Teaching QKD in 5 Minutes: An Experience Report on Two Events with Physical Model Qubits

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***Abstract*—Quantum mechanics is notoriously abstract because there are no human-scale objects that obey its rules. Qubi is a hand-held device that mimics a qubit's dynamics for learning and communication. Users can bump two Qubis together to entangle them, and jab either one along a chosen axis to perform a measurement in that basis. A novel spherical LED display renders intuitive visualizations of the underlying quantum state. Our aim is to let learners acquire quantum intuition by direct interaction; the mathematics then quantifies the behaviors they have already internalized. Two deployments are reported. *KID Museum 2025 Invent the Future Expo:* an open-format booth ran a simplified five-minute version of the Ekert 91 quantum-key-distribution protocol [1] for roughly two hundred elementary- and middle-school visitors. Participants walked away with two intuitions: how a qubit measurement produces a 0 or a 1, and how two entangled qubits can be used to generate a shared secret key. *Eleanor Roosevelt High School:* a 90-minute classroom pilot used the same hardware to explore measurement, basis choice, and singlet-state entanglement in more depth. Seven student pairs, grades 9–12, went from no prior familiarity to answering complex conceptual questions about the singlet state by the end. Some students arrived at the Born rule and the no-signaling theorem through reasoning and experimentation alone. We frame the paper as an experience report rather than a controlled study and discuss the limitations.**

***Index Terms*—quantum education, quantum key distribution, hands-on learning, classroom deployment, qubits, K–12 STEM, experience report**

(a) Entangled pair, $|\psi\rangle = \frac{1}{\sqrt{2}}\big(\,|01\rangle - |10\rangle\,\big)$

(b) After Z-basis measurement: $|1\rangle$

Fig. 1. The Qubi tangible qubit instrument. (a) A bumped pair displaying the singlet state; brightness encodes marginal measurement probabilities, and hue encodes the conditional collapse map between the paired qubits (see Fig. 5). (b) After an up-and-down jab on one device (a measurement in the Z basis), the qubit has collapsed to $|1\rangle$, shown by the dot near the bottom of the sphere.

I. Introduction

Most students' introduction to physics doesn't happen in a classroom. It happens in play. Every time they throw a ball, they build deep intuition about gravity and kinematics. When they later learn Newtonian mechanics in a classroom, they are simply formalizing what they already know.

Quantum mechanics lacks an everyday analog. As a result, intuition typically arrives, if at all, only after prolonged work with the mathematics. Most students encounter quantum mechanics through one of two channels. The first is a symbolic introduction in the language of complex amplitudes and Dirac notation, which presupposes a linear-algebra background few pre-calculus students have. The second is a screen-based simulator. Drag-and-drop tools like IBM Quantum Composer [2] and Quirk [3] include a graphical component but the qubit remains an abstract object on a screen; programmatic tools like Qiskit [4] trade the math prerequisite for a Python one. Stadermann et al. [5] survey secondary quantum-physics curricula across fifteen countries and document considerable variation in how (and whether) the topic is approached; the gap is not specific to any one country. The U.S. quantum workforce gap is a stated national priority [6]–[8], and broadening the pool entering quantum-adjacent fields requires getting more students past this intuition barrier.

This paper presents an alternative. Qubi is a pair of model qubits that students hold in their hands, described in Section III. Two early deployments follow. Section IV reports an outreach booth at a children's museum, run as an open-format station for an elementary- and middle-school audience. Section VI reports a 90-minute classroom pilot at a U.S. public high school. Both were run as outreach events rather than research studies. We did not seek IRB approval, collect demographic data, or run a controlled comparison. We report what we observed because there are still few reports on a tangible qubit instrument used in K–12 instruction, and we expect the observations to be useful to other practitioners designing similar activities.

This paper makes three contributions. (1) A tangible qubit instrument that holds a live quantum state across activities and renders single- and two-qubit states on its own surface. (2) A five-minute outreach activity that conveys the core idea of the Ekert-91 quantum key distribution protocol to elementary- and middle-school audiences. (3) A 90-minute introductory lesson plan that takes pre-calculus students from no prior familiarity to explaining the singlet-state correlation rule, without linear algebra, probability theory, or Dirac notation.

Section VII reports our observations and lessons learned from the classroom pilot. Section VIII discusses what to do next; Section IX concludes.

II. Background and Related Work

A. Cloud Simulators and Symbolic Tools

Introductory quantum computing instruction relies heavily on cloud-based circuit composers and simulator libraries. IBM Quantum Composer [2], Qiskit [4], and the open-source visualizer Quirk [3] all let learners build circuits gate-by-gate and inspect the resulting amplitudes. The pedagogical pattern across the three is similar. The learner reads about a gate, places it on a circuit, runs the simulation, and inspects a numerical or graphical state vector. Geometric structure tends to get hidden along the way. It is not visually obvious, for instance, what applying a rotation to one qubit of an entangled pair does to the joint state. These confusions are common in first-time learners and often persist long after the symbolic mechanics are mastered.

B. Visualization and Lab Modality

A parallel line of work focuses on building intuition through visualization rather than symbol manipulation. The QuVis project at St Andrews [9] produced a curriculum and a set of interactive simulations targeted at conceptual difficulties documented in the physics-education-research literature [10], [11]; the Quantum Flytrap virtual lab [12] takes a similar approach for optics-based quantum mechanics; and a recent review by Seskir et al. [13] finds the broader inventory of quantum games and interactive tools growing but overwhelmingly screen-based. The broader question of whether physical or virtual lab experiences are better for concept acquisition has been studied in physics and chemistry education for decades [14]–[17], and the answer depends on the specific learning goal.

C. Teaching with Two-State Systems

A growing line of physics-education research argues that two-state quantum systems (spin, photon polarization, the qubit) are the right place to start when introducing quantum mechanics, especially at the secondary level, because they expose measurement, basis choice, and entanglement without needing to introduce continuous variables. Krijtenburg-Lewerissa et al. [18] survey teaching strategies for quantum mechanics at the secondary and lower-undergraduate level and document the variety of two-state framings in use. Bitzenbauer et al. [19] develop and validate a questionnaire to assess understanding of quantum measurement across different two-state contexts, and find that the choice of context (photon polarization, double-well potential, or which-path single photon) matters for what students learn. A follow-up field study [20] reports that two-state approaches outperform traditional historical-development presentations at the secondary level. The instrument reported in this paper sits in this two-state-systems tradition: a Qubi is a single-qubit two-state system rendered as a tangible object.

D. Embodied and Tangible Approaches

Embodied learning approaches to quantum mechanics are rarer. Quantum-themed games such as Quantum Chess [21] introduce conceptual vocabulary through play, but they remain software. Some tangible alternatives exist, but they are uncommon. TeachSpin's commercial single-spin teaching instruments [22] bring real spin-precession and Stern–Gerlach demonstrations into undergraduate labs, and the interactive electronic quantum dice of Folkers et al. [23] let learners explore entanglement correlations through a pair of haptic dice. Classroom analogies using polarizers or paper-based gate cards also appear in practitioner accounts but have not been broadly characterized. Merzel et al. [24] survey the current state of secondary-level quantum education and find tangible hardware is rare. The instrument reported here sits in that small region; Section III describes it in detail.

III. The Qubi Platform

The instrument is designed to behave operationally as a qubit, with human-friendly interactions:

1) *Shared global state.* When two or more devices are within Bluetooth range, they share a single quantum state.
2) *Bloch-sphere visualization.* When a qubit is not entangled, its state appears on the sphere's surface as a single dot, at the position the Bloch vector points to.
3) *Entanglement via bumping.* Bumping two devices applies a fixed entangling operation, such as a CNOT. In the demonstrations in this paper, bumping simply

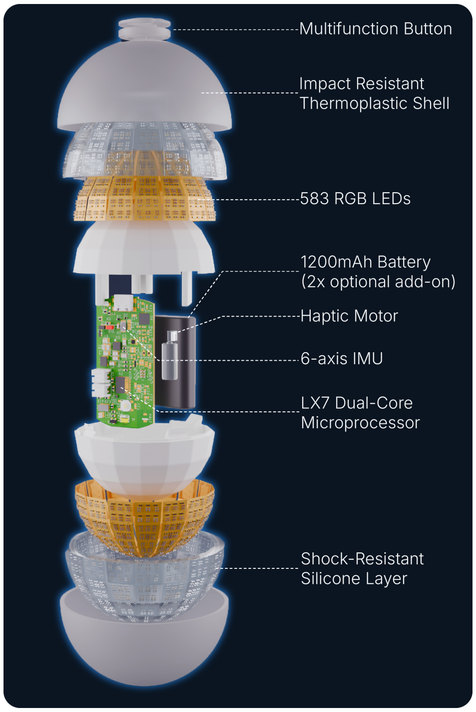


Fig. 2. Exploded view of a single Qubi, showing its main components.

evolves the qubits' state directly to the singlet (a state preparation). This lets us set up common experiments quickly.

4) *Unitary evolution via rotation.* Rotating a device rotates its Bloch vector on the display. (Not exercised in this paper.)
5) *Projective measurement via jab.* Jabbing the device along an axis performs a projective measurement in the corresponding Pauli basis.

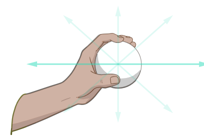
The rest of this section describes the hardware, the visualization, and the interaction model in more detail.

A. The Device

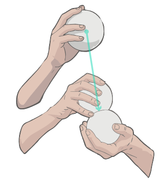
A Qubi (Fig. 2) is a 90 mm rigid sphere designed to sit on a classroom desk and survive being picked up by a teenager. It is cordless, rugged, and designed to be used in pairs. The entire surface is the display: 583 RGB LEDs in a spherical arrangement sit just beneath a translucent outer shell. A six-axis inertial measurement unit lets the device interpret jab and bump gestures as quantum operations. A haptic motor returns a tactile pulse at the moment of measurement, so the student feels collapse as well as sees it. A Bluetooth connection between the spheres keeps them in sync, sharing the same statevector. A 1200 mAh battery powers about four hours of continuous classroom use. An ESP32 microcontroller drives the renderer and the gesture pipeline. The pilot reported in this paper used five paired sets.

B. Visual State and Display Modes

A single qubit's state is shown as a small dot on the sphere's surface, at the position the corresponding Bloch vector would



(a) Jab



(b) Bump

Fig. 3. The two gestures used in the pilot. (a) A jab is a single straight-line motion ending abruptly; the direction of the jab selects the measurement basis. (b) Bumping the two paired spheres together creates an entangled pair (the singlet state); the devices flash yellow to confirm.

point to (Fig. 1(b)). The firmware exposes two display modes that the facilitator switches between for pedagogical effect:

- *Realistic mode* shows only the outcome of an explicit measurement. The dot is hidden between measurements and reappears at the projected outcome when the user performs a jab. We call it realistic because this is how real qubits behave: we only ever see measurement outcomes. Visually it is fairly boring: the sphere is white between jabs.
- *Omniscient mode* shows the qubit's state continuously: the dot for single-qubit states (Fig. 1(b)), and the rainbow surface visualization (Fig. 5) for entangled pairs (Fig. 1(a)).

A typical classroom lesson begins in realistic mode, where students have to perform measurements to see anything. Once they have worked out the basic pattern from their own data, the facilitator switches to omniscient mode so they can verify their hypotheses against the full state.

C. Interaction Model

Two gestures drove the activities reported in this paper (Fig. 3):

- *Jab.* A jab is a single motion, along a straight line, ending abruptly. Its direction selects the measurement basis (up/down, left/right, or front/back), and the resulting state is one of the two endpoints of the chosen axis. Each jab is therefore a projective measurement in the basis the student picked. A haptic pulse on the device signals the collapse, and the same pulse fires on the partner device when its entangled qubit collapses in response to a measurement on this one.
- *Bump.* Lightly bumping the two paired spheres together creates an entangled pair, specifically the singlet state. The devices flash yellow to confirm.

The pilot did not use the additional gestures (such as twist-based rotations) that the platform supports.

From a jab to a measurement basis: A jab (Fig. 3(a)) is detected when an exponential moving average of accelerometer magnitude over a 50 ms window exceeds 1.3 g. To avoid ambiguous directions, we additionally require gyroscope magnitude to stay below 2.0 rad/s; this is what distinguishes a fast straight-line motion from a rotation.

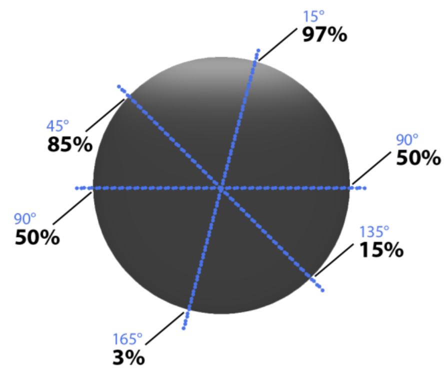


Fig. 4. Born-rule probabilities of measurement outcomes after a previous measurement collapsed the qubit to the top of the sphere, as a function of the angle between the jab and the original axis. The probability of collapsing to a given spot drops smoothly as the angle from the original axis grows.

Once a jab has been detected, we convert the direction of the acceleration peak into a measurement basis as follows. A unit vector $\mathbf{n} = (n_x, n_y, n_z)$ on the Bloch sphere corresponds to the single-qubit observable

$$\hat{O}_{\mathbf{n}} = n_x\sigma_x + n_y\sigma_y + n_z\sigma_z = \begin{pmatrix} n_z & n_x - in_y \\ n_x + in_y & -n_z \end{pmatrix},$$

whose eigenstates are the antipodal points $\pm\mathbf{n}$ on the sphere. Measuring with $\hat{O}_{\mathbf{n}}$ collapses the qubit onto one of these two eigenstates, with probabilities given by the Born rule. We take $\mathbf{n}$ as the unit-normalized direction of the acceleration peak. A jab along Z then yields the Z observable, and similarly for X and Y.

To avoid user error, we optionally snap the detected direction to the nearest entry in a configurable set of measurement bases. Three candidate sets are available in firmware: the Z-axis only, the six major axes ($\pm X$, $\pm Y$, $\pm Z$), and a 26-direction set that adds the face- and body-diagonals. We switch between these modes as the lesson requires.

Once a measurement basis has been determined, it is fed to the projection logic, the LEDs animate the collapse, and the haptic motor returns a tactile pulse.

The discretization is a pedagogical choice. In continuous mode, a jab in any direction performs a measurement along exactly that axis: in X, Y, Z, or anywhere in between. Continuous mode is required for advanced demonstrations like eavesdropper detection in Ekert-style QKD and the CHSH game, both of which need measurements at intermediate angles.

Bump-to-entangle classification: The bump gesture (Fig. 3(b)) is detected by a small machine-learning classifier rather than by a fixed force threshold. We use a decision tree, chosen for fast on-device inference on the sphere's microcontroller. The classifier takes the feature vector described in Appendix A as input and reports an intentional bump when its predicted probability exceeds 0.5; the firmware then entangles the paired devices into the singlet state.

We trained the classifier on roughly 1000 collisions covering a variety of hand positions and bump patterns. The data was collected and manually labeled using an internal tool that time-aligns IMU readings with synchronized video so that a human can mark each collision as intentional or incidental.

D. Visual Model for Two-Qubit States

The goal of the visualization is to map a two-qubit statevector $|\psi\rangle$ to an RGB color for each of the 583 LEDs on each sphere, in a way that lets students read the quantum state directly off the surface. We work in HSV space, computing the three channels independently and converting to RGB at the end. Saturation and value share a common formula across both spheres; the hue channel is computed differently.

The visualization is built around a simple observation. A two-qubit pure state is fully determined by two pieces of information:

- *Single-qubit marginals:* the probability of every measurement outcome on qubit A alone (and similarly for qubit B). This is captured by the qubit's reduced density matrix.
- *Conditional collapse maps:* given that qubit A is measured and produces some outcome $|a\rangle$, to which single-qubit state does B collapse? Symmetrically, if B is measured first, where does A collapse?

Since measurements can be taken sequentially without loss of generality, and the single-qubit case is already understood, these two pieces fully specify the joint behavior. Our goal is a visualization that shows both pieces in tandem.

This section, and the pilot reported here, focuses on maximally entangled states, specifically the singlet state, where a measurement on one qubit reciprocally collapses the other. Partially entangled states are also supported, and we cover them in detail in an interactive whitepaper.[1]

For an entangled pair (Fig. 5), brightness encodes the *single-qubit marginals*: at any point on the sphere, the brightness is proportional to the probability that a measurement would collapse the qubit to this state. Hue encodes the *conditional collapse map*: a hue on sphere A corresponds to the same hue on sphere B if and only if measuring A to that point would collapse B to the corresponding direction.

A detailed description of how the visualization is computed is given in Appendix B.

IV. Outreach Deployment: KID Museum Quantum Booth

The first demonstration was at a children's museum, where we wanted to teach kids about quantum in a short, outreach-style session.

[1] https://qolour.io/whitepaper

Fig. 5. Hue-matched conditional collapse for a maximally entangled two-qubit state. If a measurement on the left device collapses the qubit to the location showing yellow on its surface, the partner device on the right will collapse to the location showing the same yellow. The hue-matching rule holds across the full surface: every direction on one device pairs with the corresponding direction on the other.

A. Setting and Format

The booth was at the KID Museum's 2025 Invent the Future Expo in Bethesda, Maryland. The expo drew roughly four thousand attendees over the day. About two hundred passed through our booth, most in elementary and middle school grades. The centerpiece was a simplified Ekert 91 quantum-key-distribution demo, alongside two supplementary stations running short circuit puzzles and a guided walkthrough of basic quantum operations. Each station was self-contained on the 5–10 minute time scale typical of museum visits.

B. The QKD Demo

The demo is a simplified version of the Ekert 91 quantum-key-distribution protocol [1] (Fig. 6). It is framed as a spy game: two participants are told they need a shared secret codeword, and the only thing they have is a pair of entangled qubits. The flow:

1) **The premise.** "You two are spy teammates — *spymates* — and all good spymates need a secret codeword that nobody else knows!"
2) **Demonstrate a jab.** The facilitator jabs a single Qubi up-and-down; the dot collapses to one of two outcomes.
3) **Bump and split.** The devices are handed to the participants. The two participants bump their Qubis together to entangle them, then take one each and stand back-to-back.
4) **Measure together.** Both jab up-and-down at the same time, and both qubits collapse.
5) **Reveal and label.** The facilitator asks one participant what they got. "Up." — "We call that a 0." The other reports "down," which is labeled 1.
6) **Repeat.** The bump-jab-record sequence runs three times. Each participant ends up with a three-bit string.
7) **Codebook lookup.** Each participant looks up their bit string in a small printed animal codebook (Fig. 6(b)). The two codebooks are bit-flipped versions of each other, so the anti-correlated outcomes from singlet measurements still map to the same animal on both sides.
8) **Reveal.** On the count of three, both shout out the animal. They reliably name the same animal.

"TIGER!!!"

— Both participants, in unison

The activity gave participants a hands-on demonstration that entanglement produces correlated outcomes a pair of users can treat as a shared secret.

C. Other Stations

Two supplementary stations ran alongside the QKD demo. One presented short quantum circuits as physical puzzles, where participants performed gate sequences on their device through hand motions and then ran a rhythm-game variant ("Qubi Hero") in which the sequence had to be performed in time. The other was a guided walkthrough of the core operations of a quantum computer (gate, measurement, entanglement) with the device in hand.

V. Observations from the Outreach Booth

A. Keep it simple

We were able to simplify the QKD demo into something short and punchy. The activity is a stripped-down Ekert 91; it omits eavesdropper detection for brevity. Occasionally a participant asked why QKD is better than classical alternatives, and we would explain how QKD enables eavesdropper detection. For the vast majority, though, the simplified version was the right level of depth.

B. The jab gesture needs explicit modeling

Off-axis jabs can produce strange-looking outcomes. We found it helpful to have one participant jab at a time, and to demonstrate the jab one time before handing the device over.

C. Jab threshold tuned for older users

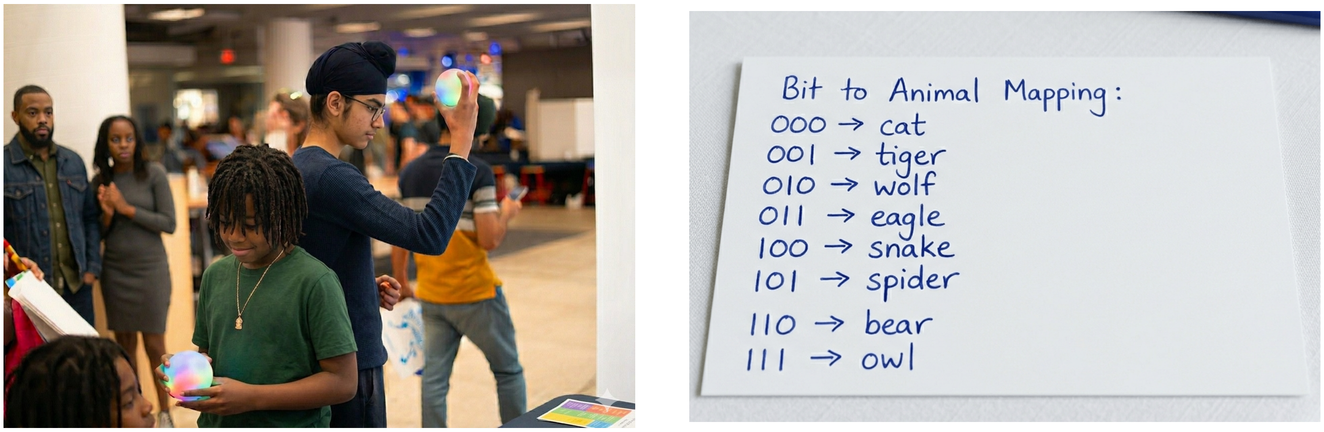
The acceleration threshold that registers a jab is currently tuned for older students and adults. Younger visitors often had difficulty getting it to fire, and we plan to expose a per-device sensitivity setting.

D. Qubit-to-bit framing landed quickly

Framing the result as "you'll get a 1 or a 0" turned out to be a remarkably quick way to teach the qubit-to-bit mapping. We had no trouble getting kids to absorb this.

E. The reveal

The final moment, when the two participants shout out their animal, is the cathartic payoff — and also the point of greatest anxiety, since kids worry about getting it wrong. We scaffolded by privately asking each child what they got just before the public shout, so we could nudge if anything looked off.



(a) QKD activity

(b) Animal codebook

Fig. 6. Quantum key distribution activity at the museum booth. (a) Two participants, each holding one device of an entangled pair, stand back-to-back and jab to measure. (b) The shared three-bit string is looked up in an animal codebook; both participants find the same animal, demonstrating that entangled measurements produce a shared secret. The photograph in (a) has been AI-modified to render the faces and clothing of all depicted individuals unidentifiable.

Fig. 7. Auditorium delivery. Students were seated in the front rows; facilitators worked from the base of the stage and circulated during the experimentation phases.

F. Engagement and durability

The devices withstood the day, and kids stayed at the booth longer than we expected; several of the youngest visitors asked unprompted questions about entanglement. The KID Museum's Chief Experience Officer wrote afterward: *"Qolour was a standout at KID Museum's 2025 Invent the Future Expo. Qubi sparked a passion for problem-solving in everyone from children to adults."*

VI. Classroom Deployment

The natural follow-up to the museum demo was to see what the same instrument could do with more time and a structured lesson. The classroom pilot was a 90-minute deep-dive into quantum entanglement. We covered measurement, the singlet state, and all the nuances related to measuring in different bases.

A. Setting

The classroom pilot was hosted by Eleanor Roosevelt High School, a public high school in Prince George's County, Maryland, in October 2025. Eight student pairs in grades 9–12 took part across two deliveries on the same day. The first delivery was in the school auditorium (Fig. 7) and drew students from the general student body; facilitators worked from the base of the stage and circulated during the experimentation phases. The second delivery was an after-school session later the same afternoon, in a smaller room, and used the same lesson plan with the on-the-fly adjustments described in Section VII-H.

B. Pedagogical principles

Three design principles shaped the lesson plan.

1) *Testable hypotheses.* Students develop their own hypotheses about the laws of quantum mechanics and have the tools to verify them without asking a facilitator.
2) *Group work is the default.* Two-qubit phenomena require two devices, so the activity is collaborative by construction. Typical group size is two or three students.
3) *No formal prerequisites.* The lesson assumes no linear algebra, no probability theory, and no Dirac notation. Students work in the language of dot directions, colors, and gestures.

C. Lesson Structure

The lesson plan, designed for a 90-minute slot, follows seven phases:

1) **Warm-up concept check** (7 min). Students answer a brief set of conceptual warm-up questions.
2) **Motivation and qubit intro** (˜10 min). A slide-guided framing of quantum vs. classical computers, qubits as abstract objects, and measurement as the only way to extract information from a qubit.
3) **Single-qubit measurement experiment** (10 min). Each group of 2–3 students receives one Qubi in realistic

mode and is asked to discover the rule that determines where the dot appears after a jab. Suggested probes: jab in the same direction, in a slightly different direction, in a perpendicular direction.

4) **Born rule synthesis** (~5 min). A facilitator-led recap converts the empirical pattern into the Born rule. Devices are switched to omniscient mode at this point so that students can verify their hypotheses with the state visible.
5) **Bases as procedural choices** (~5 min). The direction of the jab is named as the measurement basis.
6) **Entanglement experiment** (10 min). A second Qubi is distributed to each group. Students are told that bumping the two devices together entangles them, and are asked to discover the rule that governs paired measurement outcomes. The state used is the singlet.
7) **Wrap-up reflection** (10–15 min). Students discuss the same conceptual targets, in writing in some sessions and as a guided whole-group discussion in others.

D. Ethics and Consent

The activities described in this paper were conducted as educational outreach and classroom instruction, not as a pre-specified human-subjects research study. They do 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. Permission for descriptive reporting was obtained from the host institutions. No identifiable student data, formal assessment scores, or photographs of identifiable minors are included. The museum-booth photograph has been AI-modified to render the faces and clothing of all depicted individuals unidentifiable, and the classroom photograph shows a co-author.

VII. Observations from the Classroom Pilot

The two deliveries took different shapes. The first ran a wrap-up exercise in pairs; the second ran a guided whole-group discussion.

A. Initial concept check

Seven of the eight pairs took part in both the warm-up and the wrap-up. At the warm-up, none of these pairs had prior familiarity with qubits, measurement, or entanglement.

B. What students could do by the end

By the wrap-up, all seven pairs identified the singlet-state anti-correlation: when one qubit of an entangled pair is measured along a chosen axis, the partner, measured along the same axis, gives the opposite outcome.

C. Reasoning to no-signaling

In the discussion-format wrap-up, the after-school group worked through the advanced questions and arrived, with facilitator scaffolding, at the conclusion that entanglement does not permit faster-than-light signaling. The facilitator's notes record the moment. Students realized that, with no information about the other qubit, every basis they chose still produced a 50/50 outcome distribution. They could imagine no protocol that would let one party signal the other through measurement choice alone. This is the no-signaling theorem. Reaching it through guided reasoning rather than direct presentation was the most striking single qualitative outcome we observed across the two sessions. We do not claim the same outcome would arise without facilitator scaffolding. We report it as one example of what was possible in 90 minutes with this material.

D. Understanding was age-dependent

12th graders reasoned about the geometry of the sphere comfortably, and one 12th-grade pair drew the Born-rule probability table on paper from their own observed frequencies. 9th graders worked through the same material more slowly, particularly when the argument required relating two directions on the sphere or comparing outcomes across different bases. Trigonometry and geometric intuition seemed to be the prerequisites that mattered most.

E. Framing as "what is a computer" is necessary

We noticed that starting from the basic question of what a computer *is* was helpful: it pulled students away from thinking of a computer as a laptop or a gaming device, and toward thinking of it as a problem-solving machine. We illustrated this with two ways of computing the volume of an irregular object: one a manual procedure that inspects the object and applies complicated geometry, the other submerging it in a vat of water and reading how far the water rises. Both arrive at the same answer, but one is much faster. While we found this introduction useful for most students, we believe we can compress it for future deliveries.

F. Haptic feedback communicated collapse effectively

Students seemed to understand that a haptic vibration communicates an instantaneous collapse-type event.

G. Team-based activities framed around how quantum connects us were very effective

Giving one qubit to each student worked better than handing a paired set to a group: each student had something to do at every moment, and the entanglement between the two devices became the natural reason to talk to a partner.

H. Omniscient mode accelerates understanding

In the first delivery we forgot to switch to omniscient mode during the single-qubit phase, and the cost was visible: pairs that would otherwise have moved on stayed stuck on whether their measurement outcomes were really consistent with what they expected. In the second delivery the switch happened on cue and helped struggling groups reach the Born rule.

I. An on-the-board logic table for entanglement

This was the single largest pedagogical improvement of the day. Added between the two deliveries, the table walks through a sequence of measurement outcomes and asks, for each row, whether that row is consistent with prior entanglement. The chart clarified that entanglement is "used up" after one qubit is measured. It is reusable and is now part of the lesson plan.

J. Asynchronous experimentation produced wide variance

Ten free-form minutes per group meant that some pairs reached a clean Born-rule pattern within the block while others took more guidance to arrive at the same conclusions. We plan to replace the long blocks with shorter, whole-room synchronous experiments and class-aggregated data.

K. Entanglement was hard to verify experimentally

Correlated outcomes look the same as classical correlation until the bases are mismatched. Switching to omniscient mode clarified this for the room.

L. Entanglement is more than the singlet state

By using only the singlet, the lesson presented entanglement as if it were always anti-correlated, when anti-correlation is a property of the singlet specifically. Students who internalized that as a general rule walked away with a partial picture that will need correction later. The fix is to introduce at least one other Bell state in the entanglement phase, but we have not yet revised the lesson plan.

VIII. Limitations and Future Work

This paper is an instructor-perspective experience report, not a controlled study. The classroom pilot was a single 90-minute session at one school; audiences were small. The warm-up and wrap-up exercises were instructional check-ins rather than a formal pre/post test, and the after-school portion drew students who self-selected into the activity. We did not run a comparison condition or collect demographic data. Claims throughout the paper are limited to what we observed in the room. The directions below are what we plan to pursue.

Replication in regular classes. The most informative next data points are sessions run in regularly scheduled physics or computer-science classes, with IRB oversight and a peer-reviewed pre/post test.

Facilitator guide. The biggest single planned change is to replace the long asynchronous experimentation blocks with shorter, whole-room synchronous experiments and class-aggregated data. A more developed facilitator guide is in development. We expect it to reduce facilitator load.

Curricular extension beyond fundamentals. The lesson reported here covered measurement, basis choice, and singlet-state entanglement. Modules in development cover quantum communications (BB84), algorithms (Grover, simple oracles), sensing, and basic error correction. The CHSH game is of particular interest: it combines probabilistic reasoning with a non-locality argument that symbolic and screen-based tools have struggled to teach. A CHSH-focused module is the subject of a forthcoming paper.

Multi-qubit visualizations. The Schmidt-based surface lighting described in Section III is exact for two-qubit states. For three or more qubits, a measurement no longer produces only single-qubit states, so our visualization no longer works. An extension we informally call the "multistate" visualization is in development to convey similar intuition for larger systems; it will be required for algorithm-level activities.

IX. Conclusion

We have presented a tangible qubit instrument and reported two early deployments in outreach and classroom settings. The outreach booth ran a hands-on quantum-key-distribution game for roughly two hundred elementary- and middle-school visitors at the museum's annual expo, letting participants see how a qubit measurement produces a 0 or 1 and how two entangled qubits can be used to share a secret key. The classroom pilot extended the same modality into a longer, more structured 90-minute lesson on the mechanics underneath: seven of the eight student pairs went from no prior familiarity to identifying the singlet-state anti-correlation by the end of the session, and an after-school discussion reached the no-signaling theorem through guided reasoning. The most informative next experiments are replications in regularly scheduled classes, conducted with IRB oversight and a peer-reviewed pre/post test.

Appendix A
Machine-Learning Features for Bump Detection

The bump-to-entangle classifier described in Section III consumes a 60-dimensional feature vector. The vector is constructed in two stages. First, fifteen *channels* aggregate the raw IMU stream over short lookback windows (Table I). Then, for each channel, the firmware tracks four windowed statistics (mean, standard deviation, max, and min) over a longer model window, giving the 60 inputs the classifier sees.

Appendix B
HSV Computation for the Two-Qubit Visualization

The visualization is a mapping from each LED position $\mathbf{d}_i \in \mathbb{R}^3$ on the sphere's surface (for $i = 1, \ldots, 583$) to an RGB triple, parameterized by a two-qubit statevector $|\psi\rangle = a\,|00\rangle + b\,|01\rangle + c\,|10\rangle + d\,|11\rangle$:

$$|\psi\rangle \;\longmapsto\; \{\,\mathrm{RGB}_i\,\}_{i=1}^{583}, \qquad \mathrm{RGB}_i = f(|\psi\rangle\,, \mathbf{d}_i).$$

We compute the three HSV channels (using the asymmetric reference scheme of Section III) independently, then convert to RGB. The channels are:

Value (both spheres). The firmware first extracts the marginal Bloch vectors $\mathbf{a}$ and $\mathbf{b}$ for the two qubits, obtained from

TABLE I
SIGNAL CHANNELS FEEDING THE BUMP-DETECTION CLASSIFIER.

Channel	**Computation**
Accelerometer-derived	
Per-axis acceleration	Latest sample of a_x, a_y, a_z (3 channels)
Accel. magnitude max	Max of $\|\mathbf{a}\|$ over the last 4, 10, or 15 samples (3 channels)
Accel. magnitude std	Standard deviation of $\|\mathbf{a}\|$ over the last 3 or 12 samples (2 channels)
Jerk magnitude	Root-sum-square of consecutive $\|\mathbf{a}\|$ differences over the last 4 samples (1 channel)
Gyroscope-derived	
Per-axis angular velocity	Latest sample of ω_x, ω_y, ω_z (3 channels)
Angular acceleration max	Max consecutive-sample difference $\|\Delta\boldsymbol{\omega}\|$ over the last 3, 5, or 6 samples (3 channels)

the reduced density matrices $\rho_A = \mathrm{Tr}_B\, |\psi\rangle\langle\psi|$ and $\rho_B = \mathrm{Tr}_A\, |\psi\rangle\langle\psi|$. In closed form,

$$\mathbf{a} = \big(2\,\mathrm{Re}(a\bar{c} + b\bar{d}),\ -2\,\mathrm{Im}(a\bar{c} + b\bar{d}),\ |a|^2 + |b|^2 - |c|^2 - |d|^2\big),$$
$$\mathbf{b} = \big(2\,\mathrm{Re}(a\bar{b} + c\bar{d}),\ -2\,\mathrm{Im}(a\bar{b} + c\bar{d}),\ |a|^2 + |c|^2 - |b|^2 - |d|^2\big).$$

For each LED with surface direction $\mathbf{d}$, the value channel is the Born-rule probability of measuring this qubit along $+\mathbf{d}$ and getting the $+1$ outcome:

$$\text{value}(\mathbf{d}) \;\propto\; \tfrac{1}{2}\big(1 + \mathbf{r}\cdot\mathbf{d}\big),$$

where $\mathbf{r}$ is the marginal Bloch vector of *this* qubit ($\mathbf{a}$ for sphere A, $\mathbf{b}$ for sphere B).

Hue on sphere A. For each LED with surface direction $\mathbf{d} = (d_x, d_y, d_z)$, we take the direction itself, remapped to $[0, 1]$, as the RGB triple:

$$(R, G, B) \;=\; \tfrac{1}{2}\big(d_x + 1,\ d_y + 1,\ d_z + 1\big).$$

The result is a smooth tricolor rainbow over the surface.

Hue on sphere B. Computing the partner direction $\mathbf{r}_{\text{partner}}$ requires the *spin correlation tensor*,

$$T_{jk} \;=\; \langle\psi|\,\sigma_j \otimes \sigma_k\,|\psi\rangle, \qquad j, k \in \{x, y, z\}.$$

Each entry T_{jk} is the expectation value of measuring σ_j on qubit A and σ_k on qubit B simultaneously and multiplying outcomes (each outcome is ± 1). So T_{jk} is just the correlation between matched-axis outcomes:

- $T_{zz} = +1$: when you measure both in Z, you always get the same answer.
- $T_{zz} = -1$: anti-correlated.
- $T_{zz} = 0$: independent.

The singlet has $\mathbf{T} = -I$, perfect anti-correlation in every basis; a product state has $\mathbf{T} = \mathbf{a}\mathbf{b}^\top$, rank one: two independent qubits. Together $\mathbf{a}$, $\mathbf{b}$, and $\mathbf{T}$ parameterize the Bloch-tensor decomposition of the joint density matrix:

$$\rho \;=\; \tfrac{1}{4}\big(I \otimes I + \mathbf{a}\cdot\boldsymbol{\sigma} \otimes I + I \otimes \mathbf{b}\cdot\boldsymbol{\sigma} + \textstyle\sum_{jk} T_{jk}\,\sigma_j \otimes \sigma_k\big),$$

the two-qubit analog of $\rho = \frac{1}{2}(I + \mathbf{r}\cdot\boldsymbol{\sigma})$. Each entry of $\mathbf{T}$ has a closed form in the amplitudes; for example, $T_{zz} = |a|^2 - |b|^2 - |c|^2 + |d|^2$ and $T_{xx} = 2\,\mathrm{Re}(a\bar{d} + b\bar{c})$.

Read $\mathbf{T}$ as a linear map: it takes the direction we measured A in and outputs the direction B is now pointing. The partner direction is

$$\mathbf{r}_{\text{partner}} \;=\; \frac{\mathbf{T}\,\mathbf{d} - \mathbf{a}}{1 - \mathbf{d}\cdot\mathbf{b}},$$

normalized to the unit sphere. For the singlet this reduces to $\mathbf{r}_{\text{partner}} = -\mathbf{d}$, which is why anti-correlation appears as a 180° hue rotation on sphere B in Fig. 5. The LED on sphere B is then assigned the RGB color produced by the sphere-A formula at $\mathbf{r}_{\text{partner}}$.

Saturation (both spheres). Saturation tracks the local qubit's entanglement with its partner. We define the entanglement level as $1 - \|\mathbf{r}\|$, where $\mathbf{r}$ is the marginal Bloch vector of the local qubit, and take the saturation to be linear in this quantity:

$$\text{saturation} \;=\; 1 - \|\mathbf{r}\|.$$

A product state (no entanglement with the partner) gives $\|\mathbf{r}\| = 1$ and zero saturation, rendering the sphere white; a maximally mixed marginal (full entanglement) gives $\|\mathbf{r}\| = 0$ and full saturation.

ACKNOWLEDGMENTS

The authors thank the students of Eleanor Roosevelt High School who participated, and educators across several U.S. universities and high schools for ongoing input into the platform's design and curriculum.

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