Teaching Quantum Mechanics to Over 28,000 Nonscientists

Cite as: Phys. Teach. **57**, 326 (2019); https://doi.org/10.1119/1.5098924
Published Online: 18 April 2019

J. K. Freericks, D. Cutler, A. Kruse, and L. B. Vieira

Teaching Quantum Mechanics to Over 28,000 Nonscientists

J. K. Freericks, D. Cutler, and A. Kruse, Georgetown University, Washington, DC
L. B. Vieira, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil

We describe a new style of MOOC designed to engage students with an immersive multimedia environment including text, images, video lectures, computer-based simulations, animations, and tutorials. Quantum Mechanics for Everyone[1] is currently running on edX and has been successful by a number of different measures. Building on the pioneering work of many,[2-6] it illustrates both how one can teach complex quantum phenomena to nonscientists and how one can develop high-quality interactive computer simulations that engage students and can be widely deployed.

We have been told a lie. We propagate the lie. We perpetuate the lie. And we don't even know where the lie originated. The lie is that *one needs to have a sophisticated math background and significant physics background in order to understand complex quantum phenomena.* This article shows one way to dispel the lie. It shows you how to bring the most exciting and counterintuitive physics concepts to the forefront of the curriculum. While our initial emphasis has been to reach nonscientists via a MOOC format, many of the techniques we employ can be rolled out in a classroom setting and included in introductory curricula. It can be done in a meaningful way that is honest to the science. It can be done without requiring sophisticated math.

But don't just take our word for it. The initial idea comes from Richard Feynman, and is eloquently expounded in his book entitled *QED: The Strange Theory of Light and Matter.*[2] There Feynman illustrates how the path-integral method for quantum mechanics can be developed by just drawing arrows on a piece of paper! He discusses much of the quantum mechanics of light, ranging from everyday phenomena, such as partial reflection, mirrors, and lenses, to more exotic phenomena, such as the two-slit experiment. The idea was further developed by Daniel Styer, who in *The Strange World of Quantum Mechanics*[3] applied the Feynman methodology to Stern-Gerlach experiments that were then modified to allow him to describe the two-slit experiment, Wheeler's delayed choice experiment, the Einstein-Podolsky-Rosen paradox, and Bell's theorem experiments. Our work also builds on the computer simulations of Visual Quantum Mechanics[5] and PhET.[6] In our MOOC, which is running on edX until the spring of 2019, we combine all of these different ideas and more into a multimedia educational experience (see Fig. 1).

Soon after Feynman's book came out, Edward Taylor realized that animations of the material in the book would enhance the learning process.[4] He developed a series of computer-based tutorials that employed the cT programming environment to run these animations. These computer tutorials were further developed by Hanc and Tuleja, who rewrote

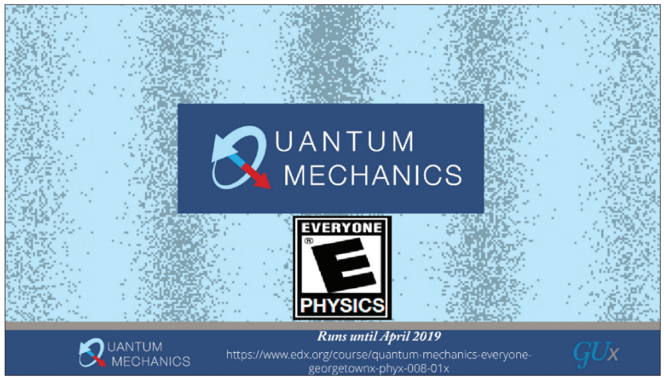

Fig. 1. Logo for the MOOC.

them in Java and provided an enhanced learner experience.[7] Unfortunately, neither of these approaches works well for web delivery of materials, where Java programs suffer from numerous security concerns and there is no web interface to run cT programs. As we worked on developing the materials for our MOOC, we focused on creating platform-independent computer tutorials that would run off JavaScript and be deployed via iframes on a web browser. This industry-standard approach allows for the computer simulations to have the widest reach and the highest impact.

Because modern browsers and JavaScript have numerous high-quality graphics libraries and 3D imaging tools, we could produce animations that were engaging and realistic using modest resources. The end result is a professional, game-quality series of animations that work on a wide range of different platforms, including computers, tablets, and phones. We incorporate dozens of these simulations within the MOOC.

Quantum Mechanics for Everyone delivers a self-contained treatment of quantum theory that is accessible to students with a modest knowledge of high-school-level algebra. The initial results, after the 24-month run, are impressive—we have over 28,000 learners enrolled, the course is the highest-rated quantum MOOC (and an all-time top-50 MOOC) on class-central.com, was a finalist for the 2018 edX prize, and over 375 students have already completed the final (self-paced MOOCs often have lower completion rates than scheduled MOOCs). Every week we average more than 500 students logging into the class, 250 watching a video, and about 150 answering a problem. Over 5500 have watched the first-week videos and tried at least one problem. There isn't enough research yet to know precisely how to gauge success in a MOOC, but initial work has pointed to MOOCs being as effective as on campus classes.[8-10] The issue of high dropout rates has also been examined,[11] but one of the reasons for high dropout is that students must enroll in a class in order

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to see any of the content, implying that many enrollees never planned on actually taking the class.

• *Course structure:* The class is organized into four modules—each intended to be covered in one week. The math background that we require is minimal—proficiency with high-school-level algebra and some familiarity with trigonometry are all that is needed. The first two modules are heavily influenced by Styer's book, the second two by Feynman's. The first module covers an introduction to quantum mechanics, in which we describe classical expectations for a Stern-Gerlach experiment, which would separate atoms according to their spin projection, and then illustrate that the quantum systems separate into only two projections. This leads into the need to describe systems probabilistically and allows us to introduce a self-contained unit on probability theory to ensure students understand how to determine the probabilities for different events to occur. The second module, on advanced quantum mechanics with spin, develops the concept of the Stern-Gerlach analyzer loop, which involves two inverted Stern-Gerlach analyzers hooked back-to-back to allow for quantum interference effects to be carefully examined. Armed with these devices, we introduce an analog of the two-slit experiment, Wheeler's delayed choice variant and the quantum eraser, the EPR experiment, and a Bell-state experiment, which allows us to rule out hidden variables. We end with a discussion of the technology behind magnetic resonance imaging. The third module involves the quantum mechanics of light, in which we describe partial reflection, the single-slit experiment, the two-slit experiment (both watched and unwatched), multi-slit experiments, mirrors, and lenses. This module employs Feynman's path integrals by summing arrows. It connects the total probability amplitude to the probability for an event to occur. The fourth module concludes the course with the phenomena of quantum seeing in the dark (or interaction-free measurements) by first illustrating the principle within a two-slit experiment, then describing the Mach-Zehnder interferometer and how this improves the efficiency. We follow with treatments of the polarization of light and the quantum-Zeno effect, which are assembled into the quantum seeing in the dark experiment (and involve seeing an object *without* shining light on it). The unit concludes by describing the properties of bosons and indistinguishability as evidenced by photon bunching in the Hong-Ou-Mandel experiment. For further details, please visit the edX course site at https://www.edx.org/course/quantum-mechanics-everyone-georgetownx-phyx-008-01x.

This journey through quantum mechanics takes the learner on a trip that visits increasingly complex and abstract phenomena, but at a level that is easy to follow and understand. The journey is made possible only through the use of sophisticated computer-based simulations and animations, which engage the students but also allow them to visualize the abstract phenomena and make them real. Furthermore, the simulations and animations perform the complex quantum calculations for the students, so they can focus on understanding the concepts and the methodology without getting caught up in the minutiae of the details. We include many forms of computer-enhanced instruction: linearly directed visual tutorials; virtual experiment simulations with user control over parameters; and free-exploration experiences. We believe this wide breadth of materials helps actively engage the student.

• *Strategies for interactive computer simulations and tutorials:* Since the development of the computer tutorials is so germane to the course, we take a moment to describe some of the issues one must deal with if one wishes to embark on a similar endeavor for another topic (of course, if you wish to use any or all of our tutorials, they are freely available for download under the LGPL 2.1 license at our GitHub repository https://github.com/quantum-mechanics-for-everyone/simulations). As previously mentioned, it is vital that the tutorials rely only on standard and widely deployable features of major web browsers. The maturity of JavaScript and WebGL in modern browsers (desktop and mobile) is a key factor for our success. Modern browsers are powerful multimedia platforms and so are an ideal medium for interactive educational content that can be widely deployable—now freed from third-party software such as Java or Flash.

In order to have a flexible system to develop the tutorials, they are envisioned as simulations based on a custom-built framework featuring visually distinct modular devices, with inputs and outputs, which may be attached to one another, rotated, and labeled at will. This core simulation engine allows us to quickly develop many different experimental setups with great flexibility (see Fig. 2).

In our engine, particles are released by sources and pass through these devices until they reach detectors, at which point a measurement result is tallied up and displayed in bar charts. Specific care is taken to avoid classical vs. quantum misconceptions with this visual approach: quantum behavior always occurs inside the devices, hidden from view. A textbox accompanies all simulations and gently guides the learner through the various steps, providing explanations and posing questions to enhance the experience.

A probabilistic model is automatically computed by the engine to reproduce the results expected of these "virtual experiments," which allow us to abstract the software development away from the technical details in each tutorial and focus on the narrative and presentation.

Each object is given a distinct shape and name (e.g., "atom source," "Stern-Gerlach analyzer," "detector") so as to be immediately recognized, and is introduced and explained in detail and in terms of previously established concepts. Care was taken to ensure possible questions about their behavior were addressed early on ("What happens if we flip this upside down, or attach it to the other output?"). This way, students are quickly familiarized with the full range of behaviors and usage. Questions to be addressed in later experiments are also mentioned earlier in order to prevent leaving the more curious and attentive students empty-handed.

An important aspect of the probabilistic model for the simulations is that it allows us to visually emphasize the probabilistic nature of quantum mechanics. Experiments always

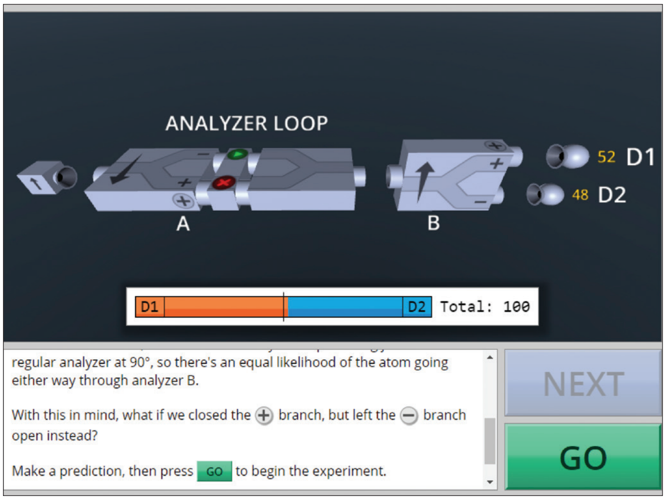

Fig. 2. An example of a virtual experimental setup. On the left, a spin-up "atom source" releases atoms with a known spin state (+*z*, vertical). This atom passes through a Stern-Gerlach analyzer connected to a partially open "gate" object, which in turn is connected to a "quantum eraser." These three objects combine to form an "analyzer loop." The atom then goes through a second Stern-Gerlach analyzer before reaching detectors D1 or D2. Below, a color-coded proportional bar chart displays the result of the experiment.

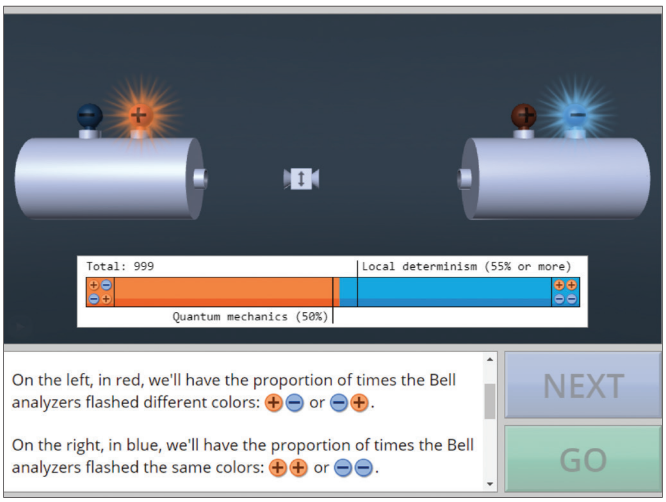

Fig. 3. Bell experiment using two "Bell analyzers" and a source of entangled atom pairs. Each Bell analyzer contains a three-positioned Stern-Gerlach analyzer and two detectors inside, as previously assembled in an earlier tutorial.

consist of hundreds of consecutive trials until conclusions can be drawn from the results. They are displayed using intuitive visuals like color-coded proportional bar charts, which give an immediate intuition for probabilities between two events. As results start to accumulate, the student can see the results converging to the predicted value, despite the random fluctuations. We believe this enhances learning by making the thought experiments more concrete and tangible, as opposed to simply reporting the final result (see Fig. 3).

Each experiment is built piece by piece based on previous ones. Once set up, we discuss what we have found so far in previous tutorials, then pose questions about the new experiment. Before any experiment begins, we encourage (but do not force) students to make predictions of the results. We believe this helps engage students with the material and encourages critical thinking. After each experiment, we ask if the results were what the student expected.

Sometimes, we deliberately play with classical intuition by presenting an unexpected quantum result, followed by a discussion of the incorrect assumptions. In this way, we create a narrative that deconstructs classical ideas in favor of quantum ones. More complex experiments are first simulated step by step, pausing at important points, so aspects of each device can be explained in more detail, before being run a series of times in succession.

Finally, in order to make the simulations visually engaging, we also included smooth movements and transitions when moving the camera or devices in the experiments. Devices are always brought from outside or taken from inside the experiment and moved out, and the camera position and angle are chosen to accommodate the new experimental setup.

• ***What we have learned.*** Advice we offer to other MOOC developers includes:

- **(i)** *do not underestimate the time it takes to develop materials*—this four-week course took three years to complete;
- **(ii)** *be sure to test your materials multiple times prior to release*—watch every video, read every transcript, try every problem, look at every answer, select alpha-testers from your target audience to give learner-appropriate feedback;
- **(iii)** *be prepared to correct your course as errors are found*—no course is error-free and students will find many during the initial course roll-out; and
- **(iv)** *be responsive on the discussion boards*—nothing is more annoying to students than having limited staff participation to ensure the course is running smoothly and that problems are being fixed.

How well did we do? While we did not engage in any pre-testing, we find that, on average, students get about 80% of the course questions correct, and also about 80% of the final exam questions (passing level is 70%). This implies that students leave the course with a mastery of the material. We do note that the entry level for these students is high (over 60% have a bachelor's degree or higher), but we also note that much of the material covered in the MOOC is not commonly found in other external sources.

So what is the implication for education? As we often bemoan the shrinking numbers of physics majors (in spite of some recent reinvigoration of numbers nationwide), we should ask ourselves how we can best excite students to want to learn more physics. While some may say that focusing on the traditional methods with blocks and pulleys and charges and fields is the way to go, we feel that the physics community should include some quantum mechanics in the curriculum earlier than normally done to benefit all.

You might ask whether this conceptual focus is all that can be taught in quantum mechanics without requiring a sophisticated mathematical edifice? The answer here is also no! By employing only operator methods, one of us (JKF) is developing a new methodology for a book entitled *Quantum Mechanics Without Calculus*, which will move from the conceptual through the undergraduate and graduate curricula and even reach into active research fields, yet it employs no math above high-school-level algebra. While students will need to be *masters* of high school level algebra to finish such a book, one can cover nearly all of quantum mechanics by employing these operator-based methods and not ever needing to calculate a derivative or an integral! It is time we bring this excitement to our students as soon as we can. We hope this MOOC will only be the first step on this journey—and our students will all be the better for it.

Acknowledgments

This work was supported by the National Science Foundation under grants numbered PHY-1314295 and PHY-1620555, by an ITEL grant from Georgetown University, and by the McDevitt bequest from Georgetown University.

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Jim Freericks *is a professor of physics and a McDevitt Chair at Georgetown University. Quantum Mechanics for Everyone is his first MOOC, loosely based on a classroom course The Quantum World Around Us, taught at Georgetown for many years. He is currently extending this work to teach more traditional undergraduate quantum curricula with only high-school-level algebra in a book project called* Quantum Mechanics without Calculus. *He is a Fellow of the American Association for the Advancement of Science and the American Physical Society.*
James.Freericks@georgetown.edu

Dylan Cutler *is a Georgetown alumnus who is currently a software engineer at Google. During his time studying math and physics at Georgetown, Dylan co-developed JavaScript simulations for the MOOC Quantum Mechanics for Everyone. For his work on the course, Dylan received the Undergraduate Physics Research Award from the Georgetown Department of Physics in 2016.*

Anna Kruse *is an assistant director at Georgetown University's Center for New Designs in Learning and Scholarship. Since 2013, she has supported the design, development, and implementation of massive open online courses. She has co-authored a number of articles exploring the implications and impact of open online courses, including the chapter "Digital Change: How MOOCs Transform the Educational Landscape" in* The Palgrave Handbook of Managing Continuous Business Transformation.

Lucas Vieira *is a physics student and educational writer, illustrator, and animator with an extensive list of contributions to educational projects related to mathematics and physics. He co-developed JavaScript simulations for the MOOC. Since 2004, he has been a frequent contributor of high-quality illustrations and animations to Wikipedia and its sister projects, and is one of the few featured illustrators on the site. Lucas is currently completing his master's degree in quantum information theory at the Federal University of Minas Gerais, Brazil, and is working on an educational YouTube channel that features high-quality, accurate and accessible visual explanations of topics in physics and mathematics.*