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Quantum Leap

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Building quantum computers to perform at extraordinary speed is still in its early stages, but UC Santa Barbara?s physicists and engineers are leading the way.

The field of quantum information suffers a pachyderm-sized problem: there currently is no quantum computer. The enormity of the challenge contrasts with the nature of quantum mechanics?the science of harnessing the state of particles?which is usually carried out at the subatomic scale.

At UC Santa Barbara, a keen-eyed and clear-speaking A-team of physicists, mathematicians, and engineers are taking on a computing technology game-changer ? development of elements for a quantum computer. Many of them are working alongside physicist David Awschalom at the Center for Spintronics and Quantum Computation, which is part of the California NanoSystems Institute. They are devouring this particular elephant using tools as varied as their disciplines, from home-grown diamonds and state-of-the-art clean room facilities, to a humble whiteboard packed with diagrams and equations.

To say that quantum information technology impacts such tasks as imaging, probing and communications is an understatement, but the holy grail remains quantum computing. To get there, the multi-disciplinary UCSB team must take the leap beyond classical physics and into an entirely new paradigm.

?As you make things smaller and smaller, you leave this regime of the world of classical physics and classical behavior and enter this new area of quantum behavior,? explains UC Santa Barbara physicist David Awschalom, whose team is developing new schemes for processing quantum information with electron and nuclear spins in semiconductors.

?As objects become smaller and smaller, unusual properties of matter?quantum properties?that are normally invisible in our everyday world eventually emerge.? Those properties?which include tantalizing things like time travel and teleportation?open up startling new realms even as they push the current ability to wrangle particles.

?So quantum information scientists pose this question: ?Can you use these quantum properties of matter to build a new technology?? ? Awschalom says. ?Not by replacing the word ?classical? with ?quantum? but by doing things that are completely different, that you couldn?t do with classical technology.?

Quantum computing think tank

?Although there?s a lot of fancy physics going on inside your laptop, the logical processes are classical,? explains mathematician Michael Freedman, the recipient of a Fields Medal?the math equivalent of a Nobel. He heads the on-campus Microsoft research group known as Station Q, which focuses on topological quantum computing. ?It?s been realized in the last twenty years that information can be processed in a more powerful way by inherently using quantum mechanics in the storage and manipulation of information.?

?This is what quantum computing is about,? Freedman says. ?But the question is, ?How are you going to store and manipulate quantum states?? ?

?There are lots of fascinating conversations going on at different points of the problem,? Freedman observes, contrasting the work of theorists at Station Q to, say, UCSB materials scientist Chris Palmstrom or physicist John Martinis. ?But ultimately we have the same job?figuring out what?s going on, what can be done to make it work better.?

Quantum computing must pass from the most abstract to the most concrete before it becomes reality. The quest starts with mathematical imagining, Freedman says, ?a sort of very high level mathematical view which doesn?t include even the notion of an electron or an atom or materials science or anything like that. It floats above the constituents of the real world.?

To translate that mathematical ideal into what would be a programmable machine, he continued, we must pass through layers of knowledge and expertise??from math to theoretical physics to sort of quasi-theoretical physics. And then those people work with bench-top experimentalists, and those experimentalists interact with materials scientists, growers who make certain exotic crystal structures that can be probed.?

?Santa Barbara is uniquely qualified to explore some of these areas,? says Awschalom, ?because to make the small boxes, to make the small devices, in which you can start to explore some of these quantum properties, you need very good materials science, very good physics, very good electrical engineering, very good theoretical science. Here you have all these people in the same place to bounce ideas off of. The DNA of Santa Barbara is very different?people are in the mode of collaborating.?

UCSB physicist Andrew Cleland calls it ?cross-pollination? fostered by shared first-class facilities and faculty that likes to reach consensus??actually a pretty rare combo.?

The researchers share a contagious excitement, with many likening their quest to the breakthrough in transistors half a century ago. But their exact road forward remains a bit

mysterious.

?It?s a little like driving really fast on low beams,? Awschalom suggests: both exhilarating and scary.

?My research could become obsolete within a year if someone else comes up with a really great idea,? observes Martinis, who with Cleland was credited with last year?s greatest scientific breakthrough by the journal Science. ?I think that?s unlikely,? he admits, adding, ?or maybe we?ll be the ones with the idea.?

Applications light years beyond binary code

Most technology today is based on the classical behavior of matter, like electrons moving in circuits. It?s deterministic?in a transistor, for example, the electron is there or it?s not. In quantum mechanics, you can ask the same questions?is it a wave or a particle, is it a one or a zero??and the answer can be yes and no, as well as everything in between (albeit with different probabilities for each value).

Freedman describes these quantum states as fundamental degrees of freedom, the ?degrees that nature hands you, like the spin of an electron or the spin of a nucleus, the polarization of a photon.?

Harnessing these properties would give a quantum computer huge abilities toward solving nettlesome problems in areas like number theory and topology. A quantum computer?s cascade of parallel calculations wouldn?t necessarily be better at solving every problem ever thrown at a machine, but it could address some that are impossible or wildly impractical for classical computers.

Some of the specific problems a quantum computer might crack include designing high-temperature superconductors, simulating concrete but complex physical problems like air flow around jets, crafting amazing information memory banks, speeding up the screening for new pharmaceuticals?or even, Freedman says just a bit woefully, paving the way for ?quantum quants? on Wall Street.

?The scientific capabilities associated with a quantum computer,? Freedman says, ?will be as much ahead of those associated with a classical computer as a computer is over pencil and paper.

?We grope around unaware of the quantum mechanical nature of the universe. We live in this world of averages, which is the classical world. We lose at least half of what?s going on. When our eyes are opened to this other world, and our information can be processed in the full richness that physics allows, then we?ll finally be able to see.?

A quantum computer, in short, would speak the same language as our quantum world.

Station Q tackles topology in quantum computing

At UCSB, that mathematical imagining at the genesis of quantum computing entrains at Station Q. Microsoft debuted the quantum computing think tank six years ago at Freedman?s instigation.

He had spent the previous nine years at Microsoft?s Redmond, Washington campus working on several problems, including the topological mathematics at the core of Station Q?s theorizing.

Freedman describes Microsoft?s corporate research division as a new Bells Labs, the private industry research colossus that in its prime developed things like transistors, lasers and even basic research concepts such as the universe?s background radiation. As such, he said Microsoft?s research arm can be more interested in the long term than the next fiscal quarter.

?It wouldn?t make sense for a computer company with that large of a research investment?certainly the largest of all the computer companies?not to have a presence in this new frontier,? Freedman says. If nothing less, Microsoft could not afford to be blindsided by these developments.

?So instead of just wanting to be clueless,? he adds with a hint of mischief, ?we?ve decided to build a quantum computer.?

Such an undertaking required an academic locale with a strong physics center; the presence of the Kavli Institute for Theoretical Physics sealed the deal for Santa Barbara.

Station Q?s 10 scientists?mostly physicists?and many visitors focus on topological field quantum computing theory, one approach to storing and manipulating quantum states.

Topology?s advantage lies in preserving the stability of information, although Freedman admits that devising the exotic physical materials needed for implementation can seem like taking a ?detour.?

One of the best-known concepts of quantum mechanics recalls that observing the quantum state changes it. ?So if you?re talking to electron spin, you?re trying to speak to it?but the whole universe is also trying to speak to it,? Freedman says.

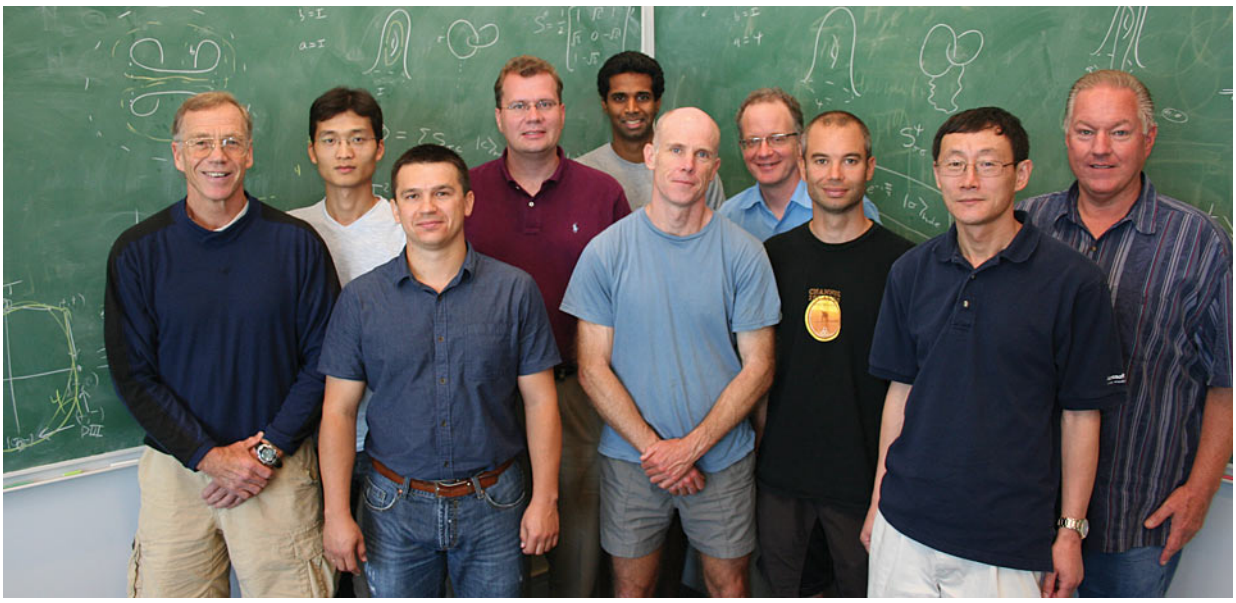
?The virtue of using topological degrees of freedom is that they?re not stored in one place. They have a collective aspect? that?s been likened to a hologram. While this makes it harder for people to manipulate them, it also makes it harder for the environment to influence them. ?It doesn?t know how to speak to these degrees of freedom, so they?re all yours. You have their attention alone.?

Right now, much of Station Q?s attention is glued to providing the mathematical firepower to guide the detection of a low-energy particle known as majorana fermion. That?s a necessary next step to confirm the station?s theoretical approach, and after it?s found, others will ?engineer a habitat for the majorana and have it do the computations we require.?

?Although we do not have a quantum computer,? says UCSB computer science theoretician Wim van Dam, ?we understand how such a device would work.?

He conjures algorithms in which ?a quantum computer would outperform any possible classical computer.?

Van Dam?s efforts underpin the rationale for a quantum computer in the first place. ?We already have some reasons, but the more reasons we have, the more likely it will be that we build one.?



Station Q Microsoft : Front row, (left to right) Michael Freedman, Roman Lutchyn, Kevin Walker, Matthew Hastings, Zhenghan Wang. Back row, (left to right) Hongchen Jiang, Simon Trebst, Chetan Nayak, Paul Fendley, and Sean Fraer. (Not pictured: Bela Bauer, Parsa Bonderson and Lukasz Fidkowski.)

Quantum computing has a particular affinity to number theory and topology, two fields that stoutly resist efficient assault by classical computers and algorithms.

?A lot of problems in computer science are not about number theory, they are like optimization?find the shortest route or optimize the schedule,? says van Dam. ?But a lot of the quantum computing problems discovered since Peter Shor have to do with number theory.?

Challenges in quantum algorithms

The big breakthrough in quantum algorithms, van Dam explained, came in the mid-1990s when Shor, an MIT mathematician, created an algorithm for finding the prime factors of an integer?like five and three for 15. While easily enough done for 15, it?s devilishly harder for big numbers. Codes and encryption live or die based on that difficulty, which explains why the U.S. military and intelligence agencies foot the bill for much of the work on quantum computing at UCSB and elsewhere.

Shor?s breakthrough created expectations that all sorts of problems could be solved in short order. It hasn?t turned out that way.

?Quantum information theory?what you do with quantum mechanics?has been relatively easy. What has been harder than expected is quantum algorithms. ?You know that you can do the following with quantum bits and so forth, but how can I do this efficiently, how can I implement this algorithm to where the running time is not like two centuries? That has been unexpectedly hard, how to do things efficiently.?

But van Dam remains sanguine.

?It?s kind of hard finding such a good algorithm at the beginning of the field, then not finding another good algorithm each year.? But while ?some people say we haven?t discovered anything good since Shor,? van Dam recently co-authored a review paper that enthuses over algorithms developed in the last half decade.

?This has been somewhat frustrating, but also kind of fascinating, to see the weird algorithms that you come up with that nobody would have predicted. Then there are the kind of standard problems that you would think of that you want to solve that we haven?t been able to find an algorithm to solve. It?s kind of humbling??

Perhaps it?s not surprising that such a paradigm shift requires a new way of approaching problems.

?It is a very bad idea to come up with the problem that you want to solve and then to come up with a quantum algorithm; the discovery tends to go the other way around,??van Dam says. ?You find some sort of quantum mechanical phenomenon, and then we see what this is a good tool for. So first we find the hammer, then we find the nail.?

Expanding vistas for the use of quantum mechanics

Quantum mechanics informs more than the quest for a quantum computer. To Freedman, we?ve always lived in a quantum world, but until now have only been able to view it classically. To extend that metaphor, that vision would allow us to see many obscured vistas much clearer, perhaps in a very literal way with magnetometers with unprecedented resolution or maybe with an amazingly better microscope.

While this might seem an obvious need for spies or soldiers, it offers benefits for the movement of financial information?whether foreign exchange transactions or your bank record?or whatever personal material individuals might someday store in the cloud.

Quantum computing in its infancy

The existence or nonexistence of a ?quantum computer? is, appropriately, a probabilistic matter. Lockheed Martin, for example, says it has purchased one from the Canadian company D-Wave Systems?but it won?t be available for 10 years.

Freedman said he doubts anything like a programmable quantum computer is in the cards in the very near future. ?It?s a ways off, but maybe not as long as many people have thought. I?d say right now we are engaged in the fundamental research which will determine whether a quantum computer can be built with essentially present technology. If we find there are no showstoppers, then I would say the quantum computer could be built very fast.?

Experimentalists like Martinis and Cleland, meanwhile, have created a circuit that looks like a classical chip but that computes things using quantum states. But its abilities are sufficiently limited so that the researchers are reluctant to call it a quantum computer.

As Cleland says with a laugh, ?This whole circuit is quantum mechanical?and if you look at it that way, it?s not that interesting.? He too is wary of anyone suggesting we have quantum computers now, suggesting there?s a fair bit of hype and simulation in such claims.

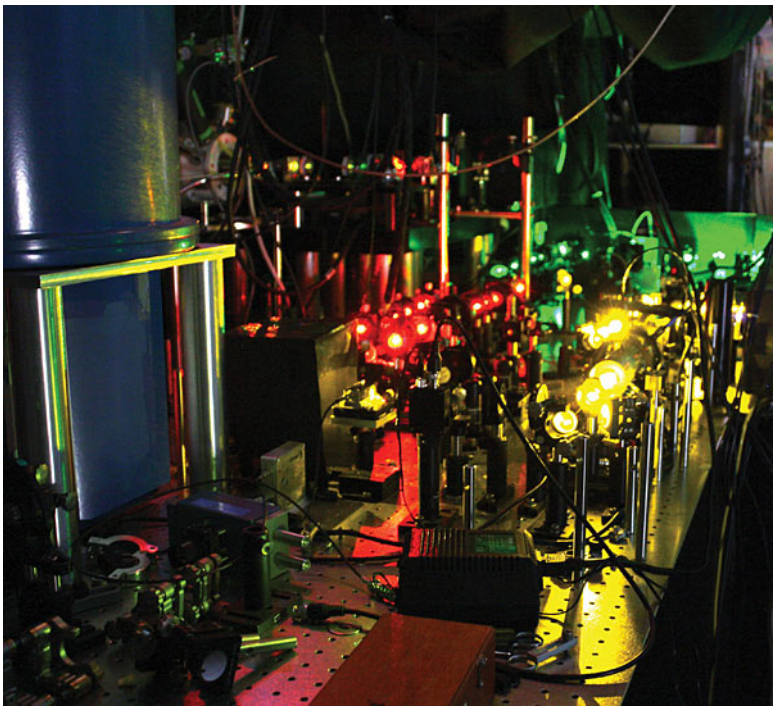
As we?ve seen, there is no single approach being taken to create a quantum computer. ?There?s probably half a dozen physical systems out there,? Cleland says. ?Each has their strengths but each has their weaknesses.?

The ion trap breakthrough

The leading technology is the ?ion trap,? in which ions are captured in a magnetic field and its state manipulated there. Martinis and Cleland pioneered a different direction, using low-temperature superconductors, that the journal Science called the biggest breakthrough of 2010 in science.

Martinis explains that a lot of what made their effort noteworthy is that it?s an exceptionally rare animal?a quantum device that works on a macroscopic scale. ?Usually they?re a very small system,? he says of other approaches, ?and it?s a single electron or a single atom. What people have been figuring out is how to manipulate a single bit or a single atom or a single electron, which is a very interesting development in its own right.

?It has great coherence?you put it in quantum state and it will stay there for a long time. What happens is it?s very challenging to couple them together. The problem is that constituent element is an atom, and to put these atoms together someway to talk to each other, it?s just very, very hard because typically you have to master very small dimensions.?



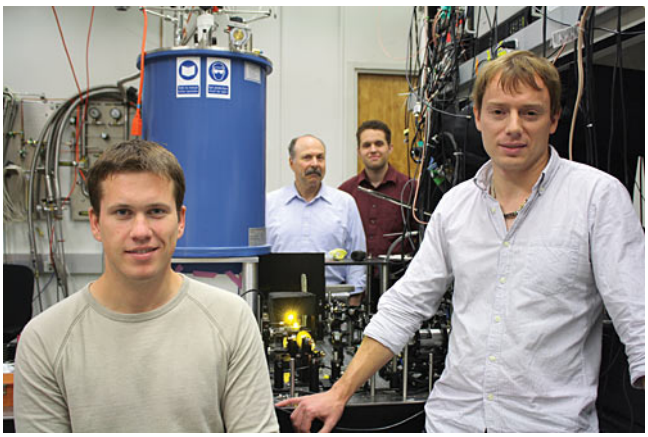
Ultrafast optical pulses are used to manipulate and measure the spin of a single electron in diamond.

Their approach, as the editors of Science wrote, was visible:

The UCSB team ?designed the machine?a tiny metal paddle of semiconductor, visible to the naked eye?and coaxed it into dancing with a quantum groove. First, they cooled the paddle until it reached its ?ground state,? or the lowest energy state permitted by the laws of quantum mechanics (a goal long-sought by physicists). They then raised the widget?s energy by a single quantum to produce a purely quantum-mechanical state of motion.?

?Instead of our quantum system being a single atom, a single electron, it is the currents and voltages flowing in a macroscopic number of atoms. This quantum wave function exists in millions or billions of atoms.

?Since this wave function lives in many, many atoms, you have a big quantum mechanical system, something you can readily make with integrated circuit fabrication.?



Graduate student Will Koehl and CNSI postdoctoral researcher Lee Bassett (left to right) stand in front of an experiment built to explore quantum information processing in semiconductors. Behind stands Professor David Awschalom and graduate student David Christle.

The end result resembles a classical integrated circuit. ?We do it here in the clean room,? Martinis says. ?It requires great infrastructure?it?s difficult to do anywhere, but it?s fairly straightforward.? The ground state is just above absolute zero, but then, ?refrigeration technology is very well developed.?

The numbers that give the circuit its classical beauty are its biggest downside. The circuit?s size means it is touching lots of atoms, and those introduce defects. As Freedman might say, the environment interrupts the conversation. The defects can cause the quantum state to lose its memory?its coherence?quickly.

Ion traps have great coherence?they hold onto the state information tenaciously?but they can?t couple together and scale up easily. ?You need like 10,000 to 20,000 entangled systems, and they?ve got more like a dozen now,? Cleland says. The superconductor approach scales marvelously, but its coherence is a wasted asset. ?It?s the opposite problem?we could build a system with 10,000 qubits, but it wouldn?t work because we?d lose coherence.?

?Having both good coherence and coupling together in a way that you can scale up, that?s very hard to have together,? Martinis says. ?Nature does not make it impossible, but nature makes it hard to do those two things. That?s our job?to beat nature into submission.?

Referring to the ?qubit??the quantum bit that is the fundamental building block of a quantum information system and is essentially a subset of Freedman?s degrees of freedom?Martinis said his team has been able to put together various demonstrations with one, two and three qubits, all the way nine. (Thanks to their properties, even small numbers of qubits can do yeoman?s work; one proposal for encoding routine financial transactions, for example, uses three.)

?We?ve been able to put together a system in an architecture that we think mimics, in at least a small scale, a quantum computer. Certainly not enough to do major computation tasks, but it?s a kind of good demonstration system for showing how you would put together a quantum computer, says Cleland.?

For the last two decades, Awschalom explains, scientists have been developing new experimental techniques and engineering materials from the nanometer scale upward to control and manipulate electron spins and their properties??but always many of them.?

Quantum chips and home grown diamonds

Integrated circuits, which form the backbone of today?s information technology, function by coordinating the movements of electrical charges in a carefully choreographed dance directed by billions of electrical gates. In addition to charge, however, the electron has a magnetic property known as ?spin,? a purely quantum mechanical state of the particle that can also be manipulated using forces applied from outside. Contrary to theoretical expectations, researchers in the Awschalom group have demonstrated that electron spins and their quantum properties can be surprisingly accessible and far more robust than anyone anticipated.

Industry has already found some uses for spin?hard drives became much smaller and faster fourteen years ago with the commercialization of a spin-based electronics technology made from alternating layers of magnetic and non-magnetic metals called the giant magneto-resistance (GMR) read head. During the last decade, Awschalom and his students have discovered and unraveled the physics behind fundamentally new phenomena that allow them to generate, manipulate, and transport electron spins along with their quantum properties in a variety of semiconductors ? a surprising development in the field of semiconductor science and technology.

By showing that electron spins in semiconductors and semiconductor nanostructures can be carefully controlled, their experiments have shown that spin offers a unique opportunity to develop new information technologies that exploit the seemingly otherworldly rules of quantum physics. ?For a truly quantum technology one challenge is to manipulate a single elementary particle, which until recently has been a significant obstacle?to control just one electron spin, or even one nuclear spin,? Awschalom says. ?And as is often the case in our world, the answer appeared through a combination of materials development and new physics.?

In this case, the ?new physics? comes from a material that is actually a very old: diamond. And in Awschalom?s group, they?ve been growing them. But rather than making flawless diamonds, his team is intentionally building defects into the structure ? and the defects are what make these diamonds so valuable. Oddly enough, their idea is based on abandoning the traditional goal of fabricating ?perfect? nanostructures, and to embrace defects. ?After all,? says Awschalom, ?in semiconductors, like people, it?s the defects that make things interesting.?

The perfect carbon lattice of a pure diamond doesn?t do much for the quantum experimentalist. But remove one of those carbon atoms??make a defect you normally don?t want??and if there?s a nitrogen atom nearby, you can trap a single electron surprisingly well. ?The spin of this single electron can be controlled with exquisite precision using electrical techniques up to gigahertz frequencies, and then read-out using a simple hand-held laser. This ability to measure and manipulate a single quantum state on the desktop opens the door to a host of new quantum physics experiments that had previously been simply unthinkable?, says Awschalom.

Recently, Awschalom and his students have demonstrated a scheme in which they are able to move the quantum state of an electron spin into the adjacent subatomic core of a nitrogen atom: a true quantum memory based on a single nuclear spin. This quantum gate operates on nanosecond time scales, and offers a scalable pathway to subatomic storage of extraordinary densities.

Other factors make this diamond approach even more attractive?the diamond protects the electron from the quantum-mechanical noise of the outside world, allowing these delicate

quantum processes to function at room temperature rather than the near-absolute zero temperatures required for most other approaches. And perhaps even more important for future technological uses, the process can be scaled beyond one qubit and integrated with existing semiconductor technologies, possibly leading to new hybrid quantum-classical machines.

Professor Ania Bleszynski Jayich of the physics department, has also caught the quantum fever, pursuing research to probe quantum effects at the nanoscale. Exploiting the ease of monitoring a single electron spin in diamond, she is developing a new imaging tool to detect the very small magnetic fields produced by single electrons and nuclei. Jayich says ?It?s pretty amazing to think that our magnetic field sensor is a single atom-sized object.? The far-reaching potential of this tool in biology and materials science is extremely exciting. ?Just imagine doing magnetic resonance imaging (MRI) of individual proteins inside a cell, ?states Jayich.

?My group is not building a quantum computer,? Awschalom says. ?At the moment this is simply not our goal ? rather we are interested in how we can manipulate quantum states of matter, how to entangle them to create unique opportunities for fundamental measurements, and how quantum physics may be exploited for new technologies. We are confident that the applications will move far beyond computing into areas we have yet to imagine. As new results emerge from groups around the world, people will realize, ?You know, that?s a solution to something we?ve been thinking about, and we have this great idea?we?re going to make this thing.? And that?s part of the excitement of this field.?

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