NSF’s Quantum Leap

Saúl González (MPS/PHY), Sohi Rastegar (ENG/OAD)
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

Understanding natural and engineered quantum systems

Fundamental science

Materials, metrology, sensing, secure communications, computing

Entanglement, coherence, squeezing

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

**Distance limits:** How far can we entangle quantum states?

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

**Expected advances**

Quantum Communications across the Globe

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.

Are there fundamental thermodynamic limits?

Scalable quantum computer

www.wired.com/2011/01/timelike-entanglement/
Answering Big Questions

Topological Quantum Computing: An Emerging Area

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?

1. Initialize
2. Create quantum states
3. Braid
4. Fuse
5. Readout

BRAIDING, ALGORITHMS
DMS

DEVICES, CONTROL
ENG

SYSTEMS, ARCHITECTURES
CISE

NEW QUANTUM MATERIALS
DMR

Quantum Biology

Light Harvesting

Quantum Smell

Bird Navigation

[Filippo Caruso (Lindau Meeting, 2016)]
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.

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

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)
Our Approach

The 3 C’s

\[ \text{Quantum Workforce} = C_1 + C_2 + C_3 + C_4 \]

Materials Researchers & Chemists

Engineers

Physicists

Mathematicians & Computer Scientists

Convergence

Community

Collaboration

Education and Workforce

Electrical, Communications and Cyber Systems

Industrial Innovation & Partnerships

Information and Intelligent Systems

Computing and Communication Foundations

Advanced Cyberinfrastructure
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

**Technologies and devices**
- Q-AMASE-i: Discovery Foundries for Quantum Materials Sci., Eng., and Information
- EFRIs: quantum memory, repeaters, topological metamaterials, networks
- Enabling Practical-scale Quantum Computing: Expeditions in Computing
- DCL: Braidings
- NSF/DOE/AirForce summer school

**Fundamental science**
- DCL: Engineering Quantum Integrated Platforms for Quantum Communication (EQuIP)
- DCL: Enabling QL: Achieving room-temperature quantum logic
- DCL: RAISE: Transformative Advances in Quantum Systems (RAISE/TAQS)
- DCL: Enabling Quantum Leap in Chemistry (QLC)

**FY 17-18 Activities underway**
- Triplets
- Enabling Practical-scale Quantum Computing: Expeditions in Computing
- NSF/DOE/AirForce summer school

Notes:
- DCL: Engineering Quantum Integrated Platforms for Quantum Communication (EQuIP)
- DCL: Enabling Quantum Leap in Chemistry (QLC)
- DCL: RAISE: Transformative Advances in Quantum Systems (RAISE/TAQS)
- DCL: Braidings
- Q-AMASE-i: Discovery Foundries for Quantum Materials Sci., Eng., and Information
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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”

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

Fresh from the @NSF Ideas Lab: $15 million towards building the world's first practical quantum computer!

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)

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http://news.uchicago.edu/article/2018/05/08/nationwide-program-launches-train-new-generation-quantum-engineers
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)
- Convergence QL: NSF/DOE Quantum Science Summer School” DMR-1743059 (Funded by: NSF; DOE/BES, DOE/ASCR, + (recent) AFOSR)
  - Convergent teams working to develop experimental demonstrations of transformative advances towards quantum systems
- 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)

The Quantum Leap: Leading the Next Quantum Revolution

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• 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 NSF Quantum Leap (Structure)

NSF QL Working Group

Program Directors

NSTC QIS&T Subcommittee

Inter-Agency

NSF QL Steering Committee

WG co-Chairs

MPS AD + 1

DDD, DDs, ADs