Research-based interactive simulations to support quantum mechanics learning and teaching

Antje Kohnle
School of Physics and Astronomy, University of St Andrews

Abstract

Quantum mechanics holds a fascination for many students, but its mathematical complexity can present a major barrier. Traditional approaches to introductory quantum mechanics have been found to decrease student interest. Topics which enthuse students such as quantum information are often only covered in advanced courses.

The QuVis Quantum Mechanics Visualization project (www.st-andrews.ac.uk/physics/quvis) aims to overcome these issues through the development and evaluation of interactive simulations with accompanying activities for the learning and teaching of quantum mechanics. Simulations support model-building by reducing complexity, focusing on fundamental ideas and making the invisible visible. They promote engaged exploration, sense-making and linking of multiple representations, and include high levels of interactivity and direct feedback. Some simulations allow students to collect data to see how quantum-mechanical quantities are determined experimentally. Through text explanations, simulations aim to be self-contained instructional tools. Simulations are research-based, and evaluation with students informs all stages of the development process. Simulations and activities are iteratively refined using individual student observation sessions, where students freely explore a simulation and then work on the associated activity, as well as in-class trials using student surveys, pre- and post-tests and student responses to activities.

A recent collection of QuVis simulations is embedded in the UK Institute of Physics Quantum Physics website (quantumphysics.iop.org), which consists of freely available resources for an introductory course in quantum mechanics starting from two-level systems. This approach immediately immerses students in quantum phenomena that have no classical analogue, using simpler mathematical tools that allow a greater focus on conceptual understanding. It allows from the start a discussion of interpretative aspects of quantum mechanics and quantum information theory.

This article gives an overview of the QuVis resource and describes the development and iterative refinement process based on student feedback.

Keywords

Quantum mechanics, computer simulations, conceptual understanding.

Introduction

Quantum mechanics holds a fascination for many students, but learning quantum mechanics is difficult. The counterintuitive behaviour of quantum systems often disagrees with our classical ideas, leading to student difficulties that arise when classical thinking is applied to quantum systems (see e.g. Singh 2001, Cataloglu 2002, Wittmann 2005, Baily 2010 and Zhu 2012). Quantum phenomena typically cannot be observed directly and are far-removed from everyday experience. Complicated mathematics including calculus, complex numbers and differential equations are required to describe even simple phenomena. Linked to this, instruction often focuses on particularly simple abstract and idealized systems that are mathematically tractable but may not help learners make real-world connections to quantum phenomena.

Research-based interactive simulations can address these challenges of quantum mechanics instruction and support quantum mechanics learning and teaching. Simulations can help students develop mental models by reducing complexity, focusing on fundamental ideas and making the invisible visible (Adams 2008a, Adams 2008b, McKagan, 2008). Through high levels of interactivity coupled with direct feedback, they can promote engaged exploration, sense-making and linking of multiple representations (Clark 2011). Through careful interaction design and accompanying activities, students can be guided towards the learning goals (Podolefsky 2010). Simulations can visualize complicated time-dependent behaviour such as the motion of wave packets that help build physical intuition but may be too complex for students to calculate themselves (Belloni 2006). Simulations can allow students to collect data to see how quantum-mechanical quantities are determined experimentally. Simulations can help build physical intuition by allowing students to compare and contrast classical and quantum behaviour under the same experimental conditions (Kohnle 2014). They can challenge students' classical ideas by allowing them to assess whether they can explain experimental outcomes.

The QuVis Quantum Mechanics Visualization project aims to support the learning and teaching of quantum mechanics through the development and evaluation of interactive simulations with accompanying activities. This article gives an overview of the QuVis simulations and describes the research-based development process that aims to optimize simulations and accompanying activities in terms of clarity, ease-of-use, promoting exploration, sense-making and linking of multiple representations. It gives examples of features of the simulations that are aligned with previous work on developing effective educational simulations. It gives examples illustrating how student feedback from individual student interviews and in-class trials was used to optimize the resources. Finally, it summarizes future plans.

Overview of the QuVis interactive simulations

The QuVis Quantum Mechanics Visualization Project (www.st-andrews.ac.uk/physics/quvis) develops interactive simulations for the learning and teaching of quantum mechanics concepts (Kohnle, 2010 and Kohnle, 2012). The QuVis website now includes over 90 research-based interactive simulations. Simulations are research-based, with student feedback informing all stages of the development process. Simulations are freely available for use online or download. Simulations cover a wide range of quantum mechanics topics, ranging from the introductory to the more advanced undergraduate level. Simulations include many topics not covered in other multimedia collections. Some of the QuVis simulations make topics typically covered at the advanced level (entanglement, hidden variables, quantum cryptography) accessible to introductory level students. The majority of simulations include an accompanying activity available for download from the website. Full solutions to these activities are available on the website, but password-protected for instructor access only. Instructors who wish to obtain the password for the solutions are asked to email the author.

The QuVis website groups the simulations into four collections: simulations for physics students, for physical chemistry students studying introductory quantum mechanics, simulations to support a new introductory quantum mechanics curriculum based on two-level systems and a recently-launched collection of HTML5 simulations that run on both desktop computers and tablet-based devices. The previous three collections were coded in Adobe Flash.

The "QuVis simulations for physics" collection includes mostly older simulations developed in 2009 to 2011, with 50 simulations in total available. The majority of simulations are aimed at the intermediate level and focus on wave mechanics and angular momentum. A smaller number of simulations are aimed at the introductory level (e.g. probabilistic analysis of classical systems, the photoelectric effect, the Bohr atom) and the more advanced level (e.g. the density matrix, spin clusters and spin chains).

The "QuVis simulations for physical chemistry" collection includes 18 simulations that are less mathematical compared with the physics collection, and include text explanations tailored to chemistry students. Topics of the simulations link to Atkins' "Physical Chemistry" textbook, with most simulations developed so far focusing on basic quantum theory. A number of simulations were adapted from the physics collection, others were newly developed specifically for physical chemistry students.

The "New Quantum Curriculum sims" collection consists of 17 simulations with accompanying activities that were developed in 2012 to 2013 as part of the UK Institute of Physics (IOP) Quantum Physics resources (Kohnle 2014). These simulations are available both on the IOP website quantumphysics.iop.org and on the QuVis website. The IOP resources were developed as a national UK project. They include around 80 short articles centred on questions with multiple paths through the material. Articles were authored by researchers in quantum information theory and foundations of quantum mechanics. Problem sets, simulations and activities are embedded into the articles. Resources provide material for a full course in introductory quantum theory focusing on two-level systems. Examples of such systems are a spin ½ particle, a two-level atom with a ground state and a single excited state, and a single photon in an interferometer with two possible paths. Developing quantum theory using two-level systems has a number of advantages (Michelini 2000, Scarani 2010, Beck 2012, Kohnle 2014 and Malgieri 2014). It allows from the start a focus on experiments that have no classical explanation. It allows from the start a focus on interpretive aspects of quantum mechanics and quantum information technology. It is also mathematically less challenging, requiring only basic algebra versus differential equations and calculus for the more traditional wave mechanics approach. The IOP resources are freely available but require registration. The simulations cover the topics of linear algebra, fundamental quantum mechanics concepts, single photon interference, the Bloch sphere representation, entanglement, local hidden variables and quantum information.

The recently launched collection of HTML5 simulations includes a revised layout optimized for both desktop computer and touchscreen use. Controls are more widely spaced, and the active area around each control has been increased for ease-of-use on smaller touchscreen devices. Graphics and displayed quantities are mostly positioned at the top of the window and controls mostly at the bottom, in order to reduce hand obscuration of feedback on touchscreens. Simulations in this collection include both recoded simulations from other collections as well as newly developed simulations. Older simulations from the physics collection are being revised in terms of layout and graphics prior to the recoding. For the New Quantum Curriculum simulations, revisions from in-class trials are being incorporated where needed prior to recoding.

Overview of the research-based development process

Figure 1 depicts the stages of the QuVis simulation development and refinement process. Ideas for simulations come from lecturing and tutoring experience and the literature on student difficulties in quantum mechanics.
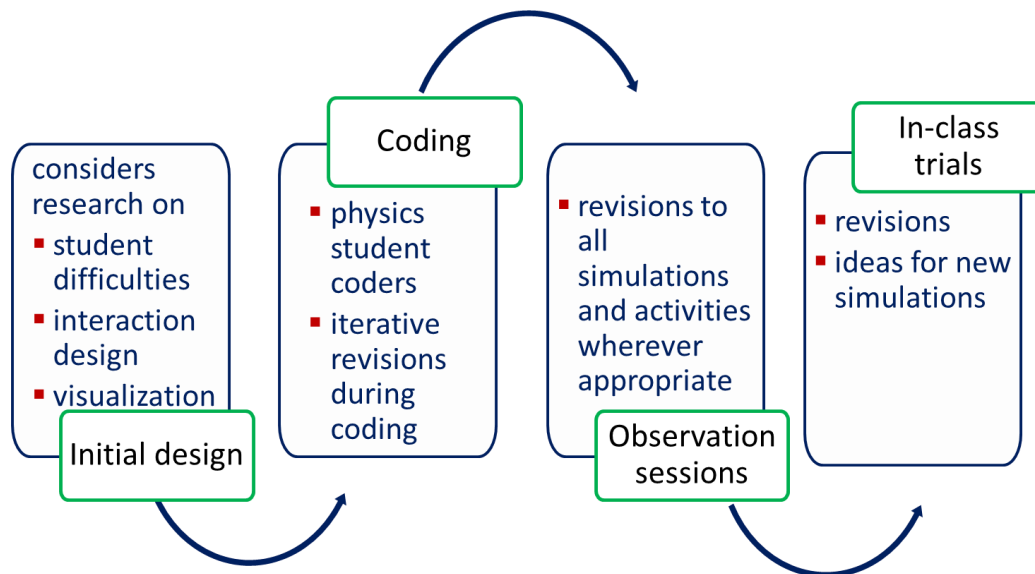

Figure 1. Overview of the simulation development process.

The development process starts by defining learning goals for a simulation. Learning goals inform the development of the simulation, activity and assessment instruments used to evaluate effectiveness. The learning goals are typically limited to a single concept per simulation (e.g. degeneracy of states or single photon interference). This reduces complexity and allows the simulation to focus on key ideas, reducing cognitive load. It also allows the simulation to lead students towards the learning goals through the interaction design, e.g. the number and types of controls, their ranges and layout. The initial design considers the literature on interaction design (Saffer 2010), research into student difficulties and research into what makes a good visualization (López 2013 and Chen 2014).

After initial drafting, simulations are coded by undergraduate physics students. These students often have suggestions for revisions to layout or content based on aspects they find confusing or non-intuitive. Thus, student input already informs the development phase. During the coding, the layout is iteratively revised based on experience interacting with draft versions.

Once the simulation is fully coded, it is refined using student feedback from the appropriate level, first in individual student observation sessions and then using in-class trials (Kohnle 2013). Figure 2 shows the research methods used in these trials and their primary focus.

In the individual student volunteer sessions, students first interact freely with a simulation until they feel they are finished. The free exploration phase makes it possible to assess the implicit scaffolding, e.g. whether students are guided through the interaction design towards the learning goals. Students are asked to think out loud during this process, and to describe what they are making sense of and what they are finding confusing. After freely exploring the simulation, students work on the accompanying activity. This makes it possible to assess whether questions are unambiguous and whether the simulation and the activity provide sufficient scaffolding for students to successfully complete the questions. During this process, the only interventions made are to remind students to articulate their thoughts, and to probe further when a student states they are confused and unable to make progress. If this latter situation arises, the student is first asked whether they can find anything in the simulation itself to help them overcome their difficulties. If not, further questions aim to discern how the student could overcome their difficulty, e.g. through an additional control in the simulation, additional information or rephrasing of text. The aim of posing these questions is to find patterns in student difficulties and ways to overcome them.

Directly after working with the simulation, students then complete survey questions on their experience of using the simulation. Survey questions ask about clarity of graphics, displayed quantities, texts and the activity, ease-of-use, perceived usefulness in enhancing understanding and how enjoyable students found working with the simulation. Students are asked to make comments on points found confusing and suggestions for improvement. These observation sessions are typically two hours in duration, with mostly two and sometimes three simulations used.
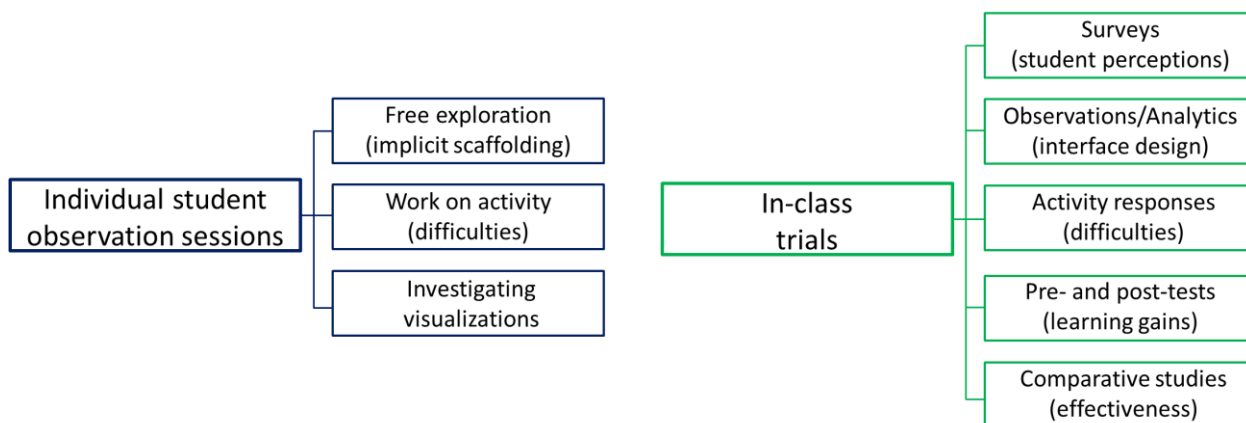
Figure 2. Overview of research methods used in the development and evaluation process and their primary focus.

The observation sessions are audiorecorded and use screencapture. Observers take notes during the sessions, and write detailed session notes with impressions after the sessions. These individual sessions typically lead to revisions to interface and content, which are incorporated into all simulations wherever relevant. Especially for more substantial revisions, a second round of observation sessions is carried out to assess the impact of revisions. This typically leads to a second round of more minor revisions. Observation sessions are also used to investigate the effect of different visualizations on student understanding, e.g. the visualization of the photon superposition state on student understanding of quantum superposition.

While the observation sessions give in-depth information on students' interactions and perceptions and make it possible to ask questions to explore possible changes to the simulation and the activity, they are carried out with only a relatively small number of students that have volunteered for this activity. Thus, issues identified may not be representative, and generalization of outcomes raises issues of validity.

Once revisions from observation sessions are incorporated, in-class trials are used to evaluate simulations with a larger number of students. For the in-class trials, a range of methods are used to evaluate the simulations and accompanying activities (see Figure 2), with a subset of these methods used for each of the trials. Directly after working with a simulation, students complete the same survey questions as in the observation sessions on perceived clarity of different elements, ease-of-use, perceived usefulness in improving understanding, points found confusing and suggestions for improvement. For in-class trials that use simulations in computer classroom sessions, students are observed during these sessions. Google Analytics is used to monitor usage of individual controls, e.g. to determine the fraction of students in a class that used a particular control and the average number of times a control was used. Thus, it is possible to assess whether students find and use all the controls and the frequency of control use. Students' responses to the activity questions are marked as correct or incorrect to assess whether any questions are on average not answered well. Activity questions not answered well point to issues with the simulation and/or the activity. For simulations with in-built challenges, it is possible to assess student success in completing these challenges, which form part of the activity problems. For a subset of simulations, short pre- and post-tests have been developed that students complete prior to and after working with a simulation. These pre- and post-tests assess learning gains through working with a simulation. The pre- and post-tests are mostly in multiple choice format, but also ask students to explain their reasoning and to rate their confidence in their answer. This makes it possible to verify that students choosing the correct answer have come to their answer using correct reasoning. Finally, a small number of comparative studies have been carried out. These studies have investigated student learning with two groups of students using somewhat different versions of a simulation, compared students' interactions with a simulation with one group using the simulation to learn a new concept, the other using the simulation to consolidate the concept, and compared use of a simulation with a pencil-and-paper activity. These comparative studies can evaluate the effectiveness of simulations compared with other instructional strategies, and assess the effectiveness of using simulations in different settings or with different visualizations.

Data collected from the evaluation studies include student responses to survey questions, activities, pre-tests and post-tests. Data analysis uses a combination of quantitative and qualitative techniques. Free-text survey responses are grouped according to common themes and patterns in student responses. For the activity, pre-test and post-test responses, student answers are marked as correct or incorrect to assess the fraction of students with correct responses, and incorrect responses are grouped into common ideas. Some of the in-class trials point to further revisions needed, which are typically minor compared with revisions from the observation sessions. All simulations and activities are revised based on evaluation outcomes wherever appropriate.

For the 17 simulations in the "New Quantum curriculum sims" collection, in total 42 hours of observation sessions were carried out with 19 student volunteers, 17 of which were from the introductory level. Much of the content of the simulations was new to these students. In-class trials have so far been carried out with 9 of these simulations, 5 at the introductory level and 4 at the advanced undergraduate level.

Aspects of simulations and activities that make them useful for learning

Figure 3 shows student perceptions of the usefulness of QuVis simulations in improving their understanding for an introductory quantum physics course (using 5 simulations in total) and an intermediate-level quantum mechanics course (using 17 simulations in total). This data is from end-of-course surveys conducted at the University of St Andrews in the 2013/14 academic year. Figure 3 shows that students across both levels find the simulations useful for their learning. Our experience is that these positive results are only possible due to our iterative development and refinement process informed by student feedback.
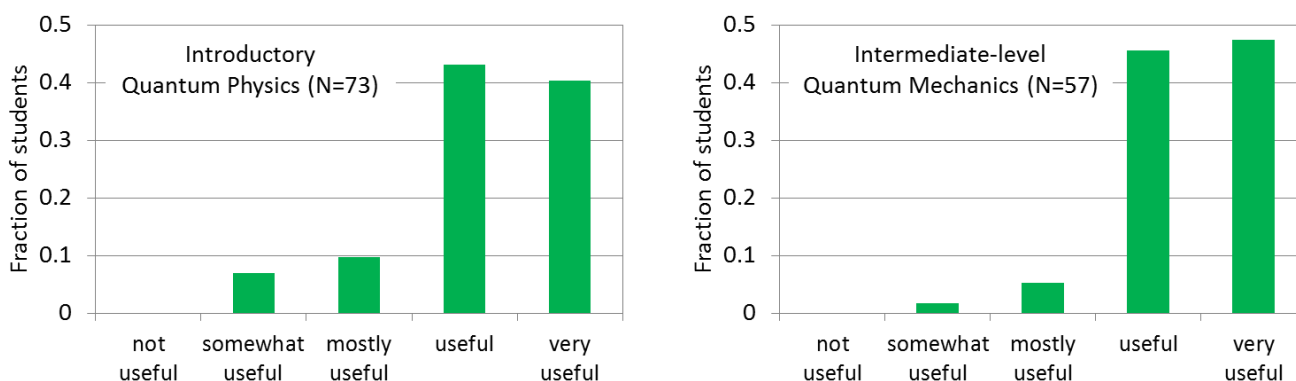

Figure 3. Student responses to an end-of-course question *"How useful for learning quantum physics have you found the simulations used in the course?"* for two course at the University of St Andrews in the 2013/14 academic year.

This section describes how aspects of the simulations are aligned with previous work on developing effective educational multimedia resources. Examples are given of student feedback from individual student interviews and in-class trials, and how this feedback was used to optimize the simulations and accompanying activities.

Implicit scaffolding using interaction design principles

Simulation controls that are difficult to master or non-intuitive lead to a focus on the control and user frustration instead of a focus on the content (Adams 2008a and Podolefsky 2010). Limiting the number of controls and complexity of simulations and avoiding extraneous material not directly linked to the key learning goals are important to enhance learning (Podolefsky 2010 and Clark 2011). The QuVis simulations are designed according to principles of interaction design and refined using outcomes from our evaluation studies.

These points are illustrated using the *Interferometer experiments with photons, particles and waves* simulation (Figure 4). This simulation aims to help students develop an understanding of single photon interference by allowing students to compare and contrast the behaviour of classical particles, electromagnetic waves and single photons when passing through the same experimental setup. Students can insert a single beam splitter or build an interferometer, and for waves and photons insert a phase shifter to vary the relative phase between the two arms. The simulation depicts single photons and the photon superposition state in order to help students develop a productive mental model of single photon interference. This simulation was trialed in five individual student observation sessions and used in introductory courses in 2013 and 2014, with somewhat different photon visualizations used in each of the in-class trials.

The QuVis simulations have a similar look-and-feel, so that students recognize the same interactive features and experimental apparatus across simulations. For example, the design of the optical components and detectors in the *Interferometer experiments with photons, particles and waves* simulation is consistent across all single photon simulations. Simulations use interactive controls such as sliders, radio buttons and tick boxes that are familiar to students. The layout is similar across all simulations, with displayed quantities and controls clearly separated from the graphics or experimental apparatus.
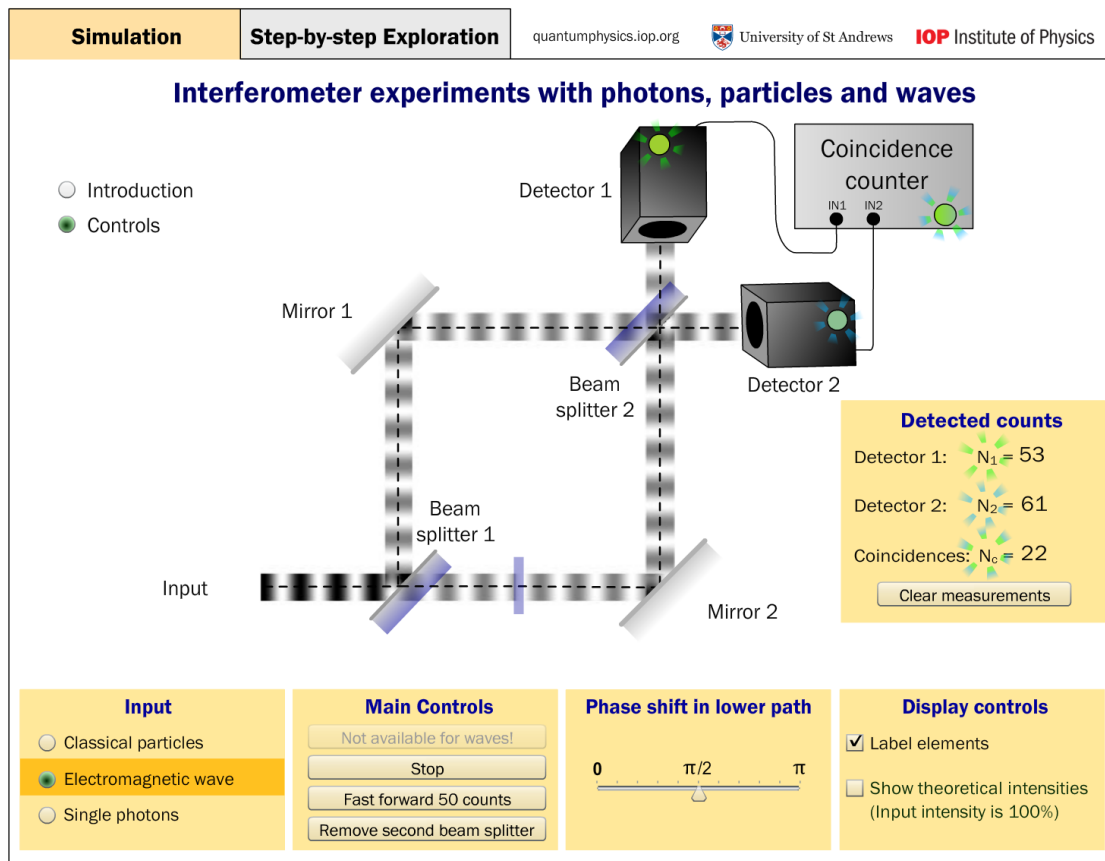
Figure 4. A screenshot of the *Interferometer experiments with photons, particles and waves* simulation, which allows students to compare and contrast the behaviour of single photons, particles and waves under the same experimental conditions.

The QuVis simulations make use of the fact that in the Western world controls are typically explored from top to bottom and left to right (Saffer 2010). This behaviour is also seen in the observation sessions. Thus, features students should find early on are placed at the top and left. Input states that can be chosen via radio buttons are ordered to progress from simpler to more complex states from top to bottom. In Figure 4, the order of the input controls helps scaffold students' exploration to first set up experiments with classical particles and electromagnetic waves before exploring the single photon case. Thus, the order of controls helps students to activate prior knowledge before exploring a new situation. Grouping of controls using panels makes use of the fact that adjacent controls are perceived to be related (Saffer 2010).

Initial configurations need to be kept simple, to encourage exploration and avoid overwhelming students (Adams 2008a and Clark 2011). The initial configuration in all simulations includes introductory text to give context to the situation shown. For the *Interferometer experiments with photons, particles and waves* simulation, the start-up screen is an Introduction view where students are asked to select the individual components of the experiment to learn more about them. Selecting a component brings up a brief text explanation directly adjacent to the component. The Introduction view tells users to choose the Controls button once they have learned more about the individual components of the experiment. Separating the Introduction and Controls views in this form allows us to scaffold students' exploration, so that students first learn about the components of the experiment in order to make sense of experimental outcomes when they progress to the Controls view.

The form of this introductory text was revised based on outcomes of the observations sessions. Initially, the introductory text was a single block of text. In the observation sessions, while students found this introductory text very helpful for making sense of the simulation, some students found the amount of text was overwhelming. Some students also commented that they amount of text made the simulation less enjoyable to work with. Thus, the Introduction view was revised to include user-controlled text-on-demand in small chunks and placed in proximity to the physical components. In observation sessions where students experienced both forms of introductory text, this text-on-demand was always preferred.

In all simulations, the initial Controls view shows a particularly simple and illuminating case, and tick boxes are unchecked. This aims to avoid overwhelming students and encourages exploration and sense-making. Simulations that allow students to take data include a "Clear measurements" button, so that students can reset the simulation. This creates a safe and non-threatening environment for exploration.

Simulation controls that are difficult to activate lead to a focus on the control and user frustration. Fitts's Law (Fitts, 1954) states that the time needed to activate a control is related to its size and positioning. In earlier versions of the simulations, controls could only be activated by selecting the actual control. In the observation sessions, some students clicked on the text labels for radio buttons and tick boxes instead of the actual controls. Thus, all controls were revised to be clickable via the associated text as well as the actual control. The recently developed HTML5 simulations have a large invisible active area around each control and more widely spaced controls, to ensure controls are easily activated on smaller screens and for touchscreen use. This design was developed using student observation sessions with students working with simulations on tablet-based devices. In the original layout, in the observation sessions students sometimes struggled to activate a control and required multiple attempts to do this.

From the in-class use of the *Interferometer experiments with photons, particles and waves* simulation, some negative student comments pertained to controls becoming inactive while photons were fired through the experiment, and that this made taking data and comparisons between different inputs time-consuming. All simulations in which data is collected were revised so that controls remain active when the input is sent through the experiment in continuous stream mode. In response to student suggestions for improvement to speed up data collection, a "Fast forward 50 counts" button was added to facilitate gathering of large numbers of counts to all simulations where students can collect data.

Using simulations to perform virtual experiments

Quantum mechanics textbooks define quantities such as probabilities, expectation values, quantum-mechanical uncertainties and correlation coefficients for entangled particle pairs in terms of mathematical formulas, but often do not describe how these quantities would be determined experimentally using many measurements on identical input particles or particle pairs. This may lead to these quantities being perceived as abstract and far-removed from experiments. One of the key aims of many of the QuVis simulations is to allow students to experience how such quantities can be determined experimentally and to understand inherent statistical fluctuations. Ten of the QuVis simulations in the "New Quantum Curriculum sims collection" allow students to send particles or photons through experiments, and seven simulations show how the experimental quantities approach the theoretically predicted values in the limit of a large number of measurements.
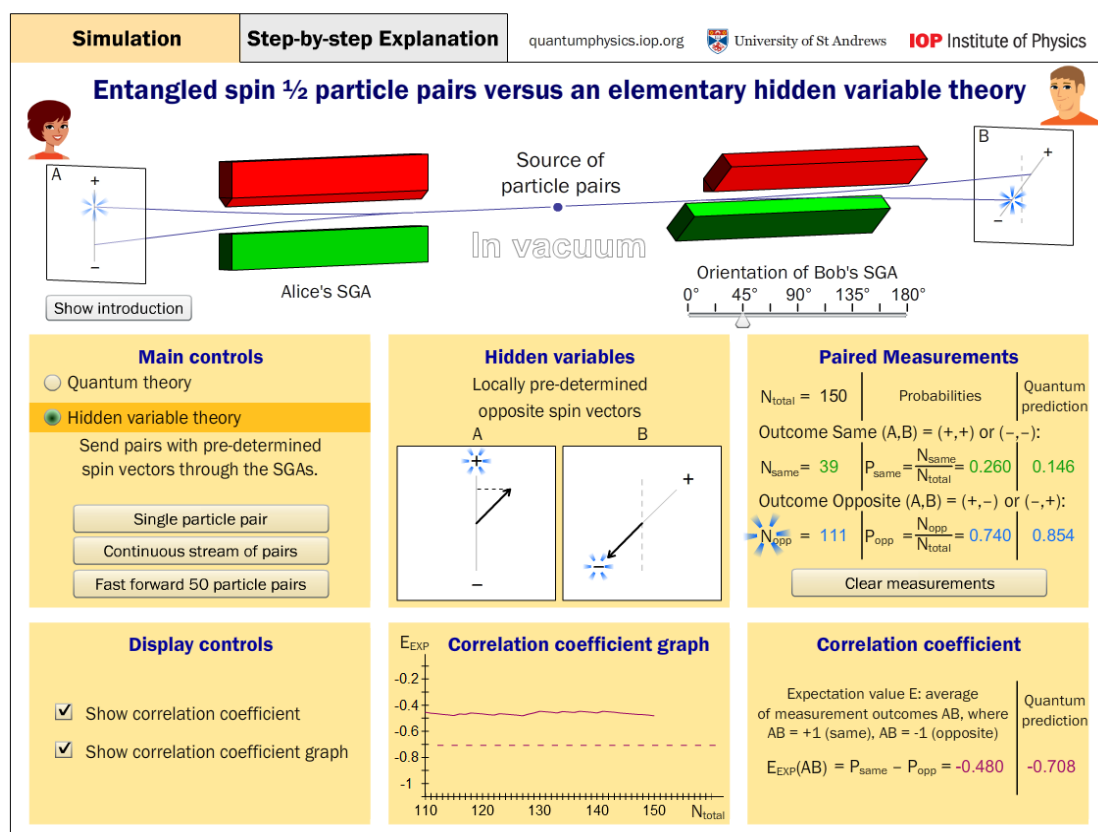

Figure 5. A screenshot of the *Entangled spin ½ particle pairs versus an elementary hidden variable theory* simulation. In this simulation, students can assess whether a simple hidden variable theory agrees with measurement outcomes predicted by quantum theory.

For example, the *Entangled spin ½ particle pairs versus an elementary hidden variable theory* simulation (Figure 5) allows students to assess whether a simple hidden variable theory would agree with measurement outcomes predicted by quantum theory. The simulation shows a source of particle pairs in the middle of two Stern-Gerlach apparatuses, one of which can be

rotated with respect to the other. The observers measure outcomes of + or − irrespective of orientation depending on whether the deflection is positive or negative along the measurement axis. When the main controls are set to "Quantum theory", the particles pairs are entangled and always give opposite results when both Stern-Gerlach apparatuses have the same orientation. When the main controls are set to "Hidden variable theory", the particles in the pair have pre-determined opposite spin vectors that are randomly oriented in space. By setting up different experimental configurations, students find that the two theories give different outcomes for some orientations of the second Stern-Gerlach apparatus. Hence the simulation allows students to deduce that this hidden variable theory must be incorrect.

Use of multiple representations
By using multiple representations to illustrate phenomena, interactive simulations can help students develop visual mental models and encourage them to make connections between different representations. Many of the QuVis simulations aim to help students make connections between multiple representations. Simulations make use of physical, mathematical and graphical representations, with consistent representations across different simulations.

In the *Entangled spin ½ particle pairs versus an elementary hidden variable theory* simulation (Figure 5), flashes are used to help students make connections between the measurement outcomes on the screens, the hidden variables (the opposite spin vectors) and the number of particle pairs with same and opposite measurement outcomes. Flashes are used in similar ways in all simulations which allow students to take data (see also Figure 4). Colour is used to help students differentiate between quantities, such as the detections by detectors 1 and 2 in Figure 4 and the same and opposite measurement outcomes in Figure 5. Colour is also used to help students make connections between experimental outcomes, calculated quantities and graphs. In Figure 5, colour is used to link the number of opposite measurement outcomes and the probability for the outcomes to be opposite, and to link the mathematical and graphical representations of the correlation coefficient.

Optimizing simulation activities
Strongly guided activities can inhibit students' exploration and reduce interaction with a simulation in terms of the number of controls used and total exploration time (Adams 2008c). Studies have shown that getting students to freely explore a simulation before working on an activity can encourage exploration and sense-making (Moore 2013).

The QuVis simulation activities aim to scaffold students' exploration by progressing from simpler to more complex situations. They ask students to compare and contrast classical and quantum behaviour, make sense of their observations, calculate displayed quantities and make connections between multiple representations. Adding questions that explicitly ask students to compare their calculations with their observations in the simulation helps them make connections between mathematical and visual representations (Kohnle 2013).

For the "New Quantum curriculum sims" collection, all activities start with a question asking students to have a play with the simulation for a few minutes, getting to understand the controls and displays, and to note down a few things about the controls and displayed quantities they have found out. Success on the activity as a whole was investigated depending on whether or not students have completed this question. This analysis used student responses to the *Quantum key distribution with entangled spin ½ particles* (quantum cryptography) simulation used in an introductory quantum physics course taken by students in their first or second year at the University of St Andrews. The activity was given as an online homework assignment, and did not form part of the course assessment. There were 79 students in the class, and 65 of them completed the assignment. Students had not encountered quantum cryptography in class, and thus they were learning new material using the simulation.

Student responses to each of the activity questions were marked as correct, partially correct, incorrect or unanswered. The activity consisted of 8 questions in total. The analysis compared the distribution of fully correct responses to questions 2 to 8 (so excluding question 1 asking students to freely explore the simulation and note down things they have found out) for those students that had completed question 1 (N=52) with those that had not answered this question 1 (N=13). Students that had not completed question 1 had completed the other questions, excepting three students who did not complete the final question of the activity. On average, students completing question 1 had 5.2 other questions correct, students not completing question 1 had 4.1 other questions correct. Thus, there is a difference in the mean number of questions answered correctly, with on average greater success on the rest of the activity for those students that had answered question 1. An independent t-test showed that the difference in questions answered correctly is statistically significant between the two groups (t=2.634, df=63, p=0.011, two-tailed). The mean difference of 0.93 is of medium size as measured by Cohen's d=0.63 (the mean difference divided by the average standard deviation).

This result only demonstrates a correlation, not a causal relationship, between answering question 1 and success on the rest of the activity, and this only for a single study. Further studies are planned to assess the impact of asking students to first explore a simulation freely on sense-making and success in achieving the learning goals.

Conclusions and Outlook

Research-based interactive simulations can address challenges of quantum mechanics instruction through user agency, implicit scaffolding, feedback on actions allowing trial-and-error exploration and the use of multiple representations. An iterative development process informed by student feedback from individual sessions and in-class trials is key to developing educationally effective resources. Initial evidence from observation sessions and in-class trials shows that QuVis simulations are helping students learn quantum mechanics topics, including topics such as entanglement and hidden variables at the introductory level that are more commonly discussed at the advanced level. Further evaluation studies at multiple institutions are planned to ensure simulations are useful to students from a wide range of backgrounds.

Current work aims to extend the QuVis HTML5 collection, both in terms of redesigning and recoding old simulations, as well as developing new simulations. Future development will include amongst other topics more simulations on quantum information processing and single photon experiments, as well as a larger collection of simulations suitable for the school level. Future work will aim to make simulations more engaging by including game-like elements aligned with learning goals. Future development will also include more open and exploratory activities, including intrinsically collaborative activities that require students to bring together their individual contributions.

Acknowledgements

References

Adams, W. L., Reid, S., LeMaster, R., McKagan, S. B., Perkins, K. K., Dubson, M. and Wieman C. E. (2008a). A Study of Educational Simulations Part I - Engagement and Learning, *Journal of Interactive Learning Research* **19**, 397-419.

Adams, W. L., Reid, S., LeMaster, R., McKagan, S. B., Perkins, K. K., Dubson, M. and Wieman C. E. (2008b). A Study of Educational Simulations Part II - Interface Design, *Journal of Interactive Learning Research* **19**, 551-577.

Adams, W. K., Paulson, A. and Wieman, C. E. (2008c). What Levels of Guidance Promote Engaged Exploration with Interactive Simulations? *2008 PERC Proceedings* (edited by C. Henderson and M. Sabella). AIP Conference Proceedings 1064, 59-62.

Baily, C. and Finkelstein, N. D. (2010). Teaching and understanding of quantum interpretations in modern physics courses, *Phys. Rev. ST Phys. Educ. Res.* **6**, 010101-1 to 11.

Beck, M. (2012). *Quantum Mechanics: Theory and Experiment*, Oxford University Press, New York, USA.

Belloni, M., Christian, W. and Cox, A. J. (2006). *Physlet Quantum Physics: An Interactive Introduction*, Pearson Prentice Hall, Upper Saddle River, NJ, USA.

Cataloglu, E. and Robinett, R. W. (2002). Testing the development of student conceptual and visualization understanding in quantum mechanics through the undergraduate career, *Am. J. Phys.* **70**, 238-251.

Chen, Z. and Gladding, G. (2014). How to make a good animation: A grounded cognition model of how visual representation design affects the construction of abstract physics knowledge, Phys. Rev. ST Phys. Educ. Res. **10**, 010111-1 to 24.

Clark, R. C. and Mayer, R. E. (2011). *E-Learning and the science of instruction,* John Wiley, San Francisco, USA.

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement, *Journal of Experimental Psychology* **47**, 381-391.

Kohnle, A., Douglass, M., Edwards, T. J., Gillies, A. D., Hooley, C. A. and Sinclair, B. D. (2010). Developing and evaluating animations for teaching quantum mechanics concepts, *Eur. J. Phys.* **31**, 1441-1455.

Kohnle, A., Cassettari, D., Edwards, T. J., Ferguson, C., Gillies, A. D., Hooley, C. A., Korolkova, N., Llama, J. and Sinclair, B. D. (2012). A new multimedia resource for teaching quantum mechanics concepts, *Am. J. Phys.* **80**, 148-153.

Kohnle, A., Baily, C., Hooley, C. A. and Torrance, B. (2013). Optimization of simulations and activities for a new introductory quantum mechanics curriculum, *2013 PERC Proceedings [Portland, OR, July 17-18, 2013]*, edited by P. V. Engelhardt, A. D. Churukian, and D. L. Jones, 209-212.

Kohnle, A., Bozhinova, I., Browne, D., Everitt, M., Fomins, A., Kok, P., Kulaitis, G., Prokopas, M., Raine, D. and Swinbank, E. (2014). A new introductory quantum mechanics curriculum, *Eur. J. Phys.* **35**, 015001-1 to 9.

López, V. and Pintó, R. (2013). Students' difficulties when reading interactive scientific visual representations. *Proceedings of the ESERA Conference*, European Science Education Research Association, Strand 4 Digital resources for science teaching and learning, 46-56.

Malgieri, M., Onorato P. and De Ambrosis, A. (2014). Teaching quantum physics by the sum over paths approach and GeoGebra simulations, *Eur. J. Phys.* **35**, 055024-1 to 21.

McKagan, S. B., Perkins, K. K., Dubson, M., Malley, C., Reid, S., LeMaster, R. and Wieman, C. E. (2008). Developing and Researching PhET simulations for Teaching Quantum Mechanics, *Am. J. Phys.* **76**, 406-417

Michelini, M., Ragazzon, R., Santi L. and Stefanel, A. (2000). Proposal for quantum physics in secondary school, *Phys. Educ.* **35**, 406-410.

Moore, E. B., Herzog, T. A. and Perkins, K. K. (2013). Interactive simulations as implicit support for guided-inquiry, *Chem. Educ. Res. Pract.* **14**, 257-268.

Podolefsky, N. S., Perkins, K. K. and Adams, W. K (2010). Factors promoting engaged exploration with computer simulations, *Phys. Rev. ST Phys. Educ. Res.* **6**, 020117-1 to 11.

Saffer D. (2010). *Designing for Interaction*, New Riders, Berkeley, USA.

Scarani, V., Chua L. and Liu, S. Y. (2010). *Six Quantum Pieces: A First Course In Quantum Physics,* World Scientific Publishing, Singapore.

Singh, C. (2001). Student understanding of quantum mechanics, *Am. J. Phys.* **69**, 885–896.

Wittmann, M. C., Morgan, J. T. and Bao, L. (2005). Addressing student models of energy loss in quantum tunnelling, *Eur. J. Phys.* **26**, 939-950.

Zhu, G. and Singh, C. (2012). Improving students' understanding of quantum measurement. I. Investigation of difficulties, *Phys. Rev. ST Phys. Educ. Res.* **8,** 010117-1 to 8.

Antje Kohnle
School of Physics and Astronomy
University of St Andrews
North Haugh
St Andrews
KY16 9SS
United Kingdom
email: ak81@st-andrews.ac.uk