or "Very Good" ratings from all reviewers. These items are listed below with descriptions, comments, and recommendations from the reviews.

QUVIS:
http://www.st-andrews.ac.uk/physics/quvis/, http://quantumphysics.iop.org/
This is an extensive collection of Flash and HTML5-based tutorials with interactive simulations of quantum systems and step-by-step explanations of the concepts involved. The presentations have very attractive graphics and clear explanations, with the step-by-step tutorials particularly noteworthy for helping students focus on the important physics. The Physics Simulations take students through the traditional sequence used in most quantum courses, from the concepts of probability to perturbations and Fermi and Bose statistics. The New Quantum Sims are used as the multimedia resources in the IOP Quantum Physics web site. This work focuses on quantum optics and quantum information theory, with many simulations using Stern-Gerlach experiments as their example. Almost all of the items include student activities and didactic recommendations, with the IOP site providing extensive tutorial and reference resources supplemented by the simulations. The translation of this material to HTML5 for use on all platforms is of particular note.

An excellent example of the QUVIS materials is the Hidden Variables simulation. This is one of the culminations of the entire collection. It shows the virtual experiment and the different results of quantum and hidden-variable theories.
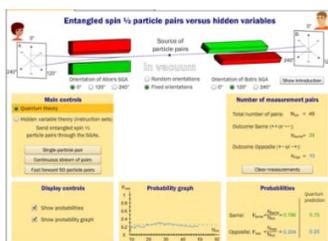
Figure 1. QUVIS: Quantum Mechanics vs Hidden Variables

PhET:
http://phet.colorado.edu/en/simulations/category/physics/quantum-phenomena
This is a collection of easy-to-run simulations suitable for middle-school (a few), high school, and college. These simulations are highly interactive and open environments with drag-and-slide user interfaces and game-like immediate feedback. The simulations can be used in a range of different ways, homework, pre-labs, and in-class explorations. Most of the simulations have recommendations for instructors, including learning goals and example activities. General recommendations for using simulations are also available. The reviewers also emphasized the fact that the PhET materials are available in a wide range of languages.

The PhET simulations are carefully researched and designed for interactivity and student learning. Many of these simulations are connected to "modern physics" experiments, such as lasers, the photoelectric effect, Stern-Gerlach, and Davisson-Germer experiments rather than "pure quantum theory". The Teacher Tips provide some information about the models and approximations used in the simulations, as well as student understanding of the topic and details about operation of the simulation.

An excellent example of a simulation of standard quantum problems is the Quantum Bound State. A noteworthy example of a virtual experiment is the Photoelectric Effect.
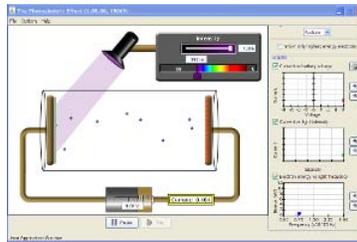

Figure 2. PhET Photoelectric Effect Simulation

Physlet Quantum Physics:
http://www.compadre.org/pqp/
This online textbook supplement of interactive illustrations and problems covers topics ranging from experiments demonstrating quantum phenomena, through standard bound and scattering state physics, to applications in atomic, nuclear, and statistical physics. Users can control states, energy levels, potentials, etc. and observe the resultant changes. Students may explore quantum systems for themselves with the help of guiding questions that range from qualitative ranking tasks to quantitative calculations.

One reviewer felt that the Physlet Quantum Physics simulations' graphics are somewhat dated and simple. They also noted that words such as "psi*(x) * psi(x)" are used in simulations rather than Greek letters.

Those interested in exploring Physlet Quantum Physics might consider Problem 9.4, Scattering in 1D. This is an example of the type of questions that encourage explorations. The physics behind an animation of a scattering state needs to be understood to answer questions about energy and potentials. Similarly, Problem 13.7 is an interesting exploration of the level dependence of the probability density for a Hydrogen atom.
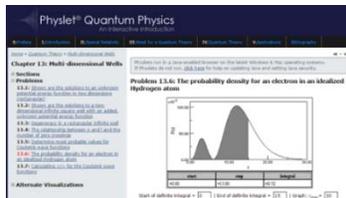
Figure 3. Physlet Physics Exploration of Probability Density

Quantum Lab:
http://www.didaktik.physik.uni-erlangen.de/quantumlab/english/index.html
This is a set of Interactive Screen Experiments covering quantum optics. Each of the experiments are illustrated with images of real experiments. Real data is provided when the experiments are "turned on". Quantum entanglement, quantum cryptography, and other quantum information experiments are included along with more basic examples. This content can be used as pre-labs for schools with the facilities to perform quantum optical experiments, or as entirely virtual labs. Each experiment is well described, with motivating introductions and explanations of the observations.

Reviewers noted that some design and layout of the controls is problematic, with control placement and design changing in different experiments. The ability to zoom in on parts of the experiment is a plus. Some of the data is in German.

To start exploring this material, the Existence Photon experiment can give an indication of its interface and display of real optics experiments. A more sophisticated experiment, such as Entanglement, will show how data is displayed.
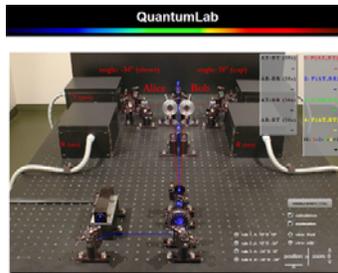

Figure 4. QuantumLab Entanglement & Non-locality

Spins Physics:
http://www.physics.orst.edu/~mcintyre/ph425/spins/index_SPINS_OSP.html,
http://www.compadre.org/osp/items/detail.cfm?ID=7329
The Oregon State University SPINS web site provides a complete set of course materials (worksheets, virtual labs, in-class activities, and homework) for a quantum mechanics course that begins by studying spin systems. The Open Source Physics (OSP) package integrates these tutorials with simulations for student investigations. The software allows students to drag, drop, and connect elements of a Stern-Gerlach experiment including spin analysers, magnets, and detectors. The interface allows students to create many different experiments on quantum dynamics and quantum measurement. The simulation is simple to use, but is rather schematic so students may not understand precisely what is being observed. The software can be used for different sorts of learning activities. This work is based on the "SPINS" software package that has been developed over the years by several different programmers [Schroeder 1993].

A good example of the Spins tutorial material can be found under "Exercises" and the tab for "Spin Precession" at the bottom of the page. This series simulations are arranged to help students understand the quantum rotation of spins in magnetic fields.
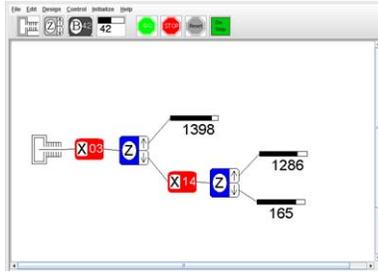
Figure 5. Spins Stern-Gerlach Simulation

Falstad Quantum:
http://www.falstad.com/mathphysics.html
This well-known web site provides good qualitative illustrations of quantum mechanics and complex systems. Some of the physics topics simulated are unique. Of note are the dynamic quantum transitions applets for a bound state interacting with a classical oscillating electric field.

This material, however, is somewhat limited in the topics covered and lacks didactic materials or recommendations. Rather basic explanations about the simulations are provided, most covering only how to run the simulation. Details about the physical models and simulation methods use are not available for many of these programs.

One excellent example of the Falstad work is the Atomic Dipole Transitions applet. It considers the dynamics of an atom interacting with different types of electric field. The Rigid Rotator and the Square Well applets illustrate the displays provided.
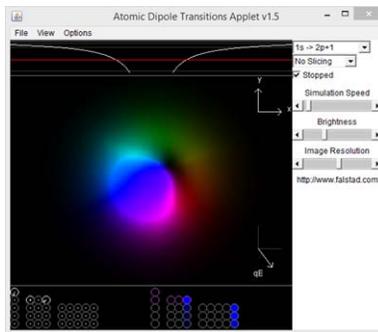
**Figure 6: Paul Falstad Atomic Dipole Transition**

Quantum Mechanics:
http://www.embd.be/quantummechanics/default.html
This combination of text and videos provides a multimedia tutorial on quantum mechanics. Topics include wave motion and interference, Aharonov-Bohm effect, and identical particles. The sequence of topics leads the reader through important aspects of quantum physics.

The video simulations are somewhat dated and lower resolution, and are not interactive. One reviewer felt that there could be more questions and tasks for the student.

For those interested in this work, the Aharonov-Bohm section is a rather unique study of this physics.

Excited States and Photons:
http://concord.org/stem-resources/excited-states-and-photons
This material is a secondary school level introduction to the interaction of light and matter, including quantization of energy. The connection between atomic energy levels and emitted photons is stressed. Multiple choice and free-response questions throughout provide tutorial guidance. The materials are easy to follow and the goals and learning approaches are clear. The coordinated use of pictures, animations, words, and interactive simulations was noted by one reviewer. This could also be used in conceptual physics classes at the college level.

An example of the tutorial nature of this work is the second half of the activity where atomic energy levels, photon colour, and kinetic energy are connected.

General Observations

From the results of this review and a comparison to previous years, some general observations can be made.
- Several of the recommended items (PhET, Physlets, SPINS, Falstad, and Quantum Mechanics) were recommended in the 2008 Quantum review. The other recommended items are new.
- Three items from 2008 were not recommended this year. One of these, Visual Quantum Mechanics from Kansas State University, received good marks, but some reviewers had difficulties running the items and some links between the VQM tutorials and simulations were broken due to recent updates of the simulations and web site.
- All of the 2008 recommended materials are still available on the web, although some have changed URL. In fact, four of the six recommended items from 2002 are still available. However, if teachers are going to continue to have access to the resources, a means for providing updated links to materials is needed, such as an indexing service or curated digital libraries.
- Java, Flash, and Shockwave, the programming languages of most of the resources reviewed, are becoming increasingly problematic to use. This is because of security issues, constant updates, and new devices not designed to run these languages. Some reviewers had difficulty starting and running a few applets or applications.
- On a related note, some of the established developer groups (PhET, QuVis, OSP, Concord Consortium) are working at providing resources through html5 and javascript. This will expand the types of devices that can access the materials. However, individuals who have created materials probably will not have the time and resources to do these updates.

- As has been true for several years of reviews, resources that are more comprehensive, cover multiple topics, and provide tutorial and didactic support received the highest reviews.
- There were several items that received "Very Good" and "Average" ratings, meaning that they are probably quite useful for teachers or students but are not included in our "Recommendations".
- The review group also explored apps designed specifically for either iOS or Android devices. Although some examples were found, these were mostly illustrations of quantum states with little interactivity or direct pedagogical use.
- As has been noted in several past reviews, there are many video collections available on the web covering physics topics. These have not been included in this review process because of the lecture-like nature of most. Though potentially useful, these videos do not have the interactivity, student engagement, immediate feedback, or multi-modal features stress in the multimedia review rubric.

There were two items reviewed that were not included in the "Recommended" category, because they are not applicable for quantum physics courses, but the reviewers felt were noteworthy. "Quantum Made Simple", http://www.toutestquantique.fr/, is quite interesting and unique. The material is designed as a very brief introduction to quantum for a general audience. It gives a layman's introduction of topics such as quantization, spin, and lasers, and adds animations and applications of the concept to laboratory or real-world uses. Another item of interest is the Open Source Physics Quantum Magnetism simulation, http://www.compadre.org/osp/items/detail.cfm?ID=12308. This is a very specific modelling simulation for the spectrum of coupled spins in a magnetic field. It is designed for more advanced users but provides an interactive environment for exploring an interesting topic in quantum physics.

The MPTL multimedia evaluation group members plan to continue to perform this activity in future years. The topic for review in 2015 will be optics.

Appendix

Table 1 is a list of resources that either received full reviews or were high on the review priority list but were immediately below the cut-off for review. The list is in alphabetical order by title.

Table 1. Items reviewed and near the review cut-off

Title	URL
1-d Schrodinger Equation Eigenstates	http://www.fen.bilkent.edu.tr/~yalabik/applets/1d.html
Bernd Thaller VQM	http://vqm.uni-graz.at/
Circular Well Superposition Model	http://www.compadre.org/osp/items/detail.cfm?ID=8327
Concord Consortium: Excited States & Photons	http://concord.org/stem-resources/excited-states-and-photons

Concord Consortium: Introduction to Quantum Mechanics	http://concord.org/stem-resources/introduction-quantum-mechanics
EJS Photoelectric Effect	http://www.compadre.org/osp/items/detail.cfm?ID=10272
Expansion and Time Development using Eigenstates	http://www.fen.bilkent.edu.tr/~yalabik/applets/superp.html
Gallery of Quantum Optics States	http://gerdbreitenbach.de/gallery/
HydrogenLab - Pictures of the Hydrogen Atom	http://www.hydrogenlab.de/
IOP Quantum Physics	http://quantumphysics.iop.org/
Math, Physics, and Engineering Applets	http://www.falstad.com/mathphysics.html
Molecular Workbench: Physics examples	http://mw.concord.org/modeler/showcase/physics.html
Momentum Space Package	http://www.compadre.org/osp/items/detail.cfm?ID=7304
Numerical Time Development in Quantum Mechanics Using a Reduced Hilbert Space Approach	http://www.compadre.org/osp/items/detail.cfm?ID=6475
OSP: Quantum-mechanical Measurement	http://www.compadre.org/osp/items/detail.cfm?ID=3943
Path Integrals in Quantum mechanics	http://fisteo12.ific.uv.es/~santamar/qapplet/metro.html
PhET Simulations: Quantum Phenomena	http://phet.colorado.edu/en/simulations/category/physics/quantum-phenomena
Physics 2000: Quantum Atom	http://www.colorado.edu/physics/2000/quantumzone/index.html
Physics 2000: Wave Interference	http://www.colorado.edu/physics/2000/schroedinger/index.html
Physics Virtual Bookshelf	http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/#qm
Physlets Quantum Physics	http://www.compadre.org/pqp/
QM Measurement Program	http://www.compadre.org/osp/items/detail.cfm?ID=6814
QM Projection Program	http://www.compadre.org/osp/items/detail.cfm?ID=7010
QM Superposition Package	http://www.compadre.org/osp/items/detail.cfm?ID=7295
Quantum Computation	http://math-it.org/Quantum/index.html
Quantum Made Easy	http://www.toutestquantique.fr/
Quantum Magnetism Analysis Model	http://www.compadre.org/osp/items/detail.cfm?ID=12308
Quantum Mechanics	http://www.embd.be/quantummechanics/
Quantum Mechanics: Sum over paths	http://www.eftaylor.com/quantum.html
Quantum Physics Online version 2.0	http://www.quantum-physics.polytechnique.fr/

QuantumLab	http://www.didaktik.physik.uni-erlangen.de/quantumlab/english/index.html
QuVis	http://www.st-andrews.ac.uk/physics/quvis/
Rectangular Well Superposition Model	http://www.compadre.org/osp/items/detail.cfm?ID=9637
Six Ideas that Shaped Physics	http://www.physics.pomona.edu/sixideas/sicpr.html
SPINS Java Homepage	http://www.physics.orst.edu/~mcintyre/ph425/spins/index_SPINS_OSP.html
Spins Package	http://www.compadre.org/osp/items/detail.cfm?ID=7329
The Basics of MRI	http://www.cis.rit.edu/htbooks/mri/index.html
The Stern-Gerlach Experiment	http://www.if.ufrgs.br/~betz/quantum/SGtext.htm
The Stern-Gerlach Experiment, Electron Spin, and Correlation Experiments, Linked Animations	http://www.upscale.utoronto.ca/PVB/Harrison/SternGerlach/SternGerlach.html
Visualizing Quantum Dynamics	http://comp.uark.edu/~jgeabana/blochapps/
VQM Software Page	http://web.phys.ksu.edu/vqm/software/online/vqm/index.html
VQM Tutorials Page	http://web.phys.ksu.edu/vqm/tutorials/

References

ComPADRE (2014), ComPADRE Digital Library, http://www.compadre.org, (Accessed 11/11/2014).

Dębowska, E., et al. (2013). Report and Recommendations on Multimedia Materials for Teaching and Learning Electricity and Magnetism, *Eur. J. Phys*. **34**, L47 – L55.

Diddatica (2014), Risorse per la didattica di Fisica, http://zitogiuseppe.com/didattica.html, (Accessed 11/11/2014).

McKagan, S., et al. (2008), Developing and researching PhET simulations for teaching quantum mechanics, *Am. J. Phys* **76**, 406-417.

MERLOT/Quantum (2014), MERLOT Quantum Physics, http://www.merlot.org/merlot/materials.htm?category=2736, (Accessed 1/11/2014).

MPTL (2014), MPTL website, http://www.mptl.eu/, (Accessed 11/11/2014).

Multimedia Physik (2014), website, http://www.schulphysik.de/ (Accessed 11/11/2014)

Schroeder, Daniel V., Moore, Thomas A. (1993), A computer-simulated Stern-Gerlach laboratory, *Am. J. Phys*. **61**, 798 – 805.

Singh, Chandralekha (2008), Interactive learning tutorials on Quantum Mechanics, *Am. J. Phys*. **76**, 400 – 405.

Zollman, Dean A., Rebello, N. Sanjay, Hogg, Kirsen (2002), Quantum mechanics for everyone: Hands-on activities integrated with technology, *Am. J. Phys.* **70**, 252 – 259.