Proposal for the Associated Colleges of the South Teaching with Technology Fellows Program

Title: Open Source Physics Curricular Material and Programs
for Teaching Spin in Quantum Mechanics
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1. Background

We propose to adapt and develop approximately 5 new programs (applications and applets) and supporting curricular material for intermediate and advanced courses in quantum mechanics. The programs and exercises will stress the conceptual understanding of spin (intrinsic) angular momentum in quantum mechanics. The programs and curricular material will be distributed under the GNU open source model.

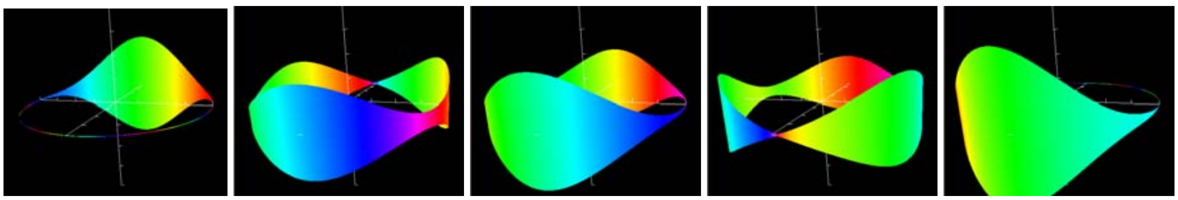

Figure 1: Screen shots of an OSP3D QM program of a Gaussian wave packet confined to a ring. The wave function is shown in color-as-phase notation at $t = 0$, $T_{rev}/6$, $T_{rev}/4$, $T_{rev}/3$, and $T_{rev}/2$, respectively. The packet moves clockwise (looking down from above) and interferes with itself as it spreads out over time. It eventually forms mini-packet clones of the original packet, and finally exactly reforms (revives).

With previous ACS Teaching with Technology Fellowships, we created curricular material in support of a one-semester, intermediate course in quantum mechanics [1-2]. This work was also summarized in an invited paper for ACS's on-line journal *Transformations* [3]. The interactive curricular material uses Physlets [4] and Open Source Physics applets [5] to visualize standard one-, two-, and three-dimensional problems in quantum mechanics. We can further enhance the effectiveness of these exercises by developing new advanced exercises dealing with spin angular momentum.

2. Description

In order to fully understand quantum mechanics students must realize that there are several formulations in which quantum mechanics can be expressed [6]. The four main formulations can be associated with a particular "heavyweight" of quantum theory: Heisenberg, Schrödinger, Feynman, and Wigner. In particular they are:

- Heisenberg's matrix formulation
- Schrödinger's wave formulation
- Feynman's path-integral formulation
- Wigner's phase-space formulation

The typical formulation students see is that of Schrödinger's wave mechanics which is governed by the Schrödinger equation. There are several reasons for this. For problem solving, using the Schrödinger equation to solve for the wave function is ideal. Nonetheless, other formulations are useful for other circumstances [7]. For spin angular momentum, Schrödinger's wave mechanics is insufficient and we must use Heisenberg's matrix (operator) formulation. By its very nature, spin angular momentum is a very abstract concept. In fact, nothing is actually spinning. Instead, this

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spin angular momentum is due to the fact that certain particles have an intrinsic magnetic dipole moment which behaves like an intrinsic angular momentum which we call spin. This abstraction is made worse by the use of the matrix (operator) formulation. As a consequence of these abstractions, students have a hard time understanding and visualizing systems with spin.

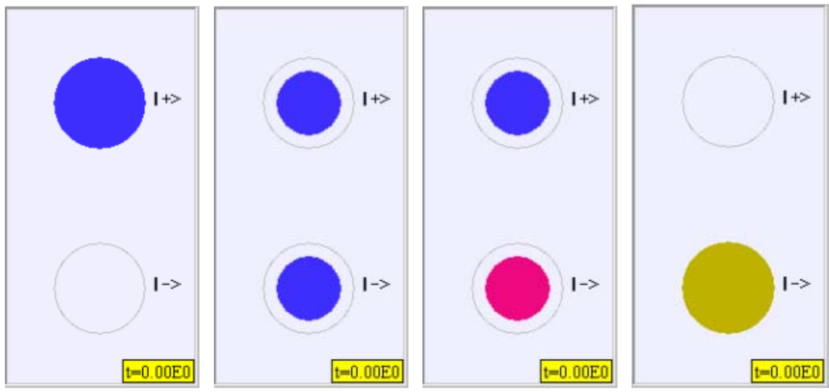

Figure 2: Screen shots of a beta version of an OSP Java program that simulates the measurement of the z component of spin for a single spin-1/2 quantum-mechanical particle. The particle starts off with spin up, |S_z+>, and through subsequent measurements of S_x, S_y, and S_z, the particle ends up with spin down, |S_z–>. The diameter of the circle represents the amplitude while the color represents the phase of the state.

The Open Source Physics (OSP) project [5] provides a synergy of curriculum development, computational physics, computer science, and physics education for scientists and students wishing to write their own simulations. The core of this project is a collection of educational programs being distributed under the GNU Open Source license agreement. A number of software developers have already adopted the OSP model for their own development projects. These projects include *Simulations in Physics* (3rd Ed.) by Harvey Gould, Jan Tobochnik, and Wolfgang Christian, *Statistical and Thermal Physics* by Harvey Gould and Jan Tobochnik, *Easy Java Simulations* by Francisco Esquembre, and OSP 3D applet by Adam Abele and Wolfgang Christian.

The material we create will be part of OSP's growing set of open-source programs and curricular material. This project will focus on spin angular momentum, in particular individual particles and ensembles of particles as shown in Figures 2 and 3.

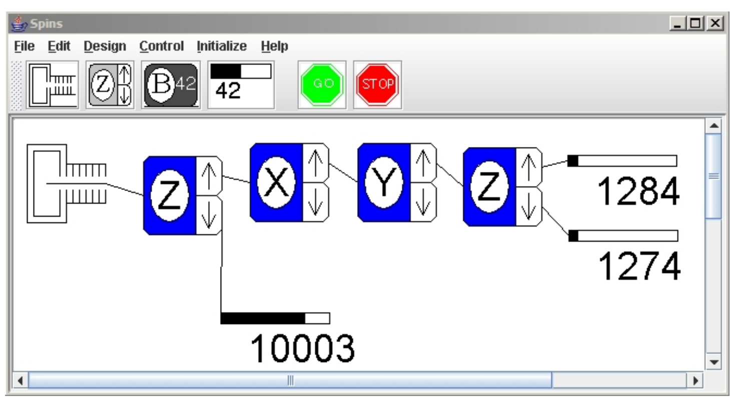

Figure 3: Screen shot of the open source Java program, SPINS, that simulates the measurement of different components of spin for an ensemble of spin-1/2 quantum-mechanical particles. The particles start off with a random distribution in the direction of their spin and then encounter multiple Stern-Gerlach devices that measure a component of spin for each particle. Over 20,000 particles are simulated in the above figure. Note that as in Figure 2, there is still a possibility of measuring spin down, |S_z–>.

A list of proposed simulations is described below:

- Individual Spin State Simulations: These programs will simulate multiple spin measurements on the same quantum-mechanical particle. This will be accomplished by allowing students to make measurements of spin in a particular direction as well as choose the spin quantum number (s = 1/2, 1, 3/2, etc.) and the spin basis (eigenstates of x, y, or z) under which these measurements are made. In addition to determining what happens after measurement, we will also include quantum-mechanical time evolution of the state. One goal is to have students experimentally determine the maximal set of operations that will leave a quantum-mechanical spin state invariant.

- Ensemble of Spin States Simulations: These programs will simulate the measurement of components of spin on an ensemble of particles. The original program, SPINS, is open source. We will rewrite this program in terms of the OSP code library and in doing so enhance the capabilities of this applet. At the moment one must manually set up scenarios within the applet. Our improvements will include the ability to script the applet to enable different scenarios to be loaded quickly and easily thereby allowing students to spend more time on the physics and less time on setting up the animation.

- Density Matrix Simulations: These programs will simulate the density matrix. They will serve as a bridge between the simulations which focus on one particle and the simulations which focus on multiple particles.

3. Timeline
The new material will be completed by September 2005.

4. Technology
The Physics Department maintains its own servers and therefore server space and server access is not an issue. Both of us have office computers powerful enough to complete this project. In addition, the College supports our preferred authoring tools, such as Borland JBuilder and Microsoft FrontPage. In addition Wolfgang Christian is author of much of the OSP libraries.

5. Other Support
2001, 2002, and 2003 ACS Teaching with Technology fellowships have already supported our work. Please see the attached outcomes summary from previous ACS grants.

6. Learning Outcomes
Learning advanced concepts in quantum mechanics is difficult for many students. Much of the difficulty comes from the fact that students have a hard time visualizing quantum-mechanical concepts and spin angular momentum is no exception. There is clearly a need for better visualization techniques. The visual nature of Open Source Physics programs and exercises we create will aid students in understanding both the concepts and the mathematics behind advanced quantum theory.

7. Curriculum
MB and WC have alternated teaching the intermediate course in quantum mechanics for the past 6 years and WC will be teaching this course next year. Consequently, we will be using the materials developed from this grant during fall 2005.

8. Assessment
We will continue to evaluate our materials by administering the Quantum Mechanics Visualization Instrument [8]. We will administer the QMVI as a post-test at the end of the semester Fall 2005

semester. Preliminary results will be available December 2005. Figure 4 shows the results (out of 100) presented in Ref. [8] for modern physics (28.5), undergraduate quantum mechanics (51.1) and graduate quantum mechanics (55.5) next to the results from the Fall 2001-2003 Davidson College undergraduate quantum mechanics courses (66.3, 57.0, and 70.7, respectively) and the average of all three courses (63.0).

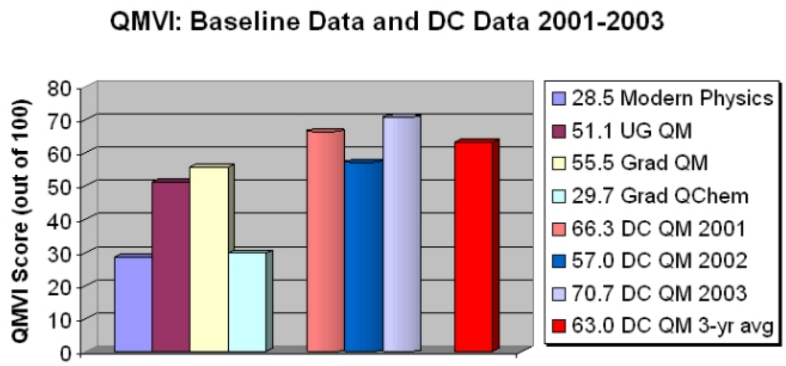

Figure 4: The Quantum Mechanics Baseline Instrument (QMVI) baseline data from Ref. [8] and additional data from the Fall 2001-2003 Davidson quantum mechanics courses that used curricular materials developed as a result of ACS Teaching with Technology Fellowships.

9. Dissemination

Our materials will be available on the OSP website. Chairs will be sent a letter with the link and asked to distribute the materials to their colleagues. In addition, MB and WC will disseminate the materials developed from this grant through talks and workshops at local and national meetings.

Please see the attached outcomes summary from our previous Teaching with Technology Fellowships for a detailed description of our previous outcomes and dissemination activities.

Bibliography

[1] The results from our first two Teaching with Technology Fellowship (the curricular material and the Instructor's manual) are available at: http://webphysics.davidson.edu/qmbook/.

[2] The results from our third Teaching with Technology Fellowship are available on the Web at: http://www.opensourcephysics.org/applets/ospqm/default.html.

[3] "Using Physlets and Open Source Physics to Make Quantum Mechanics Visual and Interactive," Mario Belloni, Wolfgang Christian, and Larry Cain, *Transformations: Liberal Arts in the Digital Age*, Volume 2, Number 1 (2004). Paper is available on the Web at: http://www.colleges.org/transformations/index.php?q=node/view/77.

[4] *Physlets: Teaching Physics with Interactive Curricular Material*, W. Christian and M. Belloni, Prentice Hall, Upper Saddle River, NJ, 2000.

[5] The Open Source Physics project is available on the Web at: http://www.opensourcephysics.org/.

[6] There are at least nine formulations, although we only discuss four. For all nine see, D. F. Styer, *et. al*, "Nine Formulations of Quantum Mechanics," *American Journal of Physics*, **70**, 288-297 (2002).

[7] The path-integral formulation of Feynman is useful for seeing ties with the minimization principle of Hamilton and the phase-space formulation of Wigner is useful in seeing the relationship between classical and quantum systems.

[8] "Testing the Development of Student Conceptual and Visualization Understanding in Quantum Mechanics through the Undergraduate Career," E. Cataloglu and R. Robinett, American Journal of Physics, 70, p. 238 (2002).

Outcomes from Previous ACS Teaching with Technology Fellowships

This work was reported at:

- January, 2004: Mario Belloni, Wolfgang Christian, and Anne J. Cox, "Physlet-Based Ranking Tasks: From Introductory Physics to Quantum Mechanics," *Contributed Talk*, Winter Meeting of the American Association of Physics Teachers, Miami, Florida.

- November 2003: Wolfgang Christian and Mario Belloni, Curriculum Development and Open Source Physics Workshops," *Contributed Talk*, Joint Fall Meeting of the North Carolina and Southern Atlantic Coast Sections of the American Association of Physics Teachers, Wilmington, North Carolina.

- August, 2003: Mario Belloni, Adam Abele*, and Wolfgang Christian, "One-, Two-, and Three-dimensional Quantum Mechanics Using Java3D," *Contributed Talk*, Summer Meeting of the American Association of Physics Teachers, Madison, Wisconsin.

- April, 2003: Mario Belloni, "Making Quantum Mechanics Visual and Interactive with Physlet-Based Curricular Material," *Invited Talk*, Joint Meeting of the American Physical Society and the Division of Particles and Fields, Philadelphia, Pennsylvania.

- September, 2002: *Opening Plenary Talk,* "Using Physlets to Teach Quantum Mechanics," 7th Workshop on Multimedia in Physics Teaching and Learning, Parma, Italy.

- August, 2002: Material posted on the MERLOT (Multimedia Educational Resource for Learning and Online Teaching) Digital Library.

- August 2002: *Invited Talk*, "The Development and Assessment of Interactive Exercises for Quantum Mechanics," Summer Meeting of the American Association of Physics Teachers, Boise, ID.

- August 2002: *Invited Talk*, "The Development and Assessment of Interactive Exercises for Quantum Mechanics," Summer Meeting of the American Association of Physics Teachers, Boise, ID.

- August, 2002: Material posted on the MERLOT (Multimedia Educational Resource for Learning and Online Teaching) Digital Library.

- June 2002: *Invited Special Curriculum Session*, "Physlet-Based Media-Focused Education: Making Quantum Mechanics Visual and Interactive," Gordon Research Conference on Physics Research and Education: Quantum Mechanics, South Hadley, MA.

- April 2002: *Invited Talk*, "Using Physlet-Based Interactive Exercises to Enhance Student Learning," Spring Meeting of the Southern Atlantic Coast Section of the American Association of Physics Teachers, Gainesville, GA.

- April 2002: *Invited Colloquium*, "Making Quantum Mechanics Interactive with Physlets and Just-in-Time Teaching," Physics Department, Indiana University-Purdue University, Indianapolis, Indianapolis, IN.

- January, 2002: *Workshop*, "Using Interactive Java-based Pedagogies in the Classroom" winter meeting of the American Association of Physics Teachers Philadelphia, PA. 50 CDs were distributed to workshop participants and other interested faculty from around the country.

- November 3, 2001: *Contributed Talk*, "Using Just-in-Time Teaching and Physlets in Undergraduate Quantum Mechanics," Southeastern Section of the American Physical Society, Charlottesville, Virginia.

- September, 2001: Web site, http://webphysics.davidson.edu/qmbook/, officially on-line with the quantum mechanics exercises. We e-mailed a letter to each physics department chair in the ACS and the members of the ACS-PHYSICS e-mail list to inform them of our work. We sent our materials on a CD to ACS physics chairs.

- July, 2001: *Invited Talk*, "Using Physlets and Just-in-Time Teaching in Quantum Mechanics," national American Association of Physics Teachers meeting, Rochester, NY. The talk is available at: http://webphysics.davidson.edu/mjb/rochester2001.

- February, 2001: Syllabus column in the Chronicle of Higher Education. Profiled teaching methods (Physlets and Just-in-Time Teaching) and the (then) future work on quantum mechanics. This article is available at: http://webphysics.davidson.edu/mjb/syllabus_02_16_01.html.

This work is referenced in:

- *Physlet Quantum Mechanics*, Mario Belloni and Wolfgang Christian, Prentice Hall, June 2005. ISBN 0-13-101970-8.

- "Using Physlets and Open Source Physics to Make Quantum Mechanics Visual and Interactive," Mario Belloni, Wolfgang Christian, and Larry Cain, *Transformations: Liberal Arts in the Digital Age*, Vol. 2, No. 1 (2004). http://www.colleges.org/transformations/index.php?q=node/view/77.

- "Teaching Special Relativity with Physlets®," Mario Belloni, Wolfgang Christian, and Melissa H. Dancy, *The Physics Teacher*, **42**, 284-290, (2004).

- "Developing Open Source Programs for Upper Level Science and Mathematics," Wolfgang Christian and Mario Belloni, Proceedings of the 7th Workshop on Multimedia in Physics Teaching and Learning of the European Physical Society. October 2003.

- "Teaching Thermodynamics with Physlet® in Introductory Physics," Anne J. Cox, Mario Belloni, Wolfgang Christian, and Melissa H. Dancy, *Physics Education*, **38**, 433 (2003).

- "Physlets® for Quantum Mechanics," Mario Belloni and Wolfgang Christian, *Computing in Science and Engineering* **5**, 90-97 (2003).

- "Teaching with Physlets®: Examples from Optics," Melissa Dancy, Wolfgang Christian, and Mario Belloni, *The Physics Teacher*, November 2002.

- "Physlets: Web-based Java Applets for Physics Education," Wolfgang Christian, Mario Belloni, and Melissa Dancy, *Fall 2001 Newsletter of the American Physical Society Forum on Education.* Web Address: http://www.aps.org/units/fed/fall2001/index.html.