Reflections of a (Skeptical) Experimental High-Energy Physicist after Teaching a Course on Quantum Computation

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`http://kirkmcd.princeton.edu/examples/ph410problems.pdf`

The reason that faculty teach courses is so that they can learn from the students.
— J.A. Wheeler

Physics of Quantum Computation

Such was the title of the course.

`http://kirkmcd.princeton.edu/examples/ph410problems.pdf`

The bulk of the course was an extended exercise in linear algebra.

Where's the physics?

"Quantum information is just elementary quantum mechanics pushed a few steps further." — C.A. Fuchs

Is there any NEW physics in quantum information?

Remediations:

Quantum mechanics is not just partial differential equations.

Pauli spin matrices are examples of rotation matrices.

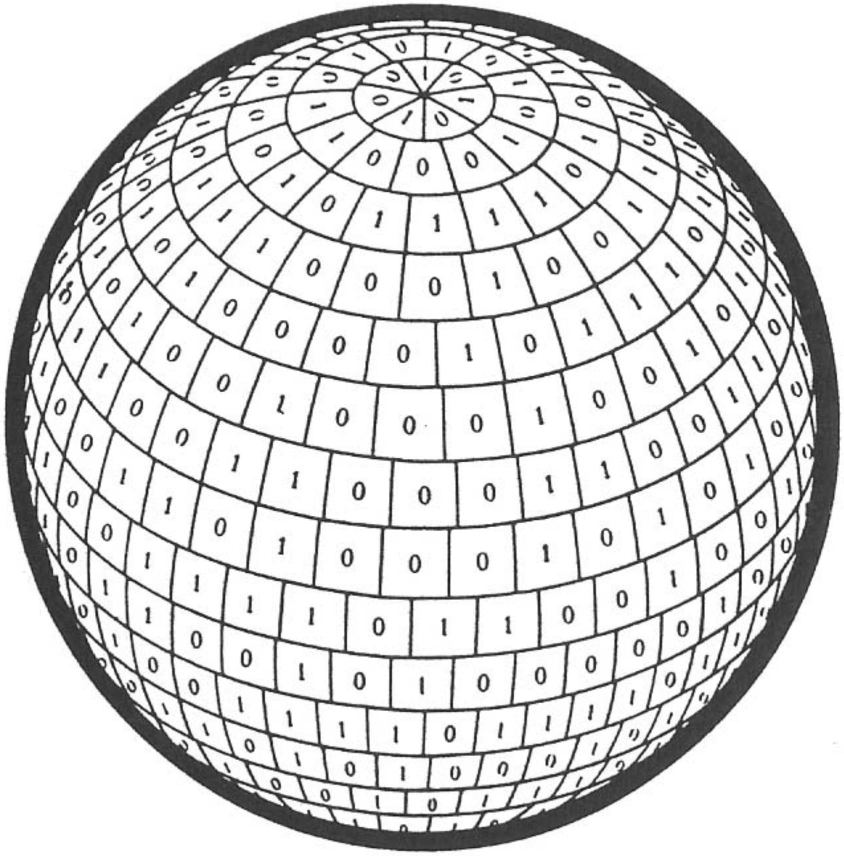
Classical optics = quantum mechanics of single photons; quantum optics = $\cdots$

Measurement takes time; measurement requires entanglement.

Entanglement is an essential difference between classical and quantum systems.

(H *is not Planck's constant, and is not the Hamiltonian, but is the Hadamard transformation.)*

“It from Bit” — J.A. Wheeler



The **conjecture** is that the quantum Universe may be better understood as an information processing system than as a mechanical system.

Any Quantum Process is a Computation

Unitary time evolution, $|\mathrm{After}(t)\rangle = \mathsf{U}(t,t')|\mathrm{Before}(t')\rangle$**, is a quantum computation.**

But what does it compute? (to paraphrase Spock**) [Why the quantum? —** J.A. Wheeler**]**

The "result" of most quantum computations is to provide such stability over time as is observed in the Universe.

There is no stability in the classical Universe. — S. Earnshaw **(1839)**

The stability of atoms is a quantum phenomenon. — N. Bohr **(1913),** E.H. Lieb **(1976)**

How are stable records of measurements produced? — J. von Neumann **(1932),** W.H. Zurek **(1981)** *1. Entangle. 2. Separate. 3. Project. (ESP)*

Entanglement is tricky: Joint information is not localized.
(Coefficients α **and** β **of** $\alpha|0\rangle_A|0\rangle_B + \beta|1\rangle_A|1\rangle_B$ **are NOT a property of either** A **or** B**.)**
— A. Einstein, B. Podolsky, N. Rosen **(1935)**

Why don't we observe "cat" states, $\alpha|0\rangle + \beta|1\rangle$, $\alpha|0\rangle_A|0\rangle_B + \beta|1\rangle_A|1\rangle_B$, *etc.*, **more often in Nature? —** E. Schrödinger **(1935)**

The physics challenge of quantum computation is to trick Nature into being "really quantum", whereas left to itself Nature uses quantum computation to make the Universe appear "classical".

Theory Reinforces the Interest in Algorithmic Quantum Computation

Information is physical. — R. Landauer **(1961)**

Computation is reversible, except for erasure. — C.H. Bennett **(1973)**

An unknown quantum state cannot be copied exactly.
— D. Dieks, M.L. Hardies, P.W. Milonni, W.K. Wootters, W.H. Zurek **(1982)**

Classical computations can be performed by quantum devices.
— P. Benioff, R.P. Feynman **(1982)**

Quantum "parallelism" permits (some) quantum computations to be shorter than their classical versions. — D. Deutsch **(1985),** P. Shor **(1994),** L. Grover **(1997)**

$$\mathsf{U}_f|x\rangle|y\rangle = |x\rangle|y \oplus f(x)\rangle \qquad \Rightarrow \qquad \mathsf{U}_f\frac{|0\rangle + |1\rangle}{\sqrt{2}}\frac{|0\rangle - |1\rangle}{\sqrt{2}} = \frac{(-1)^{f(0)}|0\rangle + (-1)^{f(1)}|1\rangle}{\sqrt{2}}\frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

Classical error-correction procedures are readily generalized to quantum computations. — P. Shor **(1995)**

This kind of theory, which takes elementary quantum mechanics a few steps further, gives much encouragement that, but little/no guidance as to how, long-lived "cat" states and algorithmic quantum computation can be realized in practice.

The challenge of such realization is now almost purely experimental.

One Bit, Two It, Three I(nfinity) — Gamow-Wheeler