QUANTUM TECHNOLOGY: THE SECOND QUANTUM REVOLUTION*

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Who Am I and Why Am I Here?


Director, Hearne Institute for Theoretical Physics, LSU, 2004–Present.
Who Am I and Why Am I Here?


My Own Research in Quantum Technology


Classical Battle Space of Today
Quantum Battle
Space of Tomorrow
The Army’s Role?

Quantum Technology will Drive Many of the Capabilities of the Warfighter for the Next 100 Years!

The US Army Can:

A. **LEAD!**

B. **FOLLOW?**

C. **GET THE %$#@ OUT OF THE WAY!**
Nano-Technology

“There’s Plenty of Room at the Bottom.”
— Richard Feynman (1960)

Classical: Every Book Ever Written Can Be Stored in a Speck of a Quadrillion (1,000,000,000,000,000) Silicon Atoms at One Bit Per Atom.

|1010010100101101|

Quantum Technology

“There’s Plenty More Room in the Quantum!” Jon Dowling (2008)

Quantum: Every Book Ever Written Can Be Stored in Fifty (50) Silicon Atoms at One Quantum Bit Per Atom! 10 Orders of Magnitude!

|1010010100101101>
Q: Is Quantum Technology Much Smaller than Nano-Technology?

A: No — Quantum Technology is Much Weirder than Nano-Technology!
Quantum and Nanotechnology are Self Enabling

QuTech: Weirdness

NanoTech: Small Size

Nano-Electronics and Q-NEMS

QuTech Drives NanoTech

NanoTech Drives QuTech
Quantum Sciences — The First Revolution

1900s Planck Blackbody Law

1920s Quantum Mechanics Completed

1920s Relativistic Quantum Mechanics

1920s Dirac Quantizes Electromagnetic Field

1930s Bloch’s Theory of Solid State

1940s Quantum Electrodynamics Completed

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
The First Revolution Allowed Us to Understand the Quantum World!
Quantum Technology — The Second Revolution

1994 Quantum Cryptography Demonstrated over 10km Fiber

1994 Quantum Code-Breaking Algorithm Discovered

1996 DoD & Intel Funding for Quantum Information

1997 Quantum Transistors in Atoms and Photons

1999 Superconducting Quantum Transistor

2001 Quantum Cryptography Over 100km

2004 ARO Program in Quantum Imaging

2007 DARPA Program in Optical Quantum Sensors

2008 Quantum Local Area Networks and Earth-to-Space Uplink
The Second Revolution Will Allow Us to Manipulate the Quantum World!

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.
Quantum Technology

- Quantum Computing
- Quantum Cryptography
- Foundations of Quantum Mechanics
- Quantum Imaging
- Quantum Sensors
Parallel Processors — in Parallel Universes!
How Does A Quantum Computer Work?

A Car’s Six Wheel Odometer is Like a Classical Computer Register: It Shows Only One Six-Digit Number at a Time.
A Quantum Odometer Can Store All 999,999 Six-Digit Numbers at Once!
Public-Key Secret Codes On The Internet

1. Sender encrypts message using receiver's public key. Anyone who knows receiver's public key can do this.

   "Meet Me at Midnight"

   Public Key

   One-way Algorithmic Transformation

   Encrypted Message

2. Receiver decrypts the message using his private key, which only he knows.

   "Meet me at Midnight"

   Private Key

   Receiver reads message.

These Secret Codes Are Often Used by the Bad Guys!
Making Public-key Secret Codes Is Easy

Making a Secret Code is as Easy as Multiplication:
15,485,863 • 32,452,843 = 502,560,280,658,509
Breaking Public-key Secret Codes Is Hard

Breaking a Public Key is as Hard as Long Division:
502,560,280,658,509 = 15,485,863 • 32,452,843
Dividing Big Numbers Is **Very** Hard!

If every particle in the Universe was a classical computer running at full speed for the entire life of the Universe (about 12 billion years) that would be still insufficient to divide out (factor) a 2,000 digit number.

Best Internet Encryption Uses 1,000 Digit Numbers.

The Bad Guys are Safe! Or Are They!? 
Cracking The Code: Life Imitates Art

Peter Shor, MIT (1994)

Quantum Computer Could Factor a 2,000 Digit Number In Less Than a Second!
Quantum Computing Hardware

Superconductor

Atomic

Photonic

Semiconductor
The Origin of Quantum Weirdness

Collections of Quantum Particles Exhibit Bizarre, Non-Local, Action-At-A-Distance, Unreal, Correlations not Found in any Classical System.

Such Quantum Correlations are Called “Entanglement”.

Quantum Entanglement is a Feature of the Weirdness of Quantum Mechanics, not Necessarily the Size of the Particles.

Quantum Entanglement is more Apparent in Semiconductor, Superconductor, and Nanomechanical Systems which are Nanometers in Size.

But Quantum Entanglement Also Exists in Atomic Gas Clouds Millimeters in Size and in Photon Pairs Separated by Tens-to-Hundreds of Kilometers!
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 (1930)
Schrödinger’s Cat

A sealed and insulated box (A) contains a radioactive source (B) which has a 50% chance during the course of the "experiment" of triggering Geiger counter (C) which activates a mechanism (D) causing a hammer to smash a flask of prussic acid (E) and killing the cat (F).

An observer (G) must open the box in order to collapse the state vector of the system into one of the two possible states. A second observer (H) may be needed to collapse the state vector of the larger system containing the first observer (G) and the apparatus (A-F).
Paradox? What Paradox!?

(1.) The State of the Cat is “Entangled” with 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.
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."
Einstein Offers Classical Alternative

Can the Spooky, Weird, Action-at-a-distance, Entanglement Predictions of Quantum Mechanics...

...Be Replaced by Some Sort of Local, Intuitive, Statistical, Classical (Hidden Variable) Theory?
No! — John Bell (1960)

The physical predictions of quantum theory disagree with those of any local (classical) hidden-variable theory!
Clauser & Aspect Experiments (1980)

Two-Photon Atomic Decay

H \rightarrow V

A

V \rightarrow H

B

13 m

PMT

PA_1

\begin{align*}
H_A & \quad V_B \\
V_A & \quad H_B
\end{align*}

PA_2

PMT

\begin{align*}
H & \rightarrow V \\
V & \rightarrow H
\end{align*}

four fold coincidence counter

coincidence counter

Vertical Polarization

Horizontal Polarization

Alain Aspect

John Clauser
Bottom Line!?  

Quantum is Right!        Einstein was Wrong!  

Quantum Weirdness is Here to Stay — Let’s Put it to Work!
Quantum Technology

Quantum Computing

Quantum Cryptography

Foundations of Quantum Mechanics

Quantum Imaging

Quantum Sensors
One-Time Pad Private Secret Key System

Secret Code Invented by G.S. Vernan — An Army Telegraph Officer During the Civil War.

Proven Unbreakable by Claude Shannon at Bell Labs in the 1940’s.

Unbreakable by Even A Quantum Computer!
Alice Sends a Copy of the Secret Key to Bob

Problem: Classically an Eavesdropper Can Always Copy the Pad!
Eve Cannot Copy a Quantum Pad!

Solution: Pad Encoded in Quantum States of Photons!
You Can Buy a Quantum Crypto System!
Space-Based Quantum Relay
The Quantum Skynet Is Here!

In 2008 — Austrian Scientists Transmitted Single Photons to a Japanese Communications Satellite and Back.

The US Has a Similar Project. The Goals are to Re-Key Reconnaissance Satellites on the Fly and Connect Quantum Local Area Networks.
Quantum Technology

Quantum Computing

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Quantum Sensors
Quantum Sensors

Quantum Entanglement Boosts Precision, Accuracy, and Sensitivity in a Wide Array of Sensors
Quantum Sensors: Key Ideas

Classical Sensors Have an Ultimate Sensitivity in Signal-to-Noise Called the **Shot-Noise Limit**.

Quantum Sensors Have an Ultimate Sensitivity in Signal-to-Noise Called the **Heisenberg Limit**.

The **Quantum Heisenberg Limit** Can be Many Orders of Magnitude More Sensitive than the Classical **Shot-Noise Limit**.

Quantum **Entangled** Sensors Can Hit the Heisenberg Limit!
Quantum Super-Sensitivity

Signal-to-Noise = Slope of Curve
The Quantum Slope is Much Steeper than Classical

Gravity, Magnetism, Range, Time, Etc.
Quantum Magnetometers Are so Sensitive they Can Detect Camouflaged Tanks From Orbit
Quantum Atomic Gravity Gradiometer

Atom Trap

Loading the Chip

Atom Chip

Quantum Atomic Interference
Quantum Atomic Gravity Gradiometers Can Detect Man-Made Underground Structures From Orbit — or Map them Out from UAVs.
Quantum States of Light For Remote Sensing

“DARPA Eyes Quantum Mechanics for Sensor Applications”
— Jane’s Defense Weekly

Entangled Light Source
Delay Line
Detection
Loss
Target

Super-Sensitive Ranging, Velocity, Etc.

Winning LSU Proposal

DARPA
Quantum Technology

Quantum Computing

Quantum Cryptography

Foundations of Quantum Mechanics

Quantum Imaging

Quantum Sensors
Quantum Imaging

Quantum Entanglement Boosts Resolution, Cancels Atmospheric Dispersion (Twinkling), and Produces Images in Total Darkness with no Photons at all!

Sub-Diffraction Resolution

Quantum Microscope

Quantum Seeing in the Dark
Quantum Super-Resolution Beats Diffraction Limit

\[ \lambda = \text{optical wavelength} \]

\[ \frac{\lambda}{N} = \text{effective wavelength} \]

Classical Quantum

![Graph showing quantum super-resolution](image-url)
Classical Resolution

Targets with angular separation smaller than classical diffraction-limited beam width are not discernable.

\[ \theta = \frac{\lambda}{d} \]

Classical Diffraction Limit
Quantum Resolution

Entangled photons beat the diffraction-limit; allowing for quantum resolution of the two targets!

\[ \frac{\theta}{N} = \frac{\lambda}{N d} = \frac{(\lambda/N)}{d} \]

Quantum Light Source

Quantum Diffraction Limit

Photons Entangled N at a time.

Two- to Ten-Fold Improvement!

\[ \lambda \rightarrow \frac{\lambda}{N} \]

Ten Entangled Red Photons Behave Like One Ultraviolet One
Imaging with No Photons at All!

Target in Upper Path

Quantum Photon Source

No Photons Take Upper Path

Quantum Photon Imager

All Photons Take Lower Path

Complete Image Reconstruction — Even Though No Photons Ever Interact with the Target at All!