QUANTUM TECHNOLOGIES:
THE SECOND QUANTUM REVOLUTION*

Jonathan P. Dowling

Quantum Science & Technologies Group
Hearne Institute for Theoretical Physics
Louisiana State University

Tulane University, 25 April 2007

quantum.phys.lsu.edu

<table>
<thead>
<tr>
<th>Nano-Technology</th>
<th>Quantum Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;There's Plenty of Room at the Bottom.&quot; — Richard Feynman</td>
<td>&quot;There's Plenty MORE Room In Hilbert Space!&quot; — JPD</td>
</tr>
<tr>
<td>A 16 bit register stores 16 bits at a time.</td>
<td>A 16 QUBIT register “stores” $2^{16}$ bits at a time!</td>
</tr>
</tbody>
</table>
Quantum Sciences—The First Revolution

1900s Planck Blackbody Law
1920s Quantum Mechanics Completed
1920s Relativistic Quantum Mechanics
1920s Dirac Quantizes E&M Field
1930s Bloch’s Theory of Solid State
1940s Quantum Electrodynamics
1950s Nuclear Magnetic Resonance
1950s Masers and Atomic Clocks
1950s Theory of Superconductivity
1960s Invention of the Laser
1980s Laser Cooling of Atoms and Ions
1990s Bose-Einstein Condensates
Quantum Technology—The Second Revolution: Harnessing Entanglement and Coherent Quantum Systems

1970s Optical Tests of Bell’s Inequalities
1980s Quantum Cryptography (QKD) Invented
1980s Quantum Computing Invented
1980s QKD Demonstrated over 10km Fiber
1994 Factoring Algorithm Discovered
1994 Ekert’s Talk on Factoring Algorithm at ICAP
1994–95 NIST & DoD Workshops on QC
1995 DoD Funding for QC Comes Online
1996 Quantum Error Correction—QC Scalable!
1997 XOR in Ion Traps and Cavity QED
1998 Kane Scheme for QC in Semiconductors
1999 Nakamura Observes Rabi Oscillations in SQUIDs
2000 Four-Fold Entanglement in Ion Trap
2001 Scalable Linear Optical Quantum Computing
2002 Clark Constructs Four-Qubit Kane Prototype Mockup
2003 Nakamura Entangles a SQUID Pair
Schrödinger’s Cat Revisited

\[ \psi_0 + \psi_1 = \psi \]

WANTED

Erwin Schrödinger

DEAD AND ALIVE
I'm dead, I'm alive; I'm dead, I'm alive. Now I'm dead and alive. I just want out of this goddamn box.
Paradox? What Paradox!?

(1.) The State of the Cat is “Entangled” with That of the Atom.

(2.) The Cat is in a Simultaneous Superposition of Dead & Alive.

(3.) Observers are Required to “Collapse” the Cat to Dead or Alive
Quantum Entanglement

“Quantum entanglement is the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought.”

— Erwin Schrödinger
Einstein, Podolsky, Rosen (EPR) Paradox

Albert

Boris Podolsky

Nathan Rosen

“If, without in any way disturbing a system, we can predict with certainty ... the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.”
Can the Spooky, Action-at-a-distance Predictions (Entanglement) of Quantum Mechanics...

...Be Replaced by Some Sort of Local, Statistical, Classical (Hidden Variable) Theory?
The physical predictions of quantum theory disagree with those of any local (classical) hidden-variable theory!
Quantum Technology: The Second Quantum Revolution

Ion Traps
Cavity QED
Linear Optics

Quantum Optics

Quantum Information Processing

Quantum Atomics

Bose-Einstein
Atomic Coherence
Ion Traps

Coherent Quantum Electronics

Quantum Mechanical Systems

Superconductors
Excitons
Spintronics

Pendulums
Cantilevers
Phonons
Relationship Between Quantum and Nano-Technologies

QuTech Drives NanoTech

NanoTech Drives QuTech

QuTech

Quantum Computer

NanoTech
I've done it!! I've created the world's first fully-operational molecular computer!!

Amazing!! How did you account for quantum interference effects??

I incorporated them into the design, rather than trying to eliminate them!

But how did you link up all those tiny circuits?

No problem - I modified a few enzyme-linking tricks borrowed from the molecular biologists!

And can it do real calculations??

Can it!? So far, it's come up with 15 alternate proofs for Fermat's last theorem!!

Speed? I'm estimating it runs at several trillion computations per second!

In fact, at the moment I'm only having one small problem with my molecular computer...

Which is...? I can't find it again...
<table>
<thead>
<tr>
<th>Quantum Algorithms</th>
<th>Quantum Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Quantum Search and Integrals</td>
<td>• Quantum Cryptoanalysis</td>
</tr>
<tr>
<td>• Factoring Algorithm</td>
<td>• Quantum Key Distribution</td>
</tr>
<tr>
<td>• Quantum Error Correction</td>
<td>• Relativistic Quantum Information Theory</td>
</tr>
<tr>
<td>• Fault Tolerant Q. Computing</td>
<td>• Quantum Channel Capacity</td>
</tr>
<tr>
<td>• Q. Computing Complexity</td>
<td>• Quantum Message Authentication</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantum Information Hardware</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cavity QED Logic Gates</td>
</tr>
<tr>
<td>• Fiber and Free Space Q. Key Distribution</td>
</tr>
<tr>
<td>• Nuclear Spins on a Chip</td>
</tr>
<tr>
<td>• Coulomb Blockade Device</td>
</tr>
<tr>
<td>• Superconducting Quantum Interference</td>
</tr>
</tbody>
</table>

- Solid State Quantum Logic Gate
- Error Correction
- Ion Trap Q. Register
# Quantum Optics

## Single Photon Optics
- Optical Quantum Cryptography
- Interaction Free Imaging
- Sub-shotnoise Interferometry
- Photon Counting Statistics

## Single Photon-Atom Interaction:
- Optical Cavity QED
- Micromaser Cavity QED
- Photonic Band-Gap Materials
- Quantum Nondemolition Measurements
- Improved Atomic Clocks

## Quantum Noise Manipulation
- Quantum Noise Squeezing
- Improved Interferometry
- Improved Optical Lithography
- Quantum Optical Teleportation
- Quantum Zeno Effects

---

**Photonic Band Material**

**Squeezed Light**

**Micromaser Cavity QED**
## Quantum Atomics and Atom Optics

### Atom Optics
- Atom Interferometric Gyros
- Atomic Gravity Gradiometers
- Nanofabrication by Atom Interference
- Atom Holography
- Atom Lens, Mirror, Beamsplitter

### Atom Cooling and Trapping
- Laser Cooling Techniques (Nobel 97)
- Magneto-Optical Trapping
- All Optical Trapping
- Evaporative Cooling
- Improved Atomic Clocks

### Coherent States of Atomic Matter
- Bose-Einstein Condensates
- Atom Lasers
- Atom Holography
- Improved Atom Interferometry
- Entanglement-Improved Signal to Noise
Coherent Quantum Electronics

**Quantum Dots**
- Artificial Atoms
- Excitons—Artificial Atoms II
- Cavity QED in Solid Solid State
- Control of “Phonon-The-Destroyer”
- Excitonic BEC Just Around the Corner?

**Coherent Mesoscopic SQUIDS**
- Electron Phase Devices
- Superconducting Phase Interference
- Charge Based Interference
- Quantum Size Effects
- Entangled SQUIDS -- Super Mag. Sensors?

**Spintronics**
- Electron Spin Transport in Solid State
- Nuclear-Electronic Interactions
- NMR Computing Qubits
- Single Nucleus as Sensor

**Superconducting Q. Circuit**

**Q. Dot**

**Exciton**
**Quantum Nano-Electro-Mechanical Devices (Q-NEMS)**

### Coherent Phonon Manipulation
- Phonon Resonators
- Phonon Interferometer
- Phononic Band-Gap Materials
- Control of “Phonon-The-Destroyer”
- Phonon Laser and Squeezed States

### Quantum Nano-Mechanical Devices
- Cantilever
- Pendula
- Single Spin Magnetic Force Microscopy

### Macroscopic Interference
- Bucky Ball Interferometers
- Mesoscopic Cat States
- Entangled States of Mech. Resonators
Where Do You Want to Go Tomorrow? ™
I'VE INVENTED A QUANTUM COMPUTER, CAPABLE OF INTERACTING WITH MATTER FROM OTHER UNIVERSES TO SOLVE COMPLEX EQUATIONS.

ACCORDING TO CHAOS THEORY, YOUR TINY CHANGE TO ANOTHER UNIVERSE WILL SHIFT ITS DESTINY, POSSIBLY KILLING EVERY INHABITANT.

SHIFT HAPPENS.

FIRE IT UP.

I NEED A DESCRIPTION OF YOUR PROJECT AND ITS PROJECTED COST.

THAT'S IMPOSSIBLE.

THE PROJECT UNCERTAINTY PRINCIPLE SAYS THAT IF YOU UNDERSTAND A PROJECT, YOU WON'T KNOW ITS COST, AND VICE VERSA.

YOU JUST MADE THAT UP.

THAT DOESN'T MAKE IT WRONG.
“... a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery. We cannot make the mystery go away by ‘explaining’ how it works. We will just tell you how it works. In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics.” -Feynman
Traveling SALES MEN & QUANTUM Parallelism

CLASSICAL
Exponential number of classical “bees” (particles/resources) needed to examine $N!$ paths.

QUANTUM
Only one quantum bee (particle/wave) required to “learn” about $N!$ paths.
THE ROLE OF ENTANGLEMENT

Program nonlocal quantum correlations (entanglement) into the input register. Lift out shortest path by constructive interference using only $N$ instead of $N!$ q-bees. Exponential speed up in resource usage!

The readout problem: one q-bee makes one “click” on the detecting screen. Information about the $N!$ paths is lost.
Quantum Parallelism & Entanglement

Classical 16-Bit Register:

\[ [1,0,0,1,0,1,0,0,1,1,1,0,1,0,0,1] \quad 2 \times 2 \times 2 \ldots \times 2 = 2^{10} \]

Can hold only one of \(2^{10}\) possible numbers at a time.

Quantum 16-Bit Register in Superposition:

\[ [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0] + \ldots + [1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1] \]

Can hold all \(2^{10}\) possible numbers simultaneously!
Qubits can be in a quantum superposition of \{0\} and \{1\}. The general state can be represented by a vector on the unit sphere.

\[
U_\pi |0\rangle = -|1\rangle, \text{ and } U_\pi |1\rangle = |0\rangle
\]

\[
U_{-\pi/2} |0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)
\]

\[
|0\rangle = |\downarrow\rangle
\]

\[
|1\rangle = |\uparrow\rangle
\]

A universal quantum computer can be constructed using rotations on Hilbert space (sphere) and a Controlled-NOT gate (XOR).
Security of the public key cryptography depends on the assumed inability of a classical computer to factor \( C \) (public key) into \( P \) and \( Q \) (private key) rapidly. Classical sieving is exponentially slow.

A quantum state can test an exponentially large number of factors without using exponentially large amount of resources.

Constructive interference occurs for computational "paths" corresponding to divisors of \( C \) with no remainder.
Separated at Birth?

Peter Shor  

Gene Shalit
Best classical algorithm: Start at one end and prick your finger with one straw at a time until you yell “OUCH!” at the needle. Sometimes you’ll be lucky and the needle will be near the beginning, sometimes not and it will be near the end. On average, N/2 tries will be needed to find it. Best you can do.
GROVER’S ALGORITHM

- Goal: find $x_n \mid f(x_n) = 1, f(x_m) = 0$
- Initialize $L$ bit registers
- Prepare superposition of states
- Apply operator that rotates phase by $\pi$ if $f(x) = 1$
- Invert about average
- Repeat $O(N^{1/2})$ times
- Measure state

Note from classical antenna theory: Power from an unphased array of $N$ antennas scales like $N$, but when phased scales like $N^2$. 
Lov Grover at Work....

- **Rotation in 2-dimensional space**
- **Leads to algorithm for random sampling.**

Equations:

- \( [r_j, p_k] = i k s \)
- \( J = P \times B \)
- \( L_i = \epsilon_{ijk} F_j \)
- Generation: \( [L_x, L_y] = i k L \)
- \( \vec{R}^2 = \vec{R}_{L}^2 \)
Episode 12: The Getaway

At SD-6, Sloane offers Sydney a new mission: to retrieve Triad's prototype quantum gyroscope missile guidance system. She and Dixon are to intercept Carl Shatz, the courier who is transporting the gyroscope from Berlin to a lab in East France. Vaughn's countermission for Sydney is to steal the gyroscope and create a defective one for SD-6.
Quantum Sensors: Realty!

The potential payoffs are many. Entanglement and other quantum weirdness may boost the accuracy of radar, Global Positioning System (GPS) receivers, and other navigation devices.

It may improve manufacturers' ability to lay down tiny structures on microchips, expedite explorations for oil, improve the vision of telescopes, and increase the accuracy of atomic clocks.

Quantum technology might even enable us to see objects without actually looking at them — and without being seen ourselves.
Photon Laser Gyro

Atom Laser Gyro

Atom Gyro Prototype
Quantum Atomic Gravity Gradiometer

Pattern Shift Proportional to Changing Gravity Gradient
Quantum Optical Magnetometer
Entangled SQUID Magnetometer

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Approach</th>
<th>Status</th>
</tr>
</thead>
</table>
| Develop theoretical techniques to enable Heisenberg-limited magnetic and electric field measurements with superconducting circuits. | • Use quantum Optics techniques to create, manipulate and measure the collective state of an assembly of superconducting qubits.  
• cavity QED approach  
• Adapt techniques used in ion trap experiments to evaluate the uncertainty on the energy estimation (spectrometry). | Established the first relation between the uncertainty on the electric charge $Q_g$ (or magnetic flux $F_x$) estimation and the number $N$ of qubits:  
$$\delta Q_g \propto \delta F_x \propto 1/N$$ |
Quantum Clock Synchronization
Quantum Metrology

MACH-ZEHNDER INTERFEROMETER

\[ |N\rangle_A |0\rangle_B + e^{iN\varphi} |0\rangle_A |N\rangle_B \]

N-Photon Detector

\[ \varphi = kx \]
\[ \Delta\varphi: 1/\sqrt{N} \rightarrow 1/N \]

Oscillates N times as fast

\[ \frac{1 + \cos\varphi}{2} \] uncorrelated

\[ \frac{1 + \cos N\varphi}{2} \] correlated

N Photons
FROM QUANTUM INTERFEROMETRY TO QUANTUM LITHOGRAPHY

\[ |N\rangle_A |0\rangle_B + e^{iN\varphi} |0\rangle_A |N\rangle_B \]

\[ \langle \psi | a^{\dagger N} a^N |\psi \rangle \]

Oscillates in REAL Space!

\[ \frac{1 + \cos \varphi}{2} \]

uncorrelated

\[ \frac{1 + \cos N\varphi}{2} \]

correlated

\[ \varphi = kx \]

\[ \varphi \rightarrow N\varphi \]

\[ \lambda \rightarrow \lambda/N \]
Where We Want to Go Tomorrow!