Teaching Quantum Entanglement with Glowing Model Qubits

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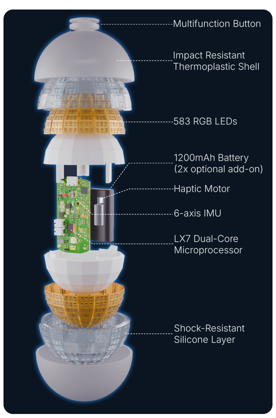
ABSTRACT

Entanglement is a foundational feature of quantum mechanics, yet learners typically encounter it only as a formula or loose analogy. We present two hands-on activities for teaching entanglement, both built on a model qubit: a handheld spherical LED display that renders qubit states in real time. Learners interact by rotating and shaking the device. Paired devices share a single statevector over a wireless link so that two-qubit correlations can be explored directly. The first activity is an outreach demonstration that captures the essence of the Bell paradox and is engaging for children as young as elementary school. The second is a two-and-a-half-hour workshop in which high schoolers and undergraduates act as experimentalists, building a theory of the qubit from their own measurement tallies. In addition, we offer a three-level categorization of quantum knowledge which avoids common misleading analogies and remains faithful to the science. We report a deployment of the outreach activity for 250 students at the Invent the Future expo in Bethesda, Maryland, and deployments of the workshop in the QCaMP high school training program and the BERQ undergraduate training program.

Keywords: quantum education, entanglement, quantum outreach, Bell paradox, tangible interfaces, model qubits, K–12 STEM, physics education



(a) The device

(b) In use

Figure 1. (a) Exploded view of a single model qubit. (b) Children measuring model qubits at an outreach booth. The photograph in (b) has been AI-modified to render the faces and clothing of all depicted individuals unidentifiable.

1. INTRODUCTION

When passionate educators propose bringing quantum education into the K–12 context, they are often met with cynicism and skepticism. Cynics say that while it sounds alluring, quantum is simply not important compared to core curriculum concepts like planets and tectonic plates. Skeptics might add that middle schoolers are not mature enough to understand such a complex science. We believe both of these issues stem from the educational tools and methodologies employed today, rather than from the science itself. Quantum is a new field, and we are still learning how to teach it effectively.

Today, if quantum is ever introduced to a young child, it is usually done through analogies and murky definitions, which does not lead to a working understanding of the concepts. Concepts like superposition and

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entanglement are introduced, but incompletely explained; they leave too many open questions. This has led to a global intellectual resignation: It is as if the world has said "if nobody understands it, then how can I?" Kids are impressionable; they give up quickly if exposed to such a belief.

The difficulty is well documented. A survey of secondary quantum curricula across fifteen countries finds wide variation in whether and how the topic is approached at all,[1] and reviews of teaching strategies at the secondary and lower-undergraduate level report conceptual difficulties that are persistent and well catalogued.[2,3] Much of the response has been software. The QuVis project built interactive simulations targeted at documented misconceptions,[4] the Quantum Flytrap virtual lab does the same for optics-based quantum mechanics,[5] and a review of quantum games and interactive tools finds the inventory growing but overwhelmingly screen-based.[6]

Tangible approaches are rarer. Bloch cubes give learners a six-faced die whose faces are the six states where the Bloch sphere meets the coordinate axes, and have been used to teach measurement, dynamics, mixed states and decoherence without equations.[7] The electronic quantum dice of Folkers et al. let learners explore entanglement correlations through paired haptic hardware.[8] Optical hardware is the most developed line. Thorlabs sells a demonstration kit that models the BB84 protocol[9] with half-wave plates and polarizing beamsplitters,[10] and Donohue et al. have built an interactive quantum key distribution kit around a laser and detector on a 3D-printed base, reporting workshop feedback from high school students, undergraduates and educators.[11] Both are explicit analogies rather than quantum systems, using pulsed lasers in place of single photons. Within the optics and photonics education community more broadly, recent work has concentrated on pathways and workforce readiness rather than on demonstration design.[12,13]

In this paper we introduce new demonstrations based on a new tool called a model qubit (nicknamed Qubi), a handheld sphere whose entire surface is a spherical LED optical display (Fig. 1). It renders the state of a qubit in real time. Learners interact with it by rotating and shaking it, with motion mapped to unitary operations and measurement outcomes, and a pair of devices shares a single statevector over a wireless link, so that two-qubit correlations can be explored directly. Section 2 describes the instrument in detail.

The first activity is a quantum outreach demonstration that presents the essence of quantum entanglement in a faithful yet accessible way. It requires no mathematics and no prior background. The objective is to motivate the impossibility of entanglement, and to tell the story of how it was discovered. We do this by asking children to play a game that cannot be won without entanglement. We report on a deployment at the Invent the Future expo in Bethesda, Maryland, which drew roughly four thousand attendees, mostly elementary and middle schoolers with their parents.

However, a five-minute demonstration cannot cover all loose ends, and is too shallow for many quantum education programs. Therefore, we also introduce a more rigorous two-and-a-half-hour entanglement workshop. The workshop claims no prerequisites except basic angles and basic probability. We report a deployment as part of the QCaMP high school training program[14] as well as part of the Boosting Employment Readiness in Quantum (BERQ) undergraduate training program.

Finally, we offer a categorization of quantum questions and a three-level progression of quantum behavioral understanding. Both are tools for deciding what to say and, more importantly, what to leave out.

2. THE MODEL QUBIT

The device, termed a **model qubit**, is a handheld sphere that behaves operationally as a qubit. It hosts a full quantum simulator and therefore maintains a statevector. If multiple qubits are entangled, that statevector is synchronized across the devices over the BLE network. All quantum simulation and rendering are performed on the microcontroller, and the device's behavior follows from the statevector using the same rules that govern a real qubit.[15]

We use the term *model qubit* deliberately, in the sense of a physical model rather than a simulation running on a screen. The devices used in this paper are models of qubits in the same way a globe is a model of the Earth, or a snap-together chemistry kit is a model of a molecule. They get the relationships right and allow for tactile exploration.

(a) Jab

(b) Bump

Figure 2. The two gestures. (a) A jab is a single straight-line motion ending abruptly; the direction of the jab selects the measurement axis. In front of an audience we call this a shake. (b) Bumping the two paired spheres together entangles them into the singlet state; the devices flash yellow to confirm.

2.1 Hardware

A model qubit is a 90 mm rigid sphere, cordless, and used in pairs. The entire outer surface is the display: 583 RGB LEDs in a spherical arrangement sit beneath a translucent shell, so the device renders its state on itself rather than on an external screen (Fig. 1(a)). A six-axis inertial measurement unit interprets gestures and tracks the sphere's orientation. A haptic motor returns a tactile pulse at the moment of measurement. A Bluetooth link between paired spheres keeps them synchronized on one shared statevector, so a measurement on one immediately conditions the other. A 1200 mAh battery supports about four hours of continuous classroom use, and an ESP32 microcontroller drives the renderer and the gesture pipeline.

2.2 The two gestures

Everything in this paper is done with two gestures (Fig. 2).

Jab (measure). A jab is a single straight-line motion that ends abruptly. It performs a projective measurement, the LEDs animate the collapse, and the haptic motor pulses. It is detected when the accelerometer magnitude exceeds 1.3 g over a 50 ms window, with sufficiently low angular motion. The direction of the jab selects the measurement axis. Jabbing upwards is the same as jabbing downwards.

Note on vocabulary: in front of an audience we say *shake* and *jab* interchangeably.

Bump (entangle). Lightly bumping two paired spheres together prepares the singlet state, confirmed by a yellow flash. The gesture is classified on-device by a machine learning model over IMU-derived features, so that incidental knocks do not entangle the pair. Each device reports potential bumps, and when two reports from different devices align and pass a third rejection model, the devices register a collision.

2.3 Display modes

The firmware exposes two display modes, which can be toggled by double-pressing the button.

Reveal mode shows the state continuously: a dot on the surface for a single qubit, and a full-surface hue and brightness field for an entangled pair. For a pair, brightness encodes the probability of each measurement outcome and hue encodes the conditional collapse map, so that a hue on one sphere marks the state its partner would collapse to (Fig. 3). The derivation of the mapping is given in our earlier work.[16]

Realistic mode shows nothing between measurements. The sphere is blank until the user measures it, at which point it displays the outcome for two seconds and then goes blank again. This is how real qubits behave: we only see the state of the qubit when it is measured.

The outreach activity in Section 3 runs in reveal mode. The workshop in Section 4 runs in realistic mode and switches to reveal only after students have drawn their conclusions.

Figure 3. Reveal mode on an entangled pair. If a measurement on the left device collapses its qubit to the point showing a given hue, the partner collapses to the point showing the same hue.

3. OUTREACH ACTIVITY

When doing quantum outreach, we've found that it's not better to start small. Introducing the rules of a single qubit is far too onerous for most casual listeners. Explaining what qubits are, what measurement means, and gates, is a valiant but futile task in the current attention economy.

Therefore, in our journey to create the most engaging quantum demonstrations, we have dropped single qubits altogether to go to entanglement directly. For entanglement, it's possible to create interactive experiments that connect two participants. We began deploying an Ekert '91 style game,[17] where students would share a secret key using entangled qubits. Kids liked it more; but even this was slightly hard to teach because it had no story to go with it.

Unequivocally, the grandest story in quantum physics is the intellectual rivalry between Einstein and Bohr.[18,19] Adding this element completed the demonstration in a way that made it exciting and educational for all age levels.

The full demo is described below.

3.1 The demo

Two volunteers are selected. They stand next to each other.

The facilitator gives the volunteers a challenge:

"You are now arch-enemies! [Volunteer 1] will point in a direction. Wherever they point, [Volunteer 2] must disagree and point in the total opposite direction."

Volunteer 1 then points in a direction, and Volunteer 2 will point in the opposite direction. Allow this to happen three times, with new directions each time.

Then, the facilitator introduces the complication:

"That was too easy. Now, you have to turn your backs and do the same thing... but you can talk to each other."

The volunteers will figure out how to share their directions by talking, and again succeed three times.

Finally, the facilitator makes it nearly impossible:

"Now, you can't speak to each other."

The volunteers will, of course, falter. This is a great moment to introduce the point of the whole exercise.

"If you found that exercise to be impossible, then you're in good company. This is actually a very famous game. It was proposed by Einstein, who thought it was impossible to win. Rather, he believed that if anyone, or anything, was to win this game, they must be communicating somehow, just like you were the first two tries."

"But Einstein had an arch-rival. His name was Niels Bohr. And Bohr famously said that he believes that something can win that game without communicating. He thought electrons win this game."

"Around 1 in 7 electrons in the universe is paired up with one other electron. Physicists call that pair an entangled pair, and you could call them arch-enemies. Whenever you check which way one of them is pointing, the other one is always found pointing the other way."

"And it took us eighty years and a Nobel Prize to finally show that they are actually not communicating. You could put a lead wall between them and separate them by a billion miles, and it would still happen, instantly."

The facilitator gives the qubits to them to allow them to win the game with the entangled qubits.

"These are models of how electrons act."

The volunteers bump them together to entangle, turn their backs, and one of them shakes. Then they both point in the direction the qubits are pointing.

This demo can be followed up by an introduction to Ekert 91 quantum key distribution[17] if there is interest.

The one-in-seven figure comes from helium. Helium accounts for roughly 8% of the atoms in the universe, and each one carries two electrons where hydrogen carries only one, which puts helium electrons at about one in seven of the total. Both electrons in a helium atom share an orbital as a spin singlet, and that is the pairing the script is describing.

3.2 Relation to CHSH

Indeed, this experiment does capture the essence of the Nobel-prize winning CHSH game.[20,21] The one difference is that CHSH assumes that we cannot see the state which the second, unmeasured qubit collapsed to, and therefore we need to construct a measurement scheme that verifies it acts as if it collapsed to the opposite side of the location of the first one.

While this distinction is meaningful, we have not found an engaging way to illustrate this yet. The demo, as it stands, captures the surprise of entanglement, but leaves out the key question: *how would you ever know the second electron flipped, if you can't see it?* That's the question CHSH answers, and it's what the intervening decades were spent on.[22,23] For students looking to build toward CHSH, the long-form education workshop in Section 4 develops the prerequisites.

3.3 Deployment

The activity was run at the KID Museum's 2026 Invent the Future expo in Bethesda, Maryland (Fig. 4). The expo drew roughly four thousand attendees over the day, and we performed the demo for 250 students, most of them elementary and middle schoolers with their parents.

3.4 Observations and learnings

Don't introduce too much. For a short demo, most participants have not heard of a "qubit" before, but they have heard of electrons. Therefore, introducing a new fact about electrons isn't so jarring for them, and will likely not bring up as many questions as the word "qubit".

Demonstrate the shake first. It's definitely important to demonstrate what a shake looks like before this demo starts, so that people don't shake incorrectly.

Figure 4. The pointing game at the expo. Two volunteers stand back to back, each indicating a direction, during the rounds played before the qubits are handed over. The facilitator is at left. This photograph has been AI-modified to render the faces and clothing of all depicted individuals unidentifiable.

4. EDUCATION WORKSHOP

This section introduces a behavior-first workshop for quantum entanglement. The premise is simple: discover the laws of quantum physics yourself by finding patterns in quantum measurements. By definition, the only way in which we extract information from qubits is by measuring them. Therefore, the model qubit has a realistic mode, in which its internal state is not displayed on the surface of the sphere unless a user is actively measuring it. Upon a measurement, the qubit reveals the measurement result, via the Bloch sphere mapping, on its surface. Then, after two seconds, the sphere becomes opaque again.

In this mode, students are expected to act like experimental physicists and perform guided experiments to discover the laws of qubits. They are told that they have been given a strange object and need to come up with a theory of how it behaves. Students begin by performing simple measurements and recording if they get "up" or "down". At the end, they are performing complicated experiments with entanglement.

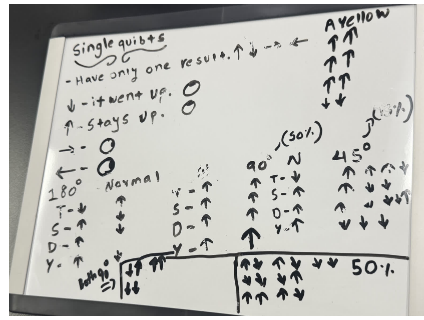
The workshop runs about two and a half hours, including two ten-minute breaks. It assumes no linear algebra, no Dirac notation, and no prior quantum coursework, but it does assume basic angles and basic probability. Materials are one notepad or whiteboard per group and two qubits per group, with the classroom split into groups of size 2 to 4.

The whole workshop is one continuous sequence of twelve exercises, given in Tables 1 and 3. The rest of this section walks the sequence from start to finish and gives the synthesis that goes between the exercises.

4.1 Experiment structure

Each experiment is a procedure involving rotations and bumps. Students are expected to follow the procedure, then measure the qubits up-and-down, and record the result. They are asked to perform each experiment at least five times as a group. Each group is asked to record their results on a whiteboard or notepad by simply drawing an arrow up if the qubit went up, and down if it went down (Fig. 5). Teams usually designate a notetaker.

(a) Measuring



(b) Recording

Figure 5. The experiment loop in progress. (a) A student measuring during Part 1. The model qubits are in realistic mode; the left qubit has just been measured and is showing a result, and the right qubit is un-measured. (b) A group's whiteboard from Part 1.

Once all the groups have recorded their results for the experiment, the facilitator surveys the groups out loud for their results. Finally, the result is revealed, and the implications are stated as the "discovery" for each experiment.

Notably, for ease of notation, we designed the experiments to only end on up-and-down measurements. Instead of measuring at an angle, we first rotate the qubits so that our desired measurement axis is vertical.

4.2 Before the lesson

Three rules are read aloud at the start:

- Ask questions whenever you need, because quantum is not supposed to be clear or easy.
- Don't press the button on the qubit unless instructed.
- For each exercise, finish listening to the instructions before doing the exercise.

4.3 Part 1: single qubits

Students are framed as scientists who have been given a mysterious object. There's only one way to get any information out of it, by measuring it. The job is to find the best way to describe how it behaves. Start with the simplest theory you can, then add complexity as the object demands it.

Table 1. Part 1 exercise sequence. Each row is run by every group, then pooled across the room before the next is posed. The italic row is the synthesis the facilitator leads between exercises.

Ex.	**Procedure**	**Discovery**
1	Orient the qubit randomly by rotating it however you like, then measure it.	It can only have one of two results, up or down.
2	Measure. Without rotating the qubit, keeping it in the same orientation, measure again.	You get the same result. The qubit has some kind of memory, or state, or it couldn't keep track of its previous outcome.
3	Measure. Flip the qubit upside down. Measure again.	100% of the time, you get the opposite result.
4	Measure. Rotate the qubit 90 degrees clockwise. Measure again.	About 50% of the time you get the same result.
A working theory is proposed here: the flat object of Section 4.3.1.		
5	Measure. Rotate the qubit less than 90 degrees. Measure again.	Most of the time you get the same outcome, but it's not guaranteed, and it depends on the angle.

Exercises 1 through 3 establish that the readout is binary, that it repeats when nothing changes, and that flipping the qubit over inverts it. Exercise 4 adds that a 90 degree rotation gives the same result about half the time. At that point the room has enough to propose a theory.

4.3.1 A working theory: the flat object

A qubit behaves like a flat object falling on a table:

- It can either face up or face down when dropped.
- If picked up and dropped again without rotating, it will have the same result.
- If rotated 180 and then dropped, it will have the opposite result.
- If rotated 90 degrees, it will have a 50/50 chance of facing up or down.

A demonstration of a flat object is given by using a cell phone. This is a good theory. It is simple, it accounts for every observation so far, and it is what a thoughtful person actually believes.

However, it differs from real qubits in Exercise 5. If a cell phone is flat on its face, rotating it less than 90 degrees will result in it falling the same direction. A qubit, however, when rotated less than 90 degrees has a chance of flipping direction! The probability of the flip depends on the angle.

Refining the theory: the Born rule. So our theory of a qubit is not like a flat object falling, it's more detailed than that. The chance that you get the same outcome as the previous one depends on the angle you rotate the qubit through. The larger the angle, the more likely you get the opposite outcome. Since we can view the state as either up or down, it's equivalent to saying whichever pole the state is closer to has the higher chance of being the result. Groups fill in the chart in Table 2 from pooled tallies.

Table 2. The Born rule chart, filled in from pooled class tallies.

Angle from previous result	**Percent chance to get the same result**
0	100%
45	85%
90	50%
135	15%
180	0%

As an aside, it is useful to mention that there is a simple equation that encapsulates the whole table, as well as all other angles that aren't listed. That equation is

$$P(\text{same result}) = \frac{1+\cos\theta}{2},$$

where θ is the angle from the previous result. This is called the Born rule.

Tying it together. This has now become the Bloch sphere. The top is the 0 state and the bottom is the 1 state, measurements always result in either 0 or 1, and quantum gates are rotations of the state around the sphere. The qubit is in superposition whenever the state is not on the top or bottom.

Part 1 closes with a set of questions that test what the room has just built.

Questions to check understanding, end of Part 1

1. If a qubit is measured and you don't know the outcome, but you turn it 90 degrees regardless, what's the probability that it measures to 1? *(50%.)*
2. You know the state is somewhere in the bottom hemisphere, but you don't know where. What can you say about the probability that it measures to 0? *(Ranges from 0% to 50%.)*
3. You know a qubit was measured to 0. Where could the state have been before the measurement? *(Anywhere on the sphere except the 1 state, but with higher probability towards the top.)*

A ten-minute break follows.

4.4 Part 2: entanglement

Two paired qubits are distributed to each group. Introduce the standard hold: hold them so the button is on top and the letter on the button is right side up. Without a shared reference the exercises that turn one qubit relative to the other cannot be interpreted.

The entangling operation is introduced without being named. The facilitator says:

"Now someone in the scientific community has discovered a special property with these qubits, which is that when you hit them together, something strange happens. This is our mystery procedure, and it produces a mystery state on our qubits."

"To do the mystery procedure, lightly hit them together. You should see a yellow flash. That means that you've done it successfully."

The word *entangle* is not spoken until after Exercise 5, which is why the procedure is referred to obliquely up to that point in Table 3 and by name afterwards.

Table 3. Part 2 exercise sequence. The italic rows are the synthesis the facilitator leads between exercises.

Ex.	Procedure	Discovery
1	Run the mystery procedure. Measure qubit A.	Up or down around half the time. Totally explainable: a state on the equator does this.
2	Run it again. Measure qubit B.	The same. Nothing yet that our previous theory can't handle.
Prediction: if hitting them together just puts both states on the equator independently, measuring both should give up-up, up-down, down-up, or down-down.		
3	Run it. Measure both qubits and note both outcomes.	Nobody got up-up or down-down. Everyone only got one up and one down.
A working theory: glove theory. Each qubit is like one glove out of a pair given out at random. You have a left or a right, the other person has the other, 50/50 each.		
4	Run it. Rotate one qubit 180 degrees and measure.	Now instead of being opposite they match. Mystery solved!
5	Run it. Rotate both qubits 90 degrees, and measure them.	It's still never up-up or down-down. No locations on two Bloch spheres can explain this.
6	Entangle. Rotate them together the same way. Measure them.	Opposite in every shared orientation.
7	Entangle. Half the group takes one qubit and half takes the other. Try to come up with a protocol where you can communicate a yes or no.	It's impossible.

Exercises 1 and 2 measure each qubit on its own and find up or down around half the time, which is totally explainable: a state on the equator does exactly this. So it seems like hitting the qubits together just does some gate that puts both states on the equator. If that's the case, measuring both should give up-up, up-down, down-up or down-down. Exercise 3 finds that nobody in the room ever gets up-up or down-down. Everyone gets one of each.

That is still explainable with glove theory: each qubit is like one glove out of a pair given out at random. You have a left or a right, the other person has the other, and you both have a 50/50 chance of getting either one. Exercise 4 appears to confirm it. Rotate one qubit 180 degrees and the two results match instead of being opposite, which is exactly what happens if you turn one glove over. Mystery solved.

However, Exercises 5 and 6 refute this understanding by adding rotations. In Exercise 5 both qubits are rotated 90 degrees the same way, and it's still never up-up or down-down. At this point we need to admit there's definitely something strange with these qubits. No locations on two Bloch spheres can explain this behavior.

The reveal: the singlet state. These qubits are entangled together in a combined two-qubit quantum state called the singlet state. Our rules before only applied to single qubits, but entangled qubits' measurement probabilities cannot be represented as two independent qubits. Exercise 6 confirms that the anti-correlation holds for any shared orientation the group tries, not just up-and-down.

Clarification. The singlet state is just one type of entanglement. The behavior we couldn't explain with independent qubits is that if we measure them up and down we get opposite results, but if we rotate them 90 degrees we also get opposite results. Other types of entanglement are different, but all have behaviors that we cannot mimic with independent qubits.

Figure 6. The thumb and middle finger construction. Students put their fingers on the same two colors on each qubit. Measuring the qubits will always result in the states pointing to two thumbs or two middle fingers, never one of each. This is true regardless of the colors chosen. This photograph has been AI-modified to render the faces and clothing of all depicted individuals unidentifiable.

4.4.1 Can we use this to communicate?

So this is pretty cool: measuring one qubit affects the measurement outcome of the other qubit. Does that mean we can communicate with it? Exercise 7 puts it to the room: entangle the qubits, half the group takes one and half takes the other, and try to come up with a protocol where you can communicate a yes or no.

It's impossible.

Part 2 closes with a set of questions that establish why no protocol exists.

Diving deeper, why entanglement cannot signal

1. Given that qubit A and qubit B were entangled, and you know qubit A was measured to 0, which of these could be true of B: not measured or gated, measured, gated, or gated and measured? *(All of them.)*
2. If qubit B was not measured or had any gates done on it, what is the chance qubit A measures to 0? *(50%.)*
3. What if qubit B was measured, but we don't know the outcome? *(50%.)*
4. What if qubit B had a gate done on it, but we don't know what gate? *(50%.)*
5. What if qubit B had a gate done on it, and then was measured, but we don't know the outcome? *(50%.)*
6. Qubit A and B are entangled here on Earth, and Alice takes A to the Moon while Bob takes B to Mars. No matter what Bob does, Alice always has a 50% chance of measuring 0. Is it possible for Bob to transmit any kind of message to Alice? *(No.)*

Question 5 is the hardest of the six, and students reason through it with the qubits in hand (Fig. 6). A second ten-minute break follows.

4.5 If time allows: create your own entanglement

Explain the CX gate, and how if the control is in Z superposition it will create entanglement. Choose a control qubit and a target qubit. If the control is 0 in the Z basis, nothing happens to the target. If the control is 1, the target flips just like an X gate. If the control is in superposition, meaning it's both 0-like and 1-like, the target flips and doesn't flip, and that flipping is dependent on the control. Essentially, superposition spreads through the CX gate and becomes entanglement. Students assemble the circuit in the app (Fig. 7).

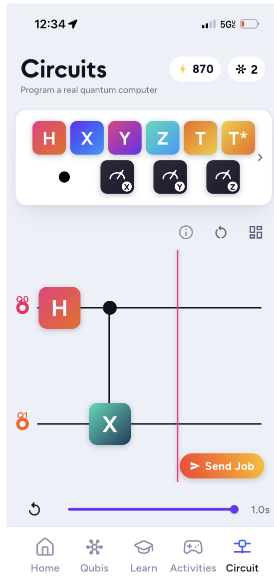


Figure 7. Students can assemble a circuit in the app and arrive at entanglement. Here a Hadamard on the first qubit followed by a CX produces a Bell state.

4.6 Deployments

High school: QCaMP 2026. The workshop was delivered as part of QCaMP, a four-week summer program introducing high school students to quantum information science, run by Sandia National Laboratories with Lawrence Berkeley National Laboratory and the Quantum Systems Accelerator.[14] Students had completed the first week of the QCaMP curriculum, which included basic gates. As delivered, the session ran three hours and reached the CX gate section.

QCaMP's founder and PI, Megan Ivory of Sandia National Laboratories, wrote afterward: *"It was really fun to see the team let students discover superposition, measurement, and entanglement without giving them the answer first."*

Undergraduate: BERQ. The workshop was also delivered as part of Boosting Employment Readiness in Quantum (BERQ), an undergraduate training program. Students had completed the first week of a QCaMP-inspired curriculum, modified for undergraduate students. That session ran two and a half hours.

Umaima Raisa, a participant in the BERQ program, said afterward: *"This was a very engaging workshop, much better than traditional lectures. I never felt like I couldn't understand something."*

4.7 Observations

This is a great exercise to convince students to take many trials. Several times, a group believed they had found the pattern and stopped taking data. When the class results were revealed, they found their pattern was wrong.

Show full-reveal mode at the end of each part. At the end of both the single-qubit section and the two-qubit section, it's useful to show students the full-reveal mode. This cements their knowledge and gives them a proper visual.

Point out what doesn't matter. There were several students who thought they had found different behavior when they jabbed up or down. It is important to note that it does not matter whether the qubit is jabbed up or down; the result is the same. Other clarifications are that the button does not perform any quantum actions; that realistic mode does not mean the state of the qubit is uncertain, only that it is hidden; and that real qubits do not have charger ports and buttons. The last is usually explained jokingly.

4.8 Ethics and consent

The workshop was delivered as educational programming within existing camp and course structures, not as a pre-specified human-subjects research study. It does not constitute human subjects research as defined under 45 CFR 46, since no systematic investigation was designed to develop or contribute to generalizable knowledge through pre-specified data collection. No Institutional Review Board review was sought, no assessment scores were recorded, and no identifiable student data appear here beyond the participant quotation in Section 4.6, which is reproduced with permission. The photographs in Figs. 1, 4 and 6 have been AI-modified to render the faces and clothing of all depicted individuals unidentifiable, so no consent from the individuals shown is required. No individual is identifiable in the remaining photographs.

5. THREE LEVELS OF QUANTUM UNDERSTANDING

In quantum outreach, one needs to be mindful; most adults enter any quantum conversation with a minefield of questions and preconceptions about the field. Some questions truly have no definitive answer yet, such as "why does entanglement happen". Some questions have answers that simply don't live up to the mystique, such as "what does it mean that the cat is both alive and dead?". It's easy for learners to feel like they are lost in how much they don't know.

It's useful to think of these questions as falling into three buckets: behavior, analysis, and interpretation. While the analysis and interpretation are rich with questions and learnings, it's the behavior which will clarify the most. The latter two are in service of the behavior.

Therefore, given the model qubit as a teaching tool, we have found it useful to introduce three levels of understanding quantum behavior. At each level, students unlock new sets of experiments that they can understand. The three levels are described below.

Level 1. If you measure one entangled qubit, the other instantly snaps the opposite way.

We've found that this is such an effective way to give context on quantum's usefulness. From just this one rule, a facilitator can already show why Einstein called quantum "spooky action at a distance" and how it can be used in communication (Ekert 91,[17] a demo we have done in the past).

On the model qubits:

1. Tapping the qubits together entangles them.
2. When you shake one, it will snap to one side or the other in the direction you shook in.
3. The other qubit will snap to the opposite point.

Level 2. If you measure a single qubit up and down, you can either get up or down. You get to choose what up and down is. How often you get each one follows the Born rule.

The reason that this is the second tier is that it involves a little math, and that it adds detail to the previous tier's demonstrations. That math is the Born rule chart in Table 2.

Level 2 is what the entanglement workshop of Section 4 teaches, and it unlocks a great deal. Once a learner can choose a measurement axis and predict how often each outcome comes up, the quantum Zeno effect, BB84 quantum key distribution,[9] and the full protocols for CHSH[21] and Ekert 91[17] all become reachable.

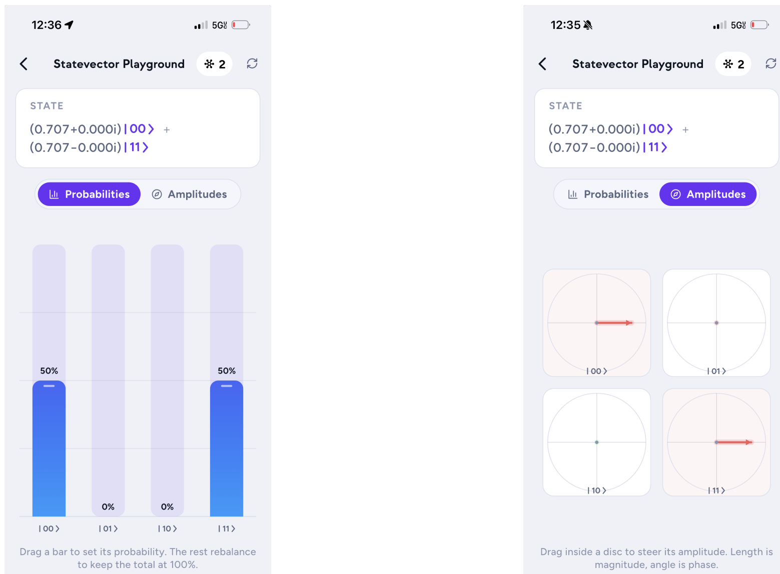
On the model qubits:

1. When you shake, the dot will snap to one side or the other in the direction you shook in.
2. When you shake a qubit that's already pointing in one direction, the probabilities that you'll get each of the two possible results depends on the angle away from the original direction.

Level 3. Qubits can be entangled in many different ways, and with more than two qubits. For any set of qubits, entangled or not, there is a corresponding statevector that tells you what results you could get if you measured the qubits.

On the model qubits:

1. You can set up all sorts of exotic entanglements with the statevector exhibit on the app (Fig. 8). You can set up states where certain outcomes can never be measured.
2. Any operations that you do on the qubits just change the statevector.



(a) Probabilities (b) Amplitudes

Figure 8. The statevector exhibit in the app. (a) Students can see what statevector they created, and modify it by dragging the bars. (b) Finer-grained control comes from viewing and modifying the complex amplitudes directly, where length is magnitude and angle is phase.

This opens up the entire field of quantum computing.

6. CONCLUSION

We have presented two hands-on activities for teaching quantum entanglement with model qubits, together with a categorization of quantum questions and a three-level progression of behavioral understanding. The outreach activity is a five-minute demonstration built around the rivalry between Einstein and Bohr, in which two volunteers first fail at a pointing game and then win it with an entangled pair; we ran it for 250 students at the KID Museum's 2026 Invent the Future expo. The workshop is a two-and-a-half-hour sequence of twelve exercises in which students act as experimentalists and build a theory of the qubit from their own measurements; we delivered it in the QCaMP high school program and the BERQ undergraduate program.

Two future directions are clear. Level 3 of the progression opens onto multi-qubit states and the statevector, but we have not yet built activities at that level; the statevector exhibit in the app is the natural place to start. Second, nothing reported here is assessment data. Both activities were delivered as outreach and instruction rather than as studies, and an IRB-supported study with pre- and post-instruction measurement is the most informative next step.

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REFERENCES

1. H. K. E. Stadermann, E. van den Berg, and M. J. Goedhart, "Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic," *Physical Review Physics Education Research* **15**(1), p. 010130, 2019.
2. K. Krijtenburg-Lewerissa, H. J. Pol, A. Brinkman, and W. R. van Joolingen, "Insights into teaching quantum mechanics in secondary and lower undergraduate education," *Physical Review Physics Education Research* **13**(1), p. 010109, 2017.
3. A. Merzel, P. Bitzenbauer, K. Krijtenburg-Lewerissa, K. Stadermann, E. Andreotti, D. Anttila, M. Bondani, M. L. Chiofalo, S. Faletič, R. Frans, S. Goorney, F. Greinert, L. Jurčić, Z. Koupilová, M. Malgieri, R. Müller, P. Onorato, G. Pospiech, M. Ubben, A. Woitzik, and H. Pol, "The core of secondary level quantum education: a multi-stakeholder perspective," *EPJ Quantum Technology* **11**, p. 27, 2024.
4. A. Kohnle, I. Bozhinova, D. Browne, M. Everitt, A. Fomins, P. Kok, G. Kulaitis, M. Prokopas, D. Raine, and E. Swinbank, "A new introductory quantum mechanics curriculum," *European Journal of Physics* **35**(1), p. 015001, 2014.
5. P. Migdał, K. Jankiewicz, P. Grabarz, C. Decaroli, and P. Cochin, "Visualizing quantum mechanics in an interactive simulation – Virtual Lab by Quantum Flytrap," *Optical Engineering* **61**(8), p. 081808, 2022.
6. Z. C. Seskir, P. Migdał, C. Weidner, A. Anupam, N. Case, N. Davis, C. Decaroli, İ. Ercan, C. Foti, P. Gora, K. Jankiewicz, B. R. La Cour, J. Yago Malo, S. Maniscalco, A. Naeemi, L. Nita, N. Parvin, F. Scafirimuto, J. F. Sherson, E. Surer, J. Wootton, L. Yeh, O. Zabello, and M. Chiofalo, "Quantum games and interactive tools for quantum technologies outreach and education," *Optical Engineering* **61**(8), p. 081809, 2022.
7. J. Levy and C. Singh, "Hands-on quantum: Teaching core quantum concepts with Bloch cubes," *The Physics Teacher* **63**(2), pp. 85–89, 2025. arXiv:2412.03003.
8. B. Folkers, A. van Rossum, A. Brinkman, and H. K. E. Stadermann, "Visualising quantum entanglement using interactive electronic quantum dice," 2025. arXiv:2510.04931.
9. C. H. Bennett and G. Brassard, "Quantum cryptography: Public key distribution and coin tossing," *Theoretical Computer Science* **560**, pp. 7–11, 2014. Originally published in Proc. IEEE Int. Conf. on Computers, Systems and Signal Processing, Bangalore, 175–179 (1984).
10. Thorlabs, Inc., "EDU-QCRY1 quantum cryptography analogy demonstration kit." https://www.thorlabs.com/quantum-cryptography-analogy-demonstration-kit. Accessed: 2026-08-04.
11. J. M. Donohue, S. Ifeanyi, A. Chisholm, J. Côté, Q. Cunningham, J. Nasser, A. Xayvongsa, E. Dryburgh, F. Dang, G. Ghrayeb, I. J. Macpherson, F. Rasheed, A. Zhao, and S. S. Saini, "Interactive and accessible quantum key distribution modules for introducing students to quantum science and engineering," 2026. arXiv:2607.20738. To appear in the IEEE Quantum Science and Engineering Education Conference (QSEEC) 2026 proceedings.
12. D. M. Silberman, "Quantum education and pathways: an open-source modifiable presentation to high school and college students," in *Optics Education and Outreach VII*, *Proc. SPIE* **12213**, p. 1221338, 2022.
13. J. Douglass, D. M. Silberman, M. K. Ivory, and T. Knight, "Building new pathways for quantum technicians," in *Optics Education and Outreach VIII*, *Proc. SPIE* **13128**, p. 1312806, 2024.
14. M. Ivory, J. Balewski, A. Bettale, J. Brewer, R. Boren, D. Camps, L. Hackett, M. Juarez, A. Kononov, K.-H. Lee, M. Long, A. Mounce, S. Mniszewski, R. K. Naik, S. Pakin, and E. Sanchez, "QCaMP: A 4-week summer camp introducing high school students to quantum information science and technology," 2025. arXiv:2504.15977.
15. M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information: 10th Anniversary Edition*, Cambridge University Press, Cambridge, UK, 2010.
16. S. Thakkar, A. Chen, O. Ozdemir, A. Katuri, R. Mao, and T. Abeje, "Teaching QKD in 5 minutes: An experience report on two events with physical model qubits." Manuscript pending, 2026.

17. A. K. Ekert, "Quantum cryptography based on Bell's theorem," *Physical Review Letters* **67**(6), pp. 661–663, 1991.
18. A. Einstein, B. Podolsky, and N. Rosen, "Can quantum-mechanical description of physical reality be considered complete?," *Physical Review* **47**(10), pp. 777–780, 1935.
19. N. Bohr, "Can quantum-mechanical description of physical reality be considered complete?," *Physical Review* **48**(8), pp. 696–702, 1935.
20. J. S. Bell, "On the Einstein Podolsky Rosen paradox," *Physics Physique Fizika* **1**(3), pp. 195–200, 1964.
21. J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, "Proposed experiment to test local hidden-variable theories," *Physical Review Letters* **23**(15), pp. 880–884, 1969.
22. A. Aspect, J. Dalibard, and G. Roger, "Experimental test of Bell's inequalities using time-varying analyzers," *Physical Review Letters* **49**(25), pp. 1804–1807, 1982.
23. B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau, and R. Hanson, "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres," *Nature* **526**, pp. 682–686, 2015.