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Special Topics : Quantum Computers : Daniel Lidar Interview - Special Topic of Quantum Computers

AUTHOR COMMENTARIES - From Special Topics

Quantum Computers - Published: March 2010
Interview Date: May 2009

PDF

Daniel Lidar

From the Special Topic of Quantum Computers

According to our Special Topics analysis of quantum computers research over the past decade, the work of Dr. Daniel Lidar ranks at #4 by total number of papers, based on 79 papers cited a total of 1,814 times between January 1, 1999 and December 31, 2009.

In the Web of Science®, *Dr. Lidar currently has 113 original articles, reviews, and proceedings papers from 1998-2010, cited a total of 3,318 times. Six of these papers have been named as Highly Cited Papers in the field of Physics in* Essential Science IndicatorsSM *from Thomson Reuters.*

Dr. Lidar is Associate Professor in the Departments of Electrical Engineering and Chemistry at the University of Southern California in Los Angeles. He is also the Director and co-founding member of the USC Center for Quantum Information Science and Technology (CQIST).

In this interview, he talks with* ScienceWatch.com *about his highly cited research on quantum computers.

SW: What first drew your interest to the field of quantum computing?

As I was finishing my Ph.D. research on scattering theory and disordered systems I realized I wanted a change of subject. A fellow graduate student told me about Shor's algorithm—the algorithm for efficient factoring which launched the field of quantum computing—and I was hooked. You can read about my educational background and research experiences at the end of this page.

This was in '96, and Shor had published his algorithm two years earlier, so the field was still relatively embryonic and unpopulated. All the papers that had been written on the subject literally fit on my desk. I thought it would be a good idea to move into an exciting young field of study which I could read everything about, and decided to switch to quantum computing. Moreover, this field seemed to contain a nice mix of fundamental questions and practical applications, both of which appealed, and continue to appeal, to me.

I wrote my first quantum computing paper with my Ph.D. advisor Ofer Biham several months later. At the time there were very few postdoc positions in the field, and I was lucky enough to find one at UC Berkeley, in Birgitta Whaley's group. Several terrific graduate students joined the group, and we worked well together. It was a very productive and inspiring period, which solidified my interest in quantum computing.

SW: What is your main focus in the field?

My main focus is on ensuring that quantum computers can work reliably in spite of their extreme fragility. Quantum computers are particularly susceptible to decoherence, which is the result of their inevitable interactions with their environments. Decoherence can be thought of the process by which a quantum system becomes classical. For a quantum computer this means the loss of any computational advantage over classical computers.

I have worked on a variety of different approaches designed to ensure the reliable operation of quantum computers in the presence of inevitable decoherence and other sources of noise and imperfections. These approaches include "hiding" a quantum computer from its environment (decoherence-free subspaces), minimizing the interaction between computer and environment (dynamical decoupling), and correcting errors induced by the environment and other noise sources (quantum error correcting codes).

Most of my recent work on overcoming decoherence has focused on dynamical decoupling. The basic idea comes from the spin-echo effect in nuclear magnetic resonance. More than 50 years ago Hahn observed that the rapidly decaying signal from nuclear magnetic resonance measurement could be revived, or "refocused," by applying a series of strong and frequent modulating pulses to the system under investigation.

This idea was picked up in the quantum computing community, starting with Lorenza Viola and Seth Lloyd in 1998, to overcome decoherence in quantum computers. In 2005 my former student Kaveh Khodjasteh (now a postdoc at Dartmouth College) and I proposed a variation on dynamical decoupling we called "concatenated dynamical decoupling," which involves recursively constructed pulse sequence and can in principle reduce decoherence to arbitrarily low levels much faster than other decoupling methods, and is inherently fault-tolerant to some degree.

> *"One reason that decoherence-free subspaces are important is because they offer a way to protect quantum information 'for free."*

Very recently we generalized these ideas, together with Lorenza Viola, to show that arbitrarily accurate quantum logic gates can also be implemented using concatenated pulses design ("Arbitrarily accurate dynamical control in open quantum systems," *Physical Review Letters* 104[9]: art. no. 090501, 5 March 2010). I continue to work on dynamical decoupling with my students Gregory Quiroz and Wan-Jung Kuo.

Another focus of my work (mostly with my former student Joseph Geraci, now a scientist at the Ontario Cancer Biomarker Network) has been the design of algorithms which could run more efficiently on quantum than on classical computers, especially those pertaining to simulations of classical physics.

I have also been quite interested in developing methods to experimentally measure and characterize quantum noise channels, technically known as quantum process tomography. My former student Masoud Mohseni (now a postdoc at MIT) and I found efficient ways to do this using techniques borrowed from quantum error correction theory.

Most recently I have been devoting much of my attention, together with my postdocs Dr. Ali Rezakhani and Alioscia Hamma (now at the Perimeter Institute) and graduate students Wan-Jung Kuo and Kristen Pudenz, to an approach to quantum computing called "adiabatic quantum computing," which I find particularly intriguing and promising.

In the adiabatic approach the idea is to very slowly change the interactions between the particles in the quantum computer, so that while the initial interactions correspond to a Hamiltonian with a very simple ground state, the final interactions correspond to a Hamiltonian with a complicated ground state that encodes the answer to a hard computational question.

There are some similarities between this idea and the well-known simulated annealing algorithm, but the difference is that in adiabatic quantum computing the system is supposed to always remain in its ground state, so that the entire evolution actually takes place very close to zero temperature. This implies some natural robustness against decoherence, as well as intriguing connections to quantum phase transitions, and more widely to condensed matter physics.

As a result adiabatic quantum computing provides a natural bridge between computer science and physics, which I find particularly appealing. I have always believed in the fruitfulness of combining ideas and techniques from a variety of different fields, which is another reason I was initially drawn to quantum computing.

SW: Your most influential paper in the field wasn't actually included in our analysis, as it was published a year prior to our 10-year time window, but it's important to address it—your 1998 *Physical Review Letters* paper, "Decoherence-Free Subspaces for Quantum Computation," (Lidar DA, *et al*., 81[12]: 2594-7, 21 September 1998). Why is this paper cited so much?

This paper was among the first to point out that symmetry can be used to hide quantum information from the detrimental effects of decoherence. Symmetry has always fascinated physicists, and putting it to use to overcome some of the initial skepticism directed at quantum computing in light of decoherence was apparently an idea that was appreciated by the community.

I should point out that my USC colleague Paolo Zanardi co-authored an earlier paper on a closely related topic (Zanardi P, Rasetti M, "Noiseless quantum codes", *Physical Review Letters* 79[17]: 3306-9, 27 October 1997) which really provided the inspiration for our 1998 paper.

SW: Many of your papers in our analysis deal with decoherence-free subspaces. Could you explain what these are and why they are important?

A decoherence-free subspace is a way to exploit a pre-existing symmetry in order to hide quantum information from the environment that tries to corrupt this information by measuring the state of the quantum computer.

Here is a classical analogy: You have two coins and want to use them to store one bit of classical information. "Easy," you say, "since two coins represent two bits of information." But now imagine that some nasty demon keeps flipping the coins at random, so that your efforts to store a bit are frustrated.

Fortunately the demon can only flip both coins simultaneously. Is it still possible to reliably store a classical bit?

> *"I have worked on a variety of different approaches designed to ensure the reliable operation of quantum computers in the presence of inevitable decoherence and other sources of noise and imperfections."*

A moment's reflection reveals that the answer is yes: define the two subspaces "equal" (even parity) and "opposite" (odd parity). The first is the subspace comprising the states {heads,heads} and {tails,tails}. The second subspace is {heads,tails} and {tails,heads}. Now call "equal" 0 and call "opposite" 1. Since the demon can only flip both coins together, these 0 and 1 are protected. Indeed, under the demon's action {heads,heads}<–>{tails,tails} and {heads,tails}<–>{tails,heads}, so that the two subspaces never get mixed.

Thus, instead of encoding a bit into each coin, we should encode a bit into the parity of the two coins. What is special about parity? It is the fact that it respects the symmetry induced by the demon's inability to distinguish between the two coins, a permutation symmetry.

One reason that decoherence-free subspaces are important is because they offer a way to protect quantum information "for free." Almost all other methods require active intervention. But perhaps more importantly, it turns out that the idea of using symmetry to protect quantum information actually lays at the heart of all other quantum information protection methods as well. Thus the concept of a decoherence-free subspace provides the starting point for a unified theory of quantum information protection.

Another important reason is that of all the ideas for quantum information protection, decoherence-free subspaces have been probably been most thoroughly experimentally tested. There is now plenty of experimental evidence, in a variety of different systems (linear optics, trapped ions, nuclear magnetic resonance, quantum dots), that decoherence-free subspaces exist and can be used as a first layer of defense in the quest to protect quantum information.

SW: The *Physical Review Letters* paper you wrote with Alireza Shabani last year, "Vanishing Quantum Discord is Necessary and Sufficient for Completely Positive Maps" (102[10]: art. no. 100402, 13 March 2009), has been receiving citation attention. Would you tell us a bit about this paper?

This paper addresses a fairly technical problem, with a foundational flavor. Almost all of the mathematical work in quantum computing, and more generally in quantum information theory, takes for granted that quantum dynamics of open (non-isolated) systems can be described using a relatively simple type of transformation called a completely positive map, which is in some sense a generalization of the Schrödinger equation.

My former student Alireza Shabani (now a postdoc at Princeton) and I wanted to understand the precise conditions under which such transformations actually apply to open quantum systems. Building on an earlier breakthrough by Cesar Rodriguez-Rosario *et al*., we showed that the necessary and sufficient condition for the validity of the completely positive map description (given certain standard assumptions) is that the system (e.g., a quantum computer) and its environment are purely classical correlated, i.e., contain no quantum correlations whatsoever.

Technically such correlations can be quantified using a quantity called quantum discord, and the case of purely classical correlations is when the discord vanishes. The implication of our result is that the standard tool of completely positive maps now has a well-defined and well-understood domain of applicability.

More fundamentally, the implication is that any correlations with non-vanishing quantum discord can be interpreted as not allowing a consistent separation between system and environment, since when the transformation describing the evolution of the system is not a completely positive map, it is well known that in some cases non-physical predictions can arise, in particular events with negative probabilities.

SW: Were there any papers not covered in our analysis that you feel are particularly key to the field? Which papers and why?

Well, clearly the 1998 *Physical Review Letters* paper mentioned above is in this category, but it wasn't covered since it was published prior to 1999.

Two other papers, which are named as Highly Cited Papers in the field of Physics by *Essential Science Indicators* from Thomson Reuters, but which were left out of the Special Topics analysis are "Concatenating decoherence-free subspaces with quantum error correcting codes" (with D. Bacon and K. B. Whaley, *Physical Review Letters* 82[22]: 4556-9, 31 May 1999), and "Quantum phase transitions and bipartite entanglement" (with L.A. Wu and M.S. Sarandy, both former postdocs of mine with faculty positions in Spain and Brazil, respectively, *Physical Review Letters* 93[25]: art. no. 250404, 17 December 2004).

The first of these established that the information-protection methods of decoherence-free subspaces and quantum error correcting codes can be combined to yield a single, more economical and robust method than provided by either methods used separately. The second paper resolved a problem at the interface of quantum computing and condensed matter theory: why quantum phase transitions are often accompanied by drastic changes in quantum entanglement.

SW: How has the field of quantum computing changed in the past decade? Where do you hope to see it go in the next?

The field has undergone tremendous progress, from one driven mostly by theoretical work to a thriving discipline with numerous experimental groups and steady progress toward the goal of building larger and more robust quantum information-processing devices, and a much clearer theoretical understanding of the source of the power of quantum computers and of means of making them robust.

The field has also gained official recognition with a topical group in the American Physical Society, several dedicated journals, special sections in established journals, and dedicated federal funding.

In the next decade I would hope to see the first generation of commercially viable quantum computers, perhaps as dedicated machines capable of performing specialized simulation tasks (the efforts of the Canadian startup D-Wave Systems Inc. are notable in this regard).

I would also hope to see a wave of new faculty positions at US institutions for quantum computation theoreticians and experimentalists. We now have the first generation of students and postdocs trained in this field, many of whom are finding it very difficult to land faculty positions in the US, and are forced to seek such employment in other countries. This is most unfortunate, and I hope that US universities will reverse this trend.

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Additional Information: Read about the educational background and research experiences of Dr. Daniel Lidar.

Daniel Lidar's current most-cited paper in *Essential Science Indicators*, with 176 cites:

Kempe J, *et al.*, "Theory of decoherence-free fault-tolerant universal quantum computation," *Phys. Rev. A* 63(4): art. no. 042307, April 2001. Source: *Essential Science Indicators* from Thomson Reuters.

KEYWORDS: QUANTUM COMPUTATION, SHOR'S ALGORITHM, DECOHERENCE, NOISE, IMPERFECTIONS, DECOHERENCE-FREE SUBSPACES, DYNAMICAL DECOUPLING, QUANTUM ERROR CORRECTING CODES, CONCATENATED DYNAMICAL DECOUPLING, QUANTUM PROCESS TOMOGRAPHY, ADIABATIC QUANTUM COMPUTING, QUANTUM PHASE TRANSITIONS, CONDENSED MATTER PHYSICS.

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