Quantum Information Science: NIST's Role and the National Agenda

Carl J. Williams
Chief, Atomic Physics Division
Physics Laboratory
National Institute of Standards and Technology

NIST Physics Laboratory

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

What is Quantum Information?

"Quantum information is a radical departure in information technology, more fundamentally different from current technology than the digital computer is from the abacus."

W. D. Phillips, 1997 Nobel Prize Winner in Physics

A convergence of two of the 20th Century's great revolutions

A new science!

Quantum Mechanics
(*i.e.* atoms, photons, JJ's, physics of computation)

Information Science
(*i.e.* computer science, communications, cryptology)

The second quantum revolution

Origin of a National Agenda

- Fall 2007, several agencies meet with Dr. Marburger (Director OSTP) and OSTP staff about QIS
- December 2007, Bill Phillips and I meet with Dr. Marburger and OSTP staff
- January 2008, Dave Wineland and I meet with Dr. Marburger and OSTP staff
- March 2008, I am detailed part time to OSTP
- June 2008, Agency heads brought together for a kickoff meeting → Decisions:
  - **Create a broad scientific agenda to build a foundation for future technologies based on QIS**
  - **Issue a vision document by end of the Administration**

The National Agenda for Quantum Information Science

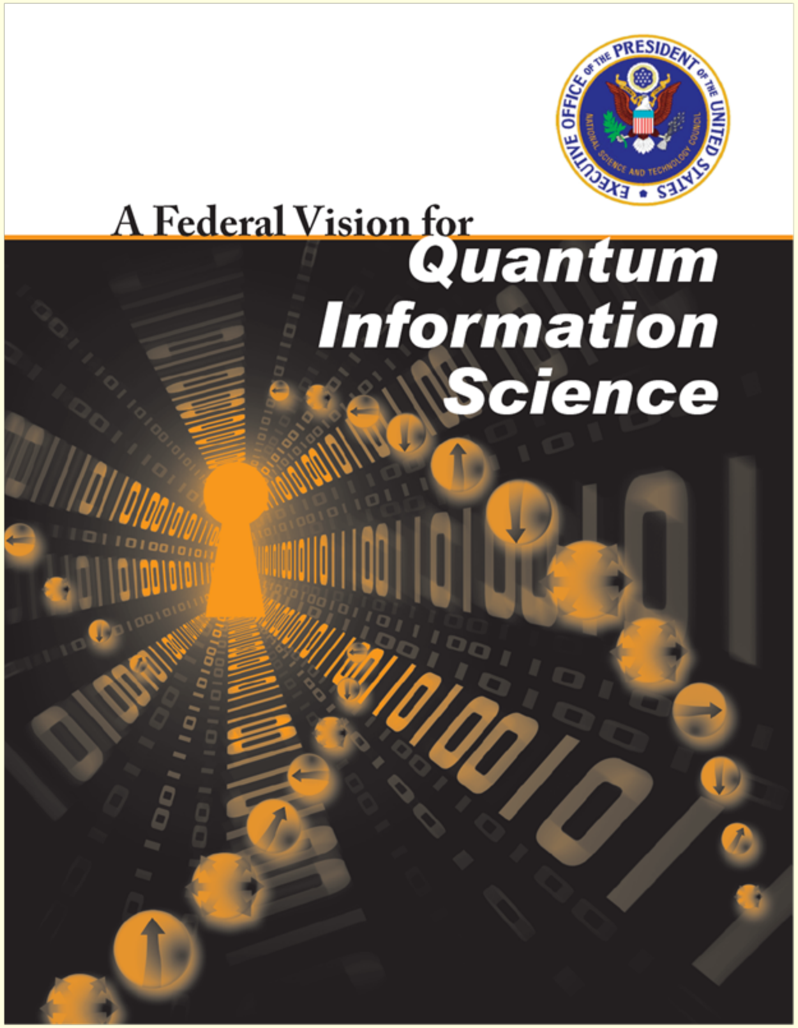
Carl J. Williams
Senior Policy Analyst
Office of Science and Technology Policy
Executive Office of the President

What is OSTP?

Office of Science and Technology Policy

- **Established 1976 by the National Science and Technology Policy, Organization and Priorities Act**
- **OSTP's responsibilities include:**
  - Advise the President in policy formulation and budget development for science and technology (S&T);
  - Articulate the President's S&T policies and programs;
  - Foster partnerships among Federal, state, and local governments and scientific communities
- **OSTP and OMB (Office of Management and Budget) annually issue a memo on S&T Budget Priorities**
- **OSTP Policy Arm is the National Science and Technology Council (NSTC) – its Committees and Subcommittees including agency representatives**

Subcommittee on QIS (SQIS)



- SQIS established under the CoT of the NSTC in December 2008
- “A Federal Vision for Quantum Information Science” released in January 2009
- January 2009, SQIS decides to host a workshop

SQIS Report

- What is the true power of a general purpose quantum computer, what problems does it allow us to compute efficiently, and what does it teach us about nature?
- Are there fundamental limits to our ability to control and manipulate quantum systems, and what constraints do they place on technology and QIS?
- Are there exotic new states of matter that emerge from collective quantum systems, what are they useful for, how robust are they to environmental interactions, and do these collective quantum phenomena limit the complexity of the quantum computing devices we can build?

→ **A follow-on Investment Strategy is in draft form**

Case for QIS

- **Quote from the SQIS Workshop Report**

  “*We do not yet have a clear picture of how QIS might influence the science and technology of the 21st century. It is likely that the most far-reaching quantum technologies have not yet been anticipated, and will emerge only as basic research in QIS continues to mature and develop. But as the NSTC report emphasizes, QIS will require long-term focused attention for a decade or more from a variety of government agencies and national laboratories if the US is to achieve and maintain a global leadership position while training a new generation of quantum scientists and engineers. We hope that the Workshop on Quantum Information Science and this report will help to nucleate a cohesive national effort that will nurture and invigorate this vitally important emerging field.*”

http://www.eas.caltech.edu/qis2009/QIS-Workshop-Report-1-July-2009.pdf

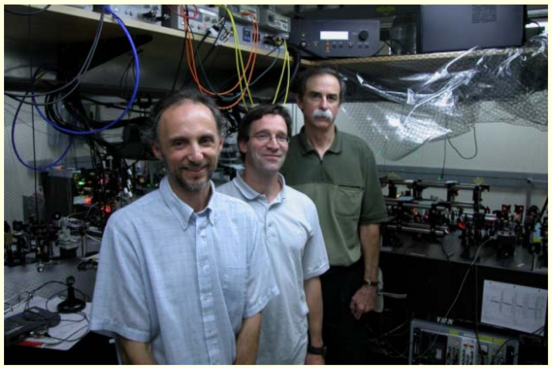
Origin of NIST's QIS R&D

- Core capability arises from NIST's control of individual quantum states of atoms → atomic clocks
- In 1992, Dave Wineland notes that certain collective ("entangled") quantum states of atoms could improve atomic clock accuracy
- In 2000, NIST initiates a focused QIS program
  - Goal to demonstrate basic quantum logic operations
  - Builds on Dave Wineland's 1995 demonstration of the first quantum-logic gate
  - Explores a number of qubit technologies
  - Supports R&D efforts of NSA, DARPA, IARPA (and predecessors)

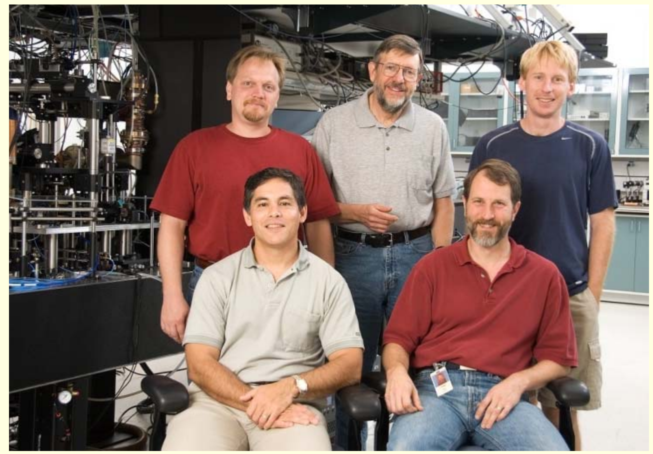
NIST QI Program

> $14M Effort

EEEL, ITL, PL

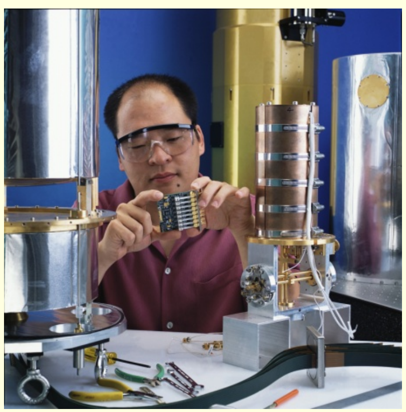


Computing with ion traps (PL, ITL)

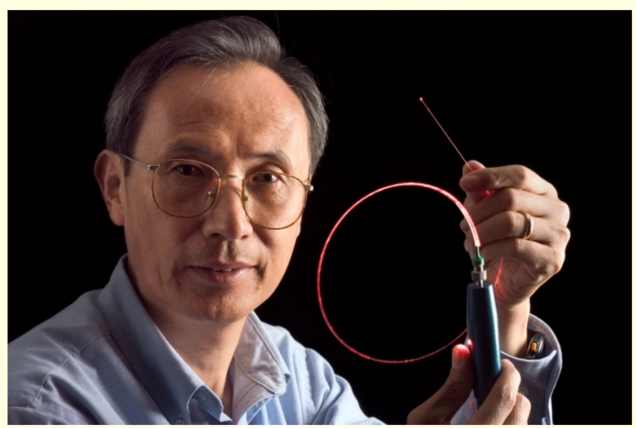


Computing with neutral atom lattices (PL)

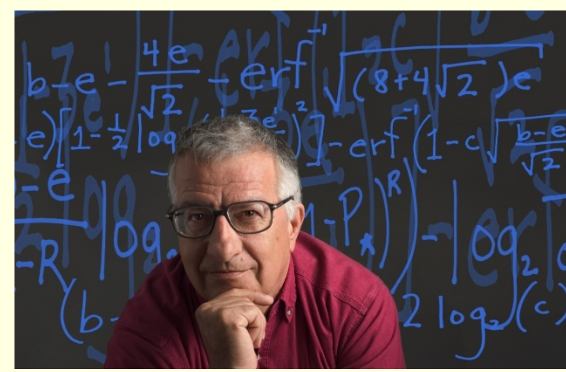
Computing with artificial atoms (EEEL)



Quantum optical metrology (EEEL, ITL); *Single photon sources, detectors* (EEEL, PL, ITL)



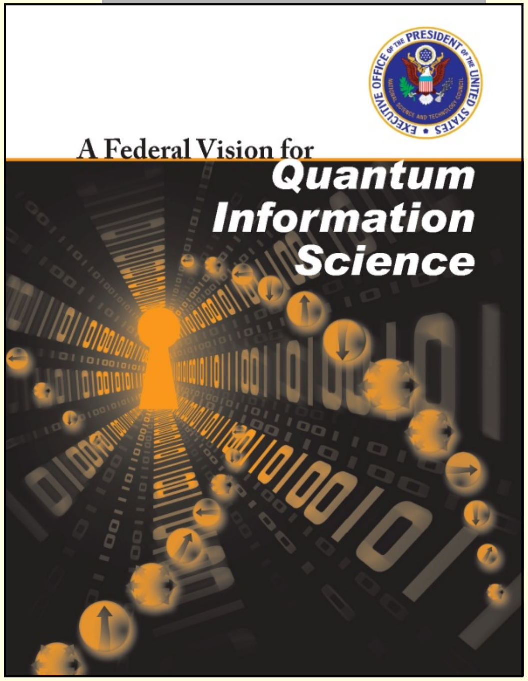
Quantum Communications (ITL, PL)



Quantum information theory (ITL)

Implications are Compelling

- … **for science & engineering**
  - Efficient solutions to challenging problems
  - Improved clocks
  - Improved measurements
- … **for national security**
  - Breakthroughs in codebreaking, pattern matching
  - Secure defense communications
- … **for commerce**
  - Obsolescence of existing public-key cryptosystems
  - Maintenance of lead in computer technology



"The United States' large stake in all these potential applications warrants a cohesive national effort to achieve and maintain leadership in the rapidly emerging field of quantum information science."

QIS Remains Very Challenging

- Quantum information is volatile
  - How to prevent information from evaporating in quantum decoherence?
- Many potential physical realizations
  - How to assess practicality for information processing?
  - What are the benefits of various qubit technologies
  - How do we transform quantum information
- Fundamentally different approach to computation: controlled unitary evolution
  - What are elementary operations and how are they physically realized?
  - How does one map a task to the physical system?
  - What new problems can be solved?
- Quantum engineering is in its infancy
  - How select/develop components suitable for engineering of quantum systems?
  - How scale up systems to be able to solve real problems?

NIST's Role in QIS

- Understand quantum computers effect on currently deployed public key (PK) cryptosystems
  - PK Infrastructure is essential to commerce
  - PK Algorithms must be quantum resistant
  - Develop new R&D capability to support cyber-security in post-quantum world
  - Hold potential new competition for PK algorithms
- Continue exploring fundamental limits of qubit control and manipulation
- Explore applications of few qubit entanglement to improved measurements (clocks, imaging, low noise amplification, …) → Quantum Based Measurements
- Explore exotic quantum states and potential emergent phenomena and their applications

Quantum Based Measurements

Existing efforts:

- Quantum Logic Clock
- Entanglement Based Clocks

New thrusts:

- Super-resolution imaging
- Improved phase measurements
- Better optical detector calibration
- Absolute optical calibration based on photon counting
- High speed low noise amplifiers
- Low noise amplifiers

Recent Local NIST Highlights

- *Randomized benchmarking of quantum gates*: accurate measurement of 1-qubit gate fidelity
- *Stylus ion trap for enhanced access & sensing:* ion traps for improved measurements of forces, magnetic fields, …
- *Frequency ratio of Al+ & Hg+ single-ion optical clocks:* quantum logic clock; measuring time variation of α
- *Infrared wavelength-dependent optical characterization of NbN nanowire superconducting single-photon detectors*
- *Josephson phase qubit circuit for the evaluation of advanced tunnel barrier materials*
- *Parametric coupling between macroscopic quantum resonators*

Summary of NIST QIS Role

- NIST is a leader in QIS
  - World class R&D effort
  - Asked to provide a detailee to coordinate national effort
  - Co-chairs the NSTC Subcommittee for QIS
  - Supports basic R&D efforts of other agencies
  - Has unique NIST implications for both measurement science as well as standards
- NIST is preparing for future measurement science needs and standards in QIS
- NIST's capabilities are built on core laboratory R&D programs but are already exploring implications for next generation measurement (clocks, candela, …)

The End: Schrödinger's Cat