Quantum Science – Update

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U.S. Department of Commerce

VCAT
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Quantum Information Science Vision

NIST will advance the metrology of quantum entanglement and superposition to provide a foundation for the encoding, transmission, and use of quantum information.

NIST QIS Program includes:

- *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.

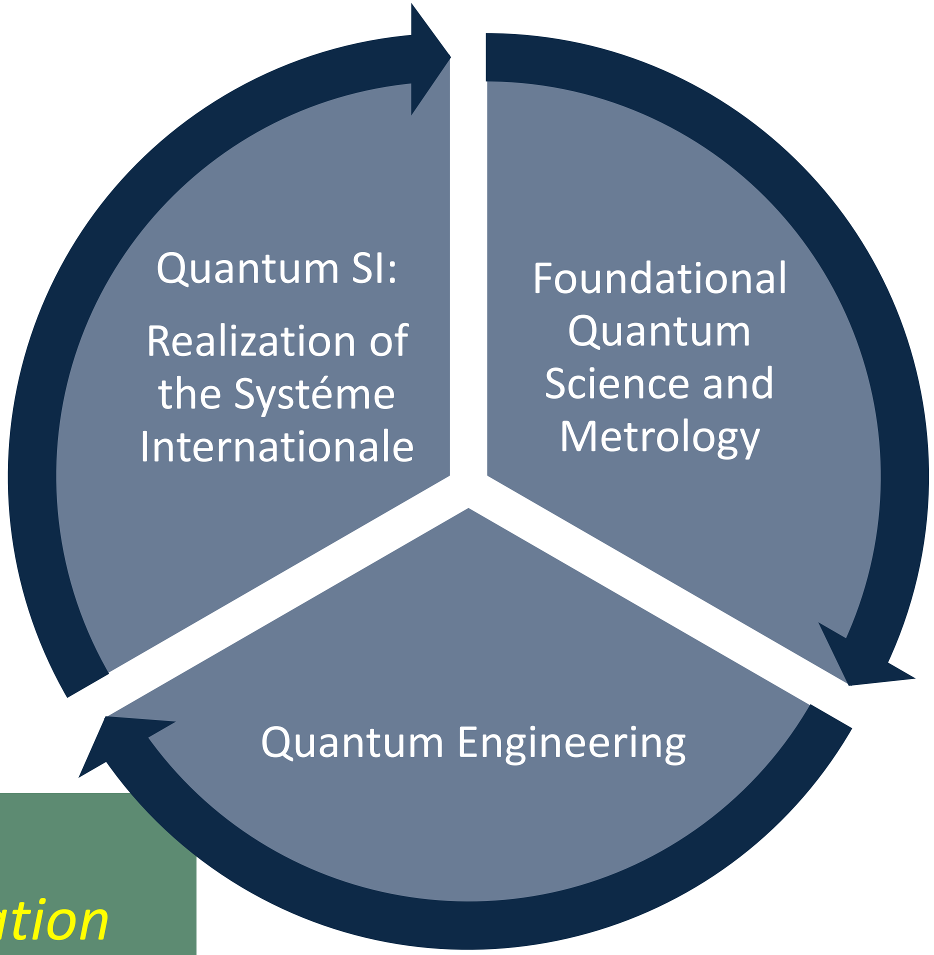
20 year QIS Program is a direct extension of our core research in precision time and electrical metrology and now represents a $40.5 M effort.

NIST QIS Strategic Vision

NIST

NIST will fulfill its mission in QIS through three coordinated efforts:

- Foundational research emphasizing QIS and Metrology
- Applied research to engineer and improve the robustness of prototypes: Quantum Engineering
- Realization and Dissemination of the units of measurement: The Quantum SI



These three activities form an interrelated and self-reinforcing system in which, for example, next-generation atomic clocks are engineered to be smaller and more robust and thereby enable tomorrow's measurement services.

Joint Institutes Critical to Success

Three collaborative institutes at two locations provide opportunities to:

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

QuICS 5 Year Anniversary

Joint Center for
Quantum Information
and Computer Science

Key QIS Policy Opportunities


H. R. 6227

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

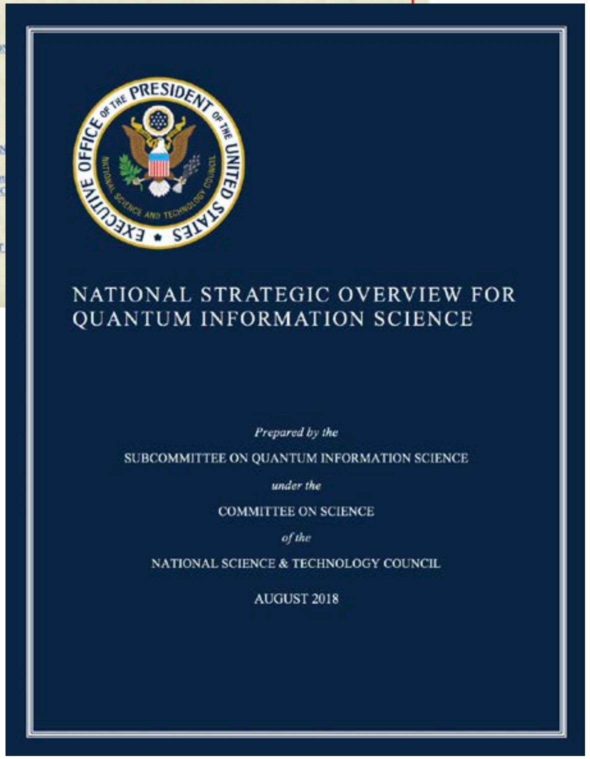
To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

(a) Short Title.—This Act may be cited as the "National Quantum Initiative Act".

(b) Table of Contents.—The table of contents of this Act is as follows:



- Choosing a science-first approach to QIS
- Creating a quantum-smart workforce for tomorrow
- Deepening engagement with quantum industry
- Providing critical infrastructure
- Maintaining national security and economic growth
- Advancing international cooperation

NIST and the NQI (SEC. 201.)

1 Basic and Applied QIST R&D

Continue and expand basic and applied R&D, including measurement and standards infrastructure necessary to advance commercial development of quantum applications

2 Workforce

Use the existing programs of the NIST, in collaboration with other Federal departments and agencies, as appropriate, *to train scientists* in quantum information science and technology (QIST)

3 Collaborate and Work with Others

Establish or *expand* collaborative ventures or consortia with other public or private sector entities, including industry, universities, and Federal laboratories for the purpose of advancing the field of quantum information science and engineering

4 From Contracts to OTA

Enter into such contracts, including cooperative research and development arrangements, grants and cooperative agreements, or *other transactions*, in furtherance of the purposes of this Act

QED-C Thriving

NIST

- Six plenaries since 8/18; next 3/20
- Recent meetings have had over 100 company participants
- Workshops:
  - ➢ Cryogenics (10/19) in Boseman, MT
  - ➢ Materials and Losses in Superconducting Qubits (1/20) in Santa Barbara, CA
  - ➢ Control Electronics (5/20) in Boston, MA
- Funded a framework report on quantum computing market value
- Working group on defense and national security led by AFRL to report to the GB

More than 100 Letters of Intent have been received

Governing Board & TACs

- Governing Board elected: 3 large and 4 small/start-up companies, 2 government agencies
- 4 Technical Advisory Committees

NIST Support

5 Year *Other Transaction Authority* in place with maximum value $50 M

Legal Structure

Potential Member Companies to get approved legal documents by early March and have 6 months to sign; Board to sign by March 2020 Plenary

Quantum Standards Development

- Standards needs solid body of validated or broadly accepted foundational work
  - Premature standardization can entrench inferior approaches
  - Competing standards can hinder marketplace adoption
  - Aggressive participation by Chinese entities; strong push for Chinese priorities
- Most mature are in Quantum Key Distribution (ETSI) and Terminology (IEEE, ISO/IEC-JTC1)
- NIST is engaged in quantum standards activities in ITU-T (Telecom)
  - Under UN auspices, focused on telecom and network standards
  - Focus Group on Quantum Information Technology for Networks (FG-QIT4N)
  - Collaboration with QED-C to provide U.S. engagement, leadership
    - Ajit Jilla – Telecom Standardization Advisory Group (TSAG) which oversees the FG-QIT4N
    - Barbara Goldstein – Lead, Standardization Outlook and Technology Maturity subgroup
    - QED-C supports James Nagel (L3Harris) as FG Co-chair and Fred Baker (Lead, Implications of QIT on Networks WG)

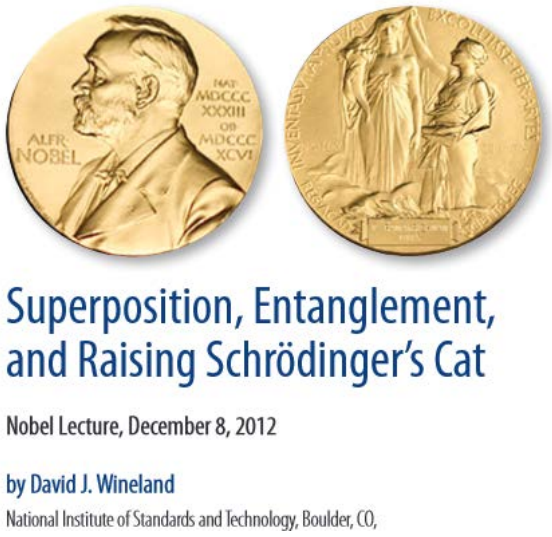
Quantum Network Grand Challenge

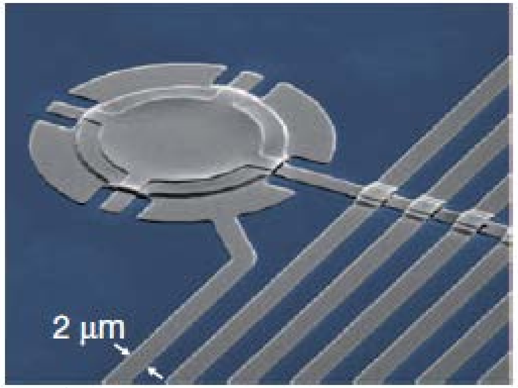
NIST

Leverage our world-leading quantum science portfolio to develop a simplified Quantum Network to identify and understand classical and quantum bottlenecks

- Grand Challenge goals:
  - Develop local testbed(s)
  - Determine interface specifications for plug-and-play components
  - Characterize components and networks, develop metrology framework
- Fundamental research provides foundation for robust standards to retain U.S. leadership in the QIS ecosystem

Credit: David Seiler





https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4674675

The Power of a Testbed

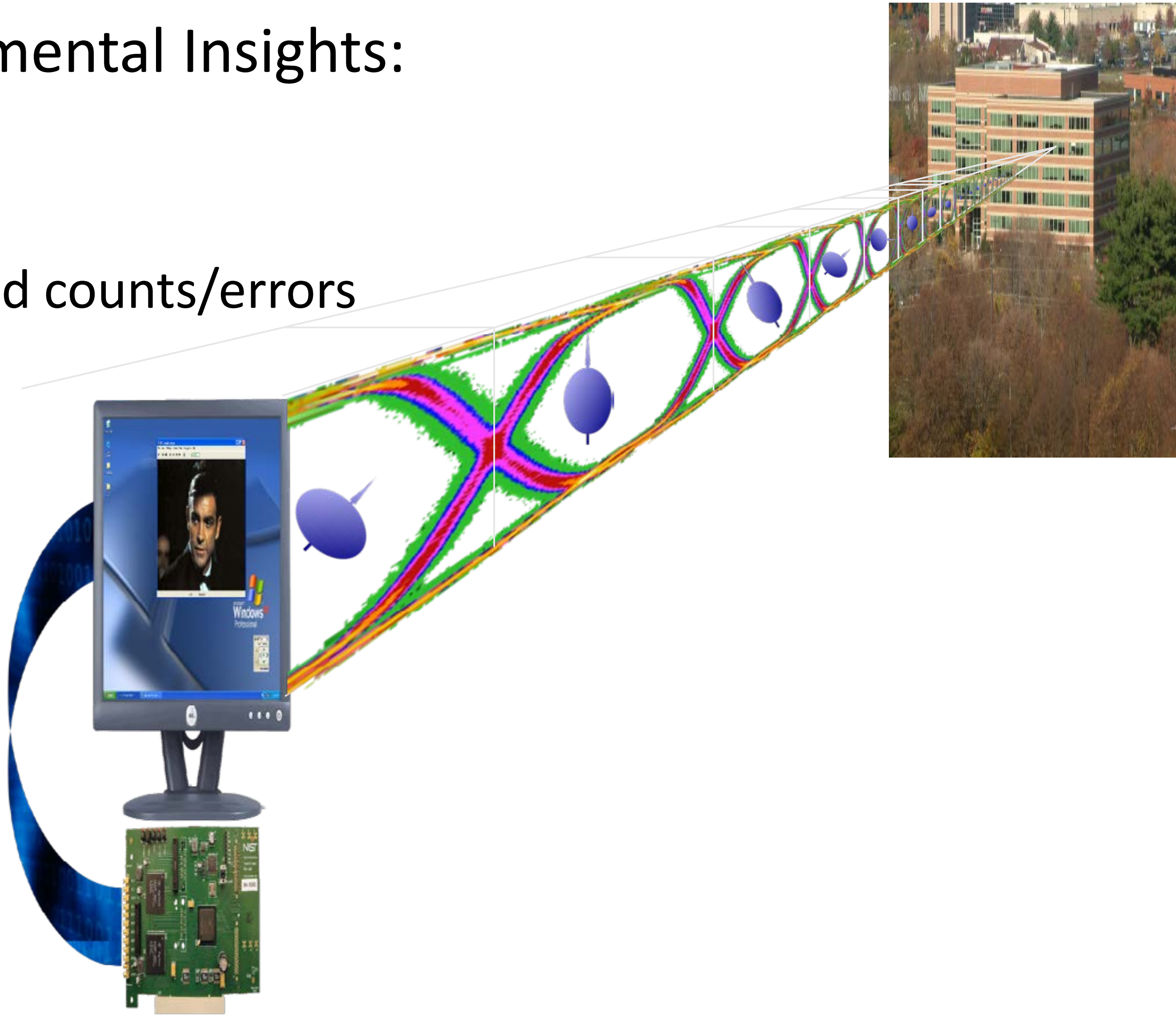
Quantum Key Distribution

QKD Demonstration Provided Fundamental Insights:

- Network timing limits total key
- Detector efficiency limits total key
- Slow detector gating increases background counts/errors
- Slow detector recovery limits total keys
- FPGA memory and distance of QKD link limits speed and total key

Result: NIST created a large program on improved detector efficiency, gating, and recovery

Ultimately, NIST also developed a program for characterizing single photon sources



Quantum Key Distribution

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Result: NI
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Loophole-Free Bell Test

- A Bell-inequality "violation" invalidates hidden-variable pictures of reality
- Paradigm shift in RNG: the only known way to certify universal unpredictability

Ultimately, NIST also developed a program for characterizing single photon sources

Quantum Network Foundations

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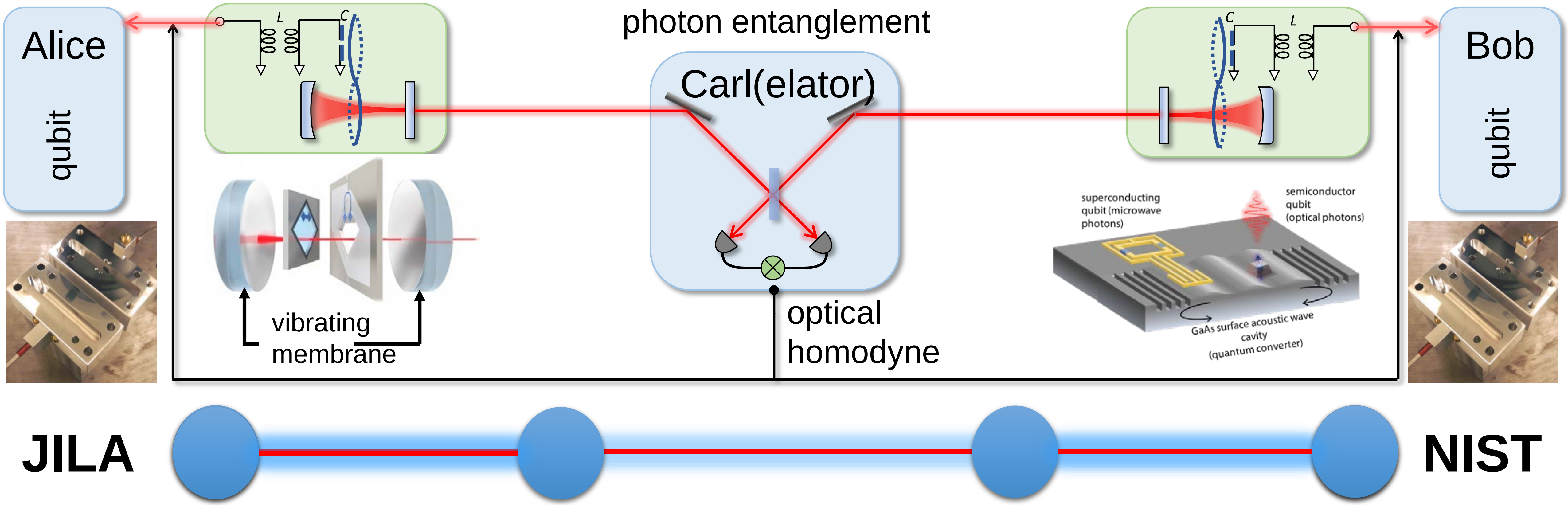
Entangling Isolated Superconducting Qubits



Primary Activities

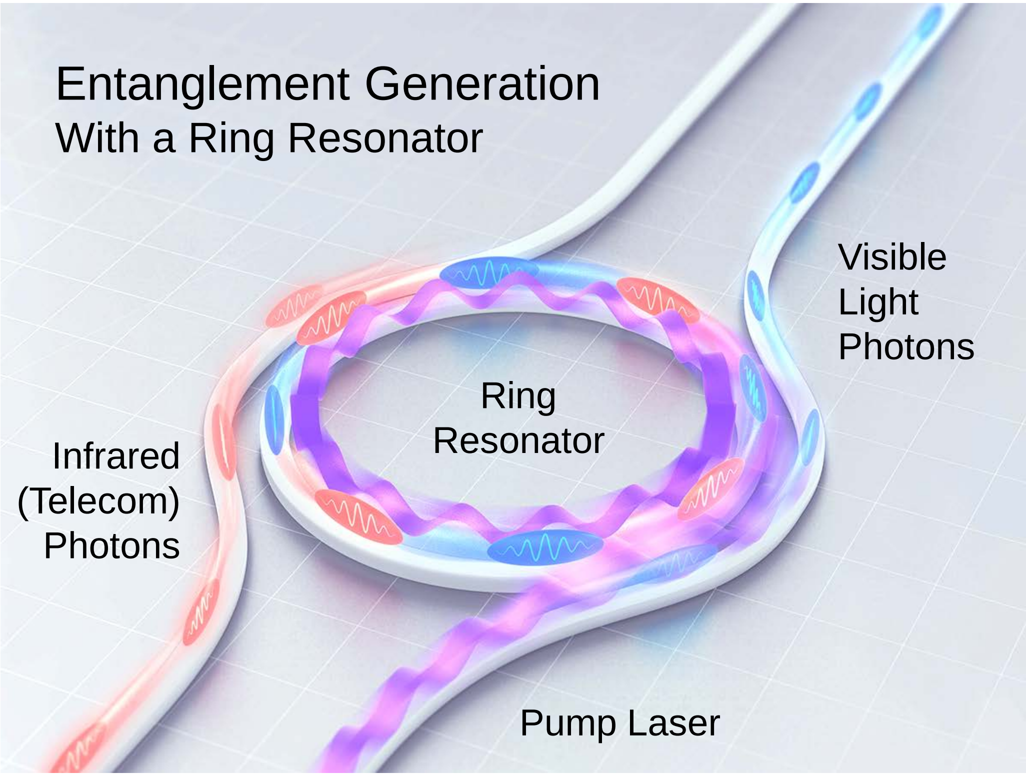
- Transduction
- Quantum correlation
- Quantum networks

Goals

- First link in a quantum network of superconducting qubits
- Expandable test-bed and technology pathfinder network
- “Plug and play” networking for disparate qubit technology

Entangled Photon Pairs of Different Colors

- Entangled pairs of photons are key building block of quantum communication
- Long-distance fiber optic communications requires specific band in the infrared
- Local processes for information storage and computation need visible-band photons
- NIST invented Si_3N_4 nanophotonic ring resonator that generates required pairs through spontaneous four-wave mixing
- Manufacturable in large numbers
  - Provisional patent, pending Bayh-Dole election

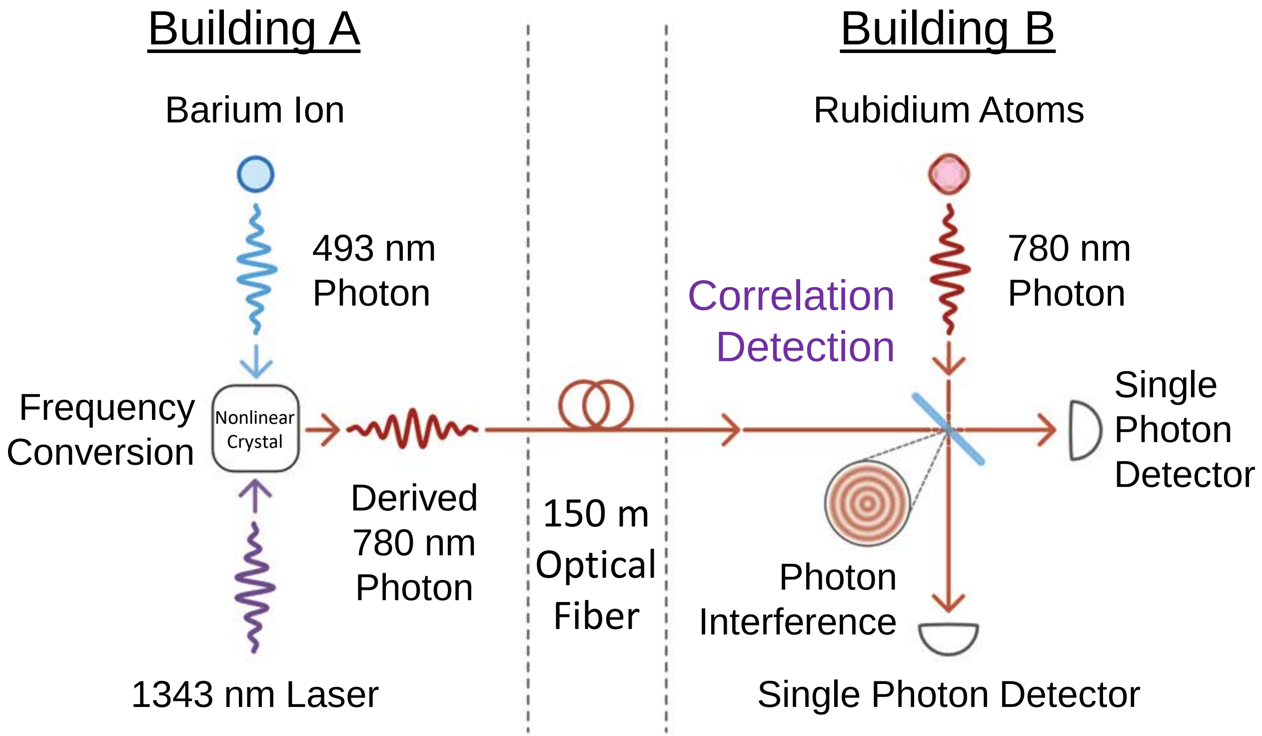


By carefully engineering the geometry of a micrometer-scale, ring-shaped resonator, researchers at NIST produced pairs of entangled photons, one at a desired visible wavelength and one for transmission over long-distance fiber optics.

https://www.nist.gov/news-events/news/2019/02/entangling-photons-different-colors

Visible to Infrared Photon Transduction

- Protocols to entangle photons remotely
  - Alternative to photon pair generation
- Photons produced on-demand simultaneously using unlike sources
- Photon-to-photon transduction to overcome spectral disparity
  - Visible band for storage and computation
  - Infrared band for long-distance communication
- Demonstrated high-visibility quantum interference between resultant photons
  - Critical step towards remote entanglement



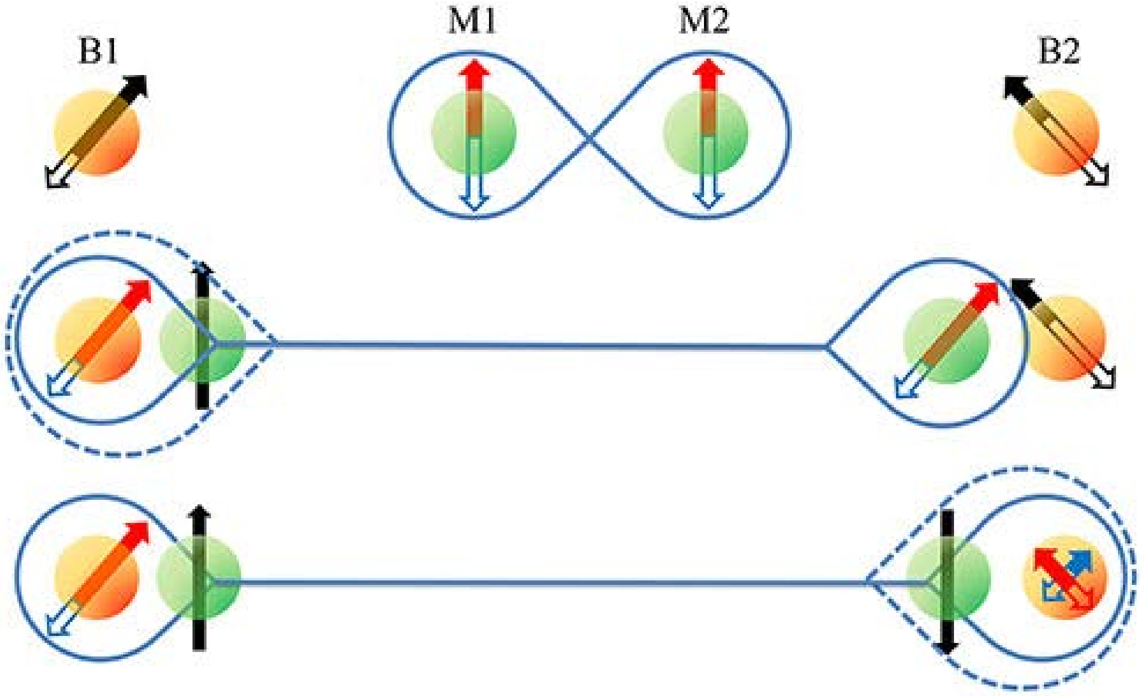
Simplified schematic of an interference experiment in which two photons having different colors (493 nm, 780 nm), generated by different sources and produced in different buildings, are made to interfere. The 493 nm photon is converted to 780 nm, which is demonstrated to be indistinguishable from the other.

https://www.nist.gov/news-events/news/2019/12/new-playbook-interference

Quantum Gate Teleportation

- Gating—
  controlling the state of one qubit conditioned on the state of another
- Key procedure in all quantum information processors
- As scale of quantum processors increases, qubits need to interact over larger distances
- Quantum gate teleportation—
  separated qubits interacting effectively

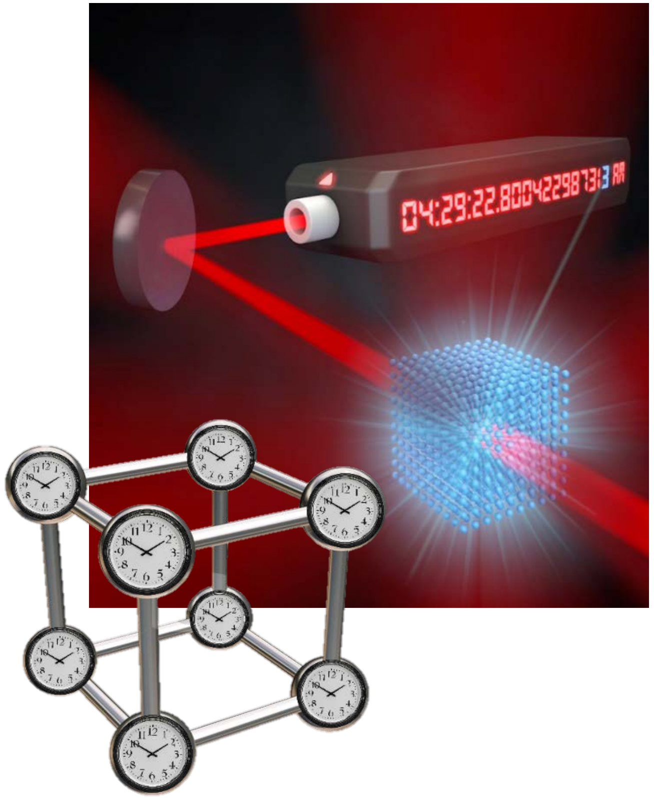
https://doi.org/10.1126/science.aaw9415

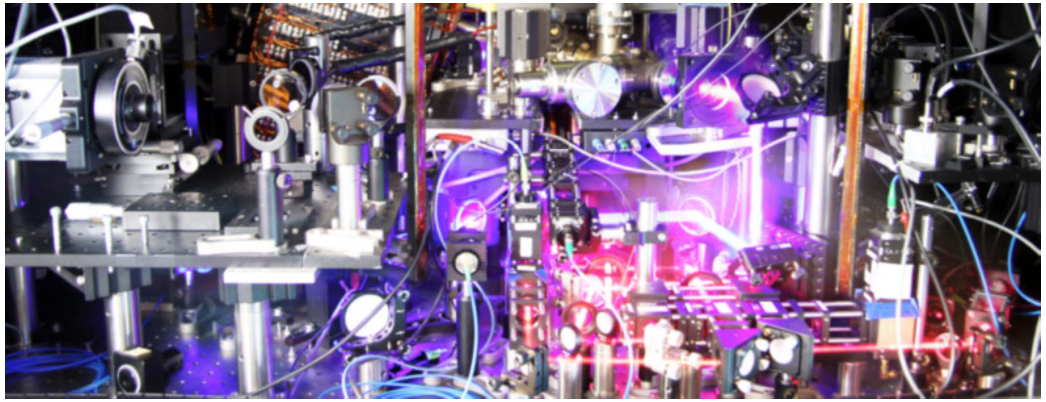


Two beryllium ions (B1 and B2) are over 300 µm apart and in a superposition of spin states. Two entangled magnesium ions (M1 and M2) are messengers. M1 is shuttled off to B1, and a CNOT operation on them leaves B1, M1, and M2 entangled if B1 is in a superposition. A measurement of M1’s spin leaves B1 and M2 entangled. Afterward, M2 is entangled with B1 and B2 through another CNOT, and a measurement of M2’s spin yields the desired CNOT operation on B1 and B2. The final gate performs as expected for an ideal CNOT 85% – 87% of the time.

Quantum Degenerate Fermi Gas Clock

3D Fermi gas strontium (Sr) optical lattice clock





S.L. Campbell *et al., Science* **358**, 90 (2017); G.E. Marti *et al., Phys. Rev. Lett.* ***120***, 103201 (2018); Norcia *et al., Science* **366**, 93 (2019).

- First application of a quantum degenerate gas to a "practical" measurement: *A quantum-enhanced precision measurement*
  - ✓ ~1 million atoms: 100 x 100 x 100 in a 3D-optical lattice
  - ✓ Pauli exclusion: Only one atom per lattice site
  - ✓ Precision 3 x 10^{-20} $Hz^{-1/2}$, on path to 10^{-22} in a few years
  - ✓ Coherence time 160 seconds and improving
- Potential laboratory *for fundamental physics, including quantum gravity, dark matter detection, and long-baseline astronomical observation*

Interagency Coordination

NIST will convene QIS leaders from other government agencies to coordinate efforts to build the quantum internet.

Looking Forward

NIST

Coordination

Continue QED-C leadership and facilitate a unified interagency strategy for Quantum Networks

Standards Development

Maintain a strong presence in relevant standards development bodies to protect US interests and promote the Quantum Economy

Research

Leverage existing expertise to develop a Quantum Network testbed

Technology Transfer

Explore possibility of a joint Quantum Engineering center to promote technology maturation and translation

Questions?