Are Universal Quantum Computers Possible - My Debate with Aram Harrow

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Are quantum computers possible?

The feasibility of computationally superior quantum computers is one of the most fascinating and clear-cut scientific problems of our time.

The main concern regarding quantum-computer feasibility is that quantum systems are inherently noisy. This concern was put forward in the mid-90s by Landauer, Unruh, and others. (Better understanding of decoherence is a problem of great importance.) Quantum error-correction and quantum fault-tolerance gave good response to these concerns.
Are (universal) quantum computers impossible?

There is surprisingly little effort devoted these days to trying to pursue a negative answer. Robert Alicki’s works (some with various coauthors) are a notable exception. My research over the past years is also geared towards negative answer and my recent paper: “How quantum computers fail: Quantum codes, correlations in physical systems, and noise accumulation,” have led to the debate that I will describe here.
Debate!

From the end of January 2012 Aram Harrow, a brilliant researcher in quantum information and computation from the University of Washington, Seattle and me are engaged in a public academic debate regarding this question. The debate was hosted on Dick Lipton and Ken Regan’s blog “Gödel’s Lost Letter and P=NP” This lecture will summarize some highlights of the debate so far. The lecture tries to touch some of the main conceptual issues discussed so far.
Gödel’s Lost Letter and P=NP

Perpetual Motion of The 21st Century?
JANUARY 30, 2012
by KWRegan

tag: BQP, Machine, quantum

Are quantum errors incorrigible? Discussion between Gil Kalai and Aram Harrow

Gil Kalai and Aram Harrow are world experts on mathematical frameworks for quantum computation. They hold opposing opinions on whether or not quantum computers are possible.

Today and in at least one succeeding post, Gil and Aram will discuss the possibility of
Background
Noisy quantum systems

The early concern that quantum systems are inherently noisy raised several questions:

- Why are quantum systems noisy?
- What is the nature and magnitude of the noise?
- Can we reduce via engineering the noise level per qubit to be $1/\text{poly}(n)$?
- Isn’t it the case that the whole universe manifests a pure quantum evolution?
- Isn’t noise (and pure evolutions) just a subjective matter?
- ...

These and other arguments led several researchers to regard noise (even before quantum error correction and certainly after) as an engineering issue which has no roots in fundamental physics.
Quantum error correction and FTQC

The theory of quantum error correction and fault-tolerant quantum computation (FTQC) and, in particular, the threshold theorem, which asserts that under certain conditions FTQC is possible, provide strong support for the possibility of building quantum computers.

FTQC allows to embed via quantum error correction a noiseless universal quantum computer inside a noisy quantum computer. (The overheads in time and space are rather small.)

Clarification: In this lecture noiseless means “noiseless for all practical purposes”. (The probability of errors is negligible.)
This lecture:

- Part I: The Debate post 1 - My conjectures, interpretation, and motivation
- Part II: Aram Harrow’s three posts, and other claims raised against my conjecture
- Conclusion
Part I: My conjectures:
Conjecture 1: No quantum error-correction

My first post described my conjectures regarding how noisy quantum computers *really* behave. Starting with

**Conjecture 1:** (No quantum error-correction): In every implementation of quantum error-correcting codes with one encoded qubit, the probability of not getting the intended qubit is at least some $\delta > 0$, independently of the number of qubits used for encoding.

Ordinary models assume the existence of some small $\delta$ for the individual qubit-noise and reduces the amount of noise exponentially via quantum fault-tolerance.
Conjecture 2: The strong principle of noise

Conjecture 2: (The strong principle of noise): Quantum systems are inherently noisy with respect to every Hilbert space used in their description; It is impossible to find noiseless subsystem embedded in a noisy system.
Conjecture 3: Two qubits behavior

A noisy quantum computer is subject to error with the property that information leaks for two substantially entangled qubits have a substantial positive correlation.

(This is a conjecture about appropriate modeling of noisy quantum computation.)
Conjecture 4: Error synchronization

In any noisy quantum computer in a highly entangled state there will be a strong effect of error synchronization.

(This is a physics conjecture.)
How to express these conjectures mathematically and one reduction

I found that the best way to express error-synchronization (Conj. 4) and positive correlation for information leaks (Conj. 3) is by the expansion to product of Pauli operators.

We need a stronger form of Conjecture 3 where “entanglement” is replaced by a measure of expected entanglement based on (separably) measuring the other qubits in an arbitrary way. **Theorem:** This strong form of Conjecture 3 implies Conjecture 4.
Three Possible interpretations

The *strong interpretation* is that the conjectures hold globally, for any quantum dynamical system on which a QC can be based.

The *medium interpretation* says they hold for processes currently observed in nature, but human artifice can create systems in which they are false, thus allowing computationally superior QCs to be built via FTQC.

The *weak interpretation* is that they only make a sharp distinction between two kinds of QC models, one supporting FTQC and the other not, and that the former kind can be built artificially and also does represent some quantum processes that occur naturally.
Censorship, smoothed evolution equations, rate

**Conjecture C:** Very highly entangled pure states cannot be approximated at all.
Steve Flammia and Aram Harrow shot down a suggested formulation; we discuss other possibilities.

**Smoothed Lindblad equations:** Detrimental noise that cannot be avoided can be described in terms of “smoothed Lindblad evolutions”.
(This was briefly discussed.)

**A conjecture regarding rate:** The rate of noise at time $t$ is bounded below by a noncommutativity measure for the unitaries expressing the evolution at $t$.
(This issue was not discussed, so far.)
Motivation

An explanation for why universal quantum computers are unrealistic may require some change in physics theory of quantum decoherence. On the other hand, universal quantum computers will be physical devices that are able to simulate arbitrary quantum evolutions, where the word “simulate” is understood in the strong sense that the computer will actually create an identical quantum state to the state created by the evolution it simulates, and the word “arbitrary” is understood in the strong sense that it applies to every quantum evolution we can imagine as long as it obeys the rules of quantum mechanics. As such, quantum computers propose a major change in physical reality.
Part II: Aram responses and other claims against my conjecture
Aram’s first post: Why classical computers are possible?

Gödel’s Lost Letter and P=NP

Flying Machines of the 21st Century?
FEBRUARY 6, 2012

by KWRegan

tags: BQP, error correction, quantum

First of three responses by Aram Harrow

Dave Bacon began the blog The Quantum Pontiff in September 2005. Thus he was among the earliest voices promoting the theory of quantum computation, and explaining it brilliantly in ways non-experts can understand. He now works at Google in the Seattle area, while his blog is staffed by “A College of Quantum Cardinals”: Charlie Bennett, Steve Flammia, and our second debate participant, Aram Harrow.

Today Aram begins a three-part rebuttal to Gil Kalai’s post with conjectures about entangled noise as an impediment to building quantum computers.

He has chosen Bacon as “patron saint” for this first part. In
Aram’s first post: Why classical computers are possible?

The first reason I’m skeptical about Gil’s conjectures is that... Gil questions the independence assumption of errors. But if highly correlated errors routinely struck computers, then they would also be a problem for classical computers.

Quantum mechanics describes everything, including classical computers. If quantum computers suffer massively correlated errors with non-negligible probability, then so must classical computers, be they Pentiums or abacuses (or DNA, or human memory).

If electrons hop from wire to wire not one-by-one, but a trillion at a time, then those correlated bit-flip errors would defeat a classical repetition code, just like they’d defeat various quantum coding schemes. To distinguish these cases, you would have to have that Z errors (the ones that only quantum computers care about) are highly correlated, while X errors are not.
Second response by Aram Harrow

Albert Einstein was a great observer of science, as well as doer of science. Most of his quotations as well as theories have proved their staying power over the past century. We, Dick and Ken, feel that some of them are better when understood narrowly within science rather than taken broadly as they usually are.

Today our guest poster Aram Harrow opens his second response to Gil Kalai’s conjectures of impediments to quantum computation by applying one of Einstein’s quotations in such a focused manner.

The quotation, and Einstein’s own clarification of it, are conveyed in this article on him and the mathematician Oswald Veblen, regarding the latter’s request in 1930 to inscribe the quotation on a plaque in the new
Aram’s second post (I): Does Entanglement Cause Correlated Errors?

Quantum computing (probably) requires producing large entangled states to be interesting. Gil suggests that this entanglement may be self-limiting, by increasing the rate at which correlated errors occur. This is one of the routes he proposes for generating highly correlated errors in quantum computers.
Aram’s second post (I): Does Entanglement Cause Correlated Errors (cont.)?

The key reason I regard this as unlikely is that quantum mechanics is linear, in the same way that stochastic maps act linearly on probability distributions. This means that there is no physical process that can distinguish an arbitrary entangled state from an arbitrary non-entangled state, just as no test can determine whether a probability distribution is correlated, given only a single sample. Specific states can be distinguished, but there is no “entanglement” or “correlation” observable that can be measured. In particular, when “noise” is modeled in the usual manner as a trace-preserving completely-positive linear map, then linearity forbids noise depending on whether the host system is entangled.
Another route to correlated errors is by piggy-backing on our computation. For example, suppose that we control our ion-trap quantum computer by blasting it with lasers. The lasers are macroscopic objects, and if there were other ions, or systems that behaved like ions, lurking near the ions we use for qubits, then these would be similarly affected by the lasers. If we were unlucky, these “shadow qubits” might interact with our computational qubits in ways that caused errors, and now these errors would exhibit complicated correlation patterns that would depend on the history of laser pulses we have used. Thus, even though there is no direct way for errors to depend on whether our states are entangled or not, errors could depend on shadow qubits, whose entanglement/correlation could be produced at the same rate as entanglement/correlation in our quantum computer.

Aram analyzed this scenario and explained why it can be resolved.
Aram’s third post: Two thought experiments

Gödel’s Lost Letter and P=NP

The Quantum Super-PAC
MARCH 5, 2012
by KWRegan

tags: BQP, Machine, quantum, randomness

What unlimited contributions might buy you in power

John Preskill is no stranger to high finance in physics. In 1997 he made a famous bet against Stephen Hawking and Kip Thorne relating to the black hole information paradox. Hawking conceded the bet in 2004, but Thorne has yet to agree. The prize was an encyclopedia of the winner’s choice, which for Preskill was Total Baseball: The Ultimate Baseball Encyclopedia.

Today we present the third of three installments of Aram Harrow’s initial response to Gil Kalai’s
Suppose we approach quantum computing with an attitude of extreme pessimism. Suppose that anything non-classical that can be correlated, probably is, and in the way that we’d least like. Might Gil Kalai’s conjectures hold in this case, and prevent the construction of a large-scale quantum computer? I will argue that even in this case, by using unlimited resources we could build a quantum computer that would address even the most dire pessimism.
Third post: Aram’s first thought experiment - intergalactic QC (cont.)

One approach would be to put the quantum computer in a place where there is very little noise other than what we introduce ourselves, like interstellar space. Then the individual components could be placed far apart, so that we are very unlikely to introduce multi-qubit errors by our inadvertent actions on shadow qubits. For example, we might construct a linear optics quantum computer with each gate a kilometer apart. Correlations between noise processes on different qubits should be essentially zero, except when qubits are interacting.
An even more imaginary quantum computer... provides another thought experiment that refutes Gils conjectures. Imagine a large quantum computer with a high rate of noise. The experimenter attempts to create entanglement between qubits, and can indeed apply the entangling operations, but this entanglement almost immediately disappears because of noise from the environment. So far uncontroversial.

But what does it mean that the entanglement disappears because of noise? The Schrödinger equation says that the state of the entire universe changes unitarily. How can entanglement disappear in such a model? This is an old problem in the interpretation of quantum mechanics. The key is a principle commonly called “going to the church of the larger Hilbert space.”
Any noisy quantum process can be modeled as a unitary interaction with the environment, followed by discarding [formally, tracing-out] the qubits of the environment. That is to say, unitary evolution only appears noisy because it involves systems, such as photons heading away at the speed of light, that are out of our control. This picture offers a way to resolve the problem of noise in quantum computers, albeit one that wont yield any practical computational speedups. We simply redefine what we call the “computer” to include all of the qubits in the environment that interact with it. This gives us a quantum computer that is definitely in a pure, highly entangled state, performing calculations that we have no idea how to simulate in sub-exponential time.
The discussion

Peter Shor
March 11, 2012 9:18 pm

The difference between (*) and (**) is that in (*) the universe needs to know what code you are using in order to foil you. This attributes both more intelligence and more malice to the universe than I am willing to believe that it has.
Other objections

- **Cris Moore:** Skepticism of quantum computers means skepticism of quantum mechanics
- **Joe Fitzsimons’s:** Blind computation
- **Peter Shor, Rachel:** Nature does not conspire
- **John Preskill:** A general model where the threshold theorem holds
- **Joe:** A 2-locality argument
My response

I will not present my response to Aram’s important objections as well to others’ in this lecture. The discussion over the blog so far, and my next (and final) two posts contain a very detailed response to Aram’s main points and to objections made by others and raise some additional important issues. (I have good answers.) Stay tuned, participate!

The discussion is related to many issues in quantum mechanics, open quantum systems, the nature of quantum approximation, cooling, topological QC, measurement-based QC, adiabatic QC, computational complexity, simulating quantum physics, perturbative methods, non-Abelian anyons, Bose-Einstein condensation, and more. In my opinion, it is a good-quality academic debate and I am thankful to Aram, our hosts, and the other participants.
The construction of universal quantum computers is a serious scientific possibility and an excellent working assumption. Building universal quantum computers will be a once-in-a-lifetime scientific and technological achievement, and even partial steps on the way will suffice for receiving the highest possible scientific recognition. Operating quantum computers will lead to further terrific scientific and technological fruits, for decades, just like the discovery of X-rays. Quantum error-correction is an important concept for building fault-tolerant quantum computers and is a fundamental scientific concept on its own. Building quantum computers is an endeavor which should vigorously be pursued, and indeed it is pursued theoretically and experimentally by top researchers who already established impressive achievements. My university, The Hebrew University of Jerusalem, just established a new Center for Quantum Information!
Conclusion (preview, cont.)

Yet, it may well be the case that universal quantum computers are not possible and that “no quantum fault-tolerance” should be taken as the guiding principle in modeling quantum decoherence. Developing a theory of non-fault-tolerant quantum evolutions, and studying how quantum computers fail, is an interesting and important endeavor. Non-FT quantum evolutions may offer new relevant models for quantum evolutions in nature, and may lead to substantial new insights on related physical models, theories, and computational methods.