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Q2B

2017

A Federal Perspective on Quantum Information Science and Quantum Computing

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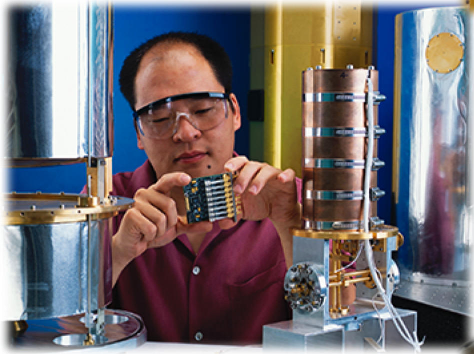
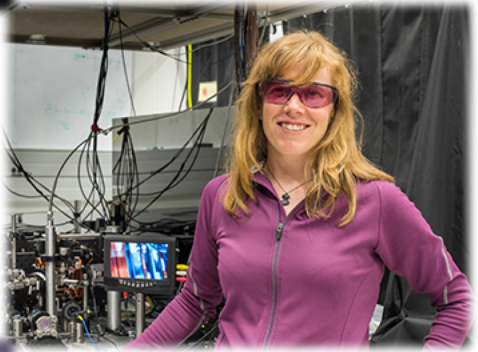


NIST
National Institute of Standards and Technology
U.S. Department of Commerce



PML
PHYSICAL MEASUREMENT LABORATORY

A Federal Perspective on QIS

Quantum Information Science in a Nutshell

Quantum information science (QIS) exploits unique quantum properties such as *coherence, superposition*, *entanglement*, and *squeezing* to *acquire*, *transmit*, and *process* information in ways that greatly exceed existing capabilities.

QIS is a field of scientific inquiry in its own right, with applications in:

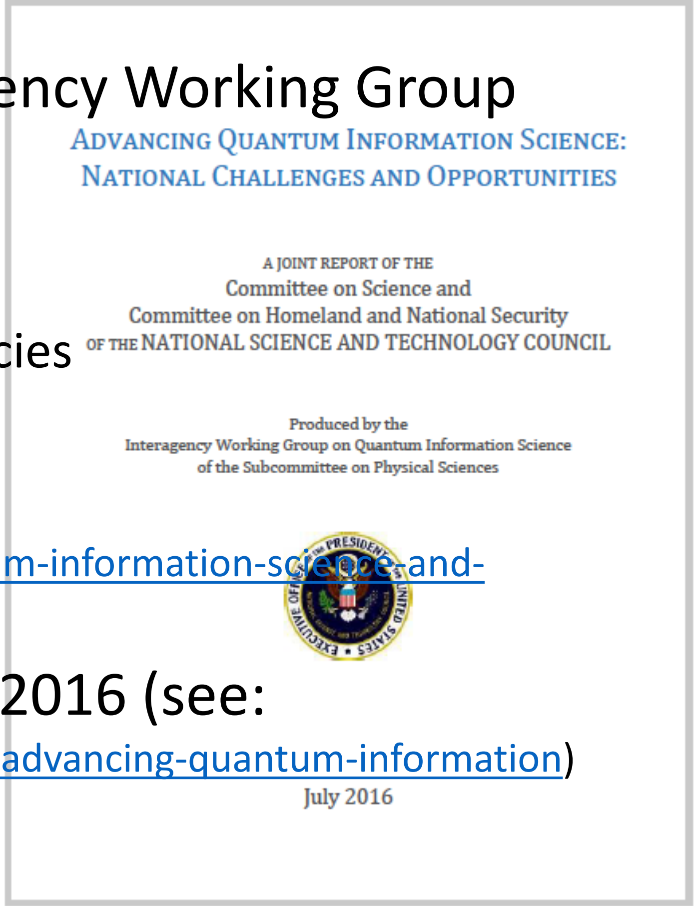
- *sensing and metrology:* precision navigation, timekeeping, magnetic fields, …
- *communication:* secure data transmission and storage, random number generation, …
- *simulation:* complex materials, molecular dynamics, QCD, …
- *computing:* cryptanalysis, quantum chemistry, optimization, quantum field theory, …

and robust intellectual connections to numerous areas of basic research.

I focus here on QIS because it is broader than quantum computing, requires same technology development, and because this is hohat the Federal government tracks!

QIS and the US Government

- QIS is coordinated across USG Agencies by the QIS Interagency Working Group (QIS IWG) – chartered Oct 2014
- QIS is of active interest to USG
  - Subject of numerous reports and focused meetings of various agencies
  - Coordinated across the agencies
  - Public report released in July 2016 → (also see: https://obamawhitehouse.archives.gov/blog/2016/07/26/realizing-potential-quantum-information-science-and-advancing-high-performance)
- White House OSTP hosted a Forum on QIS on October 18, 2016 (see: https://obamawhitehouse.archives.gov/blog/2016/10/18/identifying-strategic-options-advancing-quantum-information)


ADVANCING QUANTUM INFORMATION SCIENCE:
NATIONAL CHALLENGES AND OPPORTUNITIES

A JOINT REPORT OF THE
Committee on Science and
Committee on Homeland and National Security
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

Produced by the
Interagency Working Group on Quantum Information Science
of the Subcommittee on Physical Sciences

July 2016

https://www.whitehouse.gov/sites/whitehouse.gov/files/images/Quantum_Info_Sci_Report_2016_07_22%20final.pdf

QIS Interagency Working Group: Public Report

Purpose: to present QIS IWG's analysis to stakeholders outside the government, encourage cooperation among government, academia, and industry

Primary Audience: U.S. industry, university leadership

Reviewed: Existing QIS programs at Federal agencies, industry activity, new announcements abroad

Identified Impediments to Progress:

1. Institutional boundaries
2. Education and workforce training
3. Technology and knowledge transfer
4. Materials and fabrication
5. Level and stability of funding

Recommended Path Forward:

1. Stable, sustained, *flexible* core programs
2. Strategic investment in targeted, time-limited programs
3. Continued close monitoring of this rapidly-moving field

OSTP Forum on Quantum Information Science

Participation: 70 thought leaders from academia, industry, national labs, and Federal agencies

Purpose: (1) gather input on challenges to advancing QIS

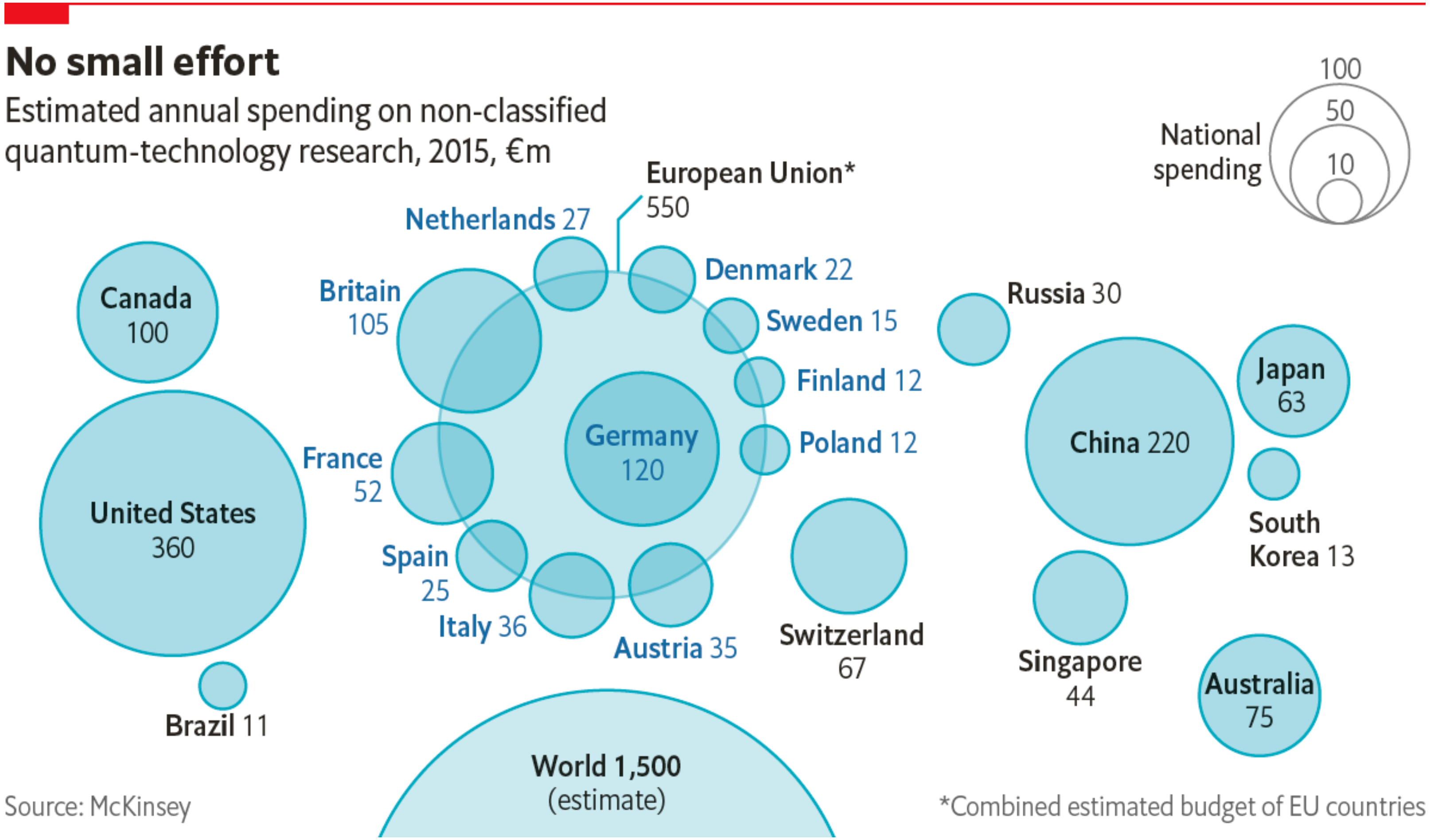
(2) identify options for addressing these challenges

Outcome:

- Validated analysis in public report
- Strong support for cooperative approach that includes all sectors
- Opportunities will be lost if agencies do not coordinate programs
- Increasing need for translational research
- Many options for addressing challenges, no clear winners

Nations and Companies are Investing

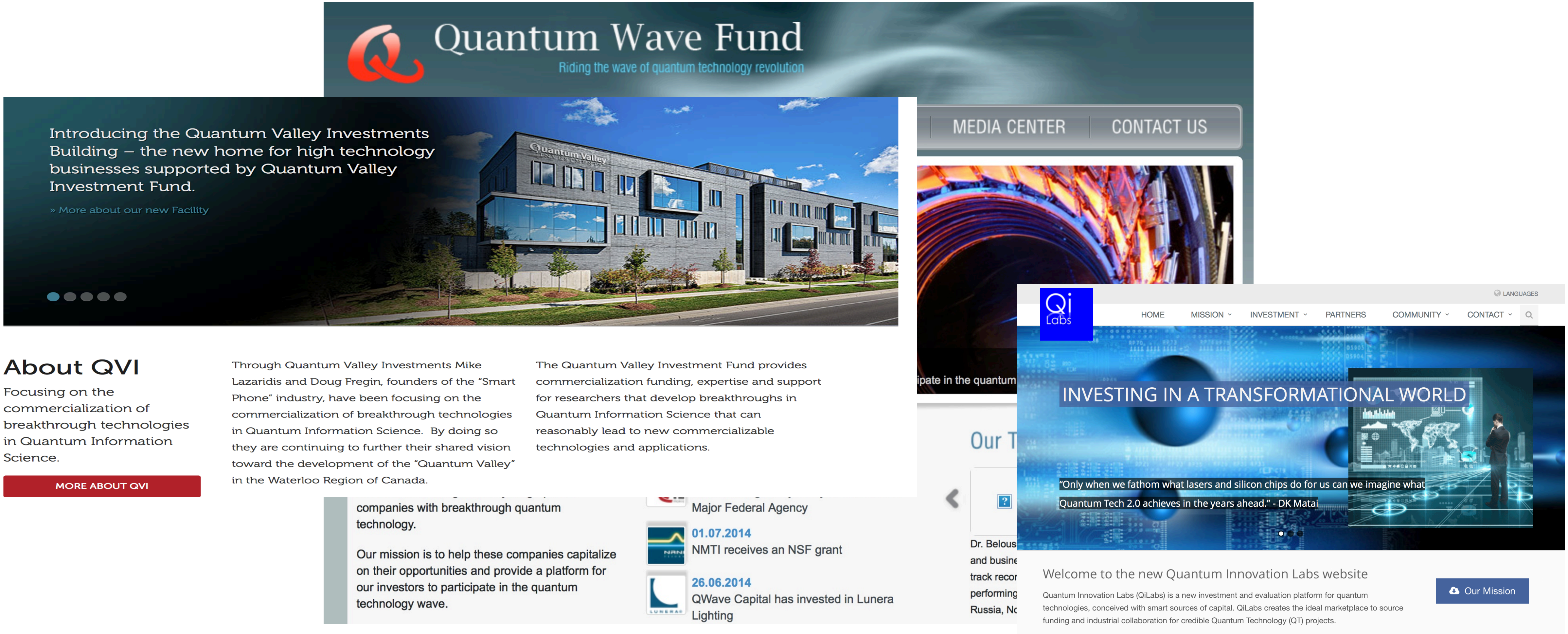
March 11, 2017



Industry is Investing

- Large Companies are investing: *e.g.* IBM, Microsoft, Google, and Intel have all have substantial quantum computing efforts
- Other large companies are exploring the broader spectrum of Quantum Technologies
- Smaller companies are interested in either *single qubit technology* or in *supporting quantum technologies: e.g.* AOSense, Cold Quanta, QDTI, Zyvex Labs, MagiQ, Microsemi, …
- Some companies are more circumspect on their interests
- Numerous Startups (too many to be listed) – some having received significant *venture capital*

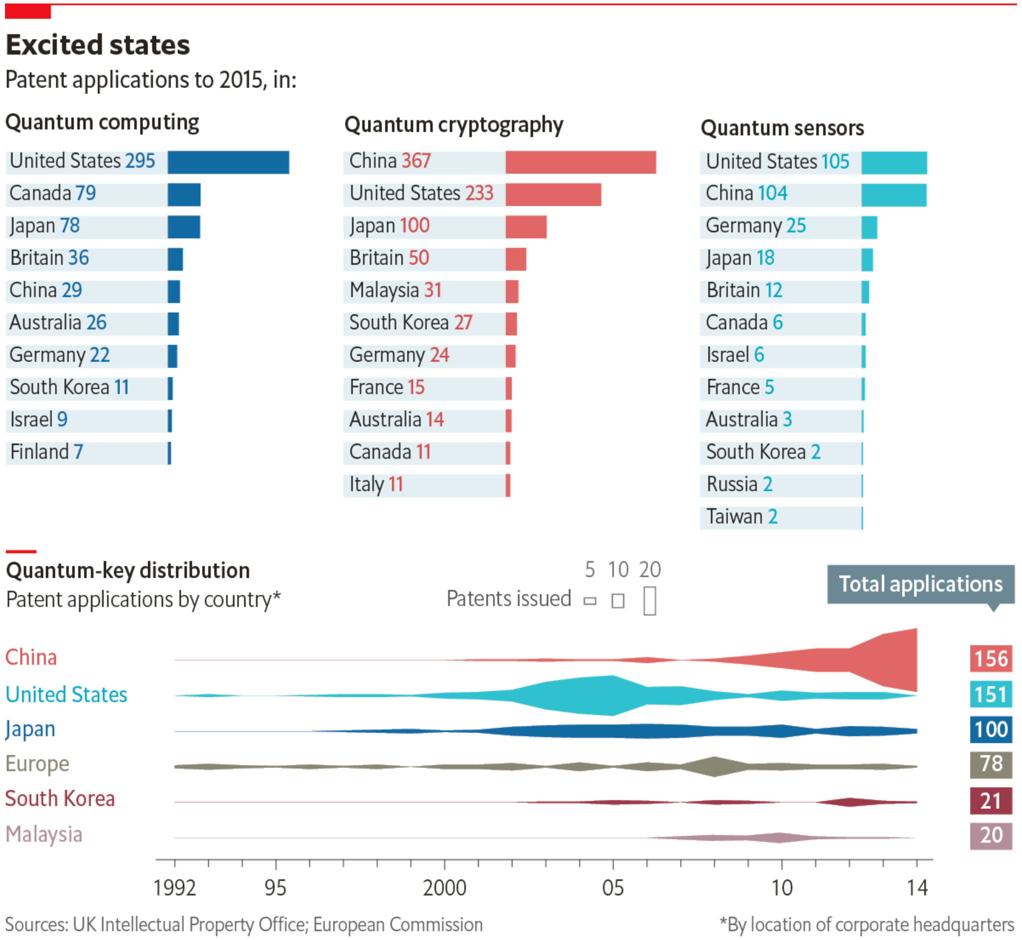
Investment Infrastructure and Venture Capital



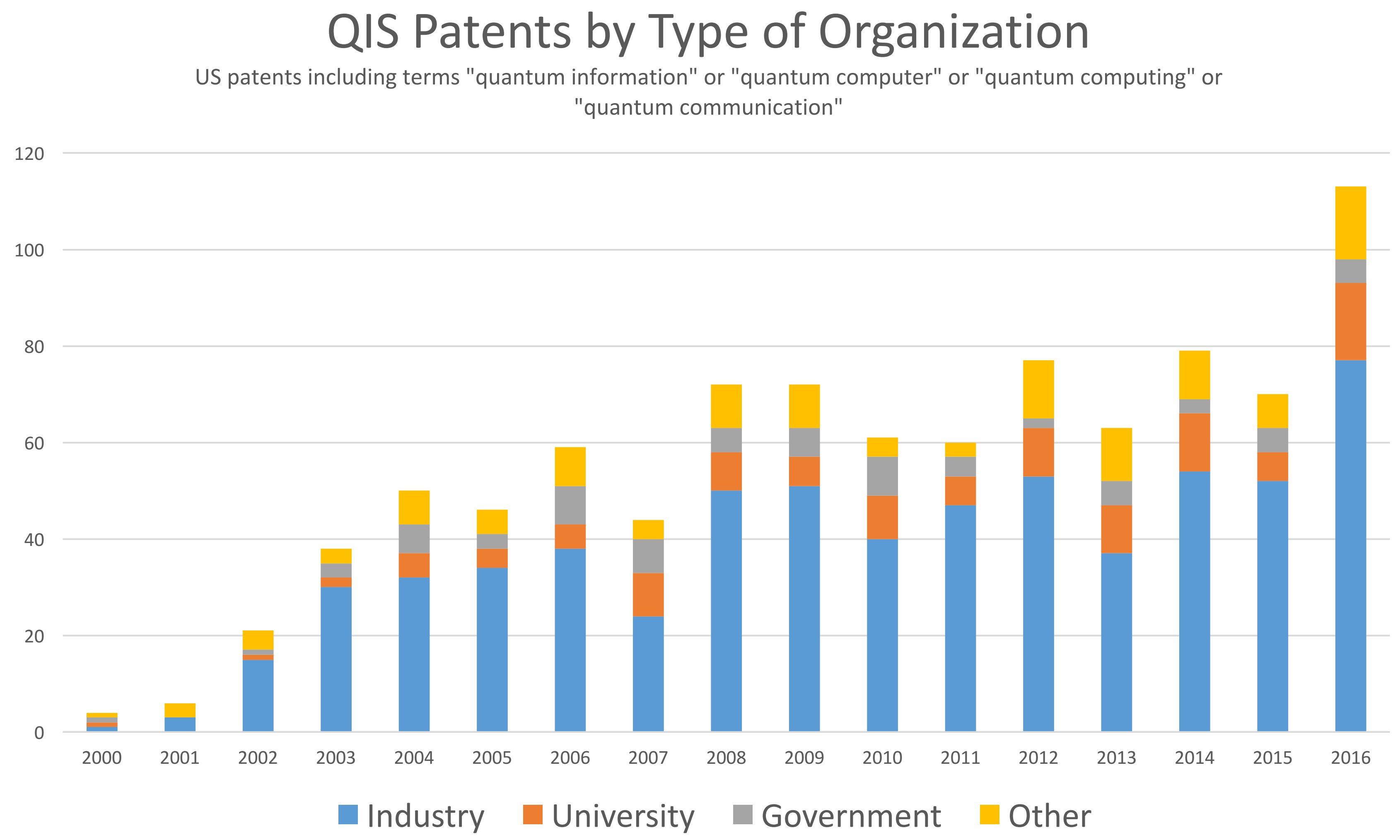
World-wide Patents

March 11, 2017

Extracted from the Economist



U.S. Patents


QIS Patents by Type of Organization
US patents including terms "quantum information" or "quantum computer" or "quantum computing" or "quantum communication"
120
100
80
60
40
20
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Industry
University
Government
Other

Why Now

- Intellectual Frontier where scientific and technical opportunities have implications for:
  - **National Security**: cryptanalysis, secure communications, inertial navigation
  - **Economic Competiveness**: new sensors and imaging tools, improved metrology
  - **Frontiers of Science**: discovery of new materials, insights into cosmology
- QIS is at a Tipping Point – U.S. and international companies are investing:
  - **Major IT industries**: *for e.g*. Google, Microsoft, IBM, Intel
  - **Technology companies**:
  - **Small and/or New companies:**
  - **Venture capital** is appearing and investing
  - **Niche products** are appearing – considered to be harbinger of a nascent field (chip-scale atomic clocks, quantum gravimeters, quantum-secure networks, …)
- Foreign competition is growing rapidly:
  - Some foreign investment levels are approaching those in the U.S.
  - Foreign governments are implementing focused QIS initiatives
    - China, UK, Germany, Canada, Japan, Australia, Netherlands, EU, …
  - Lucrative research opportunities abroad are attracting top-tier U.S. researcher’s

The Agencies' Response

- DOE has initiated a formal program; has several BAA announcements on the street including quantum testbed and quantum software; DOE effort continues to grow
- DOE effort coordinated across DOE/SC and includes ASCR, HEP, & BES
- NSF has a new multidisciplinary BAA involving MPS, CISE, & ENG
- DOD continues to invest both through core programs (AFOSR, ONR, & ARO) and through MURI's
- NIST has this as one of its programmatic priorities

Finally: Congress is showing increased interest: See "American Leadership in Quantum Technology" – https://youtu.be/nvR3z9KXnpw

Response by Broader U.S. Community

Recall the *Identified Impediments to Progress:*

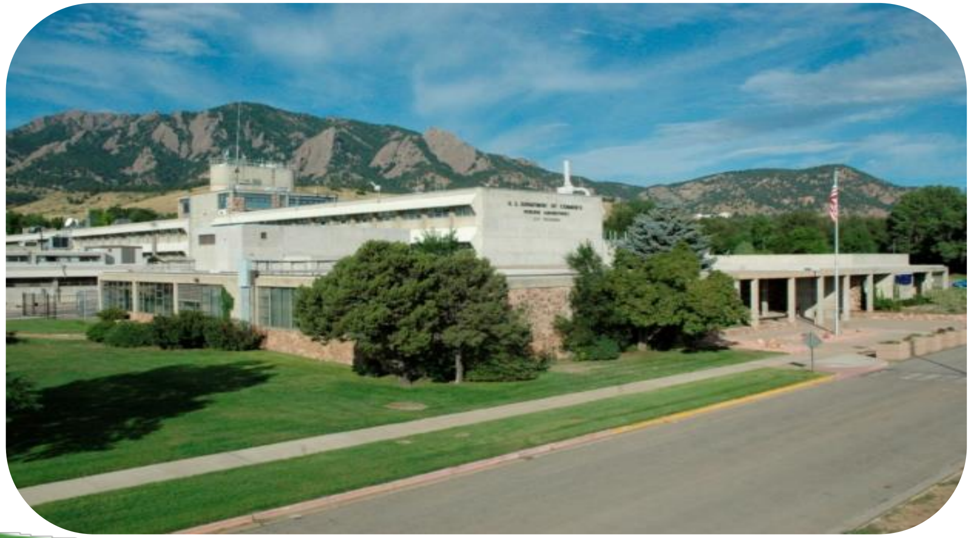
1. Institutional boundaries – response occurring by universities, companies, and government
2. Education and workforce training – beginning to see response here
3. Technology and knowledge transfer – response occurring by universities, companies, and government
4. Materials and fabrication – some response and discussion continuing
5. Level and stability of funding – response from universities, companies, and government

QIS and NIST

NIST: Bird’s Eye View

The United States’ national measurement laboratory, NIST is where Nobel Prize-winning science meets real-world engineering.

Courtesy HDR Architecture, Inc./Steve Hall © Hedrich Blessing



G. Wheeler

With an extremely broad research portfolio, world-class facilities, national networks, and an international reach, NIST works to support innovation. Sometimes we are referred to and “Industry’s National Lab”.

NIST Laboratories and User Facilities

Standards Coordination Office
Standards Services Group
NIST Quality Manager

Associate Director for Laboratory Programs

Special Programs Office
Forensics Standards, National Security Standards, Climate Assessment

Physical Measurement Laboratory QIS

Material Measurement Laboratory

Engineering Laboratory

Information Technology Laboratory QIS

Communication Technology Laboratory

Center for Nanoscale Science and Technology

NIST Center for Neutron Research

Metrology Laboratories

Driving innovation through Measurement Science and Standards

Technology Laboratories

Accelerating the adoption and deployment of advanced technology solutions

National User Facilities

Providing world class, unique, cutting-edge research facilities

PML's Core Mission

To realize, disseminate, and advance the International System of Units (SI) in the United States

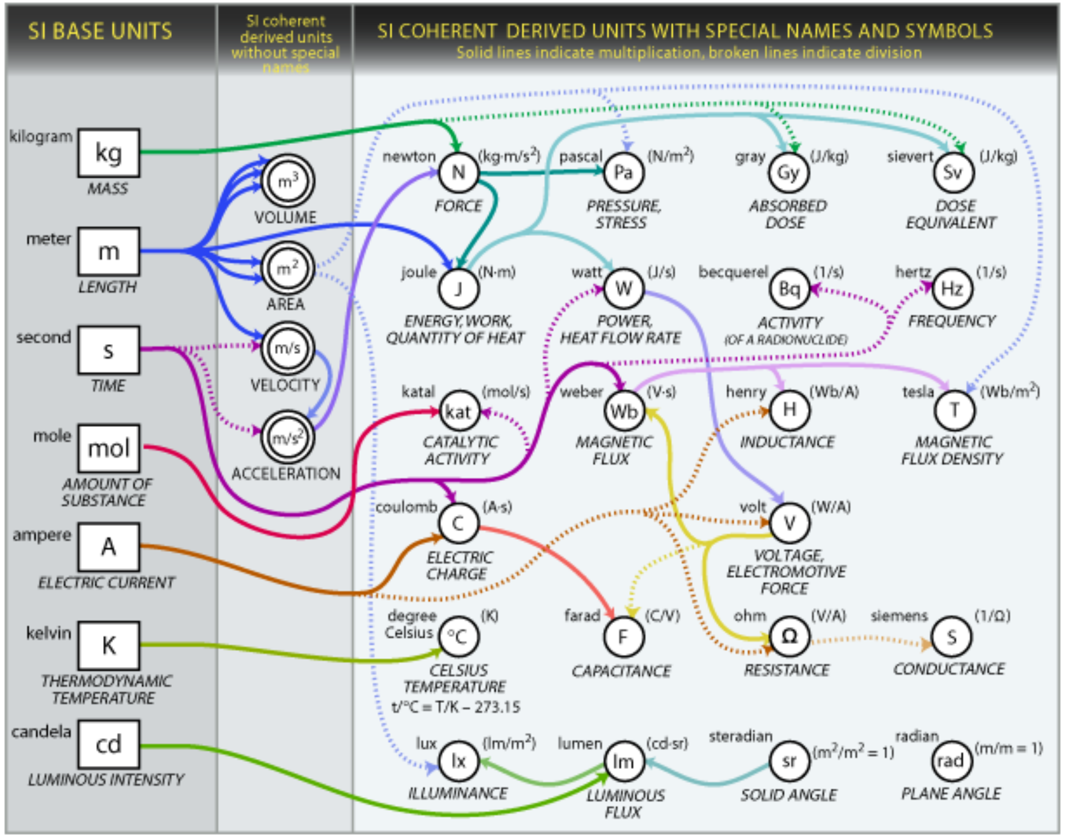
The SI is …

- Scientifically based
- Defined by consensus (CGPM/CIPM)
- Redefinition planned for 2018!

PML seeks to ensure that in the U.S. the SI is…

- Maintained and improved
- Realized in practice
- Disseminated for routine uses
- Disseminated for new and novel uses

SI underpins ***all*** measurements, whether expressed in metric units or otherwise



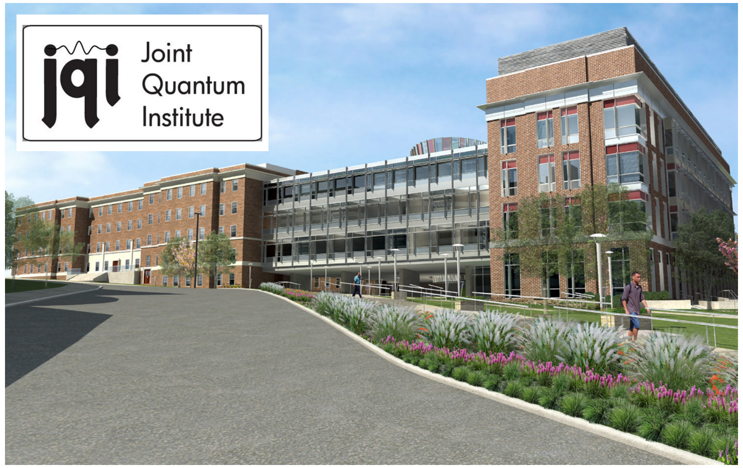
PML: Basic Stats and Facts

Major assets

- ~ $185 million budget
  [all funding sources]
- ~ 500 employees
- ~ 700 associates
- Principal activities in
  - Gaithersburg, MD
  - Boulder, CO
  - College Park, MD
  - Fort Collins, CO & Kauai, HI

Two collaborative institutes provide opportunities to:

- Attract world class scientists
- Train students and postdocs
- Transfer technology



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Some NIST Quantum Definitions

- Quantum Technology:
  - Materials/systems that provide individual sensitivity to quanta – whether light, spins, charge, …
  - Enabling technologies – *e.g.* stable chip scale lasers, chip-scale frequency combs, …
  - Enabling technology that creates high-efficiency detection and transport of quanta – *e.g.* UV fiber for UV lasers, materials with less charge trapping or fewer stray electron spins, ion traps with lower decoherence, *etc.* – basically how to beat down noise and decoherence
- Quantum Metrology:
  - The exploitation of quantum technology to improve measurement science to make better detectors, sources, magnetic or electric field sensors, improved QHR devices, improved SETs,
  - Includes clocks, magnetometers, self-correcting interferometers
  - Transduction of signals – including both classical and quantum
  - Squeezing to allow measurement beyond the Standard Quantum Limit (SQL) – this together with transduction allows amplification and parametric amplification of signals beyond the SQL
- Quantum Based Measurement:
  - The exploitation of quantum technology, quantum metrology, superposition, entanglement, or squeezing to improve a physical measurement

Why NIST was Positioned in QIS

- Extensive background in
  - Coherent manipulation of atoms and ions for clocks (power of a single qubit)
  - Superconducting electronics for Josephson Voltage Systems
  - Only National Measurement Institute (NMI) to ever close the electrical metrology triangle (V=IR or Ohm's Law) at a few parts part in 10^7 – Single electron transistors (SETs)
    - Achieved more than 20 years ago and abandoned *15 year ago* because it was *too hard and not competitive* with direct approaches (for a recent review see H. Scherer *et al.,* Meas. Sci. Technol. **23**, 124010 (2012))
    - In the next few years several other NMIs may duplicate and improve – on this *20 year old result*
    - NIST is reinvesting in SETs in Si that should not have the charge offset noise problem in the Al SETs used 20 years ago
- A long history of manipulating quanta and quantum objects

Why NIST Cares about QIS

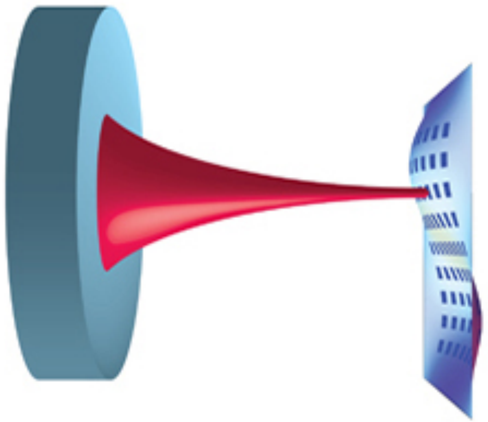
Allows better measurements

- Improved clocks
- Clocks so good they sense their environment → search for gravity waves, dark matter
- If I have technology that can integrate two legs of the electrical metrology triangle on chip then I have the ultimate self-calibrating electrical instrument
- Standards are increasingly quantum in nature – QHR, JVS, clocks, magnetometers, …
- Quantum transduction provides technology to directly convert classical rf or microwaves to optical signal
- Control and manipulation of JJs may lead to high-speed arbitrary waveform generators (100 GHz)
- Technology may enable operation in extreme environments
- Technology allows measurements beyond the shot noise or standard quantum limit

History of QI at NIST

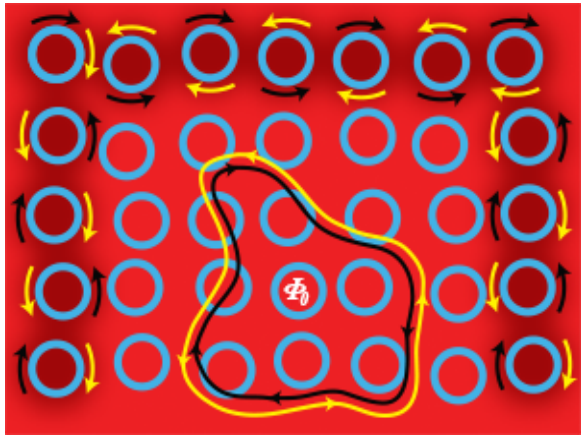
- 1992 Wineland suggests spin squeezing for improved sensitivity of clocks
- 1993 Competence project initiated to support idea
- 1994 **First Workshop focused on QI held at NIST**, Gaithersburg (August 94)
- 1994 NIST starts exploring use of correlated photons for **absolute detector calibration**
- 1995 Cirac and Zoller propose gate based on ion traps
- 1995 Wineland and Monroe implement concept
- **2000 NIST QI Program established**
- 2000 First NIST QI Competence
- 2001 DARPA supports Quantum Communication effort
- 2003 NIST QI Program broadened
- 2003 NIST holds *first* **Single Photon Workshop**
- 2005 First NIST ***Initiative*** for QI is funded
- 2006 Joint Quantum Institute established
- 2012 Wineland wins Nobel Prize for research in support of Q
- 2104 Joint Center for Quantum Information in Computer Science (QuICS) is established

Quantum Information Science at NIST



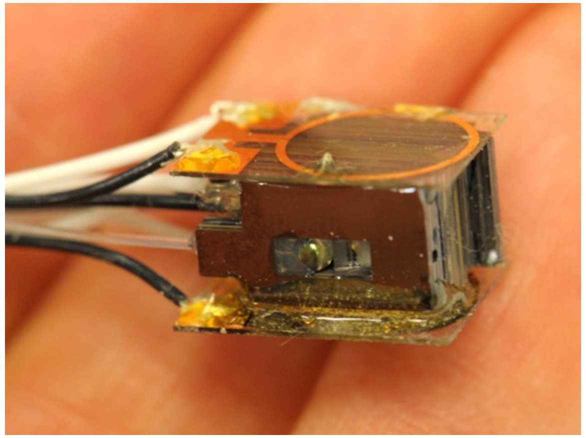
Quantum Transduction

We must realize efficient transfer of information between quanta of different types. Shown here: an optical cavity coupled to a vibrating, mechanical membrane.



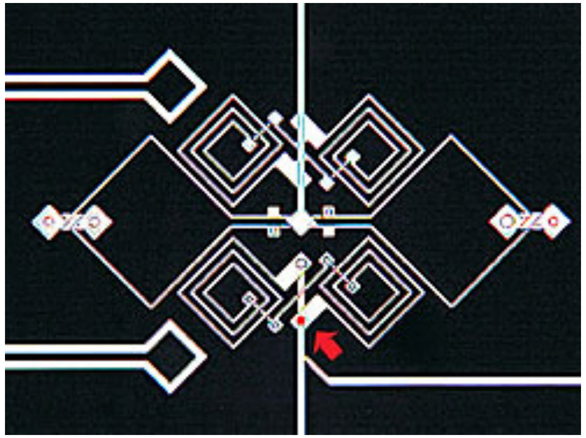
Complex Quantum Systems

We must develop tools for understanding, controlling, and measuring complex quantum systems. Shown here: a photonic chip with ring resonators provides topologically robust transport of photons.



Small Quantum Systems

Small quantum systems will be improved sensors and better standards. Shown here: a chip-scale atomic magnetometer.



Quantum Materials and Solid State Qubits

Solid state realizations of qubits are promising for mass production, though additional research is required. Shown here: a Josephson junction qubit.

Quantum Information Prospects

- Quantum Logic Clock
- Quantum Transduction
- Single photon sources and detectors – many apps.
- Low noise, high-speed, amplifiers and parametric amplifiers beyond the SQL
- Random Number Beacons
- Quantum Based Measurements – electrical, optical, …
- Improved Sensors
- Quantum Communication & Computing

Frequency Ratio of Al^+ and Hg^+ Single-Ion Optical Clocks; Metrology at the 17th Decimal Place

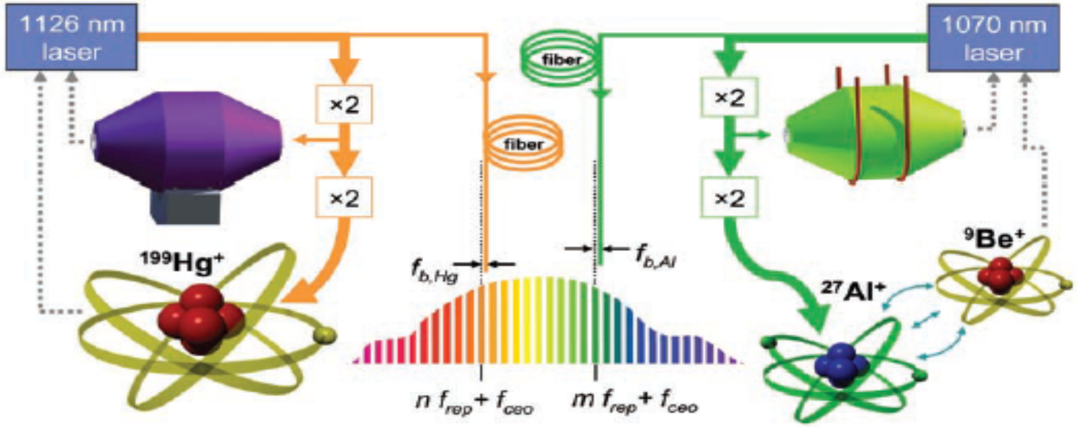


Fig. 1. Frequency ratio measurement system for the comparison of $^{199}Hg^+$ and $^{27}Al^+$ optical clock frequencies. (Left) The fourth harmonic of a 1126-nm wavelength infrared (IR) laser drives atomic-state transitions in a $^{199}Hg^+$ ion (40-ms probe time, 70% duty cycle). The transition rate yields an error signal to keep the laser frequency locked to the atomic resonance. (Right) A 1070-nm wavelength IR laser performs the same function for $^{27}Al^+$ (100-ms probe time, 45% duty cycle), which is coupled to a nearby $^{9}Be^+$ ion by their mutual Coulomb repulsion for the purposes of sympathetic cooling and internal state detection. Both lasers are prestabilized to ultralow-expansion glass Fabry-Perot cavities (purple and green ellipsoids), thereby narrowing their linewidth to about 1 Hz (*4*). Boxes marked "×2" are second-harmonic generation stages to convert IR light first to visible and then to ultraviolet wavelengths. The two laser frequencies are compared by means of a femtosecond comb (*12*), to which both clock laser systems are linked by 300-m lengths of actively phase-stabilized optical fiber. The quantities $f_{b,Hg}$ (beat note of the mercury clock laser with spectral component n of femtosecond comb), $f_{b,Al}$ (beat note of the aluminum clock laser with spectral component m of the femtosecond comb), f_{ceo} (femtosecond comb carrier-envelope-offset), and f_{rep} (femtosecond comb repetition rate) comprise the frequency ratio measurement (*12*).

Science 319, 1808, 2008

Conclusions

NIST Perspective on Future Quantum Technologies

- Ability to manipulate and detect quanta provides new tools for both classical and quantum measurables
- Emerging technologies and nanofabrication are enabling disruptive change
- Embedded standards (NIST-on-a-chip) will change everything from infrastructure monitoring to drilling and mining
- Control of quantum objects will enable high speed (300 GHz) arbitrary waveform synthesis and detection beyond the standard quantum (shot-noise) limit

Quantum Information Science Summary

QIS is a field of scientific inquiry in its own right, with applications in:

- *sensing and metrology:* precision navigation, timekeeping, …
- *communication:* secure data transmission and storage, random number generation, …
- *simulation:* complex materials, molecular dynamics, QCD, …
- *computing:* cryptanalysis, quantum chemistry, optimization, quantum field theory, …

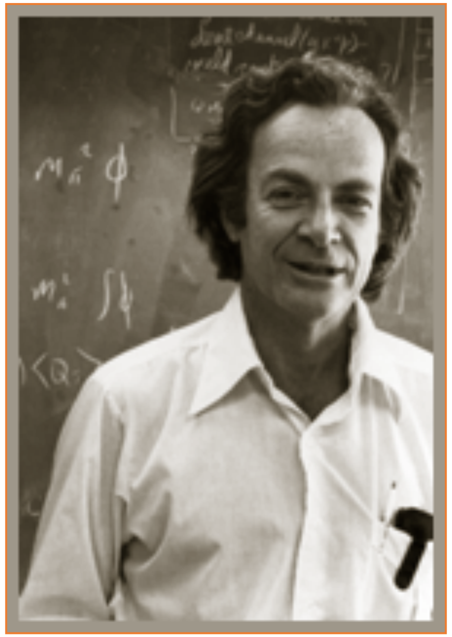
and robust intellectual connections to numerous areas of basic research.

- Quantum communication is available today – not necessarily valuable today
- Quantum sensing and metrology is in the lab and being commercialized
- Quantum simulation is an exciting research field and within the next few years will simulate a *classically incalculable problem*
- Quantum computing, especially generalized QC, is years off but companies are investing

Why is Quantum Information Useful?

We are witnessing the second quantum revolution where technology

- Will use the weird properties of quantum mechanics
- Will exploit how nature works at the quantum level



"…and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy." -- Richard P. Feynman, "*Simulating Physics with Computers*", May 1981

- In the 20th Century only atomic clocks used the strange aspects of QM (GPS)
- Now chip scale atomic clocks are available
- Related technologies include exquisitely sensitive magnetometers, accelerometers, gravimeters
- NV centers may be lead to unimaginable magnetic imaging systems

➢ A quantum computer, if it existed, could break all preser encryption systems
➢ Quantum encryption can defeat any computational atta
➢ Quantum Logic Clocks, Magnetometers, Gyroscopes
➢ Quantum Simulations, Drug Design, other problems

Thank you!

Any questions?

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