

## INTRODUCTION

The Institute of Physics New Quantum Curriculum ([quantumphysics.iop.org](http://quantumphysics.iop.org)) consists of online texts and interactive simulations with accompanying activities for an introductory course in quantum mechanics starting from two-level systems. This approach immediately immerses students in the concepts of quantum mechanics by focusing on experiments that have no classical explanation. It allows from the start a discussion of the physical interpretations of quantum mechanics and recent developments such as quantum information theory. Texts have been written by researchers in quantum information theory and foundations of quantum mechanics. One of us (AK) designed the interactive simulations and activities (17 in total) that are part of this resource.

The New Quantum Curriculum simulations make use of principles of interface design from previous studies<sup>1-4</sup>. Activities were designed to promote guided exploration and sense-making. Aims of this study were to optimize the simulations and activities in terms of clarity, ease-of-use, promoting exploration, sense-making and linking of multiple representations. We also aimed to optimize the link between the simulations and activities.

## METHODOLOGY

We conducted 38 hours of observation sessions with 17 student volunteers from the University of St Andrews Quantum Physics course (roughly equivalent to US sophomore Modern Physics). In these sessions, students first freely explored a simulation and then worked on the activity associated with the simulation, in both case thinking aloud and describing what they were investigating and explaining what they understood or found confusing. They then answered survey questions and reflected on their experience. Sessions were audiorecorded with screencapture. We were able to trial all simulations and activities excepting one (16 in total) in these sessions, with 1 to 5 students interacting with each simulation. For a number of simulations there was sufficient time between trials for us to implement changes prior to testing the simulation with subsequent students. Where needed, we implemented changes to activities between trials.

We also used three simulations in the Quantum Physics course, two in computer classroom workshops and one as a homework assignment. We used two simulations as homework assignments in the University of Colorado Boulder Modern Physics course. Analysis of difficulties was used to optimize the simulations, activities and the links between them. Revisions were incorporated into all simulations and activities wherever applicable.

## FUTURE STEPS

We will be conducting further observation studies and evaluation in courses at multiple institutions in the coming year. We plan further refinements to simulations and activities from outcomes of this evaluation. We will also be creating additional activities for the simulations that are more exploratory and promote student discussions and collaboration. For these activities, we wish to carry out observation sessions with students collaboratively working with the simulations.

## ACKNOWLEDGMENTS

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## EXAMPLES OF OUTCOMES

**Simulation** Step-by-step Exploration [quantumphysics.iop.org](http://quantumphysics.iop.org) University of St Andrews IOP Institute of Physics

### Graphical representation of complex eigenvectors

**Transformation matrix**

$$\hat{O}_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\hat{O}_2 = \begin{pmatrix} 0 & e^{-0.25i\pi} \\ e^{0.25i\pi} & 0 \end{pmatrix}$$

$$\hat{O}_3 = \begin{pmatrix} 0 & e^{-0.5i\pi} \\ e^{0.5i\pi} & 0 \end{pmatrix}$$

$$\hat{O}_4 = ?$$

Find the matrix elements!

Display help on exponential form

**Initial vector components**

Imaginary axis

Real axis

Fine controls

$$\vec{n} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ e^{i\phi} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ e^{1.250i\pi} \end{pmatrix}$$

**Transformed vector components**

Imaginary axis

Real axis

Eigenvector: YES Eigenvalue: -1

$$\hat{O} \cdot \vec{n} = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{1.000i\pi} \\ e^{0.250i\pi} \end{pmatrix} = -1 \vec{n}$$

The graphs show the components (component 1 in blue, component 2 in green) of a two-dimensional complex unit vector  $\vec{n}$  in the complex plane and the components of the transformed vector  $\hat{O}\vec{n}$ , where  $\hat{O}$  is a 2x2 complex matrix that transforms the unit vector into a new vector in the complex plane. The first component of the vector is taken (as is often the convention in quantum mechanics) to be real and positive, and here of magnitude  $1/\sqrt{2}$ . The second component however is complex.

Use the slider for the angle  $\phi$  to change the direction of the second component of the vector  $\vec{n}$  in the complex plane, and the buttons to choose different transformation matrices. Complex numbers are displayed in the exponential form ( $re^{i\theta}$ ) with modulus  $r$  and argument  $\theta$ . In quantum mechanics, such a transformation matrix would represent an operator, and the vector would represent a quantum state. Note that the radius of the circle is  $1/\sqrt{2}$ .

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### The expectation value of an operator

Input state:  $\frac{1}{\sqrt{2}} (|z \uparrow\rangle + |z \downarrow\rangle)$

VACUUM

**Main controls**

Send spin 1/2 particles through the Stern-Gerlach apparatus

Single particle

Continuous stream of particles

Fast forward 50 particles

Clickable step counter

Improved explanations of concepts and formulas

**Number of measurements**

Total measurements:  $N_{tot} = 700$

Outcome  $S_z = +\frac{\hbar}{2}$ :  $N_{+} = 568$

Outcome  $S_z = -\frac{\hbar}{2}$ :  $N_{-} = 132$

Clear measurements

**Expectation value**

Mean of measurement outcomes

Theoretical

$$\langle \hat{S}_z \rangle = (+\frac{\hbar}{2}) \text{Prob.} + (-\frac{\hbar}{2}) \text{Prob.}$$

$$\langle \hat{S}_z \rangle = 0.311 \hbar$$

0.3 h

We can experimentally find the expectation value of the z-component of spin (denoted by  $\langle \hat{S}_z \rangle$ ) as the mean value of the measurement outcomes  $+\hbar/2$  and  $-\hbar/2$  for a large number of measurements on identical particles all in the same input state. This mean value of the measurement outcomes is  $\langle \hat{S}_z \rangle = ((+\hbar/2) N_{+} + (-\hbar/2) N_{-}) / N_{tot}$ . Due to statistical fluctuations, the observed mean value is only approximately equal to the theoretical expectation value. In general, the greater the number of measurements, the smaller the observed mean value deviates from the theoretical expectation value.

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### Phase Shifter in a Mach-Zehnder Interferometer

Introduction

Controls

Single Photon Source  $\lambda = 400 \text{ nm}$  (Energy  $E$ )

Beam splitter 1

Phase shifter

Mirror 1

Mirror 2

Filter blocks 800 nm (Energy  $E/2$ )

Beam splitter 2

Detector 1

Detector 2

The detector registers a count (shown as a flash) whenever a photon enters the detector and is converted into an electrical signal. Only one or the other detector measures the photon, never both!

Filters to test ideas about superposition

Popup texts explaining the setup

Move the mouse over the individual components of the experiment about them.

After having done this, press the Controls button to send photons through the experiment and to insert and/or remove the phase shifter.

Choose the Step-by-step Exploration tab for explanations of the different experiment outcomes.

We revised the activities to help students make better connections between multiple representations and better links with the simulations, using formulations such as

“Using the simulation, come up with a general rule ...”,  
 “Explain how these calculations relate to the experimental observations in the simulation ...”,  
 “Explain how you can see these results graphically in the simulation.” etc.

For more complicated simulations such as the hidden variable simulations, we provided additional scaffolding in the activities. For example, we asked students to explain how hidden variable and quantum theory differed in their explanations of the experimental outcomes shown.

## REFERENCES

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4. A. Kohnle et al., *Am. J. Phys.* **80**, 148-153 (2012).