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Simplifying the Quantum World: Demonstrations for Young Learners in an Informal Setting

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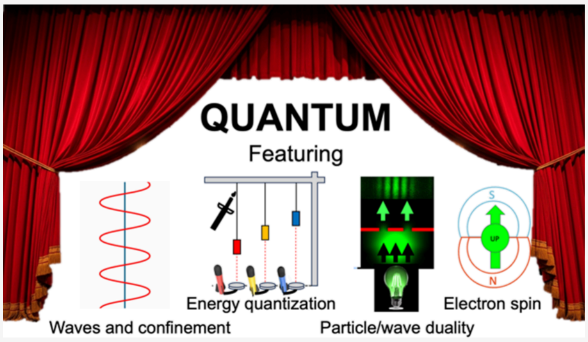
ABSTRACT: A set of modules for the informal learning of quantum science was developed. They include (1) Waves and Bottling Light in Quantum Dots, (2) Quantization of Energy Levels, (3) Particle-Wave Duality, (4) Magnetism and Electron Spin, and (5) Quantum Entanglement. Their teaching objective is to clarify concepts in quantum science, and they have been presented together as part of an hour-long show to ∼250 adults and school-age children. The learning outcomes of the modules were assessed by pre- and postevent quizzes as well as interactive clicker questions. The results suggest effective learning of all of the assessed concepts. These modules are detailed in a way that makes them deployable, together or in part, in other formal or informal settings to support the dissemination of information about quantum science to the general public.



KEYWORDS: *Informal setting, quantum chemistry, quantum science, light, wave-particle duality, energy quantization, electron spin*

■ INTRODUCTION

Quantum science attracts interest, fueled, in part, by the 2022 Nobel Prize in Physics "pioneering quantum information science"[1] and the 2023 Nobel Prize in Chemistry "for the discovery and synthesis of quantum dots".[2] The public is exposed to the word quantum on a daily basis through a growing number of companies and claims, and funding for scientists in the USA has been boosted through the 2018 National Quantum Initiative Act (H.R. 6227 of the 115th Congress).

This interest in quantum phenomena stems from their potential as next-generation technologies, some already implemented in televisions, with others promising, e.g., revolutionary encryption and computing.

Expanding scientific fields, such as nanoscience in the 2000s and, now, quantum chemistry, benefit from a trained workforce and an informed public. Quantum dot syntheses are becoming a common upper-level undergraduate chemistry laboratory,[3−6] while computational tools have been developed to assist in the teaching of quantum dynamics.[7−9] More basic concepts of quantum and nanoscience can also be integrated by exploring colors bestowed by localized surface plasmon resonances in Ag nanoparticles as well as electronic transitions in organic dyes and metal ion complexes.[10]

Beyond traditional classroom and laboratory settings, quantum science learning tools can attract and engage students at various levels. An interactive electronic notebook offers a survey of quantum dynamics,[7] while quantum tic-tac-toe promises to teach various quantum concepts including entanglement.[11,12] Musical analogies have also been deployed to convey confinement[13] and the quantum nature of atoms.[14]

Public-facing, informal learning events provide access to a different audience and can help boost scientific interest and literacy while educating the broader public. These can take multiple forms, from public art displays reaching passers-by,[15] to exhibits during broadly themed science festivals,[16] to events targeting specific populations such as visually disabled adults.[17,18]

The University of Colorado (CU) Boulder "Wizards Science Outreach" program is a long-standing venue for informative and engaging science presentations to families in the Boulder/Denver area. The program involves faculty "Wizards" from Arts, Sciences, and Engineering departments developing and presenting hour-long shows on Saturday mornings highlighting their areas of research. Starting in its current multidisciplinary configuration in 1987, CU Wizards has become a well-known

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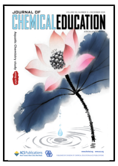

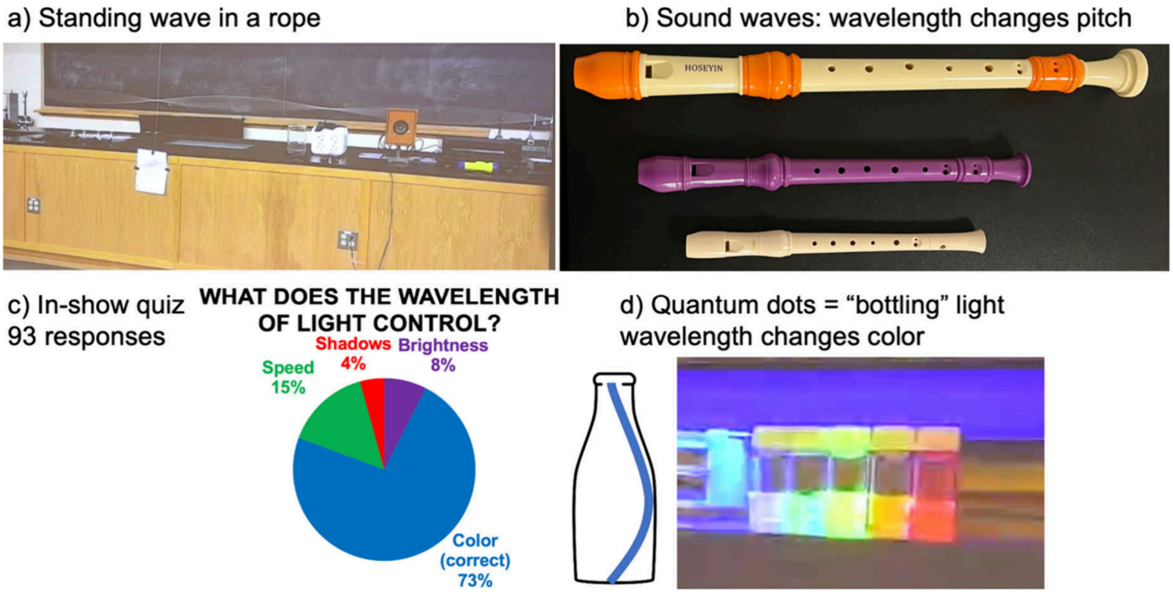

Figure 1. Waves: (a) Standing wave from a 5 m long rope, (b) recorders of various sizes, (c) responses to the in-show quiz on light, and (d) quantum dots displayed during the show.

platform for engaging the whole family in extracurricular science. The CU Wizards produces ∼10 presentations/year and, over 38 years, has reached a total of 120,000 school-age children and parents.

The focus of this paper is to describe the development and presentation of a Wizard show entitled "Simplifying the Quantum World", spearheaded by, instead of a professor, a team of CU graduate and undergraduate students. We report a collection of modules to support the teaching of quantum science in informal settings, which can be adapted to various settings from science clubs to fairs and classrooms. Detailed descriptions, expanded in the Supporting Information, facilitate implementation, and a recording is available online.[19] Further, data obtained from pre- and postshow quizzes indicate positive learning outcomes related to quantum science concepts.

■ RESULTS AND DISCUSSION

Overview

A science show was developed as part of a semester-long course on scientific communication run by Ringe and Nesbitt. Modules 1−4 were developed by one or a pair of CU students (upper-level undergraduate and graduate students), culminating in a CU Wizards show. The Saturday morning event was held in an auditorium-style chemistry classroom. Prior to the event, an email was sent to previous program participants with a link to the preshow quiz. On the day of the event, participants were reminded to complete the quiz, and it was disabled once the show started. Approximately 250 people, mostly families with school kids aged 8−14, attended the event. 99 clickers were distributed among them, enabling in-show responses.

After the 1 h long show, the preshow quiz respondents were prompted verbally and by email to fill in a separate but identical postshow quiz. Responses were anonymized and aggregated. IRB approval was not required, as confirmed by CU Boulder's assessment, as the activity does not meet the definitions of Research and Human Subjects as defined by the US Department of Health & Human Services (HHS).

Demonstrations and In-Show Responses

The show consisted of five separate modules arranged pedagogically to build on and reinforce prior knowledge. The content of each module is summarized below, with a full description in Supporting Information Sections 1−5.

Hazards. Full risk assessments are provided in the Supporting Information. Briefly, the burning of methanol is a hazard due to the possibility of flash fire—this is mitigated, as recommended by the US Chemical Safety Board,[20] by preparing separated small portions of exactly the (small) amount to be used. The metal salts used for flames and explosions are not irritants; however, ingestion of large quantities should be avoided; we suggest preparation ahead of time by gloved demonstrators. The laser used (1 mW green laser pointer, class II) does not require safety goggles as the blink reflex prevents eye damage; however, we provided laser safety goggles for extra caution and to alleviate any potential stress from the volunteers and their parents.

Module 1: Waves and Bottling Light in Quantum Dots. This module introduces early learners to waves and their relationship to color, culminating in an easy-to-understand explanation of quantum dots.

First, a demonstrator shows a 5 m long rope attached on one end to a variable speed motor (with an eccentric wheel for achieving a sinusoidally modulated vertical displacement) and on the other end to a fixed point (node) with tension maintained by weights. By increasing the motor speed, successive standing waves are produced (Figure 1a), introducing the concept of wavelength. This wave demonstration can also be performed with manual rotation of a jump rope.

Next, a demonstrator explains that sound is a wave and that the wavelength of sound is linked to its "pitch" or "note". A high note (pitch) has a small wavelength, while a low note has a long wavelength. A limitation here is that frequency is more directly relevant to notes but is more difficult to convey pictorially.

Three recorders of different sizes (sopranino, soprano, and alto; Figure 1b) were handed to volunteers. The sopranino recorder produces a high note, explained by its short size and consequently short sound wavelength. The soprano and alto recorder then produce, in succession, increasingly longer sound wavelengths and lower notes, audible in a large auditorium.

Finally, light is stated to also be a wave; an in-show quiz carried out prior to any further discussion of light revealed that 73% of respondents correctly associate light wavelength and color (Figure 1C). Quantum dots, a widely recognized quantum effect, are then introduced by analogy with the recorder demonstration. Here one now "bottles" light in a nanoscopically sized container, where the smaller the bottle, in this case electronic confinement, the shorter the wavelength and the higher the emission energy. Quantum dots from the group of Prof. Dukovic (CU) were then displayed, illuminated by a UV light. These produce a broad range of colors easily visible to the full auditorium, as shown in Figure 1d, as a result of their different "bottle" size and degree of electronic confinement.

Module 2: Quantization of Energy Levels. This module aims to introduce the concept of energy quantization with a special focus on light emission.

First, quantization is described as discrete jumps with everyday analogies. We discuss how the fabric of a t-shirt may appear smooth to the touch but is, in fact, when looked at in a microscope, composed of discrete fibers. Another analogy is that of Pokémon "evolving" after obtaining specific number of points, from Charmander to Charmeleon to Charizard: they are sharp, rather than smooth, transitions between different well-defined states. The case is made that transitions in the quantum world are similar: staircase-like, jumping from well-defined levels to well-defined levels with a specific transition energy. This Pokémon analogy was popular with the crowd, but educators should keep in mind that it only pertains to states being discrete and does not represent energy levels.

To illustrate different energy "jumps", we built a frame holding three identical water bottle weights at different heights, representing different energy levels (Figure 2a). They were suspended by a string ~0.5, 1, and 1.5 m above the air container of a commercial "stomp rocket" assembly. An in-show quiz polled the audience about which rocket would go higher, and 61% of respondents correctly identified the rocket with the highest weight (blue, Figure 2b). Volunteers then use a candle attached to a long stick to burn the string and thereby launch the rocket, with the blue rocket, as expected, flying the highest.

The quantization of light emission is then introduced as the result of fixed, quantized energy levels and demonstrated via a neon arc lamp viewed through predistributed linear diffraction grating glasses (captured in Figure 2c).

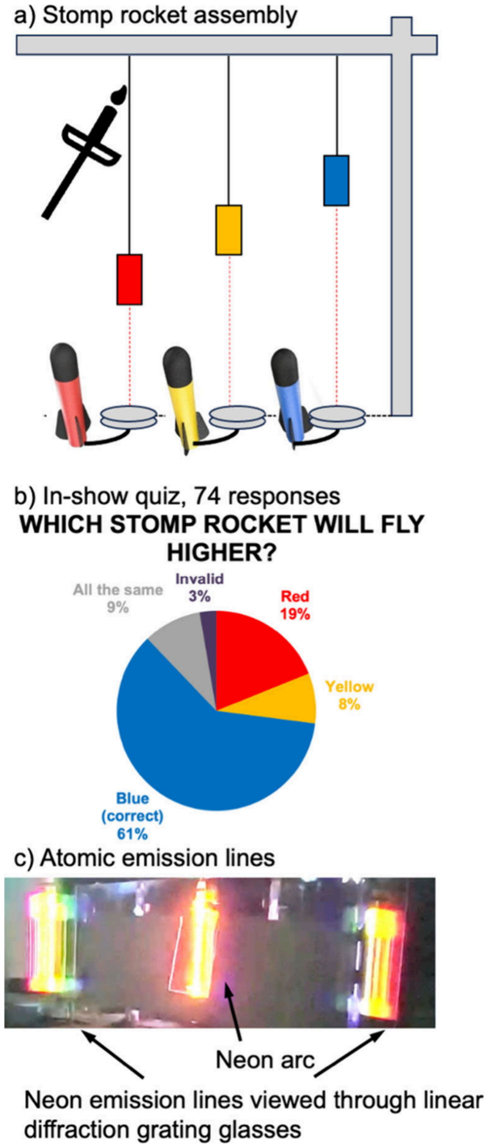

Figure 2. Energy quantization: (a) Stomp rocket assembly, (b) responses to the in-show quiz before the stomp rocket demonstration (marked invalid for a clicker choice not assigned to an answer, in this case letter E), and (c) neon gas emission and spectra viewed through a linear diffraction grating.

Atomic emission can also lead to spectacularly colored flames. Salts of various metals displaying different characteristic emission spectra are first burned (with a well-received analogy to Harry Potter) by mixing a small amount of salt with a safe, small amount of methanol (15 mL) in a Petri dish and then igniting (by a trained demonstrator). These include boric acid (green), strontium chloride (red), sodium chloride (yellow), and potassium chloride (purple). Note that alternative salt preparation and ignition methods exist, for instance coating salts on a rod and heating over a Bunsen burner flame.[21] Then, for a spectacular effect, balloons filled with 99%+ hydrogen gas and 0.5 g of various salts (either sodium chloride (yellow), potassium chloride (purple), copper(II) chloride (blue-green), boric acid (green), or strontium chloride (red)) tethered by string several meters above the demonstration bench are ignited with a candle on a meter stick. This ignition produces loud, colorful explosions, reinforcing the key concepts from the methanol/salt flame demonstration. Note that although this demonstration is enthusiastically received, it is not essential to the pedagogical flow given the technical challenge and safety issues of obtaining and working with a tank of hydrogen gas.

Module 3: Particle-Wave Duality. A quintessential topic in quantum science is particle-wave duality; this module builds on the previous wave discussions and provides a demonstration of wave-particle duality through two experiments.

First, the audience is reminded of the different types of waves discussed: rope, sound, water, and light. A quick poll then asks about the result of the two-slit experiment (Figure 3a−b); a majority (75%) of respondents identified the "stripey" pattern as the correct answer. A laser is then aimed through a single 100 μm slit at a black chalkboard and turned on, then off, by a volunteer, yielding a single spot of light.

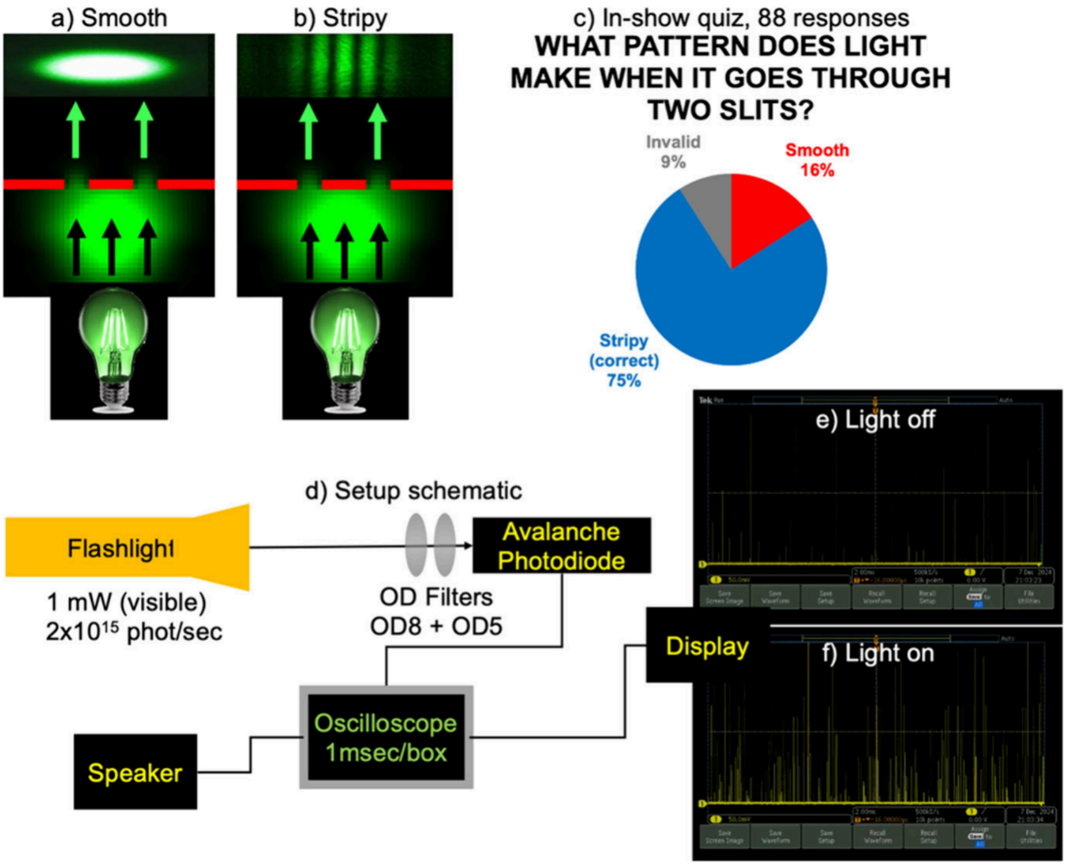

Figure 3. Particle-wave duality. (a–b) possible two-slit pattern shown for the in-show quiz, (c) responses to the quiz (marked invalid for a clicker choice not assigned to an answer, in this case letters C, D, and E), (d) instrument diagram for hearing single photon impact on a detector, and avalanche photodiode readout with light (e) off and (f) on.

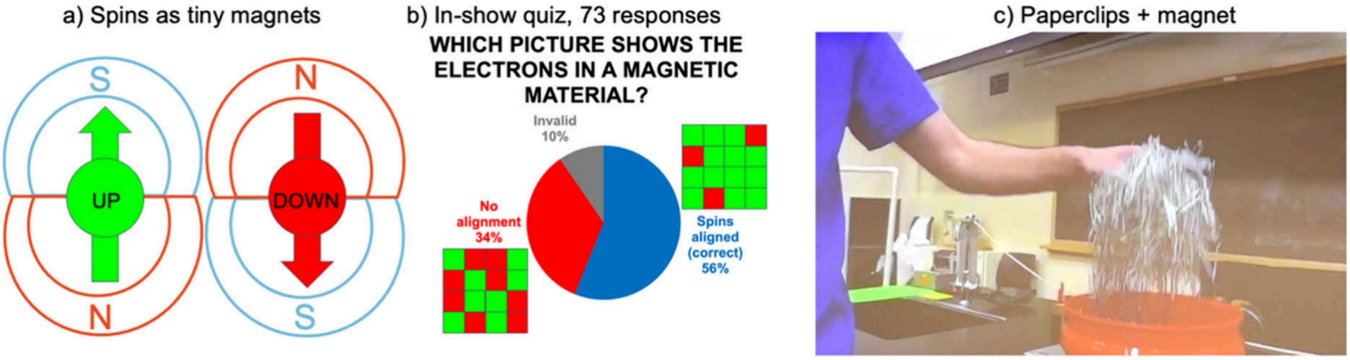

Figure 4. Quantum phenomenon of spin: (a) electron spin forms a tiny magnet pointing up or down, (b) responses to in-show quiz and aligned patterns shown on screen for the quiz (marked invalid for a clicker choice not assigned to an answer, in this case letters C, D, and E), and (c) paperclips picked up by a samarium–cobalt magnet.

Then, the slit is swapped for a double slit (<100 μm spacing) and another volunteer operates the laser. While on, the laser produces an easily visible interference pattern akin to that of water waves, demonstrating the wave nature of light (Figure 3c).

The second experiment demonstrates the light's particle nature by converting single photons into an audible signal. The setup (Figure 3d) comprises a flashlight emitting 10^{15}–10^{16} visible photons/s, with neutral density filters (8OD and 5 OD) to achieve a 10^{-13} transmission, and an avalanche photodiode detector (APD) for single photon counting. The photodiode is connected to an oscilloscope that displays the signal as narrow intensity bursts (1 μs) representing individual photons. The signal from the oscilloscope is displayed on a screen for the audience to "see" single photons as well as amplified, and "heard", with an audio amplifier. With the flashlight off, or obstructed, a diminution in signal is seen and heard (Figure 3e, dark count rate on APD is <150 counts/s). With the flashlight on, single photon bursts could be easily seen on the projection screen and heard as random noise at a rate of 100–1000 counts/s (Figure 3f), demonstrating the particle-like nature of light.

Module 4: Magnetism and Electron Spin. Magnetism is ubiquitous, yet an appreciation of the underlying concepts requires an understanding of spin and quantum phenomena. This module introduces the concept of electron spin and its implications for magnetic behavior.

First, a nonmagnetic metal (aluminum), an electromagnet (70 cm × 3 cm iron bar wound with copper wire), and a permanent magnet (4 cm × 3 cm samarium−cobalt alloy) are introduced and the elements identified on the periodic table. With three volunteers, these three objects are inserted in a bucket containing 10,000 paperclips (iron). The aluminum bar does not attract any paperclips nor does the unpowered electromagnet. However, the samarium−cobalt alloy is spectacularly attractive, picking up >1000 iron paperclips.

Once the battery hooked up to the electromagnet is switched on and current is flowing, the electromagnet does start to attract paperclips, and thus the idea of moving electric charges creating a magnetic field is introduced. Many attendees understand electrically generated magnetism. We therefore use this to emphasize that such a phenomenon cannot explain the magnetism in the samarium−cobalt alloy or any other permanent magnet.

Electron spin is then introduced as a fundamental property of electrons akin to charge. This spin, which can be either up or down but has nothing in between, essentially acts as a tiny magnet. Note that while this property is called "spin", it does not imply that the electron is making a classical orbiting or spinning motion. Rather, it is an intrinsic angular momentum possessed by the electron and truly quantum mechanical in nature.

We then introduce the notion that macroscopic magnetic behavior occurs when electron spins in a material are preferentially aligned up or down. The audience's understanding was tested through an in-show quiz (Figure 4); answers reveal spin is one of the most difficult concepts covered here. To illustrate magnetic alignment, colored cards were distributed to two audience groups. One group received an equal mix of green and red cards representing the nonaligned spins for a nonmagnetic material with an average net spin near zero. Conversely, the other group was given mostly green cards, symbolizing preferentially aligned spins in a magnetic material.

To demonstrate the strength of magnetic interactions, a large permanent pole face magnet (>1 T, from a decommissioned NMR instrument) was wheeled on stage and paperclips in the bucket were added, handful by handful, by volunteers. The entire bucket of paperclips was then poured on top, demonstrating that all 10,000 paper clips snapped quite robustly to the pole faces (removal took significant effort).

Module 5: Quantum Entanglement. Lastly, the concept of quantum entanglement was briefly discussed, enabling the mention of quantum computing. Entanglement is an extremely advanced example of quantum phenomena but also currently the most highly publicized in the media. Hence we decided that no science outreach show on the quantum world would be complete without at least some attempt at illustrating this sophisticated concept, even if only by analogy.

To illustrate quantum entanglement, the demonstrator puts a left-handed glove in a standard USPS envelope and a right-handed glove in another identical envelope and hands one envelope each to two other demonstrators. The envelopes are then scrambled with the two envelope-carrying demonstrators eventually heading to opposite sides of the auditorium. A map of the US invites the audience to imagine these two envelopes being whisked by to Los Angeles and New York City. Opening one envelope and discovering a right glove immediately reveals ("knowledge at a distance") that the other envelope must contain a left glove or vice versa. This instantaneous transfer of knowledge over large distances is used as analogy to quantum entanglement, with a slide illustrating Einstein's challenge in believing in such "spooky" nonlocal quantum behavior. It is emphasized that creating/maintaining true quantum entangled states (qubits) represents a very challenging yet crucial research frontier, with such a right/left glove demonstration serving as a very simple analogy to the challenges of building a quantum computer. Finally, reference materials including the *Great Courses series: Understanding the Quantum World*[22] and the book *The Quantum World* by J.C. Polkinghorne[23] are displayed as further learning tools, with the audience welcomed to ask questions to the demonstrators and reminded to fill in the postshow quiz.

RESPONSES TO PRE- AND POST-SHOW QUIZZES

To evaluate the learning outcomes of the event, families were asked to fill out an identical online questionnaire before and after the show, where only one answer could be selected per question (Supporting Information Section 6). 118 preshow responses were received in the 2 weeks preceding the show, while 70 postshow responses were submitted within 5 days after the show. Based on email addresses from the online Google form, 66 sets of matched pre- and postshow responses were identified, extracted, and anonymized. Questions, responses, aggregated data, and McNemar's test[24] p-values are reported in Tables 1-6 (where $p < 0.05$ represents statistical significance at the 95% confidence level). Full tables and details for McNemar's tests are reported in Supporting Information Tables S7.1−7.9.

Table 1. Question 1 of the Pre- and Post-Show Quiz

Are you filling this out as a···	Preshow	Postshow
Adult	30	27
Child working with adult	23	19
Child	13	20

The first question (Table 1) asked the respondent to self-identify as a child, a child working with an adult, or an adult. Nearly half identified as "adult," followed by a third as "child working with adult" and the remainder being "child." There were numerical differences between pre- and postshow responses, with notably more children responding on their own to the survey after the show, possibly reflecting enhanced engagement in QM science topics after the event.

The second question (Table 2) asked about interest in the quantum world, which was high both before (62/66, 94%) and after (98%) the show, as expected for voluntary participants and audience members.

Question 3 (Table 3) tested knowledge on the relationship between wavelength and color; the level of correct answer was

Table 2. Question 2 of the Pre- and Post-Show Quiz

Are you interested in the quantum world?	Preshow	Postshow
Yes	62	65
No	3	1
No response	1	-
McNemar's p-value	0.22	

Table 3. Questions 3 and 4 of the Pre- and Post-Show Quiz, Relevant to Module 1

What controls the color of light?	Preshow	Postshow
The length of the wave	59	65
Temperature	4	-
Speed of Light	1	1
Brightness	1	-
No response	1	-
McNemar's *p*-value	0.039	
Which of these is NOT a wave?	**Preshow**	**Postshow**
Wind	59	63
Ripples on a pond	4	3
Light	3	-
McNemar's *p*-value	0.18	

high preshow (89%) and slightly higher postshow (98%) with statistically significant improvement as determined by the McNemar's test. Respondents were also mostly correct in stating that wind is not a wave in Question 4 (Table 3, 89% preshow, 95% postshow), with no statistically significant improvement observed in the postshow response.

Next, Questions 5, 6, and 7 (Table 4) related to the quantization of energy covered in Module 2. Responses to "How do you think an atom increases in energy when heated up?" (Question 5) revealed that, preshow, less than a half of the respondents could identify energy increase as being quantized (47%). However, the postshow responses overwhelmingly identified (95%) the correct answer, suggesting both a good learning outcome and high statistical significance of the results.

Table 4. Questions 5, 6, and 7 of the Pre- and Post-Show Quiz, Relevant to Module 2

How do you think an atom increases in energy when heated up?	Preshow	Postshow
Smoothly, like the ramp in Picture (a)	15	-
In steps, like the staircase in Picture (b)	31	63
Both (a) and (b)	19	3
No response	1	-
McNemar's p-value	3.3×10^{-11}	
Campfires, as you may have seen in real life or on TV, are generally orange in color, like the one shown below. But...you may have also seen the famous "Diagon Alley!" scene from Harry Potter, where the Floo Powder makes the Wizards and Witches disappear magically in a green flame! Do you think that fire flames can only be orange in color, and not other colors (like green as shown above from the Harry Potter movies)?	**Preshow**	**Postshow**
Yes, fire flames can only be orange in color	2	-
No, fire flames can also be other colors than orange	56	66
Fire does not have any color	7	-
No response	1	-
McNemar's *p*-value	0.00098	
Do you think different colors of light have different energies?	**Preshow**	**Postshow**
Yes, different colors of light have different energies	56	66
No, different colors of light all have the same energy	8	-
No, light does not have energy	1	-
No response	1	-
McNemar's *p*-value	0.00098	

Responses to Questions 6 (Can fire be of different colors?) and 7 (Is color of light linked to its energy?) were largely correct both preshow (85%) and postshow (100%), achieving a McNemar's *p*-value of 0.00098. Evidently, displaying brilliantly colored flames multiple times made the concept material easy to absorb and remember, with the energy/color relationship equally well retained, despite being more subtle.

A single question was posed for Module 3 on wave-particle duality: "How would you best describe light?", with options of wave, particle, both, or neither. A statistically significant improvement was observed between pre- and postshow, with 71% and 92% of respondents correctly selecting "both a wave and a particle", respectively. This set of experiments, demonstrating both wave-like interference patterns and the "hearing" of single photons, proved effective at conveying the dual nature of light.

Table 5. Question 8 of the Pre- and Post-Show Quiz, Relevant to Module 3

How would you best describe light?	Preshow	Postshow
As a wave (like a wave in the ocean)	13	4
As a particle (like grains of sand on the beach)	2	-
As both a wave and a particle	47	61
As neither a wave nor a particle	3	-
No response	1	1
McNemar's *p*-value	0.00052	

Lastly, Questions 9 and 10 indicated that knowledge on electron spin is not widespread. Less than half of respondents (35%) linked spin to a magnetic signature, with more than half (59%) answering that electrons orbit around the nucleus, a valid statement out of context but unrelated to electron spin. Given the less well -known nature of "spin" to the preshow audience, the orbiting answer was possibly chosen as simply most familiar. However, postshow answers revealed that 86% of respondents could then correctly describe the meaning of electron spin, a very positive outcome with high statistical significance.

Preshow responses to the evidence of spin in everyday life were no better than random, with roughly a third each for magnets, electricity, and light. Once again, this result indicates that even a science-savvy crowd that mostly knows about light's energy/color relationship has not been exposed to electron spin, a quantum concept with no classical analogue. The content of Module 4 was effective in explaining electron spin, as evidenced by the increase in correct answer (magnets) from 33% to 83%, from the same 66 respondents.

■ CONCLUSIONS

This paper reports on successes and challenges in simplifying quantum concepts in an informal "show" setting. Five modules were performed and described, with further details available in the SI. Approximately 250 people, mainly families with elementary school-age children, attended the show; 99 clickers were distributed for in-show polling, with results reported in Figures 1−4. Answers to identical 10 question pre- and postshow quiz (results in Tables 1−6) were gathered from 66 respondents to more quantitatively evaluate learning achievement. All 10 questions in the quiz were answered better postshow, demonstrating that such an informal and fun event had led to positive learning outcomes. Results reveal that certain concepts not widely understood before the event, such

Table 6. Questions 9 and 10 of the Pre- and Post-Show Quiz, Relevant to Module 4

What does it mean for electrons to have spin?	Preshow	Postshow
Electrons act like teeny tiny magnets	23	57
Electrons rotate around atoms like planets around the sun	39	5
Electrons flowing through wires creates electricity	3	3
No response	1	1
McNemar's *p*-value	3.5×10^{-8}	
How do we see evidence of electron spin every day?	**Preshow**	**Postshow**
In magnets	19	55
In electricity	22	5
In light	21	6
No response	4	-
McNemar's *p*-value	7.1×10^{-12}	

as electron spin and energy quantization, were much more familiar after the event, with analysis supporting the statistical significance of this improvement. Further, even the correct response rate on more common concepts, such as the color of fire and light, also revealed a pre- vs postshow improvement.

Such show-like events are effective and attract young learners, and thus their dissemination and organization should be encouraged. University settings are well-suited for this type of learning, as the developing team (undergraduate and graduate students) can hone their pedagogy skills and scientific vulgarization approaches, logistical issues such as safety and the availability of a large auditorium are usually simple, and local and nearby population groups can easily be accommodated on campus. In summary, we encourage our colleagues to consider hosting such on-campus shows, using any materials provided herein, and developing new modules to inspire the next generation of scientists.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.5c01021.

Detailed description of demonstrations and pre/post-show quiz (PDF)

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Notes

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