NOTEBOOK · QUANTUM PHYSICS

Why a Qubit Lives on a Sphere

The Bloch sphere, decoherence, and the state of quantum computing

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Handwritten notes, typed October 2026

$$|\psi\rangle = \cos\tfrac{\theta}{2}\,|0\rangle + e^{i\varphi}\sin\tfrac{\theta}{2}\,|1\rangle$$

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> ***Editor's note — how to read this edition.*** Plain text is Sharon's own writing, retyped from 50 phone photos of a spiral notebook (sent 10 October 2026) and grouped into sections in notebook order. Headings are editorial unless they appear in quotation marks or are marked as hers. **Blue boxes** labelled *Editor's note* are added explanation. **Orange boxes** labelled *Correction* flag a physics/maths or wording fix; the text keeps her intent, and the box says what was changed. Where she wrote two drafts of the same passage, the drafts are merged into one text and nothing from either is dropped. Crossed-out words in the notebook are not reproduced. Photos with no notes on them (a personal photo and a food photo) are left out; see the Appendix.

1 North and South: the Bloch-sphere picture

Notebook photos 4–9

North Pole is $|0\rangle$. South Pole is $|1\rangle$.

The equator is equal superposition: 50/50 if you measure in the 0/1 basis.

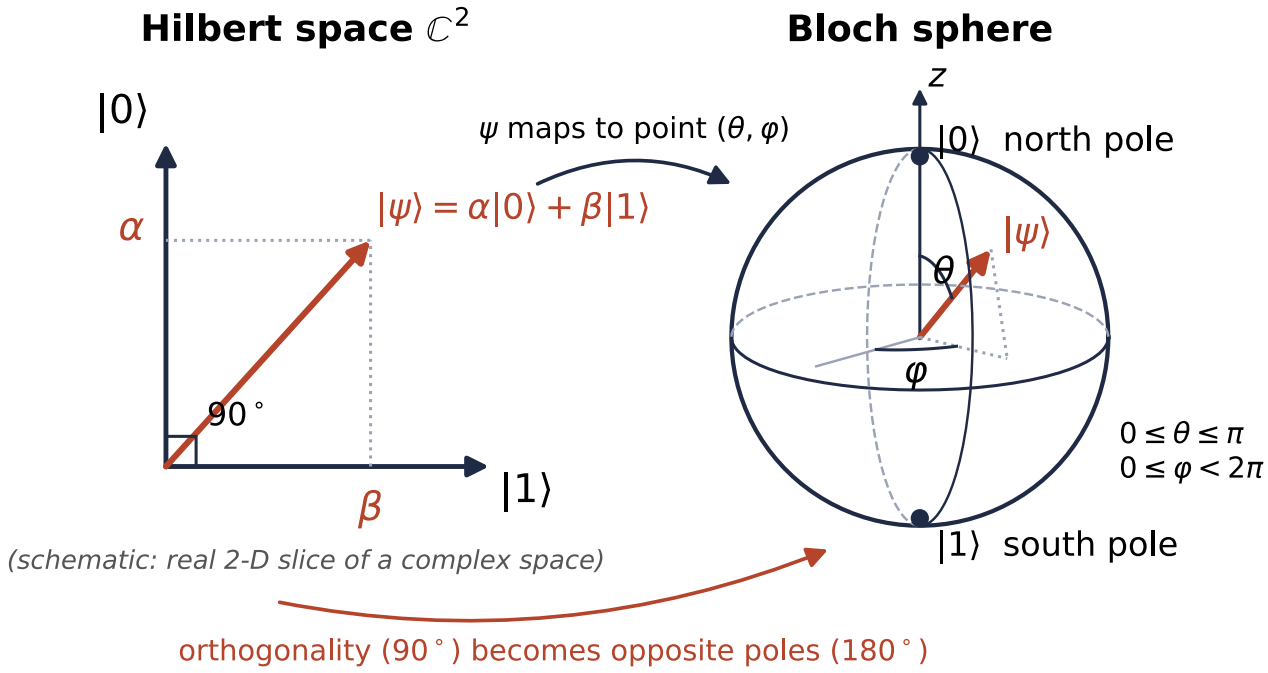
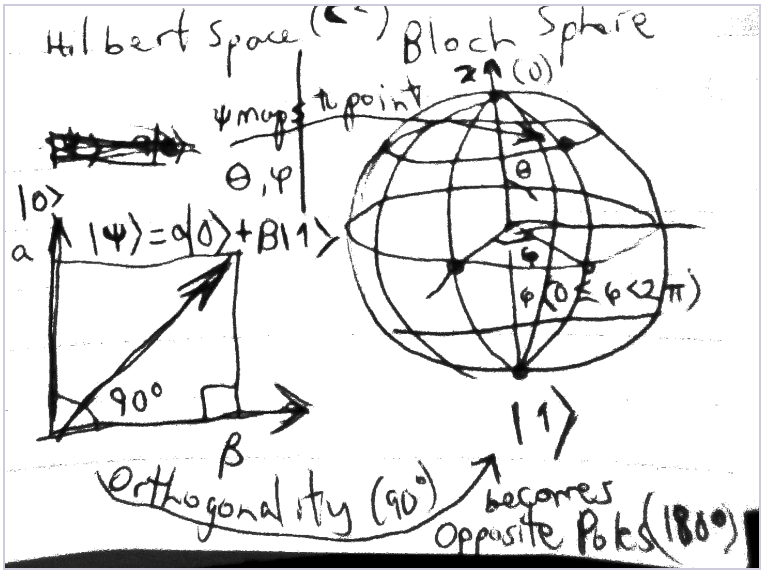


Figure 1. Her diagram from photo 4, redrawn: a state in Hilbert space $\mathbb{C}^2$ maps to a point (θ, φ) on the Bloch sphere, and orthogonality $(90°)$ becomes opposite poles $(180°)$. In the original the horizontal axis is labelled only "β"; here it is also labelled $|1\rangle$.



The original sketch (photo 4, cropped, contrast enhanced), for reference. The scribble at the upper left is crossed out in the notebook.

In this picture:

- $|0\rangle$ is placed at the North Pole
- $|1\rangle$ is placed at the South Pole.

But this positioning does not mean they are "180° apart" in the Hilbert-space sense. Rather, the Bloch sphere uses *measurement behavior*, not inner-product geometry, to place states.

2. Opposite poles represent opposite measurement outcomes

When you measure a qubit in the computational basis:

- A qubit in $|0\rangle$ is certain to give outcome 0.
- A qubit in $|1\rangle$ is certain to give outcome 1.

Since their measurement outcomes are mutually exclusive, the Bloch sphere places them at opposite ends of the z-axis. This conveys a simple message: **poles = states with completely opposite measurement properties.**

So even though they are orthogonal mathematically, they appear visually as the most separated states.

3. Orthogonality (90° in Hilbert space) becomes 180° on the Bloch sphere

In Hilbert space, orthogonality corresponds to a 90° angle.

> ***Editor's note.*** Her point 3 stops here in the notebook. The general rule behind it: if two pure states have Bloch vectors $\vec{r}_1, \vec{r}_2$, then $|\langle\psi_1|\psi_2\rangle|^2 = \frac{1}{2}(1 + \vec{r}_1 \cdot \vec{r}_2)$. An overlap of 0 (orthogonal, 90° in Hilbert space) gives $\vec{r}_1 \cdot \vec{r}_2 = -1$: antipodal points, 180° apart on the sphere. Every angle in Hilbert space is doubled on the sphere. (Her point 1 is presumably the "In this picture" paragraph above; it is not numbered in the notebook.)

"Why $|0\rangle$ and $|1\rangle$ are orthogonal but appear as North and South on the Bloch sphere?"

— source noted as "Purn's Deep Learning Blog" [blog name as written; spelling not certain]

One slightly rude fact: in the actual math, $|0\rangle$ and $|1\rangle$ are at right angles to each other. On the Bloch sphere they sit at opposite poles. The sphere stretches a 90° Hilbert-space …

[The sentence continues on a page that is not among the photos. The next photo (10) starts mid-sentence.]

2 Real qubits in the lab

Notebook photos 10–11

Superconducting qubits

… cooled near absolute zero so only two quantum levels matter. Microwave pulses rotate the Bloch vector.

It looks like a chip.

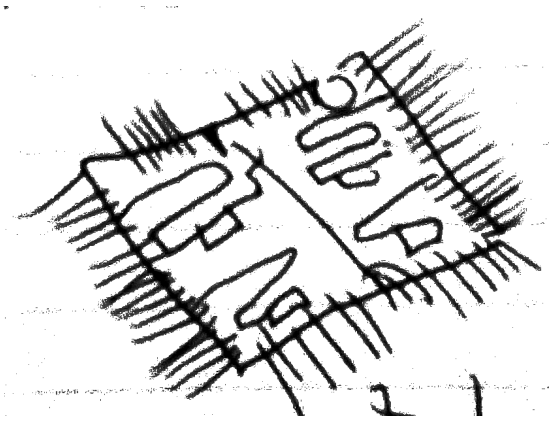


Figure 2. Her drawing of a quantum chip (photo 10, cropped, contrast enhanced). A freehand sketch, so it is shown as drawn, not redrawn.

“Quantum computation to tackle fundamental science problems.”

> ***Editor's note.*** The start of this passage is on a missing page. For context: a superconducting qubit is a tiny circuit (aluminium or niobium on a chip, with Josephson junctions) that behaves like an artificial atom. Its two lowest levels are split by $\Delta E = \hbar\omega$ with $\omega/2\pi$ a few GHz. Cooling to about 10 mK in a dilution refrigerator makes $k_B T \ll \hbar\omega$, so thermal noise cannot kick it out of $|0\rangle$, and only the two levels matter. A microwave pulse tuned to ω rotates the Bloch vector, and its length sets the angle.

Trapped-ion qubits

A trapped-ion qubit is one charged atom held in an electromagnetic trap. Two internal electronic (or hyperfine) levels are $|0\rangle$ and $|1\rangle$. Lasers do the rotations. You can literally see the ion fluoresce.

“Ion Trapped Quantum Computing: How Atoms Held in Light Are Building the Future of Computation”

3 The enemy is the environment: decoherence

Notebook photos 12–13

Either way, the enemy is the same. The environment is always watching a little. That leaks information, which is decoherence.

The point on the sphere drifts, then shrinks towards the centre (a mixed state), and the nice pure superposition dies.

That is why one qubit is easy and a useful computer is hard. One clean qubit is a solved lab project. Keeping a hundred of them coherent and talking to each other is the whole industry.

> ***Editor's note.*** "Either way" refers to the two platforms in Section 2: superconducting or trapped-ion, the same problem applies. The drift and the shrinking have standard names. Slow random rotation of the phase φ is *dephasing* (time scale T_2). Relaxation from $|1\rangle$ down to $|0\rangle$ is *energy relaxation* (time scale T_1). See also Figure 3 in Section 5.

4 Why does one qubit live on a sphere?

Notebook photos 13–20 (first draft) and 25–33 (second draft), merged. Photos 1–3 show the photo-15 page again.

Because after you throw away everything that is not physically real, two numbers are left, and two numbers on a unit constraint are a sphere.

Start with the raw object

A qubit state is:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle.$$

α and β are complex, so that is four real numbers: $\alpha = a + ib$, $\beta = c + id$.

> ***Correction.*** The first draft (photo 14) writes "$\alpha = \alpha + ib$". The real part should be a new letter: $\alpha = a + ib$, as in the second draft (photo 26). Both drafts leave "$\beta =$" blank; it is completed here as $\beta = c + id$.

Four is too many. Two of them are fake.

First fake: overall size

The state has to be normalized:

$$|\alpha|^2 + |\beta|^2 = 1.$$

That is one real constraint. You are no longer free to make the vector longer or shorter. Four numbers minus one constraint leaves three. Geometrically, that is the 3-sphere S^3 sitting inside $\mathbb{C}^2$.

Second fake: overall phase

If you multiply the whole state by $e^{i\gamma}$,

$$|\psi\rangle \longrightarrow e^{i\gamma}|\psi\rangle,$$

every measurement probability stays the same. The Born rule only sees

$$|\langle\phi|\psi\rangle|^2,$$

and a global phase cancels. Nature cannot tell $|\psi\rangle$ from $e^{i\gamma}|\psi\rangle$, so one more number is unphysical.

Two numbers, two angles

Three minus one leaves two. Two continuous real numbers that describe a compact set of states: that is a 2-sphere.

You can write those two numbers as angles:

$$|\psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}\,|1\rangle$$

> ***Correction.*** In all three versions of this formula in the notebook (photos 17, 30, 49) the line stops at "$+\,e^{i\varphi}$" at the edge of the page. The missing factor $\sin\frac{\theta}{2}\,|1\rangle$ is restored here. In the first draft (photo 17) the formula also ends up inside the sentence "Nature cannot tell …", because the lines in between were skipped. The second draft has the full text, and that is what is used above.

θ from 0 to π. φ from 0 to 2π. That is exactly the usual globe: polar angle and longitude.

> ***Editor's note.*** Strictly, φ runs over $0 \le \varphi < 2\pi$ (2π is the same as 0), as in her diagram in Figure 1. And "two numbers on a compact set" could in principle give other surfaces, a torus for example. It is a sphere because the map from the 3-sphere of normalized states to "states up to phase" is the *Hopf map* $S^3 \to S^2$. The Bloch vector itself is $\vec{r} = (\sin\theta\cos\varphi,\ \sin\theta\sin\varphi,\ \cos\theta)$.

Why $\theta/2$ instead of θ?

Because the two basis states are orthogonal in Hilbert space (90° apart as vectors), but on the Bloch sphere we put them at opposite poles (180° apart). Using $\theta/2$ stretches that 90° into 180°, so ordinary 3-D intuition works: opposite points on the sphere are opposite quantum states, and a 180° rotation on the sphere is a bit-flip. That is the whole reason.

> ***Editor's note.*** "Opposite quantum states" here means *orthogonal* states: antipodal points are exactly the pairs with zero overlap. The bit-flip is a 180° rotation about the x-axis (the Pauli-X gate), which swaps $|0\rangle \leftrightarrow |1\rangle$.

The whole reason, as a list

Not because qubits are little spinning balls. Because:

- two complex amplitudes
- minus length
- minus a phase nobody can see
- equals two angles
- two angles on a unit constraint = a sphere.

[Correction (wording): the second draft (photo 33) opens with just "Not because:"; the fuller wording here is from the first draft (photos 19–20).]

5 Beyond one sphere: two qubits and mixed states

Notebook photos 20–22 (and 33)

One extra qubit does not give you two spheres.

Two qubits live in a 4-dimensional complex space (6 real parameters after normalization and global phase). There is no simple ball anymore. Entanglement is exactly the part that cannot be drawn as two separate points on two spheres.

> ***Correction.*** The notebook (photo 21) says “15 real parameters”. A pure two-qubit state has 4 complex amplitudes, which is 8 real numbers. Normalization and global phase remove 2, leaving **6**. (15 is the number of real parameters of a general *mixed* two-qubit state, a 4×4 density matrix: $16 - 1 = 15$. That may be where the number came from.) For comparison, two separate Bloch spheres would need only $2 + 2 = 4$ numbers. The 2 extra parameters are where entanglement lives.

If you want the next layer, it is this: mixed states (a qubit that has leaked into the environment) live inside the ball, not only on the surface. The centre is “I have no idea”: 50/50 and no phase left. Decoherence is the point falling inward.

> ***Correction.*** The notebook (photo 22) says the point is “falling forward”. Given her own description in Section 3 (“shrinks towards the centre”), the intended word is *inward*.

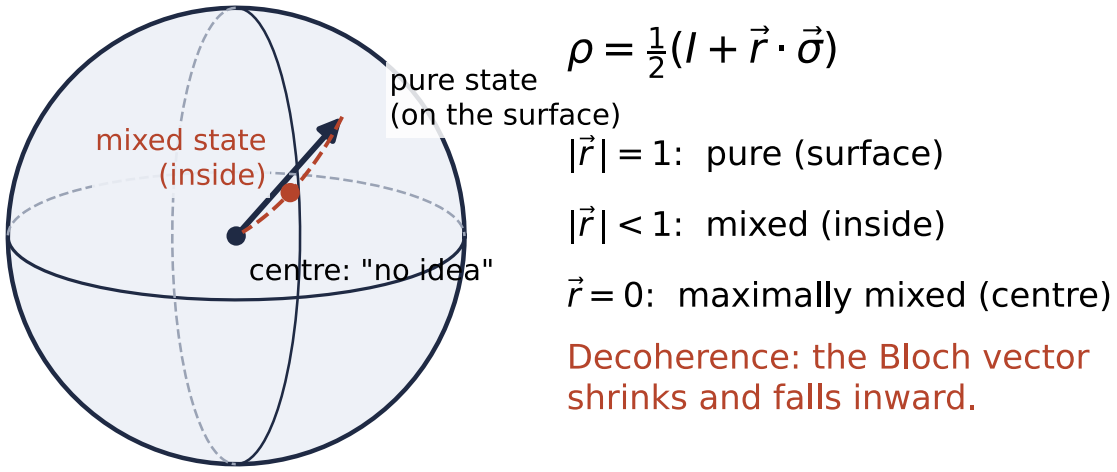


Figure 3 (editor's addition, not in the notebook). The Bloch ball: pure states on the surface, mixed states inside, and the maximally mixed state ($\rho = I/2$) at the centre.

> ***Editor's note.*** A mixed state is written as a density matrix $\rho = \frac{1}{2}(I + \vec{r} \cdot \vec{\sigma})$, where $\vec{\sigma} = (X, Y, Z)$ are the Pauli matrices and $|\vec{r}| \leq 1$. The length of $\vec{r}$ measures purity: $\mathrm{Tr}\,\rho^2 = \frac{1}{2}(1 + |\vec{r}|^2)$.

6 In short: what is a qubit?

Notebook photos 23–24, her own summary

What is a qubit, why is it on a sphere, why is it the only one on a sphere, why if you add another qubit do you not suddenly get another sphere?

A qubit (quantum bit) is the basic unit of quantum information. Its pure states map to points on the Bloch sphere from two real parameters after normalization and global phase. One qubit needs one sphere. Adding another creates a joint 4-D complex space; entanglement means states often cannot factor into independent spheres.

> ***Editor's note.*** On "why is it the only one on a sphere": only a two-level system gives a sphere. A three-level system (a qutrit) has $2 \times 3 - 2 = 4$ real parameters, so its pure states form the 4-dimensional complex projective plane $\mathbb{CP}^2$, which is not a sphere. "Its pure states" is spelled "It's" in the notebook; this has been corrected.

7 From qubits to quantum computers

Notebook photos 34–38

A classical bit is either 0 or 1. A qubit can be written as

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where α and β are complex amplitudes. Until you measure it, the qubit is in a superposition of both.

Two qubits can hold a superposition of four states, three of eight, n of 2^n. That exponential state space is the raw material.

Superposition alone is not enough. You also need **entanglement** (correlations stronger than any classical correlation) and **interference** (amplitudes add or cancel).

Algorithms are designed so wrong paths interfere destructively and the useful ones constructively. Then you measure, the wavefunction collapses, and you get a classical answer, usually after many shots, because the output is probabilistic.

> ***Correction.*** Photo 36 says "the waveform collapses". The term is *wavefunction* (or "the state collapses").

That is why quantum computers do not replace ordinary computers. They are specialist engines for a few classes of problem: simulating molecules and materials, certain optimization and sampling tasks, and (eventually) breaking some public-key crypto. They are terrible at spreadsheets, web servers, and most of what you do every day.

8 The hardware race

Notebook photos 38–41

Hardware today is several competing bets:

- **Superconducting circuits** (IBM, Google): fast gates, harder to keep coherent, need dilution fridges.
- **Trapped ions** (Quantinuum, IonQ): slower, very high fidelity, all-to-all connectivity.
- **Neutral atoms** (Infleqtion, QuEra, Atom Computing): easy to scale in number, lasers rearrange them mid-circuit.
- **Photonics** (PsiQuantum and others) and **Microsoft's topological / Majorana** approach are longer shots still in the lab.

The scoreboard has shifted. Raw physical qubit count matters less than **logical qubits**: error-corrected groups of physical qubits that behave like one reliable qubit. In the last two years the field finally showed that adding more physical qubits can lower the logical error rate (Google's Willow was the headline result). That is the threshold everyone was waiting for.

> ***Editor's note.*** "Threshold" refers to the *fault-tolerance threshold*: when every physical error rate is below a critical value, making the error-correcting code bigger (for example, increasing the surface-code distance from 3 to 5 to 7) suppresses the logical error rate exponentially instead of making it worse. Google's Willow results were published in December 2024.

9 The picture as of late September 2026

Notebook photos 42–46

> ***Editor's note.*** This section is Sharon's summary of industry news as she wrote it. Company and product names are spelled as in the notebook. Her figures and claims were not independently checked for this edition.

As of late September 2026 the picture looks like this:

- IBM is running 120-qubit Nighthawk-class processors in the cloud, and is still aiming at verified advantage this year and a fault-tolerant "Starling" machine around 2029.
- Quantinuum's Helios trapped-ion system is often the quality leader.
- Infleqtion just showed 30 entangled logical qubits from 80 physical atoms. [the number is written "30" followed by a stray stroke, so it could be misread as "301". 30 is the only reading consistent with 80 physical atoms.]
- IonQ is talking about Superion 256 systems for 2027, and demonstrated that a laptop can decode simulated error correction for hundreds of logical qubits.

- The U.S. DOE just published a roadmap aimed at a scientifically useful error-corrected machine by 2028.
- Germany is putting serious money into a 1000-qubit trapped-ion push.

None of this is a general-purpose quantum PC. Useful fault-tolerant machines (hundreds of logical qubits running millions of reliable gates) are still the late-2020s bet, not something you can buy to replace a GPU cluster. Claims of “quantum advantage” still have to be checked carefully against the best classical algorithms; some hold up, many are narrow or controversial.

The other clock that is already ticking is **post-quantum cryptography**. Even if a crypto-breaking machine is years away, governments and Microsoft are migrating now so that data stolen today cannot be decrypted later.

> ***Editor's note.*** This threat is usually called “harvest now, decrypt later”. The replacement algorithms are NIST's post-quantum standards, published in 2024: ML-KEM (Kyber) for key exchange, and ML-DSA (Dilithium) and SLH-DSA (SPHINCS+) for signatures.

10 The physics of one qubit (recap)

Notebook photos 47–49. The heading and list are hers.

"The Physics of One Qubit"

- state
- Bloch sphere
- measurement
- phase

A single qubit is just a two-level quantum system you can control: two energy levels you pick and call $|0\rangle$ and $|1\rangle$. Everything else is how that system sits between those two levels.

The full state is

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

with the only hard rule

$$|\alpha|^2 + |\beta|^2 = 1.$$

Those two complex numbers look like four real numbers, but a leftover overall phase does not change any measurement, so you are left with two real numbers. Those two numbers are two angles. That is why one qubit lives on a sphere.

The standard form is:

$$|\psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}\,|1\rangle$$

θ is the polar angle (measured down from the North Pole). φ is longitude.

> ***Correction.*** Photo 49 says "θ is latitude". θ is measured from the North Pole ($\theta = 0$ is $|0\rangle$, $\theta = \pi$ is $|1\rangle$), so it is the *colatitude* or polar angle; geographic latitude would be $90^\circ - \theta$. This matches her own earlier wording, "polar angle and longitude" (Section 4). As in Section 4, the missing $\sin\frac{\theta}{2}|1\rangle$ is restored. The count "four real numbers → two" here skips the normalization step (Section 4): normalization removes one number and the overall phase removes another.

> ***Editor's note — measurement on the sphere.*** Her list mentions measurement. On the sphere it is simple: $P(0) = |\alpha|^2 = \cos^2\frac{\theta}{2} = \frac{1+\cos\theta}{2}$ and $P(1) = \sin^2\frac{\theta}{2} = \frac{1-\cos\theta}{2}$, so the height of the point on the z-axis gives the odds. On the equator ($\theta = \pi/2$) the odds are 50/50, as in Section 1. The phase φ never shows up in a z-measurement. It only shows up after a rotation, for example $|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$ at $\varphi = 0, \pi$ on the equator, which a Hadamard gate turns back into $|0\rangle$ and $|1\rangle$.

Appendix: page concordance and editorial changes

Where each photo went

Photos	Content	Used in
1, 2, 3	Three retakes of one page held up for the camera (“Four is too many. Two of them are fake. First fake: overall size …”). The same page is photo 15. Mostly a personal photo of her, not the notes.	Duplicates of 15; not reproduced
4–9	Bloch sphere, poles, orthogonality; diagram	Section 1, Figure 1
— (gap)	A page between 9 and 10 is missing (the sentence breaks off)	Gap marked in Sections 1–2
10–11	Superconducting and trapped-ion qubits; chip drawing	Section 2, Figure 2
12–13	Decoherence	Section 3
13–20	“Why does one qubit live on a sphere?”, first draft	Section 4 (merged)
20–22	Two qubits; mixed states	Section 5
23–24	Question and short answer	Section 6
25–33	Second draft of 13–20; more complete (adds “so one more number is unphysical”, “Three minus one leaves two …”, “You can write those two numbers as angles”)	Section 4 (merged)
34–37	Bits vs qubits; entanglement, interference; what quantum computers are for	Section 7
38–41	Hardware platforms; logical qubits	Section 8
42–46	Industry status, Sept 2026; post-quantum cryptography	Section 9
47–49	“The Physics of One Qubit” recap	Section 10
50	Photo of food, no notes	Not reproduced

Corrections (summary)

- Photo 14: $\alpha = \alpha + ib \to \alpha = a + ib$; the blank $\beta =$ completed as $c + id$.
- Photos 17, 30, 49: missing $\sin\frac{\theta}{2}\,|1\rangle$ restored in $|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$.
- Photo 17: lines skipped in the first draft (the formula ran into “Nature cannot tell …”); fixed from the second draft.
- Photo 21: “15 real parameters” → 6 (15 is the count for mixed two-qubit states).
- Photo 22: “falling forward” → “falling inward”.
- Photo 33: “Not because:” → “Not because qubits are little spinning balls. Because:” (taken from the first draft).
- Photo 36: “waveform collapses” → “wavefunction collapses”.
- Photo 49: “θ is latitude” → θ is the polar angle (colatitude).
- Photo 23: “It's pure states” → “Its pure states”. Photo 9: dropped a stray “both” (“are both at right angles to each other”).
- Figure 1: horizontal Hilbert-space axis also labelled $|1\rangle$; marked as schematic.

Unclear readings

- Photo 9: blog name read as “Purn's Deep Learning Blog”; the spelling is not certain.
- Photo 43: the number reads “30” with a trailing stroke (“30l”); typeset as 30.
- No word was fully illegible, so no [illegible] markers were needed.

Typeset from Sharon's handwritten notebook, October 2026. Source: notes.src.html. Figures: fig/make_figs.py (matplotlib).