# The irony trap quantum computer.
*How does QM fail?*

G J Milburn

# EmQM & RaQM

- Emergent Quantum Mechanics (EmQM), Slagle & Preskill, PRA 108, 012217 (2023)
- Rational Quantum Mechanics (RaQM), Palmer, PNAS, 123 (12) (2026).(2026).

# EmQM & RaQM

Health warning:

Neither EmQM or RaQM are equivalent to QM.

# Quantum things vs quantum states.

Wavefunction for a particle: $\psi(\boldsymbol{x}, t)$

What spacetime event is indexed by $(\boldsymbol{x}, t)$)?

(a): The particle.

(b): The particle detector.

# Bell violation: type-II down-conversion.

$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$;
$a{=}0^\circ$, $a'{=}45^\circ$; $b{=}22.5^\circ$, $b'{=}67.5^\circ$

**Coincidence events (excerpt)**

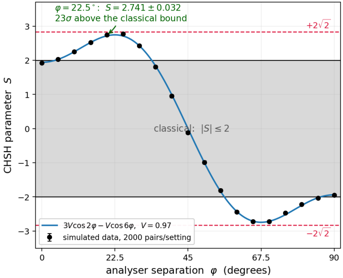
| | Alice | | Bob | |
|---|---|---|---|---|
| $t$ (ns) | set. | $A$ | set. | $B$ |
| 2860 | 0° | $-$ | 22.5° | $+$ |
| 2873 | 45° | $+$ | 67.5° | $-$ |
| 2886 | 0° | $+$ | 22.5° | $+$ |
| 2899 | 0° | $+$ | 22.5° | $+$ |
| 2912 | 0° | $-$ | 22.5° | $+$ |
| 2925 | 45° | $-$ | 67.5° | $+$ |

**Accumulated:** 2000 **pairs per setting**

| A | B | $N_{++}$ | $N_{+-}$ | $N_{-+}$ | $N_{--}$ | $E$ |
|---|---|---|---|---|---|---|
| 0° | 22.5° | 152 | 846 | 852 | 150 | $-0.698$ |
| 0° | 67.5° | 821 | 175 | 162 | 842 | $+0.663$ |
| 45° | 22.5° | 141 | 844 | 865 | 150 | $-0.709$ |
| 45° | 67.5° | 149 | 872 | 828 | 151 | $-0.700$ |

$$S = -\Big[E(ab) - E(ab') + E(a'b) + E(a'b')\Big]$$

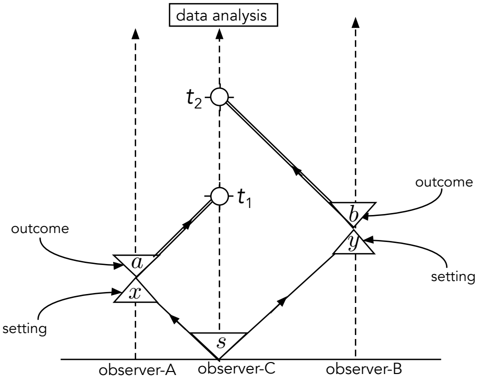
$\boxed{S = 2.741 \pm 0.032}$ vs $2\sqrt{2} = 2.828$



# Bell violation: type-II down-conversion.

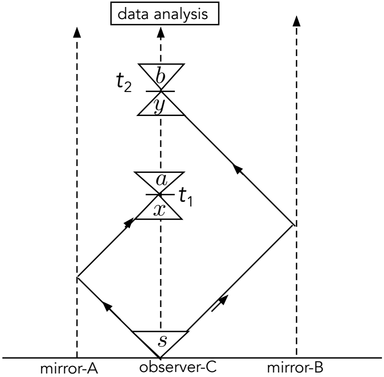
What were the spacetime coordinates of the detection events?

# Bell violation: type-II down-conversion.




The spacetime diagram I:

# Bell violation: type-II down-conversion.



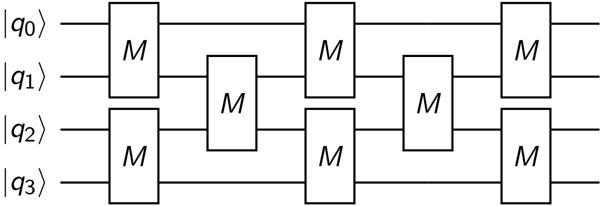

The spacetime diagram II:

# Spacetime and nonlocal corrrelations.

*no story in space-time can describe nonlocal correlations*

N. Gisin, *A*re There Quantum Effects Coming from Outside Space–Time? Nonlocality, Free Will and "No Many-Worlds", in A. Suarez and P. Adams (eds.), Is Science Compatible with Free Will?.

# Quantum things vs quantum states.




Qubit count:$n = 4$. Width:$W = 4$. Depth:$D = 5$. Gates: G=8

A two qubit gate is a 'controlled collision'

# Things, collisions, and states.

A circuit diagram is a spacetime diagram: worldlines and vertices.

**Things** — worldlines. $n$ qubits + $(n-1)$ couplers.

$$\#\{\text{things}\} = 2n - 1 \qquad \underline{\text{independent of depth}}$$

The 8 gates of the previous slide are 8 collisions on 3 couplers.

**Collisions** — vertices. Localised, two-body, one per gate:

$$G \;=\; \left\lceil \frac{D}{2} \right\rceil \left\lfloor \frac{n}{2} \right\rfloor + \left\lfloor \frac{D}{2} \right\rfloor \left\lfloor \frac{n-1}{2} \right\rfloor \;\simeq\; \frac{(n-1)D}{2}$$

**States** are not things. A pure state of $n$ qubits is $2^{n+1} - 2$ real numbers.

| $n$ | things $= 2n - 1$ | state parameters $= 2^{n+1} - 2$ |
|---:|---:|---:|
| 4 | 7 | 30 |
| 100 | 199 | $2.5 \times 10^{30}$ |
| 1000 | 1999 | $2 \times 10^{301}$ |

# One collision = one $\hbar$ = one four-cell.

A collision has a duration $\tau$ and a localisation $\ell$, so it occupies an interaction four-volume $\ell^d(c\tau)$.

Margolus–Levitin for one collision: $\Delta E \gtrsim \pi\hbar/2\tau$. Collisions on disjoint pairs do not compete, so energies simply add:

$$\mathcal{V}_4 \;=\; G\,\ell^d(c\tau), \qquad\qquad \int_0^T E\,dt \;\gtrsim\; \frac{\pi\hbar}{2}\,G$$

Both sides count collisions. Both are Lorentz invariant.

Dividing one by the other,

$$\frac{\int E\,dt}{\mathcal{V}_4} \;=\; \frac{\hbar}{\ell^d(c\tau)} \qquad \text{independent of } n \text{ and } D.$$

A quantum computer is a medium of fixed collision density. Scaling it up adds volume, not intensity.

Causal floor: entangling $n$ qubits needs $D \geq n^{1/d}$, so $\mathcal{V}_4 \geq n^{(d+1)/d}\ell^d(c\tau)$

# Shared worldlines make correlated errors.

These are entangling collisions: the participants leave correlated. What is transferred is not momentum but $\hbar$ of action.

A recycled control pulse is **one worldline undergoing many collisions**. Its errors are correlated because they share a history.

Independent controllers $=$ independent worldlines $=$ independent errors — which is what the threshold theorem assumes.

So the energetically efficient architecture (few controller worldlines, many collisions each) is exactly the one whose errors are uncorrectable.

# Quantum things require classical control.

A collision is driven by a pulse of bandwidth $\sim 1/\tau$. It must not also drive the nearest spurious level, at spacing $\Delta$

$$\textbf{minimum collision time} \quad \tau_{\min} \simeq \frac{\hbar}{\Delta}, \qquad \text{collision rate} \quad \frac{D}{T} \leq \frac{\Delta}{\hbar}$$

| | $\Delta/h$ | $\tau_{\min}$ | max. collisions/s |
|---|---|---|---|
| transmon (anharmonicity) | 200 MHz | 5 ns | $2 \times 10^8$ |
| trapped ion (motional) | 1 MHz | 1 $\mu$s | $10^6$ |

$\Delta$ is fixed by the encoding, not by engineering.

A collision of duration $\tau$ needs $\Delta E \gtrsim \pi\hbar/2\tau$, with $W/2$ collisions in flight

$$E \gtrsim \frac{W}{2}\frac{\pi\hbar}{2\tau} = \frac{\pi\hbar}{4}\frac{WD}{T}, \qquad \int_0^T E\,dt \gtrsim \frac{\pi\hbar}{2}G$$

A collision costs $\hbar$ of action, split between energy and time.

Faster collisions cost energy; slower ones cost time.
Power deployed: $E \lesssim W\Delta/2$.

# Quantum things require classical control.

Fundamental bound is $\sim 10^{10}$ below what real devices actually consume.

The real cost is precision, not speed.

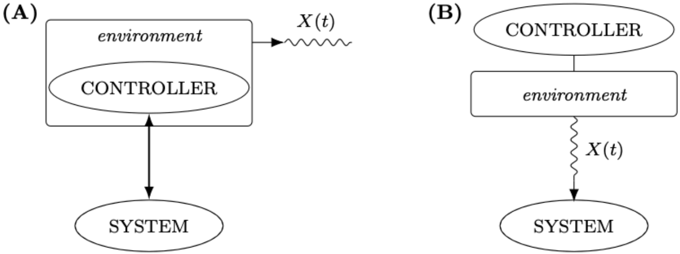
# Quantum things require classical control.

Coherent controllers are not noise free.

Ikonen, Salmilehto & Möttönen, Energy-efficient quantum computing, npj Quantum Information(2017).

Given a finite-energy quantum drive pulse, what is the smallest possible error for a qubit gate, and can the same pulse be used repeatedly without simply accumulating unacceptable control error?

# Quantum things require classical control.




G. J. Milburn, Decoherence and the conditions for the classical control of quantum systems, Phil. Trans. R. Soc. A **370**, 4469 (2012).

# Quantum things require classical control.

Example: spin-orbit control of a single spin qubit.

$$H = \frac{\hat{p}^2}{2m} + \frac{\hbar\Omega}{2}\sigma_z + 2\hbar\alpha\,\hat{p}\,\sigma_y.$$

momentum is the controller.

Implement a Hadamard gate with error probability $\epsilon$.

$$\varepsilon\, E \;=\; \mathcal{C}_{\mathrm{H}}\,\frac{\hbar^2}{8m\sigma_x^2}, \qquad \mathcal{C}_{\mathrm{H}} = \frac{\pi^2}{24} + \frac{1}{6} = 0.577900\ldots$$

the product of gate error and controller energy is fixed by $\hbar$ and the width $\sigma_x$ of the controller wave packet.

# Quantum things require classical control.

Recycling does not scale ...A shared controller produces correlated errors.

In the spin–orbit model, recycling without correction gains only

$$\frac{E^{\text{rec}}}{E^{\text{fresh}}} = \frac{1}{1 + 4/\pi^2} = 0.712, \qquad \text{independent of } N.$$

The correction step is not an optimisation. It breaks the shared worldline. One pulse driving many qubits is in direct tension with the statistical assumptions of error correction. Pulse correction is a necessity.

# Relativistic limits.

Four-volume is Lorentz invariant, and grows as $nD$. Hilbert space grows as $2^n$ and does not grow with $D$ at all.

$$\frac{\mathcal{V}_4}{\ell_P^4} \geq 2^{n+1} - 2 \qquad \Longleftrightarrow \qquad n \lesssim \log_2 \frac{\mathcal{V}_4}{\ell_P^4}$$

1000 qubits, $3\,\mathrm{cm} \times 3\,\mathrm{cm} \times 1\,\mathrm{mm}$, $10^6$ layers at 20 ns ($T = 20$ ms), $\mathcal{V}_4 \approx 6\ \mathrm{m}^4$:

| | | |
|---|---|---|
| collisions | $G \simeq (n-1)D/2$ | $5 \times 10^8$ |
| Planck four-cells | $\mathcal{V}_4/\ell_P^4$ | $10^{140}$ |
| state amplitudes | $2^{n+1} - 2$ | $10^{301}$ |

Deficit: $10^{161}$. Crossover at $n \approx 465$.

The observable universe, for its whole history: $7 \times 10^{245}$ Planck cells — enough for $n \approx 820$.

$10^{106}$ more four-volume buys 355 more qubits.

Make $D$ large instead? No: $D/T \leq \Delta/\hbar$.

Not an argument against quantum mechanics: the state is not a field on spacetime. The wavefunction is not a thing

# The wave function is a thing?

Two models:

- Slagle & Preskill (EmQM), Phys. Rev. A 108, 012217 (2023).
- Palmer (RaQM), Proc. Natl. Acad. Sci. U.S.A. 123 (12) (2026).

# Probabilities as Computation.

AI and quantum computing share two important features:

– algorithms for transforming probability distributions over data
– require specialised hardware to run.

This suggests a common framework.

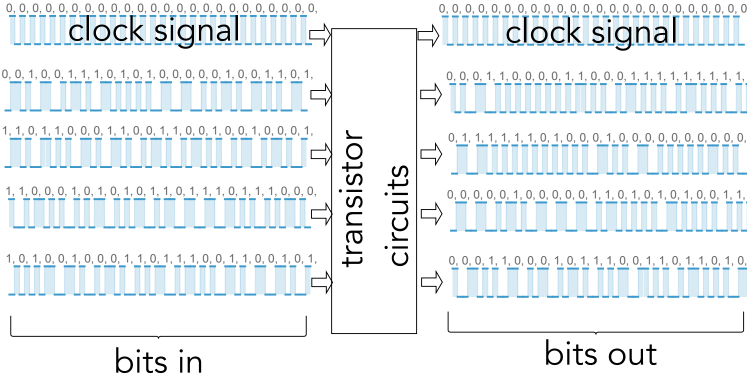
# Probabilities as Computation

Machine learning:

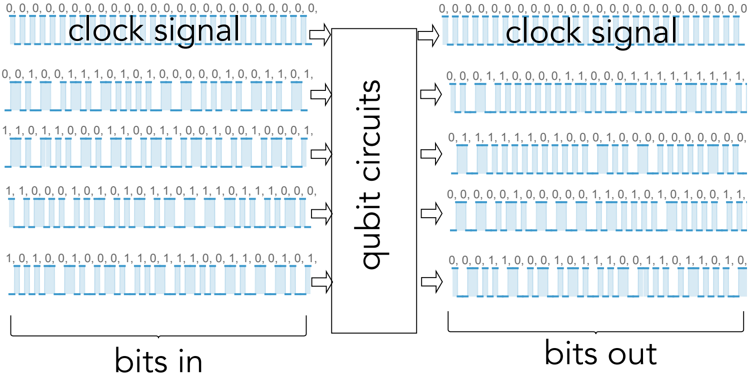
learn structure and uncertainty by modifying or mapping simpler, initial distributions to match complex statistical patterns found in real-world datasets.

$\rightarrow$ Compress information $\rightarrow$Reduce entropy.

# Universal classical probability sampling.



# Universal quantum probability sampling.



# Universal quantum probability sampling.

Quantum computation.

- A quantum computer transforms probabilities of bit strings.
- ... by transforming of probability *amplitudes*.
- Computation = controlled interference of probability amplitudes.
- Algorithms exploit this interference to achieve greater efficiency.

# Normalising flow NN.

A Normalizing Flow is a deep generative NN that maps a simple probability distribution (like a standard isotropic Gaussian) into a complex, high-dimensional target distribution using a sequence of invertible and differentiable transformations (bijections).

Given $f : \mathbb{R} \rightarrow \mathbb{R}$, compute the average

$$\mathbb{E}[f] = \int_{-\infty}^{\infty} dx\ f(x)\mathcal{P}(x) \qquad \mathcal{P}(x) = (2\pi\sigma)^{-1/2} e^{-\frac{x^2}{2\sigma}}$$

Transform the distribution

$$\mathcal{P}(x) \rightarrow \mathcal{Q}(y)$$

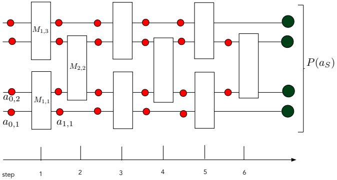
$$\int_{-\infty}^{\infty} dx\ f(x)\mathcal{P}(x) = \int_{-\infty}^{\infty} dy\ y\mathcal{Q}(y)$$

sample $\mathcal{Q}(y)$ to compute the empirical average

$$\bar{y}_N = \frac{1}{N}\sum_{j=1}^{N} y_j$$

where $y_j$ is drawn from $Q(y)$.

# Normalising flow NN.




State as a vector with components given by the probability of each of the $2^N$ bit strings

$$\boldsymbol{P} = \begin{pmatrix} P(00\ldots00) \\ P(00\ldots01) \\ P(00\ldots10) \\ P(00\ldots11) \\ \cdot \\ \cdot \\ \cdot \\ P(11\ldots11) \end{pmatrix} \tag{1}$$

The input bit values $\boldsymbol{a}_i = (a_{0,1}, a_{0,2}, \ldots, a_{0,N})$, uniformly random.

Trained by back propagation on parameters in each $M$

# Normalising flow NN.

A brickwork circuit is a stack of locally connected layers with receptive field 2, i.e. a 1D CNN with kernel size 2 and no weight sharing.

A brickwork of two-variable invertible maps is a coupling-layer flow (RealNVP, Glow, RevNets).

# Stochastic perceptrons.

A general stochastic map: $p = P(1|0)$ and $q = P(0|1)$,

$$M = \begin{pmatrix} 1-p & q \\ p & 1-q \end{pmatrix}$$

The columns sum to 1 by construction.

Measurement/control interpretation.

$$\boldsymbol{P}_i = \begin{pmatrix} P_i(0) \\ P_i(1) \end{pmatrix} \rightarrow \boldsymbol{P}_o = \begin{pmatrix} P_o(0) \\ P_o(1) \end{pmatrix}$$

$\boldsymbol{P}_o = M\boldsymbol{P}_i$, Uniform input distribution

$$\boldsymbol{P}_o = \frac{1}{2}\begin{pmatrix} 1+q-p \\ 1-(q-p) \end{pmatrix}$$

Reduces entropy ... measurement plus control.

# Stochastic perceptron.

Sigmoidal activation: $P(1|x) = \sigma(wx + b)$

Code: $s = +1$ for bit 0, $s = -1$ for bit 1.

Neuron fires with a logistic law in its local field $h = Ws + B$,

$$P(s' \mid s) = \frac{e^{s' h}}{2\cosh h}, \qquad h = Ws + B \qquad \Longrightarrow \qquad \langle s' \rangle_s = \tanh(Ws + B)$$

$$\boxed{W = \tfrac{1}{4} \ln \frac{(1-p)(1-q)}{pq}, \qquad B = \tfrac{1}{4} \ln \frac{(1-p)\, q}{p\,(1-q)}}$$

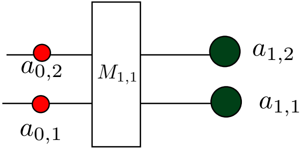
The bias is what breaks double stochasticity.

$$B = 0 \iff (1-p)q = p(1-q) \iff q = p \iff M \text{ doubly stochastic}$$

The perceptron's weight is the reversible, entropy-preserving part; the bias is the 'wavefunction'.

# Two bits.

$n = 2$, single gate




$$M = \begin{pmatrix} M(00|00) & M(00|01) & M(00|10) & M(00|11) \\ M(01|00) & M(01|01) & M(01|10) & M(01|11) \\ M(10|00) & M(10|01) & M(10|10) & M(10|11) \\ M(11|00) & M(11|01) & M(11|10) & M(11|11) \end{pmatrix}$$

columns must sum to one we need $16 - 4 = 12$ parameters

# Two bits.

Partameterisation. Index columns by $a \in \{00, 01, 10, 11\}$.

$$\alpha_a = M(00|a) + M(01|a), \qquad \beta_a = M(00|a) + M(10|a)$$

$$\gamma_a = M(00|a)\,M(11|a) - M(01|a)\,M(10|a) \;\; \left[ = M(00|a) - \alpha_a \beta_a \right]$$

so $\alpha_a = P(s_1' = 0|a), \beta_a = P(s_2' = 0|a)$, and $\gamma_a$ is the departure from independence. The column is

$$\begin{aligned} M(00|a) &= \alpha_a \beta_a + \gamma_a & M(01|a) &= \alpha_a(1-\beta_a) - \gamma_a \\ M(10|a) &= (1-\alpha_a)\beta_a - \gamma_a & M(11|a) &= (1-\alpha_a)(1-\beta_a) + \gamma_a \end{aligned}$$

# Two bits.

Change code: $s = +1 \leftrightarrow 0, -1 \leftrightarrow 1$ variables.

$$M(\boldsymbol{s}'|\boldsymbol{s}) = \frac{1}{4}\Big[1 + m_1(\boldsymbol{s})\, s_1' + m_2(\boldsymbol{s})\, s_2' + c(\boldsymbol{s})\, s_1' s_2'\Big]$$

$$m_1 = 2\alpha - 1, \qquad m_2 = 2\beta - 1, \qquad c = m_1 m_2 + 4\gamma.$$

The emergence of the Ising Hamiltonian of the Boltzmann machine is apparent.

# Two bits.

We now set

$$M = Q + m \geq 0$$

$Q$ is a permutation matrix that is fixed across the circuit,

$m$ is a stochastic matrix that can change at each step in the circuit.

# Two bits: training.

Input is uniform

$$\boldsymbol{P}_{in} = \frac{1}{N} \rightarrow \boldsymbol{P}_{out} \neq \boldsymbol{P}_{in}$$

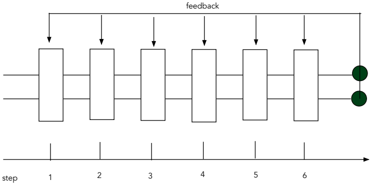
where $N = 2^n$

Seek

$$\boldsymbol{P}_{out} = \frac{1}{N} + \epsilon_\Psi \; \boldsymbol{\Psi}$$

where $\epsilon_\Psi$ is a perturbation parameter and $\boldsymbol{\Psi}$ is a real vector called a 'wavefunction'.

# Training by back-propagation

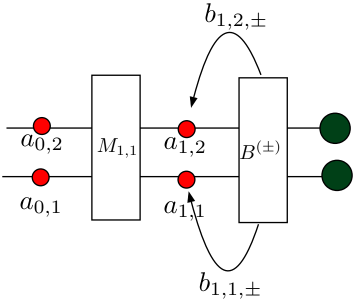



We regard the time taken for each forward/feedback step to be sequential but not processed in the 'lab time' that parametrises the changing values of the output bits.

This breaks locality, in the sense of Bell, for independent measurement on the output bits.

S &P regard each step as events occurring at a different 'place' in a hidden dimension.

# Two bits: training by back-propagation




A stochastic discrete circuit acting on two binary variables and a 'back-prop' step. The physical output bits are in black. The latent bits are in red.

# Two bits: training by back-propagation

P &S choose a pair of stochastic circuits $B^{(\pm)}$ that output two sets of bits with probability vectors $\boldsymbol{P}_\pm$ such that

$$\boldsymbol{P}_+ - \boldsymbol{P}_- = \left(B^{(+)} - B^{(-)}\right) \cdot \boldsymbol{P} = -iH\tau \cdot \boldsymbol{P}$$

$H$ is an antisymmetric matrix with pure imaginary elements that satisfies

$$\sum_i H_{ij} = 0, \quad \sum_j H_{ij} = 0$$

$m$ is updated as

$$m' = m + \Delta_{\mathrm{m}}(\hat{\boldsymbol{b}}_+ - \hat{\boldsymbol{b}}_-) \otimes \hat{\boldsymbol{e}}$$

where $\Delta_{\mathrm{m}}$ is a small constant.

$\hat{\boldsymbol{b}}_+$ is basis 4-vector indexed by two bits $b_{1,1,+}$ and $b_{1,2,+}$. The vector $\hat{\boldsymbol{e}}$ is chosen uniformly at random from the basis 4-vectors $\{(1,0,0,0),(0,1,0,0),(0,0,1,0),(0,0,0,1)\}$ with the constraint that $M = Q + m$ is non negative.

# Two bits: training by back-propagation

$$-iH = \begin{pmatrix} 0 & -1 & +1 & 0 \\ +1 & 0 & -1 & 0 \\ -1 & +1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

for $n = 2$ qubits, then we can choose

$$B^{(+)} = \begin{pmatrix} 1-\tau & 0 & \tau & 0 \\ \tau & 1-\tau & 0 & 0 \\ 0 & \tau & 1-\tau & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$B^{(-)} = \begin{pmatrix} 1-\tau & \tau & 0 & 0 \\ 0 & 1-\tau & \tau & 0 \\ \tau & 0 & 1-\tau & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

# What the extra dimension has to carry.

To linear order in $m$ the output distribution is a sum over every block in the bulk:

$$\boldsymbol{P} = \frac{\mathbf{1}}{N} + \sum_{s=1}^{S} \sum_{x} Q_{S \leftarrow s}\, m_{s,x}\, \frac{\mathbf{1}}{N}$$

$Q_{S \leftarrow s} = Q_S Q_{S-1} \dots Q_{s+1}$

A $4 \times 4$ block has $16 - 4 = 12$ free parameters. Averaged over a uniform input, only the three constants $(a_1, a_2, a_c)$ survive: 3 usable directions out of 12. The other nine are invisible at linear order.

There are $Sn/2$ blocks, and $\Psi$ lives in the $(N-1)$-dimensional zero-sum subspace. Capacity:

$$\frac{3}{2} Sn \geq N - 1 \quad \Longrightarrow \quad \boxed{Sn \gtrsim \tfrac{2}{3} 2^{n}}$$

| $n$ | depth $S \gtrsim \frac{2}{3} 2^n/n$ | bulk bits $\sim Sn$ |
|---|---|---|
| 50 | $1.5 \times 10^{13}$ | $7.5 \times 10^{14}$ |
| 100 | $8.5 \times 10^{27}$ | $8.5 \times 10^{29}$ |
| 1000 | $7 \times 10^{297}$ | $7 \times 10^{300}$ |

# Locality of the output bits is not assumed.

The feedback (delta rule) gives the boundary evolution

$$\underbrace{\partial_t \Psi \;=\; -i\,\mathcal{W}\,H\,\Psi}_{\text{pure advection}}, \qquad \mathcal{W} = \sum_{s,x} Q_{S\leftarrow s}\,\mathcal{P}_x\,Q_{S\leftarrow s}^T$$

$\mathcal{W}$ is the tangent kernel of the network. The sampled bits obey a <u>local</u> Hamiltonian only if $\mathcal{W} \propto \mathbb{I}$.

$\mathcal{W}$ is a sum of $Sn/2$ randomly rotated rank-3 projectors in $N-1$ dimensions:

$$\overline{\mathcal{W}} = \frac{3Sn}{2(N-1)}\,\mathbb{I}, \qquad \frac{\delta\lambda}{\bar{\lambda}} \;\sim\; \sqrt{\frac{N}{Sn}}$$

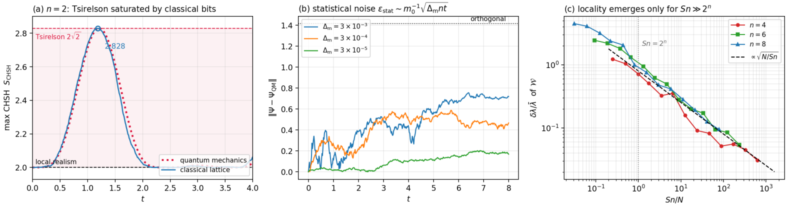
$Sn \gg N$**:** eigenvalues concentrate, $\mathcal{W} \to \mathbb{I}$, and the boundary sees $H$ — two-local, nearest neighbour, with a light cone.

$Sn \lesssim N$**:** $\mathcal{W}$ has an $O(1)$ eigenvalue spread and $\mathcal{W}H$ is geometrically nonlocal and high weight. The bit stream is then governed by a generator with no light cone at all.

<u>Locality of the sampled output is a large-$S$ phenomenon.</u>

$\varepsilon_S(t) \;\sim\; t\sqrt{N/Sn}$ — the only error that grows with $N = 2^n$.

# A Bell violation made of classical bits.




**(a)** The output bits are sampled from $P = 1/N + \epsilon_\Psi \Psi$. Reading $\Psi$ off the bit statistics and forming the CHSH correlator gives $S_{\mathrm{CHSH}} = 2.828$ against $2\sqrt{2} = 2.8284$ — Tsirelson saturated, by a random walk on $4 \times 4$ stochastic matrices.

**(b)** The only deviation visible at $n = 2$ is statistical: $\varepsilon_{\mathrm{stat}} \sim m_0^{-1}\sqrt{\Delta_{\mathrm{m}} n t}$. The violation survives as long as the feedback step is small.

**(c)** But at $n = 2$, $\mathcal{W} \propto \mathbb{I}$ identically, for every $S$: the extra dimension does nothing but rescale the learning rate. The genuine $S$-dependence is the concentration of the kernel, and it needs $n \geq 4$:

$$\frac{\delta\lambda}{\bar{\lambda}} \simeq 0.8\sqrt{\frac{N}{Sn}}, \qquad N = 2^n$$

True Bell states emerge only when $Sn \gg 2^n$ — exponentially deep bulk.

# And if the bulk bits are real?

Count things, as before. Boundary: $n$ bits. Bulk: $\sim Sn \gtrsim 2^n$ bits. The extra dimension holds <u>all</u> of the machine.

Real bits need somewhere to be:

| | |
|---|---|
| bulk bits needed at $n = 1000$ | $7 \times 10^{300}$ |
| Planck four-cells, 1000-qubit chip | $10^{140}$ |
| Planck four-cells, observable universe | $7 \times 10^{245}$ |

So one of the following must hold:

(i) the emergent locality of the output bits fails at some $n \lesssim \log_2 S$;
(ii) the bulk bits are not physical things.

Slagle and Preskill choose neither. They say for our universe $n \gtrsim 10^{23}$ would need $S \gg 2^{10^{23}}$, which they call implausible.

<u>The testable residue: deviations appear at $\tilde{n} \approx \log_2 S$.</u>

Deep circuits on $\tilde{n}$ high-fidelity entangled qubits bound $S$ from below.

# Rational Quantum Mechanics (RaQM)

Tim Palmer, PNAS, (2026).

Qubit state: $|\psi\rangle = \cos(\theta/2)|1\rangle + e^{i\phi}\sin(\theta/2)|-1\rangle$

'Behind' every qubit state is a binary string of length $L = 2^M$ defined as

$$\{a_1, a_2, a_3, \ldots a_L\} \qquad a_i \in \{-1, +1\}$$

In the case of $N$ qubits, there are $N$ such binary strings.

The number of $-1$ s determines a rational value of the probablity

$$\cos^2(\theta/2) = m/L$$

$$\phi = n/L$$

... rational QM

# Rational Quantum Mechanics (RaQM)

What is the role of $\phi$ in binary strings?

Define the cyclic shift

$$\zeta\{a_1 a_2 \ldots a_L\} = \{a_2 a_3 \ldots a_L\, a_1\},$$

and let $T(m,n) = \zeta^n\{\underbrace{1\ldots1}_{L-m}\underbrace{-1\ldots-1}_{m}\}$ , i.e. a block of $-1$s of length $m$, cyclically rotated by $n$ places.

Two integers $(m,n)$ are the hidden variables behind two continuum d.o.f. $(\theta,\phi)$ of the qubit.

# Rational Quantum Mechanics (RaQM)

In terms of the cyclic permutation operator

$$\zeta\{a_1, a_2, \ldots, a_L\} = \{a_2, \ldots, a_L, a_1\}$$

$$|\psi(m,n)\rangle \equiv \zeta^{\frac{L}{2}+n}\mathscr{I}_L(m) \bmod \xi$$

where $\xi$ is a generic permutation, corresponding to a global phase transformation in QM, and

$$\mathscr{I}_L(m) = \{\underbrace{1, 1, 1, \ldots 1}_{m \text{ times}} \; \underbrace{-1, -1, -1, \cdots - 1}_{L-m \text{ times}}\}^T$$

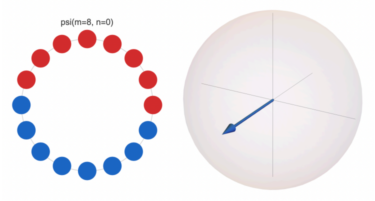
# Rational Quantum Mechanics (RaQM)

$$
\begin{aligned}
|\psi(L,0)\rangle &\equiv \zeta^{\frac{L}{2}}\mathscr{I}_L(L) \bmod \xi = \sigma_z(L)\mathscr{I}_L\Big(\frac{L}{2}\Big) \bmod \xi \\
|\psi(L/2,0)\rangle &\equiv \zeta^{\frac{L}{2}}\mathscr{I}_L\Big(\frac{L}{2}\Big) \bmod \xi = \sigma_x(L)\mathscr{I}_L\Big(\frac{L}{2}\Big) \bmod \xi \\
|\psi(L/2,L/4)\rangle &\equiv \zeta^{\frac{3L}{4}}\mathscr{I}_L\Big(\frac{L}{2}\Big) \bmod \xi = \sigma_y(L)\mathscr{I}_L\Big(\frac{L}{2}\Big) \bmod \xi
\end{aligned}
\tag{32}
$$

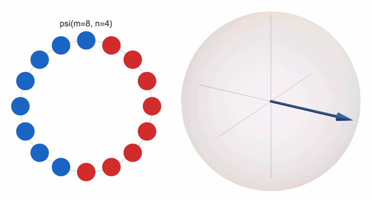
# Rational Quantum Mechanics (RaQM)

Example: $L = 16$.

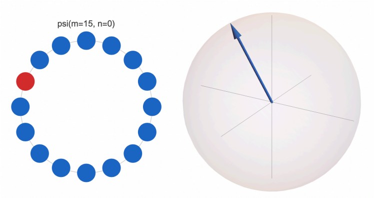
$|\psi(8,0)\rangle$



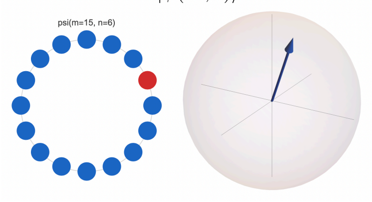

$|\psi(8,4)\rangle$




$|\psi(15,0)\rangle$




$|\psi(15,6)\rangle$



# Rational Quantum Mechanics (RaQM)

Bell states: correlated binary strings.

A product state is two independent strings. Entanglement is encoded by making the second string's structure conditional on the first.

RaQM encodes two-qubit entanglement as **conditional** sub-population structure in the second string, keyed to the first, stuck together by a shared global permutation.

# Rational Quantum Mechanics (RaQM)

Example: $\frac{1}{\sqrt{2}}(|{+}{+}\rangle + |{-}{-}\rangle)$

In the nested parametrisation: $\theta_1 = \pi/2$ (string 1 is 50/50, equator), and then the conditioning is perfect: wherever string 1 is $+1$, string 2 must be $+1$; wherever string 1 is $-1$, string 2 must be $-1$.

$$S_1 = \{+ + \cdots + \mid - - \cdots -\}, \qquad S_2 = \{+ + \cdots + \mid - - \cdots -\}$$

The global $\xi$ is the correlation 'glue'. Fix specific $\xi$ (the hidden variable), you fix both strings' actual bit-orderings together. The outcome on qubit 1 and the outcome on qubit 2 are read from a jointly $\xi$-determined pair.

The correlation is carried by the shared $\xi$ established at the source, not by action at a distance.

# Rational Quantum Mechanics (RaQM)

The problem!

The ordering conflates entanglement with a choice of factorisation, asymmetrically.

The conditional-population encoding is basis-locked, and entanglement isn't.

This is the price for making qubits into things.

In QM, entanglement is a property of the whole. It doesn't live "in qubit 1" or "in qubit 2,"

# Rational Quantum Mechanics (RaQM)

String 2 is conditioned on string 1. For a GENERAL entangled state, conditioning in the other order is a different string construction of the SAME physical state – an under - determination of the "ontology" that RaQM does not resolve .

# Rational Quantum Mechanics (RaQM)

Are $(m, n)$ physical things/events?

Not enough room in spacetime for $L$ to be arbitrarily large.

$$NL = 2^N$$

Cross over at

$$N_{max} \approx \log_2 L$$

> *... QM will start to fail before reaching $N = N_{max}$, because the QM degrees of freedom will be representable only in a increasingly granular way as $N \to N_{max}$. This will manifest itself in terms of erroneous computation (according to the rules of QM) and perhaps be diagnosed as the effects of external noise. Whether this corresponds to the type of noise which affects the accuracy of current quantum computers is worth investigating.*

Palmer 2026.

# Features of RaQM.

The string that defines states has a mean for $\langle S_z \rangle = \cos\theta$ and a standard deviation of $\sin\theta$. Discretize and use Nevin's theorem for spherical triangle geometry gives

$$\Delta S_x \Delta S_y \geq |\langle S_z \rangle|$$

RaQM: measurement complementarity as incompatible observables can't be jointly sharp.

Measurement settings cannot be chosen independently of states(hidden variable, $\lambda$). This looks like superdeterminism.

RaQM is contextual but not in KS sense. It is preparational contextual.

# Curious ML features of RaQM.

It has echoes of Hyperdimensional computing (HDC) and Vector Symbolic Architectures(VCA).

The $J_L$ matrix is exactly the transformer RoPE the most widely deployed positional-encoding primitive in ML.

# Curious ML features of RaQM.

- RaQM state is a lookup table with finite-precision entries.
- Slagle and Preskill's state is a network with finite parameters.

RaQM fails when total bits $\leq$ table size, $NL \leq 2^{N+1} - 2$.
K &S fail when parameters $<$table size, $Sn \leq 2^n$.

# Summary.

S & P keep measurement independence and sacrifice substrate locality: bulk information moves far faster than the emergent light speed.

Palmer keeps local realism and sacrifices measurement independence, via bases with irrational amplitudes being undefined rather than merely unchosen.

# Gravity.

*Things* are *discernable*.

Are spacetime events *things*?

Events are not manifold points. Events are coincidences of field values — Einstein's point-coincidence argument.

Vacuum has no events. Not because there is no field, but because there is nothing for it to coincide with.

# Gravity.

Discernible things trace distinct worldlines.

A thing's worldline is determined by the field it sources, not the field it sits in.

COW, Nesvizhevsky, Asenbaum: external gravity phases a superposition, it does not decohere it. Gravity acts on quantum things.

A quantum thing cannot source a definite gravitational field*. Falsified if gravity can entangle two masses (Bose et al.; Marletto & Vedral, PRL 119, 240401/240402).

*Francisco Pipa, arXiv:2507.05237

Thanks