NSF's Quantum Leap

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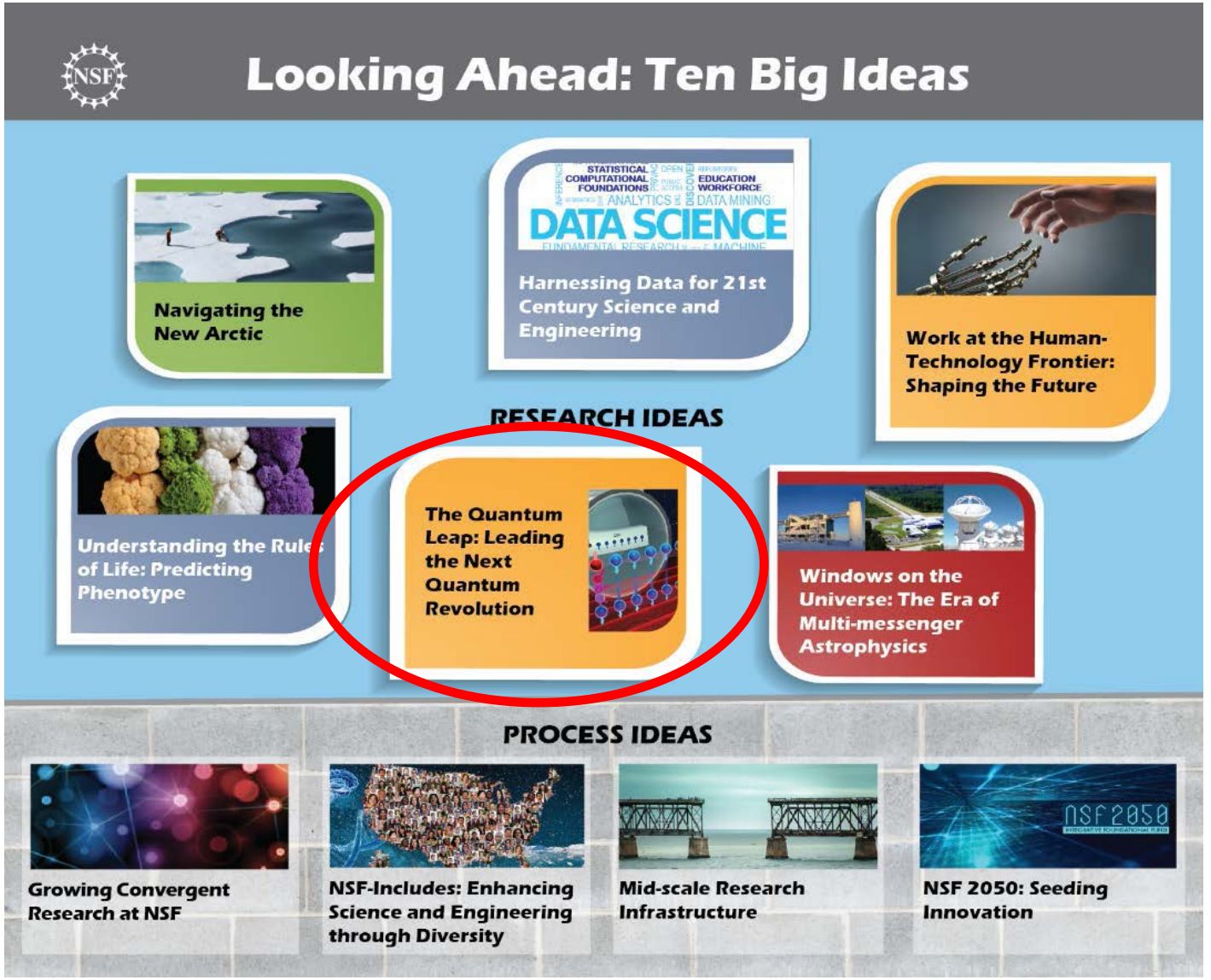
August 14, 2018

MPS Advisory Committee Meeting

NSF's Big Ideas for Future NSF Investments

- *Bold questions that will drive NSF's long-term research agenda*
- *Catalyze investment in fundamental research*
- *Collaborations with industry, private foundations, other agencies, universities*
- *Solve pressing problems and lead to new discoveries*



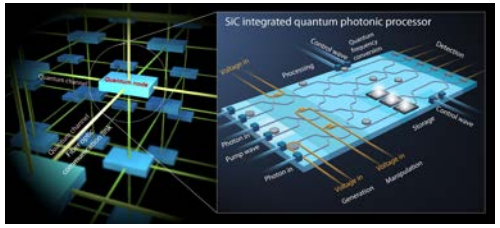
NSF's Quantum Leap: Leading the Next Quantum Revolution

Discovery and exploitation of quantum science and engineering to realize dramatic advances in devices, systems, and in science and engineering itself.

- *Exploiting quantum mechanics to observe, manipulate, and control the behavior of particles at atomic and subatomic scales;*
- *enabling breakthrough discoveries in both naturally-occurring and in engineered quantum systems; and*
- *developing next-generation quantum technologies and devices for sensing, information processing, communications, and computing*

The Quantum Leap: Realizing Ambitious Goals

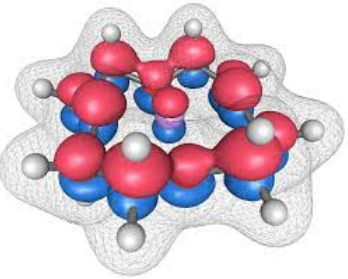
Technologies and devices



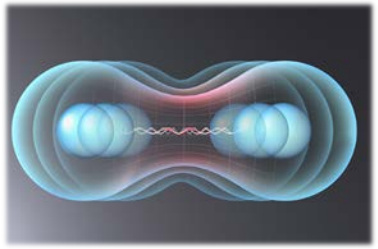
Materials, metrology, sensing, secure communications, computing

Understanding natural and engineered quantum systems

Complexity, simulation, emergent behavior, theory, quantum/classical



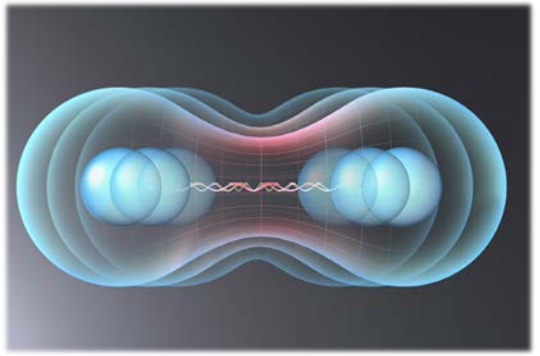
Fundamental science

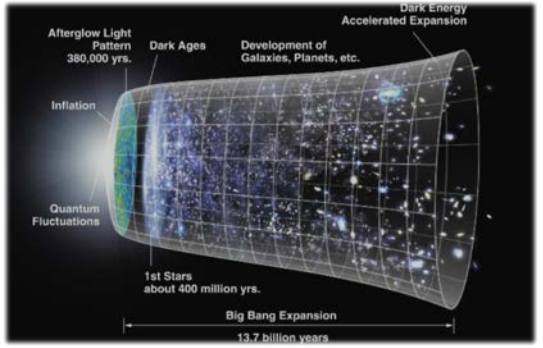


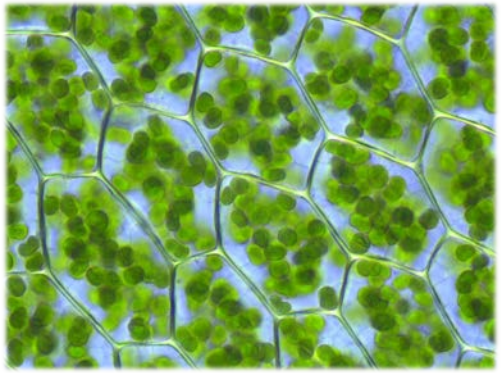
Entanglement, coherence, squeezing

Quantum Leap : Asking Ambitious Questions

Q1: Are there fundamental limits to how far we can push the **entanglement and coherence** frontiers for quantum states? Are there limits in time, distance, or scale?

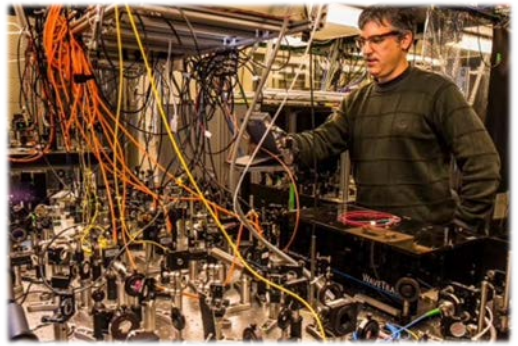






Q2: What can we learn from quantum phenomena in **naturally-occurring and engineered quantum systems**, including emergent behavior, complexity, quantum-classical boundaries, and their theoretical foundations?

Q3: How do we galvanize the science and engineering **community** to enable quantum devices, systems, and technologies that **surpass classical** capabilities?

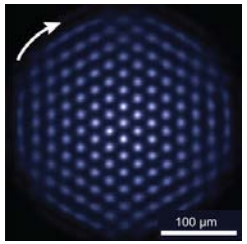


Answering Big Questions

Q1: Are there fundamental limits to how far we can push the **entanglement and coherence frontiers** for quantum states? Are there limits in time, distance, or scale?

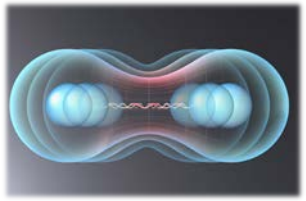
Scale limits: How many qubits can we entangle?

Sequential loading of Yb ions into a linear Paul trap. (physic.uni-siegen.de)



Quantum simulator formed with trapped Be ions in a Penning trap. Britton/NIST.

Distance limits: How far can we entangle quantum states?



Are there fundamental thermodynamic limits?

Time limits: How long can quantum states live? Can we send them into the future?

www.wired.com/2011/01/timelike-entanglement/

Expected advances

Quantum Communications across the Globe

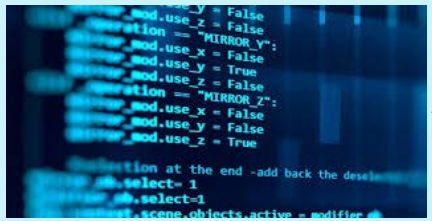
scmp.com

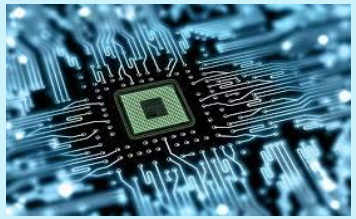
Scalable quantum computer

IBM Q

Answering Big Questions

Topological Quantum Computing: An Emerging Area

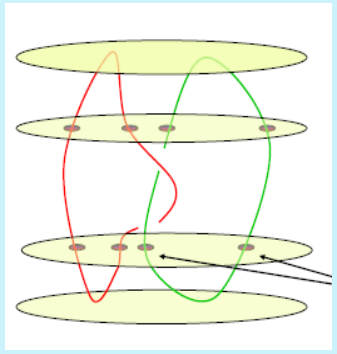




SYSTEMS, ARCHITECTURES
CISE

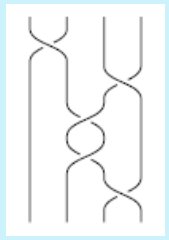
DEVICES, CONTROL
ENG

5. Readout



4. Fuse

3. Braid



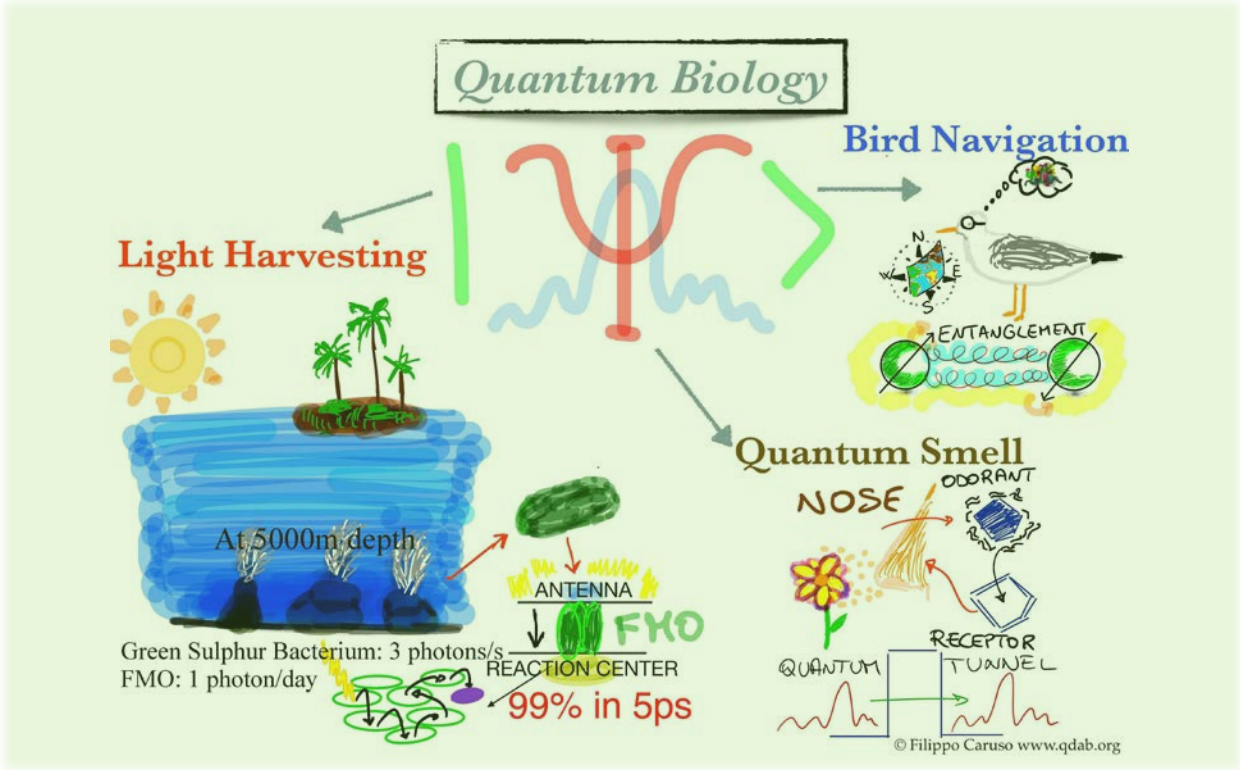
2. Create quantum states

1. Initialize

BRAIDING, ALGORITHMS
DMS

NEW QUANTUM MATERIALS
DMR

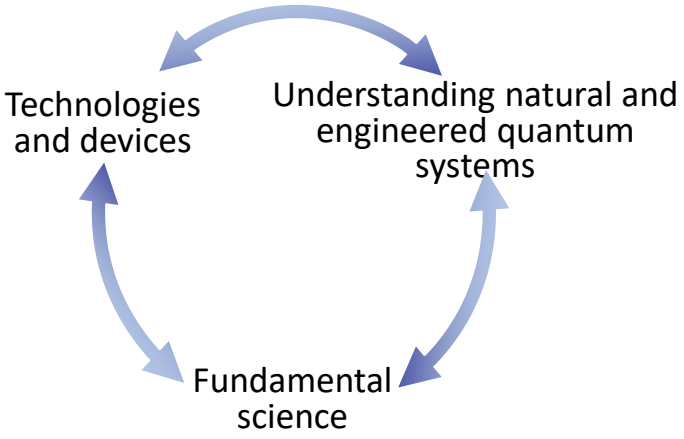
Q2: What can we learn from quantum phenomena in **naturally-occurring and engineered quantum systems**, including emergent behavior, complexity, quantum-classical boundaries, and their theoretical foundations?



[Filippo Caruso (Lindau Meeting, 2016)]

Answering Big Questions

Q3: How do we galvanize the science and engineering **community** to enable quantum devices, systems, and technologies that **surpass classical** capabilities?



- Instill quantum thinking
- New curricula in Quantum Science & Engineering
- Partnerships: federal agencies, private sector, international funders, and private foundations.

capacity building, workforce

$$i\hbar\frac{\partial}{\partial t}|\Psi(\mathbf{r},t)\rangle = \hat{H}|\Psi(\mathbf{r},t)\rangle$$

I do not like it, and I am sorry I ever had anything to do with it. – Erwin Schrödinger

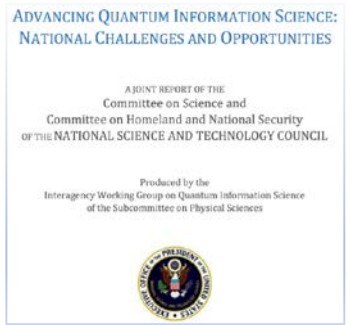
The Quantum Leap: Why Now?

- inflection point in science advances, technology/instrumentation capabilities enables opportunity, rapid advances
- international competition
- opportunities for collaboration
- “to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense...”

31 “quantum” Nobels supported by NSF (since ‘64)

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

IBM Google GORDON AND BETTY MOORE FOUNDATION


ADVANCING QUANTUM INFORMATION SCIENCE: NATIONAL CHALLENGES AND OPPORTUNITIES

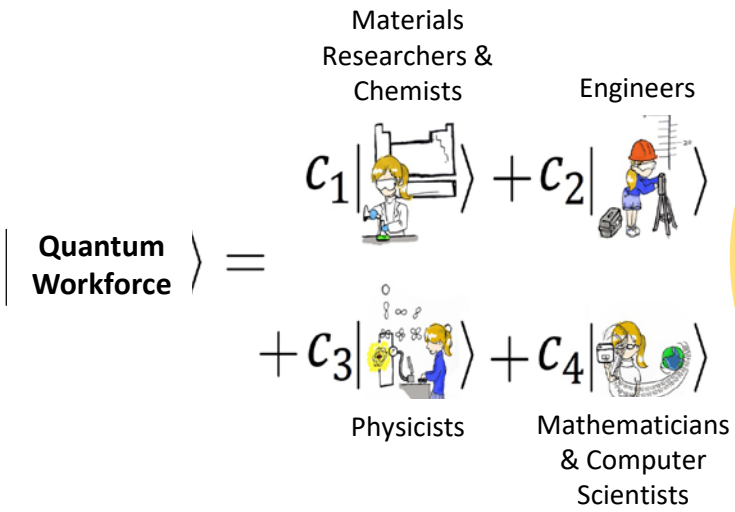
A JOINT REPORT OF THE
Committee on Science and
Committee on Homeland and National Security
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

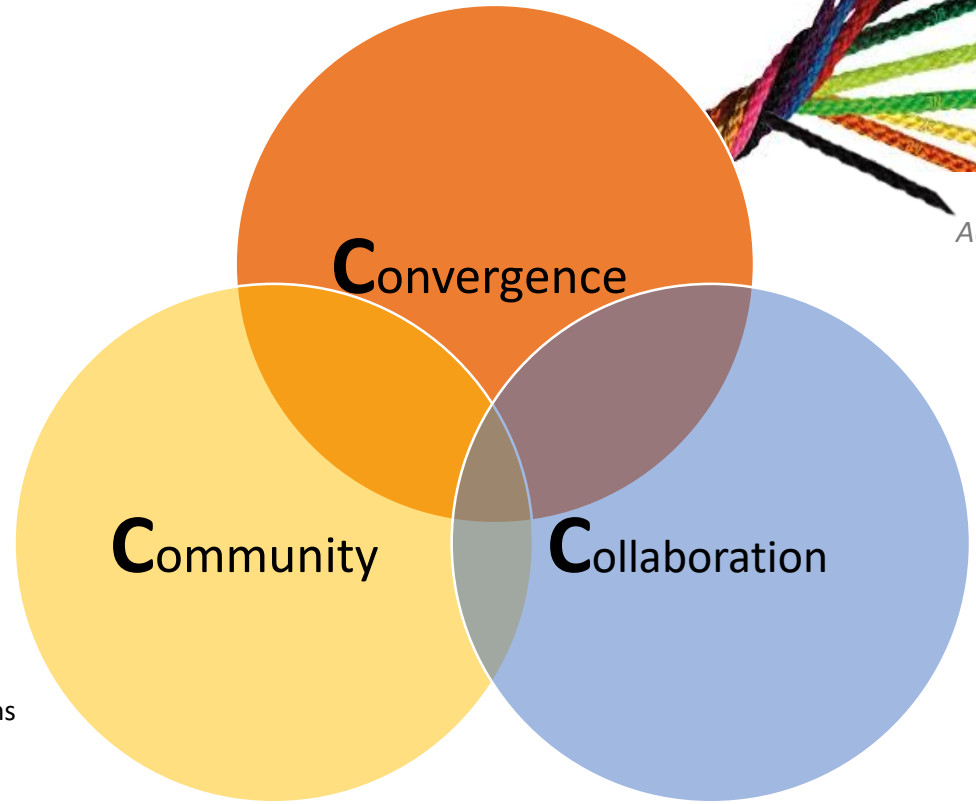
Produced by the
Interagency Working Group on Quantum Information Science
of the Subcommittee on Physical Sciences

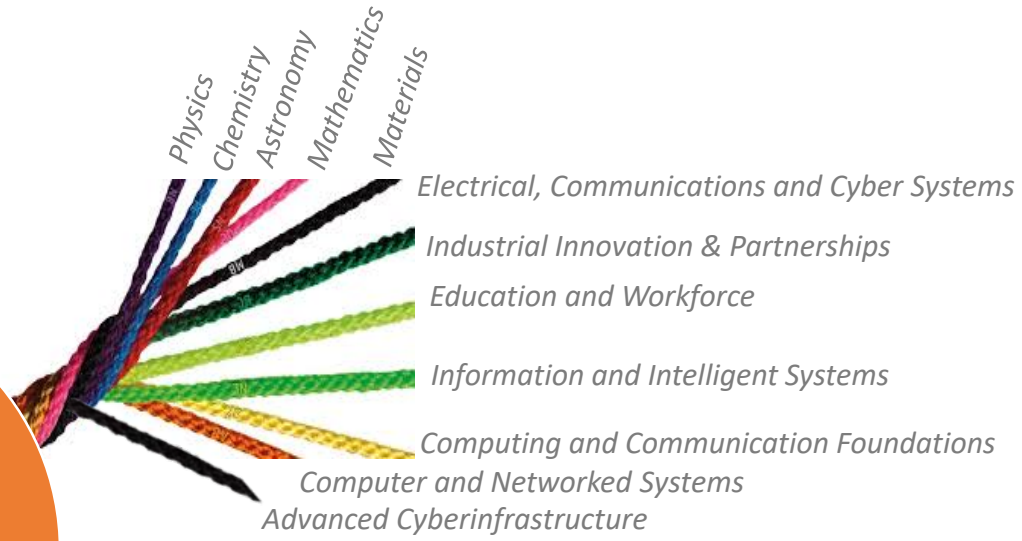
Congressional Hearing: ***American Leadership in Quantum Technology***

Our NSF Approach

The 3 C's

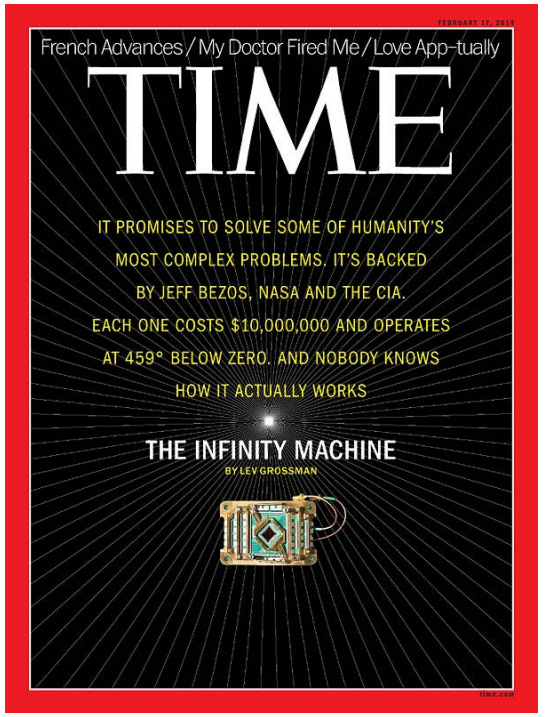






Taking the Leap

- Quantum Leap builds on years of NSF investment in fundamentals of quantum ideas, discoveries, and people
- It is high risk
  - Quantum Science, Engineering, and Technology are maturing in parallel and as separate communities
  - Convergence of disciplines is necessary (and hard)
  - And there is hype
- It is high reward
  - Future leadership: Scientific discovery, Economic growth, National security
- We have started Quantum Leap activities in FY17
  - Using existing mechanisms like RAISE, DCLs, Ideas Labs, EFRI, plus targeted solicitations
  - Planning for FY 2019 ($30M for QL in President's request)



Taking the Leap: First Steps

FY 17-18 Activities underway

Q-AMASE-i: *Discovery Foundries for Quantum Materials Sci., Eng., and Information*

EFRIs: quantum memory, repeaters, topological metamaterials, networks

DCL: Engineering Quantum Integrated Platforms for Quantum Communication (EQuIP)

Triplets

Technologies and devices

Understanding natural and engineered systems

DCL: Enabling QL: Achieving room-temperature quantum logic

Quantum workshops (Chemistry, Materials, Communications, IUCRC)

Enabling Practical-scale Quantum Computing: *Expeditions in Computing*

DCL: RAISE: Transformative Advances in Quantum Systems (RAISE/TAQS)

NSF/DOE/AirForce **summer school**

DCL: Braiding

Fundamental science

DCL: Enabling Quantum Leap in Chemistry (QLC)

Ideas Lab: Practical Fully-Connected Quantum Computer Challenge (PFCQC)

Quantum Leap: An Example

Solicitation NSF 17-548 "**Ideas Lab**: Practical Fully-Connected Quantum Computer Challenge (PFCQC)" A co-design approach to integrating hardware, software and quantum algorithms"

NEW!

NSF Award 1818914

STAQ: "Software-Tailored Architecture for Quantum co-design"

- Develop a fully-connected quantum computer with enough qubits to solve a relevant problem
- "Full stack": software, algorithms, devices, systems integration

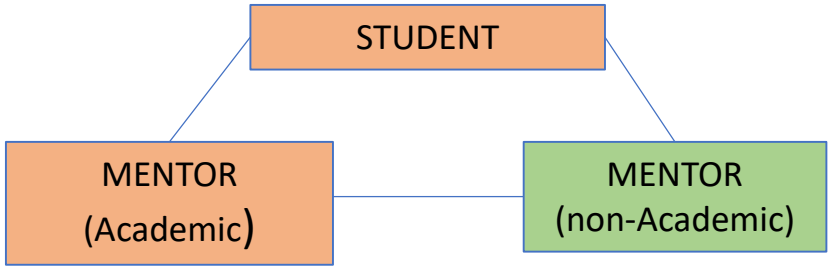
August 8, 2018

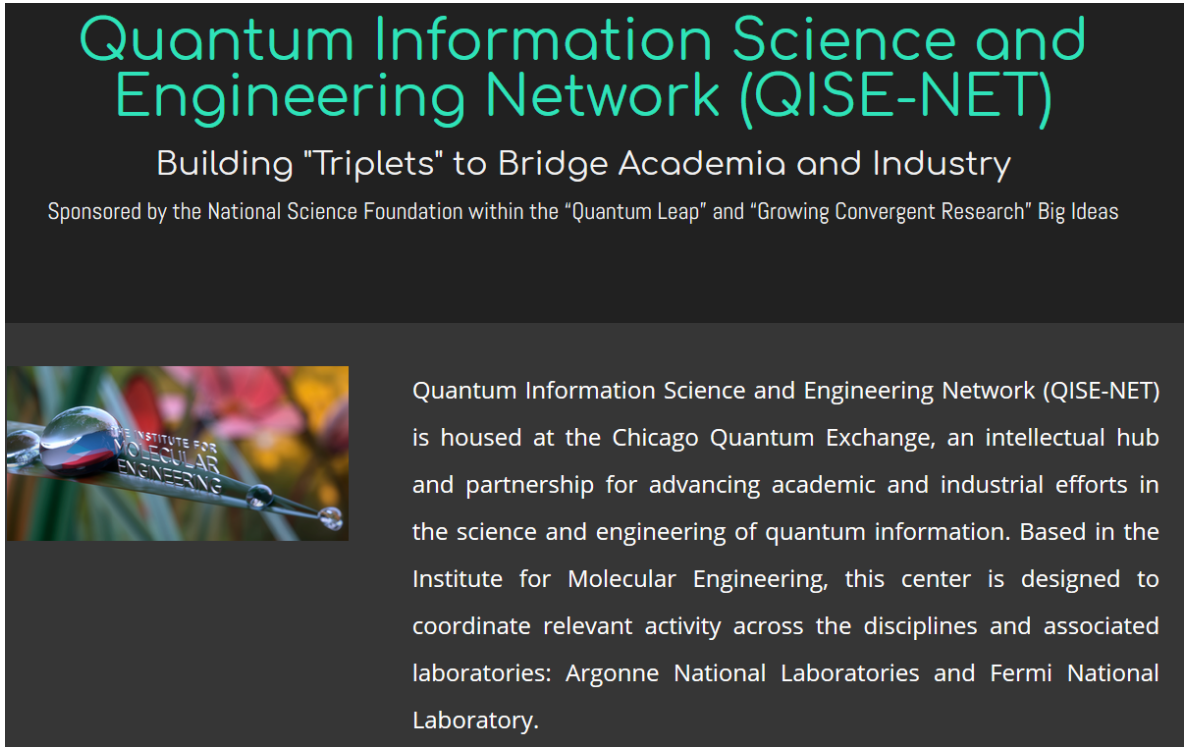
Quantum Leap: Triplets

Quantum Information Science and Engineering Network" of "triplets" of students, faculty, industry partners to work on Quantum Leap challenges (nine NSF Divisions participating)

University	*Partner*
Columbia U	Raytheon BBN
Georgia Tech	IBM Watson
MIT	Sandia Labs
U. Maryland	IonQ Inc.
MIT	Google
U. Maryland	IBM Watson
UW-Madison	Google
Georgetown	IBM Almaden
Georgia Tech	IBM
Dartmouth	Google

University	*Partner*
U. Chicago	IBM
UCSC	Argonne
UT Austin	NIST
Caltech	IBM
Caltech	Google
U. Pitt.	IBM
U. Illinois	NIST
Vanderbilt	ORNL
Sony Brook U.	BNL
UW Madison	Adamas Nano.
MT State	MT Instruments





http://news.uchicago.edu/article/2018/05/08/nationwide-program-launches-train-new-generation-quantum-engineers24

Quantum Leap: Opportunities

- Emerging Frontiers in Research and Innovation 2016 (EFRI-2016): “Advancing Communication Quantum Information Research in Engineering (ACQUIRE)”
  - NSF News Release 16-091: $12M to support six interdisciplinary teams of 26 researchers
- Dear Colleague Letter NSF 17-053: “A Quantum Leap Demonstration of Topological Quantum Computing”, EAGERs to demonstrate topological qubits (MPS/DMR)
- NSF 18-046: Dear Colleague Letter: Enabling Quantum Leap: Achieving Room-Temperature Quantum Logic through Improved Low-Dimensional Materials (issued 15 February 2018)
- CCF-1730449: “Collaborative Research: EPiQC: Enabling Practical-scale Quantum Computing”, an award **in *Expeditions in Computing*** program in CISE; See NSF news release 18-011
- Convergence QL: NSF/DOE Quantum Science Summer School” DMR-1743059 (Funded by: NSF; DOE/BES, DOE/ASCR, + (recent) AFOSR)
- **NSF 18-035 “Dear Colleague Letter: RAISE on Enabling Quantum Leap: Transformational Advances in Quantum Systems” (issued 14 December 2017)**
  - Convergent teams working to develop experimental demonstrations of transformative advances towards quantum systems
- **NSF 18-051 “Dear Colleague Letter: Enabling Quantum Leap in Chemistry (QLC) (issued 8 March 2018)**
- **NSF 18-578 “Enabling Quantum Leap: Convergent Accelerated Discovery Foundries for Quantum Materials Science, Engineering, and Information (Q-AMASE-i)” (issued 2 August 2018)**
  - Foundries to rapidly accelerate quantum materials design, synthesis, characterization, and translation of fundamental materials engineering and information research for quantum devices, systems, and networks.

NEW!

Taking the Leap: Next Steps

- ENGAGEMENT - NSF community, other Federal agencies, private sector, Foundations: Impressive community response
- CAPACITY BUILDING - Multi-disciplinary quantum science and capacity building
- NATIONAL CONVERSATION - Participating and bringing NSF perspective to national conversation on QIS.
- BUDGET - FY 2019 Budget Request: $30M for Quantum Leap (MPS/OMA)

White House approach to QIS taking shape

The National Science and Technology Council's Subcommittee on Quantum Information Science held its first meeting on April 27. The House's draft quantum bill would task this group with developing two five-year strategic plans that establish goals and metrics for a National Quantum Initiative.

(Image credit – OSTP)

https://www.aip.org/fyi/2018/science-committee-seeks-launch-national-quantum-initiative

The Quantum Leap: Leading the Next Quantum Revolution

- *Exploiting quantum mechanics to observe, manipulate, and control the behavior of particles at atomic and subatomic scales;*
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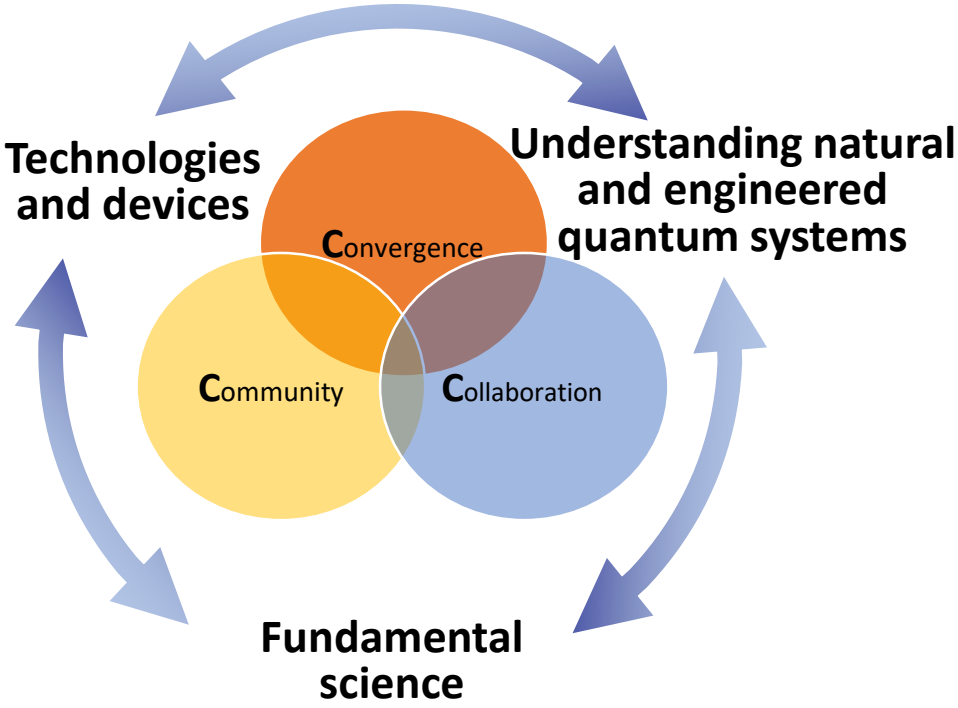

The NSF Quantum Leap (Structure)