DARPATech, DARPA's 25th Systems and Technology Symposium
August 7, 2007
Anaheim, California
Teleprompter Script for Dr. Dennis Healy, Program Manager, Microsystems Technology Office

Mathematical Toolkit for the 21st Century Quantum Mechanic

» **DENNIS HEALY:**
Fifty years ago,
when the new-born ARPA and just about everybody else was looking UP to space, visionary physicist Richard Feynman advised us there was plenty of room left,
DOWN at the bottom.

As John Zolper reminded us at the start of this session, Feynman, Gordon Moore,
and other pioneers anticipated the importance of reduction of scale and associated integration of technology –
outlining a technology roadmap to the bottom that has transformed every facet of our lives.

Today we've nearly reached the end of classical scaling --
with technology now designed at the scale of molecules we bump square into the mysterious world of quantum effects.

In past, these effects were largely washed out by the huge number of atoms in our relatively large devices.

What was left could typically be treated with small adjustments in
semi-classical models.

NO LONGER.

Nowadays, true quantum effects are getting hard to finesse, and are even seen as fundamental limits to technology advances.

In modern CMOS transistors, for example, gate oxide is so thin that electrons in the gate are able to “just appear” on the other side of the barrier.

The resulting leakage is a key limiting factor for device performance.

Clearly, there are dangerous curves ahead on the roadmap,
and they threaten to slow us way down, while everybody behind us is catching up.

But I’m here to tell you this is actually a great situation!

This nation,
this community excels when challenged like this.

The unfamiliar, even unsettling quantum world is the next frontier for technology, offering us key strategic opportunities against the rapidly increasing prowess of our competitors in conventional technology.

I say that we can learn to move systematically,
to design and control with confidence in these strange worlds,
and harvest unimaginable technological surprise.

In fact, surprises will be our milestones on this new roadmap, and the key to reaching them is the mathematics of control and robust optimization in very high dimensional space.

If the 20th Century was the age of visionary quantum scientists like

Feynman, the 21st Century is the age of the “Quantum Mechanic”

-- a more nuts-and-bolts character who’s learned to harness quantum science in innovative and practical ways.

An engineer who routinely puts together functional, controllable quantum systems on budget and on schedule, enabling regular deliveries of new technologies with near science-fictional capabilities.

(All available –
on sale this week! -- at your local Qu-Mart store.)

A good example of a Quantum Mechanic is Mike Fritze,
who just spoke to us.

Mike demonstrated that one of those interesting quantum effects, tunneling, is far from just something to work around.

It can be exploited to overcome a serious obstacle on the current semiconductor roadmap.

Way to go Mike!

Now where’s that
next MIRACLE?

To keep us ahead of the competition by mining the quantum world for wild surprises, Mike and his Quantum Mechanics need to build new intuition and design discipline to exploit what’s now seen as frustratingly unavoidable quantum weirdness.

But – come on.

How weird can it be?

Well, let me give you an example, using the double-slit interference experiment to illustrate SUPERPOSITION, where A SINGLE quantum object can exist in MULTIPLE states simultaneously.

The experiment consists of shooting small particles, like electrons or even small molecules, one at a time, through a screen with two slits in it, allowing the particles to accumulate on the wall behind the screen.

Based on classical physics, we expect the particles to form two neat piles on the wall –
one pile behind each slit.

Simple! And wrong!

Instead, the accumulated particles form a COMPLEX pattern,
with many areas of high and low density.

How did ***that*** happen?

Rather than thinking of particles as little
well-defined balls –
each of which can only pass through one slit or the other -- we instead imagine wave packets.

When a wave packet reaches the slits,
it can pass through both at the same time!

The pattern we see at the back wall is a wave interference pattern –
the result of each particle, which is also a wave interfering with itself after passing the slits!

One PART of the wave goes through one slit,
the other part passes through the second slit, and when the two parts reach a point at the back wall the SUPERPOSITON OF THE TWO REINFORCES or CANCELS according to the phase difference of their paths.

At the back wall, the wavepacket collapses back to a little ball again, usually near one of the maxima of the interference pattern.

After many particles
have hit the wall,
we see the pattern of peaks and dips of density, explained by the fact
that any particle
can split 50-50
between the two slits,
or 70-30, or whatever.

IF that's not weird enough for you-- if you observe the slits to try to identify which one the particle passes through,
you completely kill this interference pattern!

By now you're probably yearning for the days when particles didn't have multiple personality issues, but hang in there.

This quantum complexity could be great news for information technology!

In classical information, data is generally represented by the
state of a bit --
either a "0" or a "1."

Well, our double slit quantum system also has two possible states.

A particle passing through the left slit could represent “0”; through the right slit, “1.”

And, as we’ve seen,
for small particles those two states can be in superposition –
so that the resulting bit represents both “0” and “1” at the same time.

That’s a quantum bit,
or qubit for short.

This has profound implication for computation and communication.

Let’s say your classical computer evaluates functions on numbers in a 3 bit register.

At one point it might compute a bit flip on a particular input – transforming a 3-bit binary word like “001” into “110.”

If you also need a bit flip performed on “100,”
you have to wait until your processor is done…

Or get another processor!

In contrast, a quantum register of 3 qubits can represent the input “001” AND the input “100” ….
in fact, all eight possible states – simultaneously,
in superposition.

And it’s possible to evaluate the function on all of these states -- Simultaneously!
-- in a SINGLE Parallel calculation on a
SINGLE processor!

For some applications this leads to advantages growing exponentially with the size of the register.

For example, functions on 20 qubits could provide a win of more than a million to one over 20 bit classical registers

Now Quantum superposition like this can be found in many different physical variables:
the position of a single charge in a solid-state device,
the spin of an electron, the polarization of a photon, and so on.

These are the building blocks that Quantum Mechanics will use to create our future.

Already, SIMPLE qubit systems have been realized and manipulated while still preserving their delicate quantum information.

MTO is leading efforts to improve and scale up qubit technologies,
and is exploring strategies for computation and communication using quantum systems.

We’re eager to hear your ideas about this!

But don’t look to buy that quantum gaming console just yet.

There’s a flip side to the good news.

While quantum effects like superposition promise enormous,
even exponential, advantages over today’s technology,
they also present daunting complexity challenges in modeling, optimization, and practical large scale design.

Okay, perhaps exotic Quantum computation is a ways off yet, but we still have to face the quantum design challenge RIGHT NOW!

Consider the growing impact of quantum effects on our old workhorse, the transistor.

While past transistors exploited some quantum effects in semiconductors, they were still designed using ”classical intuition.”

We worked with averaged behavior for large numbers of carriers, envisioning jostling herds of charges in semiconductor devices, flowing according to classical mechanisms we understand, like diffusion.

In contrast,
next-generation transistors will have few electrons confined to tiny spaces,
traveling short distances, and acting more like waves than particles.

Classical intuition begins to fail us.

The back of the envelope isn’t big enough to capture the complexities of quantum reality.

Present day CAD tools for device design at the
10 nanometer scale are incapable of describing complex quantum electronic and transport phenomena.

Expensive experiments become the only option for determining important device characteristics such as tunneling through the gate,
source-drain current in the ballistic regime, and
other key behaviors now strongly influenced by quantum effects.

Our Quantum Mechanic’s mathematical toolkit REALLY needs an update!

The problem is the huge amount of information needed to specify true quantum systems.

The mathematical models quickly become too
high-dimensional;
the trade spaces too complex for optimization.

We need to organize and manage the level of detail in quantum search space, representing what's important for the current line of inquiry at appropriate granularity and coarse-graining the rest.

Rather than brute force optimization over billions of variables, what we need is a clever search engine for the quantum design space.

An interactive design tool using mathematical techniques like those developed for the internet to represent, organize, and exploit information in the vast world of
high-dimensional data.

With this the Quantum Mechanic can explore revolutionary classes of robust, high-performance quantum devices,
develop design intuition beyond classical experience, and optimize quantum mechanical structures for practical exploitation.

As the design exploration progresses, the models change and the objective functions vary in order to take advantage of new information and opportunities.

We call this "equation free optimization."

Others tell me it's really optimization without knowing anything!

Here's just one example of how such ideas help in the search for fundamental limits in quantum devices:
As we push devices down to the ***size scale*** of molecules, can we hope to also operate them at the ***time-scale*** of those molecules?

For instance, can we imagine CONTROLLING the fast quantum processes of molecular electron orbitals,
on the timescale of bond vibrational periods--
as short as
10 femtoseconds,
or two orders of magnitude faster than today's ultimate experimental transistors?

That's a pretty wild goal: controlling processes orders of magnitude faster than thermal and mechanical processes of conventional systems!

But today, equation free optimization is teaching us how to control a wide variety of such processes via quantum coherent feedback.

For instance,
it's been used to enhance nonlinear optical response in materials, to control energy flow in bacterial light harvesting proteins, and to manage chemical bonds, encouraging chemical reactions that otherwise would not occur, mimicking the function of an ENZYME.

Since nature hasn't time to evolve enzymes for all the bonds we'd like to control, we learn to do it ourselves.

Here's the idea: molecular bonds can be driven by specially shaped femtosecond laser pulses, shaking the bonds into a quantum superposition of evolving processes, like the ones we saw in the double slit experiment.

The goal is to STEER the resulting quantum interference pattern so that constructive interference enhances desirable process outcomes, while destructive interference cancels out undesired outcomes.

What do you do in practice?

Start by hitting the bonds with a shaped pulse and watch the outcome.

If you're not happy with it, close the loop and try again!

Tweak the pulse shape in a direction that enhances the desired result, and ***iterate*** 'til satisfied.

Simple!

Except there are on the order of 10^100, the number "one googol," of control states for the pulse shaper -- how can we hope to find the best control setting?

Trial and error?

Even if we could try one each femtosecond for a billion years, we wouldn't come close to testing even 1% of the control settings.

Trying to guide the search by working with the billions of equations in a detailed quantum physics model also takes far, far too long to be useful.

Instead, as our search for better pulse shapes progresses, we apply algorithms similar to those in internet search engines to organize the results from previous iterations and to LEARN a reduced order model of the quantum system, on the fly.

We use that MODEL to guide big jumps over search space, using the same acceleration techniques we'd use if we COULD handle the equations.

The result: equation-free searches which find good molecular controls in minutes instead of millenia!

Control of ultrafast quantum processes is a powerful new tool for the Quantum Mechanic in the search for tomorrow's devices!

This is just one example of how effective quantum design search is enabled by mathematical ideas like dimensionality-management from the internet and revolutionary robust optimization.

Strategies like these will help Quantum Mechanics amplify their experience and pattern recognition skills, helping them search effectively for tomorrow's required device functions rather than simply making do with whatever is familiar today.

Looking beyond our tentative first steps,
we should be searching the quantum world for things we haven't even guessed at yet.

What we envisioned today -- 10x faster transistors, superfast molecular control, even quantum computers -- these are extensions of what we have now .

But those same equation-free tools and quantum search engines can help us imagine things we now can't, ultimately bringing new functions into the technological realm.

In the end, the quantum limit has little to do with physics.

It has everything to do with human imagination and ingenuity.

If we are going to go after fundamental limits,
we must have tools that allow us to break through our classical conditioning and begin to think like quantum creatures.

That's what visionaries like Richard Feynman did – they changed our perceptions.

To thrive in the quantum world of tomorrow,
we must follow their lead.