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Critical Technology Area Roadmap: Quantum Science

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Image: Shutterstock

Quantum Science:
A History, and Future, of Advancing Defense Capabilities

Quantum science is fundamental to Department of Defense (DoD) capabilities development.

- Dating back to the Manhattan Project in World War II, many advancements in quantum technology have roots in DoD-funded research and development.
- The continued exploration of quantum science through basic scientific research is critical to discovering potential defense capabilities not currently considered.

Then

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Nuclear

1910–1940: Establishment of quantum theory improves understanding of the atom, commencing the nuclear arms race.

Navigation and Timing

1940–1990: Development of vacuum tubes and RADAR technology in the early Cold War gives rise to the first quantum technology—atomic clocks—enabling precision time and the Global Positioning System (GPS).

Now

Quantum Sensing

1980–Present: Modern lasers and nanotechnology advance atomic clocks, navigation, bio-imaging, and C3ISR.*

** Command, control, communications, intelligence, surveillance and reconnaissance*

Quantum Computing

1990–Present: Advanced materials, microelectronics, and information theory usher in transformative computation and communication ideas.

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The Department of Defense Enters a "Quantum-First" Era

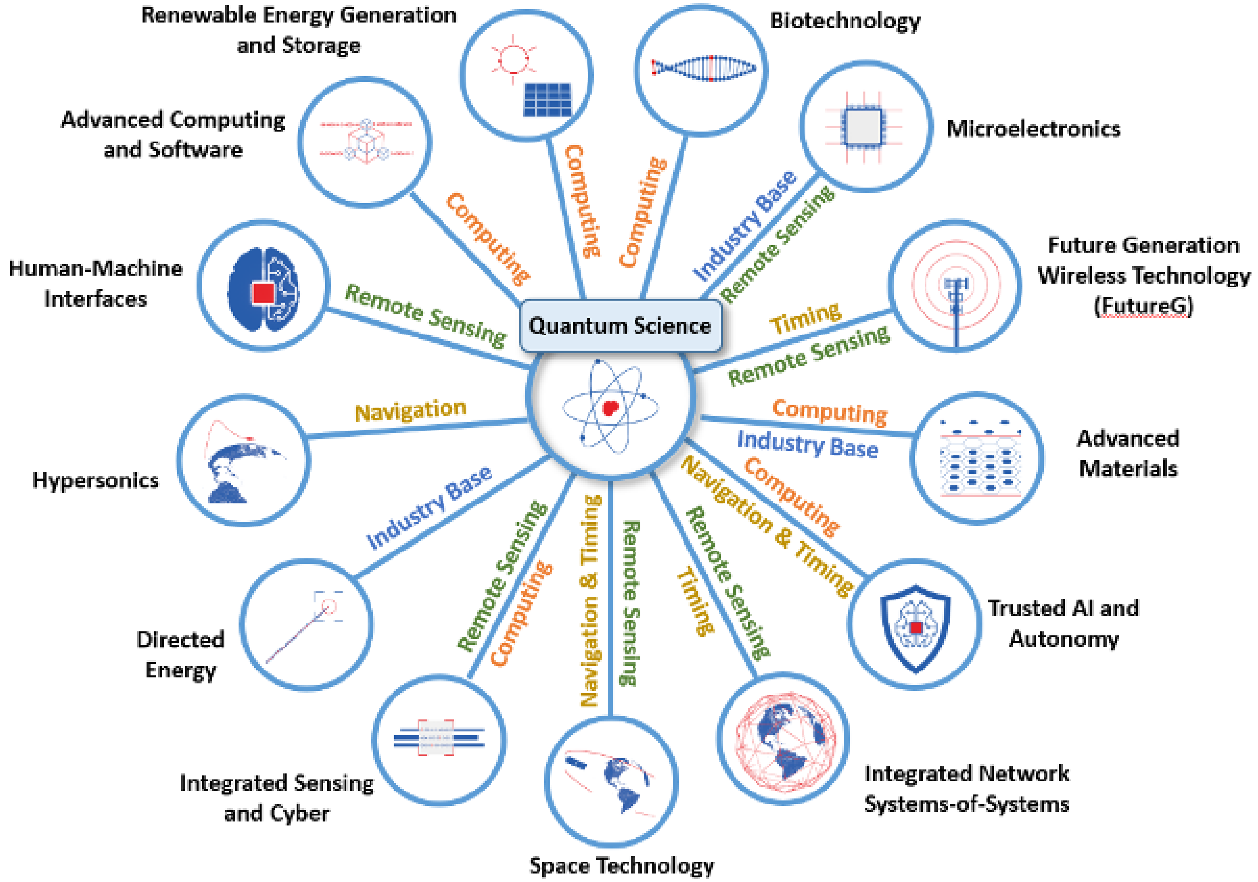
The advancement of quantum science, one of 14 DoD-defined Critical Technology Areas, contributes to all CTAs' lines of effort toward enhanced warfighter capabilities.

"We will reassess our Critical Technology Areas to sharpen our mission focus and accelerate progress in our selected areas.

In every scenario, we will be AI-first and Quantum-first. We will be bold, move faster, and embrace more calculated risk in the face of enormous challenges without being unrealistic, or worse, pessimistic."

DoD photo by EJ Hersom

Under Secretary of Defense for Research & Engineering Mr. Emil Michael's message to the workforce
May 29, 2025

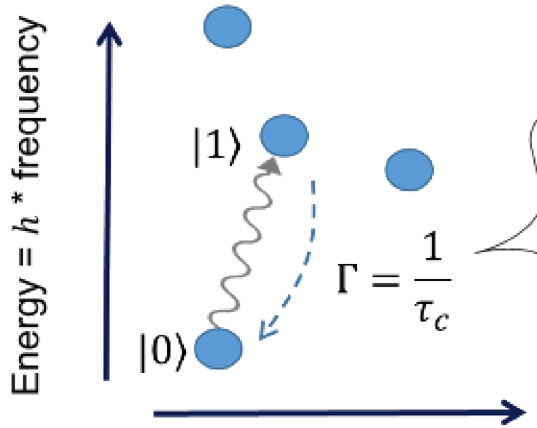


Foundations of Quantum Sensing

Quantization of Modes/States and Superposition

- **Quantum** refers to the measurement and behavior of subatomic objects like photons and electrons.
- Quantum objects can have two or more field modes, represented to the right as $|0\rangle$ and $|1\rangle$. Their behavior in these respective states produces characteristics that can be detected and measured.
- This quantum principle, **superposition**, is contrary to classic physics taught in high schools that matter can only take one state at a time.

Energy of a photon is equal to its frequency multiplied by *Planck's constant*, (h), a fundamental constant in quantum physics postulated by Max Planck in 1900.



Spatial characteristics

- Angular momentum (spin)
- Polarization
- Direction of travel

A system engineered to generate a large response to small changes in spatial characteristics → **quantum sensor**

Derived technologies:

- Atomic clocks
- Magnetic field sensors
- Accelerometers

Defense and civilian/ commercial applications:

- GPS navigation
- Medical imaging
- Threat detection

Foundations of Quantum Computing

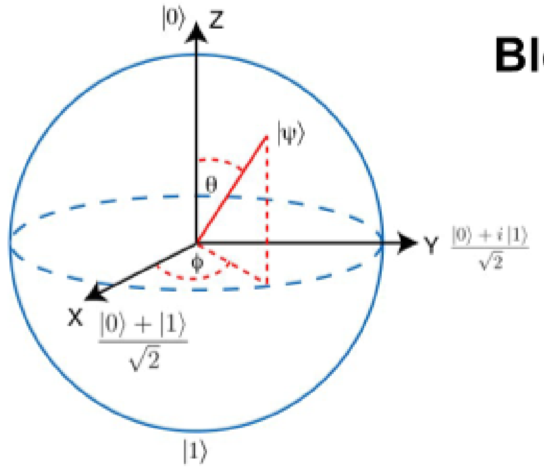
Qubits, Entanglement, and Parallelism

- Superposition permits particles to behave also like a wave.
- The three-dimensional representation of superpositioned objects produces the **qubit** (literally a "quantum bit").

Bits vs. Qubits

Classic computers understand the smallest form of digital data (a bit) in one of two states/values: 1 or 0.	**Quantum computers (QCs)** understand qubits in many states: 0, 1, and combinations of values between 0 and 1: (e.g., 0.5, 0.05 0.005, etc.).

- Given this more efficient manner of storing information, qubits can be "**entangled**" (multiqubit superposition) to contain exponentially more data.
- Leveraging superposition and entanglement, quantum computers achieve **quantum parallelism**—the ability to evaluate possible outcomes (0, 1, and everything in between) *concurrently*.
- Classic computers evaluate the same outcomes *consecutively*, taking significantly—and even prohibitively—longer to identify the optimal outcome.



Bloch (Poincare) Sphere

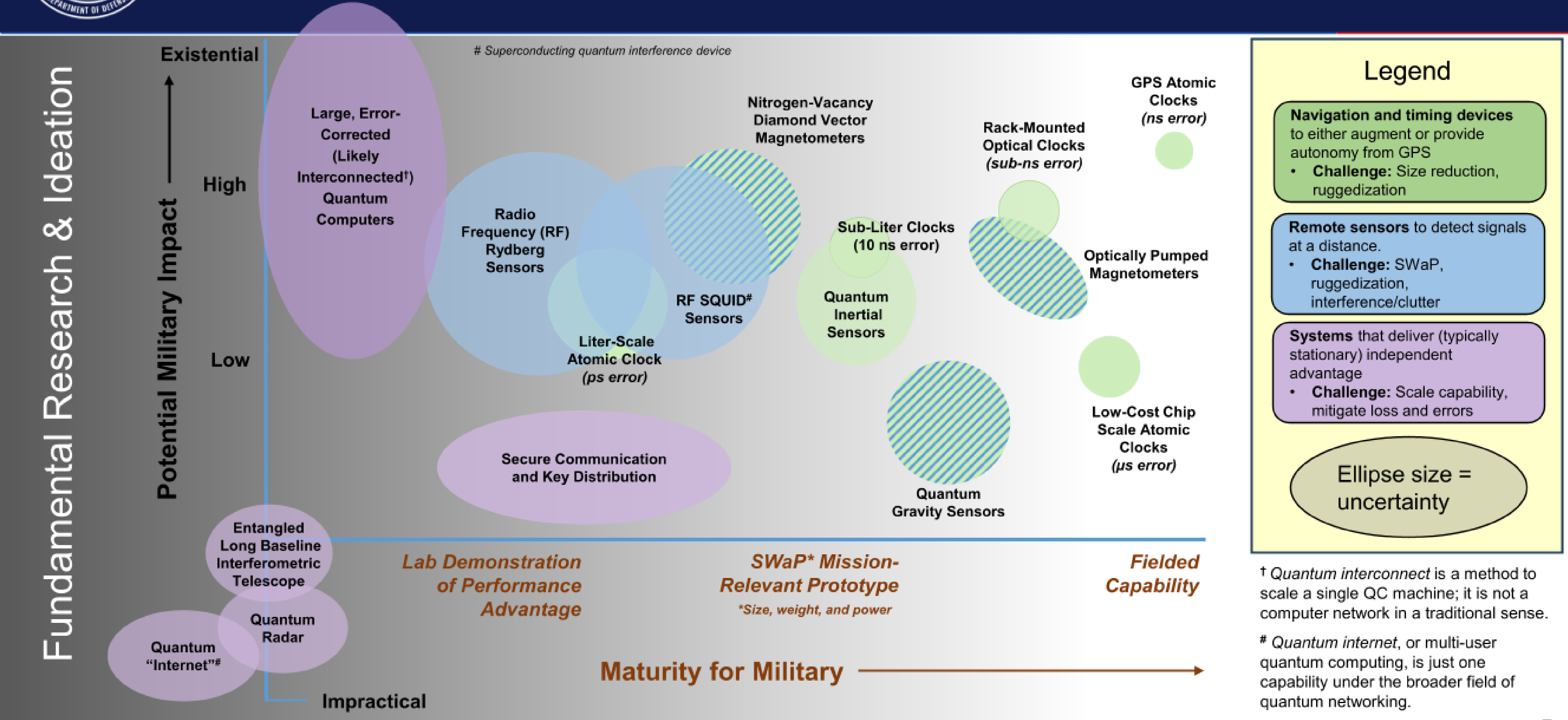
- Angle θ illustrates the linear superposition of two or more states.
- Phase ϕ illustrates the distinction between particle and wave behavior.

The Limits with Qubits (for Now)

- **More—many more—are needed.** While a QC architecture of 1,000 interacting qubits has been achieved, many state-of-the-art architectures currently have fewer than 200. Applications in a DoD mission context are expected to require computing power in the millions of qubits. *(More on slide 16)*
- **Measurement lowers utility.** Measuring quantum data reduces the output to classic binary information (1s and 0s). This constrains available problem sets for which QCs are projected to be useful to DoD. *(More on slide 17)*

Projected Military Readiness and Impact of Quantum Technologies:

Navigation and Timing Devices To Be Field-Ready in Coming Years



† *Quantum interconnect* is a method to scale a single QC machine; it is not a computer network in a traditional sense.

Quantum internet, or multi-user quantum computing, is just one capability under the broader field of quantum networking.

Overview: Quantum Sensing

Programs of Record Would Mature Tech Development Toward Capability

Priorities:

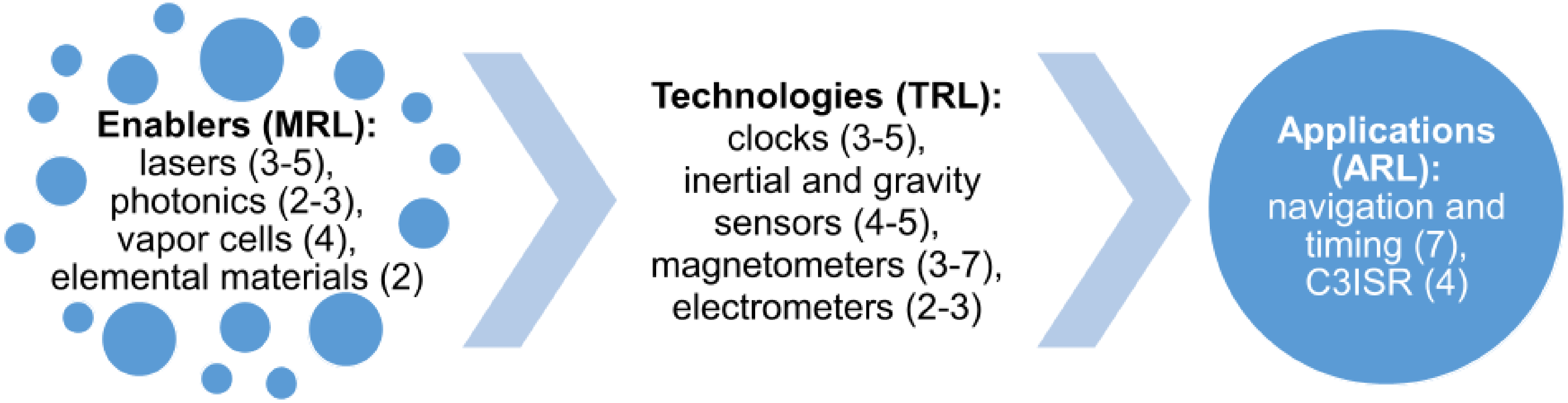
- Mature leading atomic clocks to enable PNT capabilities in GPS-denied environments.
- Transition MagNav capabilities into programs of record.
- Perform systematic engineering and testing of inertial sensors.
- Develop new proof-of-concept optical sensors.

Readiness Levels:

- **ARL – Adoption Readiness Level (1-9)**
  - Complements TRL in assessing adoption readiness for technology commercialization (DOE-originated)
- **TRL – Technology Readiness Level (1-9)**
  - Level 1 (basic principle observed) to 9 (proven in operational environment) (NASA-originated)
- **MRL – Manufacturing Readiness Level (1-9)**
  - Levels 1-3 (material solutions analysis) up to 9 (production and deployment) and 10 (operations and support) (DoD-adopted in 2005)

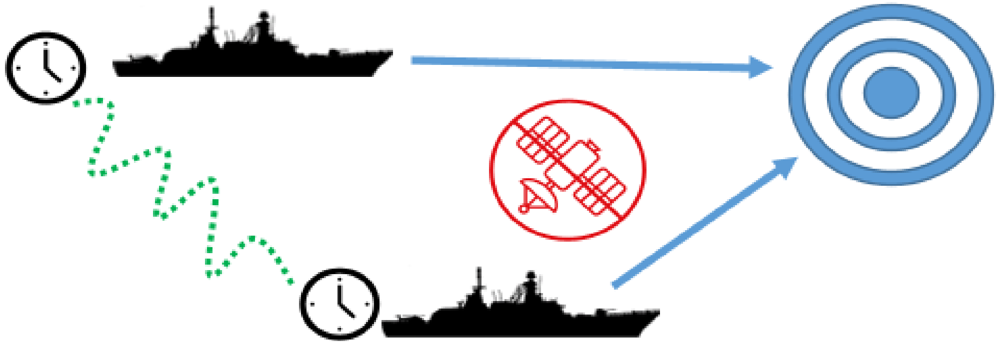
There is a high certainty that quantum sensing will have a significant impact to many DoD missions:

- **Enhanced PNT**: Positioning, navigation, and timing (PNT) capabilities enabled by atomic clocks and quantum sensors will enable mission assurance in GPS-denied or -degraded environments. New multi-platform capabilities will be unlocked for precision/joint targeting, electronic warfare, and detection within contested spectrum, space, or cyber operations. **Timescale to capability: Within five years.**
- **C3ISR Advancements**: Electromagnetic sensors and optical detectors can enable new capabilities for communications, command, control, intelligence, surveillance, and reconnaissance (C3ISR). DoD can have more capability, agility, and assurance when receiving data in the spectrum.
  Timescale to capability: 4 to 10 years.



Priority: Mature Next-Generation Atomic Clocks to Fielded Capability

- **Current state/military advantage:** Devices more precise than the ubiquitous 5071A cesium-based clock are needed to protect C3ISR systems.
- **Devices**: Three new clock prototypes would enable protection from GPS loss for mission-relevant timescales. These clocks are essential to coordinating multiple platforms in GPS-denied or -degraded environments for mission-relevant durations.



- **Current needs:** Industry partners and programs of record within Military Services are needed to transition capability to the field and further refine size, weight, and power (SWaP) of viable prototypes.

Strategic

Cesium 5071A

→ Rack-Mounted Optical Clock (RMOC)

RMOC Advantages:
- One-microsecond (μs) accuracy increases from one to six months.
- 10-nanosecond (*ns*) accuracy increases from one day to one week.
- Lower sustainment costs.

Tactical

Microchip 8200LN

→ Next-Generation Atomic Clock (NGAC)

NGAC Advantages:
- 10-*ns* accuracy increases from one hour to one day.
- 10 to 20 times-longer holdover for use in piloted vehicles.

Battery-Powered

Chip-Scale Atomic Clock (CSAC)

→ Low-Cost CSAC

LC-CSAC Advantages:
- One-μs accuracy increases from a few hours to 24.
- 10 times-longer holdover for use in handheld radios and munitions.
- Cost is 1/10th CSAC (goal)

Priority: Transition MagNav Capabilities Into Programs of Record

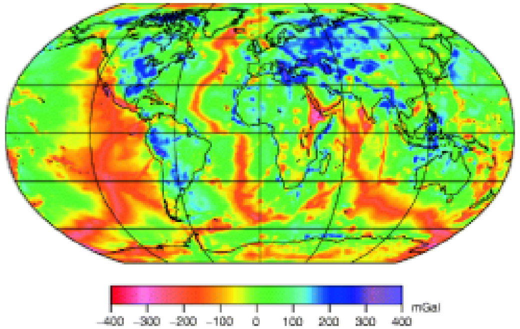
- **Current state/military advantage:** Magnetic navigation (MagNav) uses Earth's crustal anomaly fields as the navigation signal.
- **Devices**: Scalar magnetometers (measuring total field intensity, but not direction) are mature and fielded. Vector magnetometers (also measuring direction) are accurate to one nanotesla, a capability requirement. Some magnetic maps and models are available through NOAA* Earth Magnetic Anomaly Grid.
- **Current needs:** Prioritize platform integration strategies and signal-processing for clutter rejection (e.g., interference of aircraft's own magnetic field). Early work suggestions platform effects can be removed with appropriate filtering.

A quantum sensor-based magnetic anomaly navigation system gathers data on a C-17 Globemaster III cargo aircraft during a flight over Charleston, South Carolina, February 22, 2024.
USAF photo by Staff Sgt. Ashley N. Mikaio

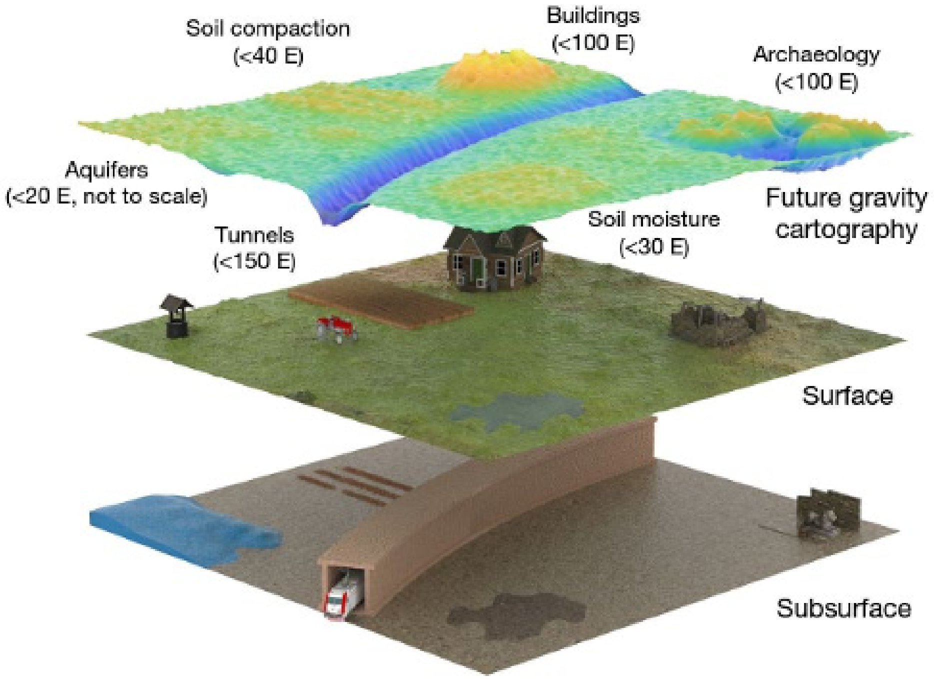
* National Oceanic and Atmospheric Administration

Priority: Perform Systematic Engineering and Testing of Inertial Sensors for Navigation and Anomaly Detection

- **Current state/military advantage:** Inertial navigation systems utilize accelerometers, gyroscopes, and gravimeters to enable GPS-free navigation of strategic assets for mission-relevant timescales.
- Gravimeters, using the Earth's gravitational anomaly fields as the navigation signal, are also instrumental in detecting tunnels and other subterranean targets.
- Gravity-matching algorithms as well as maps and models (e.g., National Geospatial-Intelligence Agency geodetic database) exist.
- **Outstanding needs/requirements:**
  - Absolute gravimeter accuracy to 1μg and gravity gradiometer accurate to ~1 Eotvos (E) (1 ng/m)
  - Rigorous engineering and testing of key components, especially lasers and electronics, which would be best performed within DoD programs of record



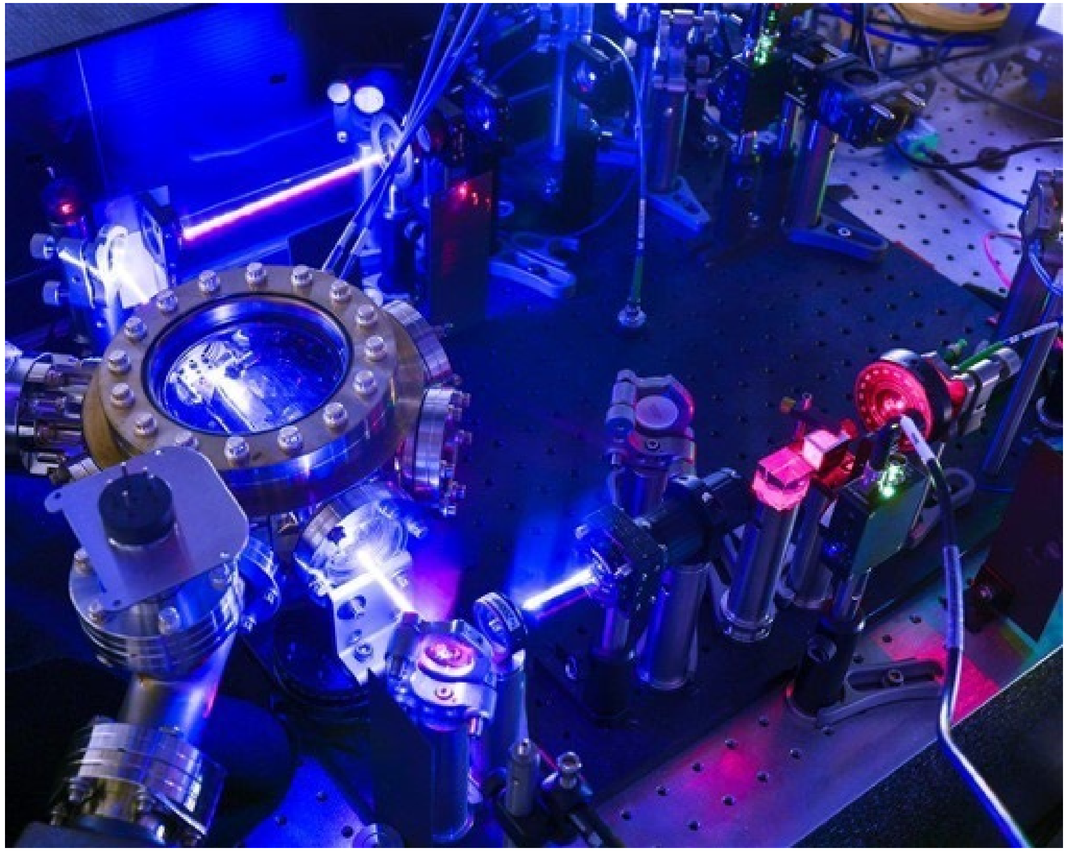
Source: "Atomic changes can map subterranean structures," Poli, Pasteka & Zahorec, *Nature*, February 23, 2022



Priority: Transition Next-Generation Remote Sensors

- **Current state/military advantage:** Electromagnetic (EM) field sensors and optical devices can detect what current sensors cannot–presenting significant potential advantages for C3ISR applications, including anti-submarine warfare.
- **Leading EM sensors (TRL 2-5)**
  - Magnetometers
    - Optically pumped (OPM)
    - Vector (nitrogen-vacancy in diamonds)
    - Superconducting quantum interference device (SQUID)
  - Rydberg atomic receiver
- **Current needs:** Several magnetometers are ready to transition into programs of record; other remote sensing technologies need to transition to commercial partners for further development toward capability.

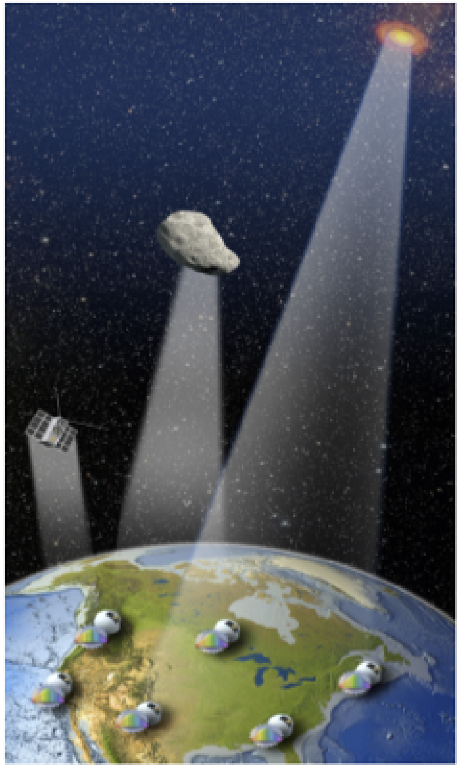
Army researchers built a quantum sensor that can sample the radio-frequency spectrum—from zero frequency up to 20 GHz—and detect AM and FM radio, Bluetooth, Wi-fi, and other communication signals. (Photo: U.S. Army)



Priority: Develop New Proof-of-Concept Optical Devices

- **Current state:** Quantum imaging and optical techniques are underexplored. The Department should evaluate and leverage concepts emerging from academia (such as, but not limited to, those illustrated below) for new mission applications.

Quantum Correlation Imaging



Keck Institute for Space Studies

Squeezing for Metrology

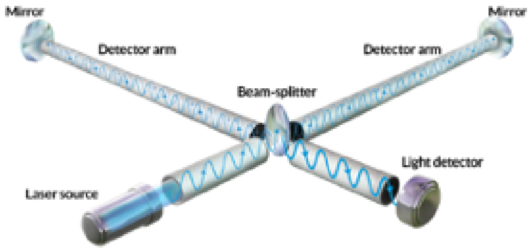
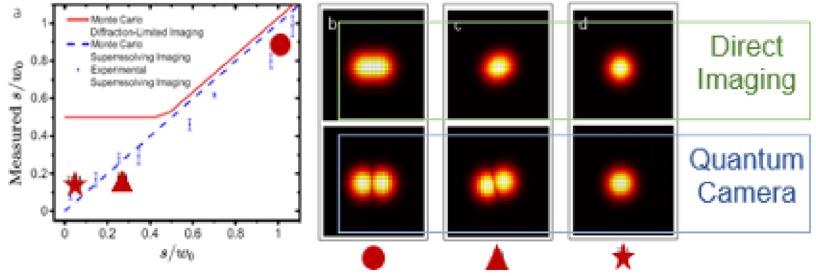


Image: Science News

Machine Learning-Based "Quantum Camera"

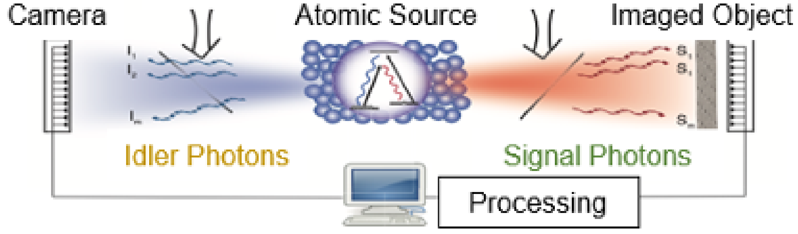
Reduces spatial noise, but with what constraints?



Louisiana State Univ.; O. Magaña-Loaiza https://arxiv.org/abs/2110.05446

Lock-in Thermometry with Photon Pairs

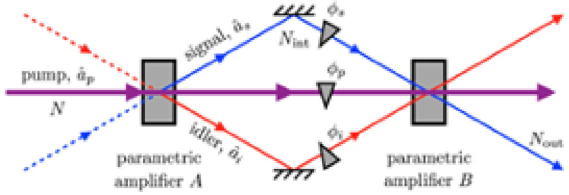
Reduces temporal noise with special illumination



Purdue University; A. Shakouri and M. Hosseini

Nonlinear Interferometer

Reach for quantum (Heisenberg) limit of phase uncertainty scaling with 1/N



Flórez, J. et al. New J. Phys. 20, 123022 (2018)

Overview: Quantum Computing

Transformative Long-Term Potential with Uncertain Prospects for DoD Missions

Priorities:

- Determine DoD mission applications of quantum computing and the prerequisites for adoption.

Readiness Levels:

- **ARL – Adoption Readiness Level (1-9)**
  - Complements TRL in assessing adoption readiness for technology commercialization (DOE-originated)
- **TRL – Technology Readiness Level (1-9)**
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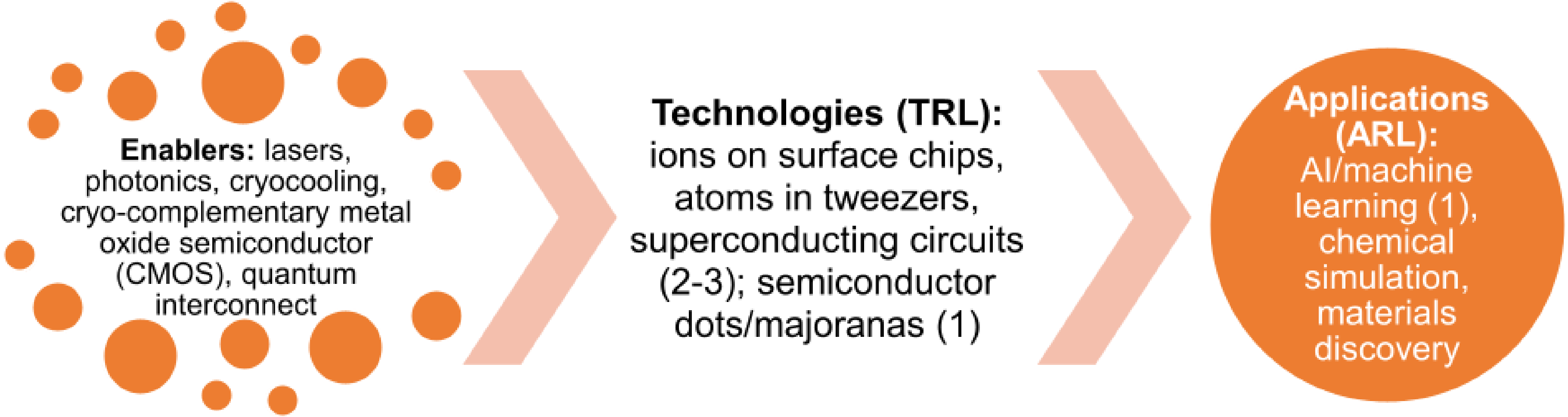
While U.S. companies lead the world in developing quantum computers, how QC can best support DoD missions remains to be determined. Current evidence does not support DoD becoming a first-buyer of QC machines:

- **Unclear DoD applications**: Enhanced computing power offers powerful simulation capabilities, but defense-specific applications require further research. The considerable research scope will encompass algorithms, computational heuristics, compilers, error correction, and resource estimation.
- **Scalability challenges**: Multiple technical approaches exist to optical-based and low-temperature QC systems, but all are immature (TRL 1-3). To address expected DoD mission challenges, any system likely requires local (i.e., room-scale) quantum interconnect, adding further complexity. **Timescale to capability: Roughly 10 years, possibly longer.**



Priority: Determine QC Applications and Adoption Requirements

While no DoD QC applications are individually proven, taken together, the probability of surprise disruption is high.

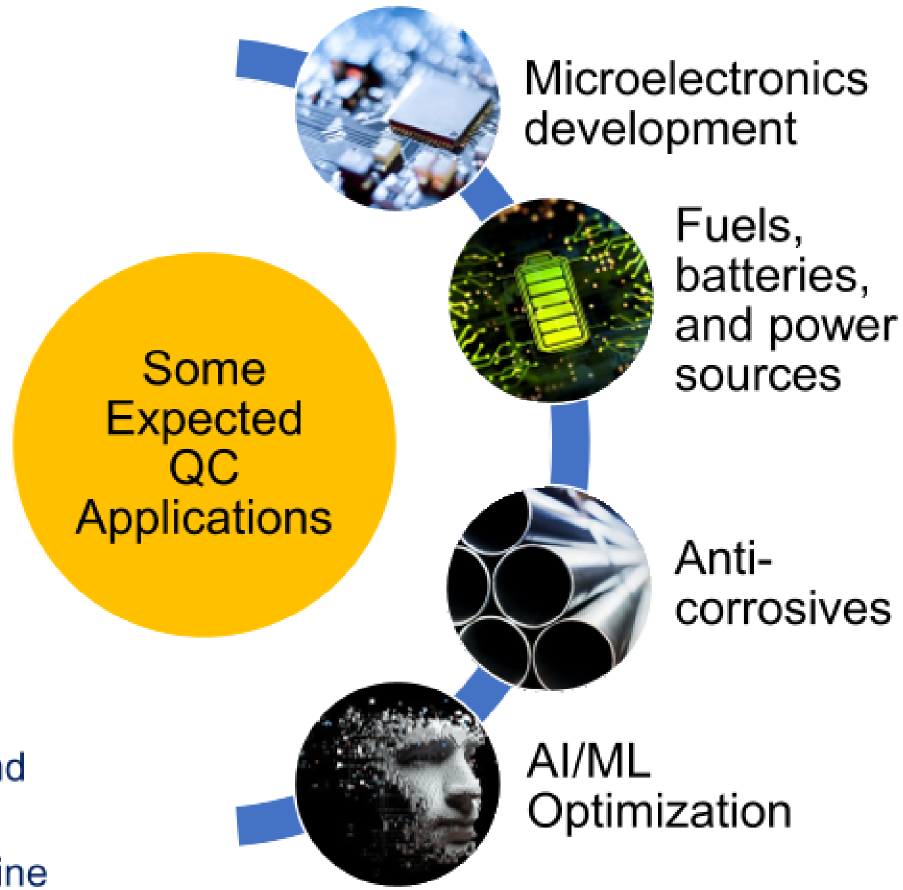
Current state/Military advantage: DoD has two lines of effort underway to explore the utility of quantum computing (QC) for defense purposes, but both are in preliminary phases (≤1 year). Most application ideas remain unevaluated. Understanding QC's role in a mission context would enable DoD to investigate operational requirements with greater focus.

Current needs:

- QC-specialized workforce to enhance knowledge base of architectures.
- Research QC architectures that optimize DoD use cases.
- Close the capability gap between theoretical QC performance and DoD mission use.
- Map DoD-specific computing problems to existing/projected QC capabilities.

Potential applications: Quantum algorithms have been evaluated to be feasible for 1) factoring large numbers for asymptotically large problem sizes and 2) chemistry simulation, which offers great potential for new advanced materials like anti-corrosives.

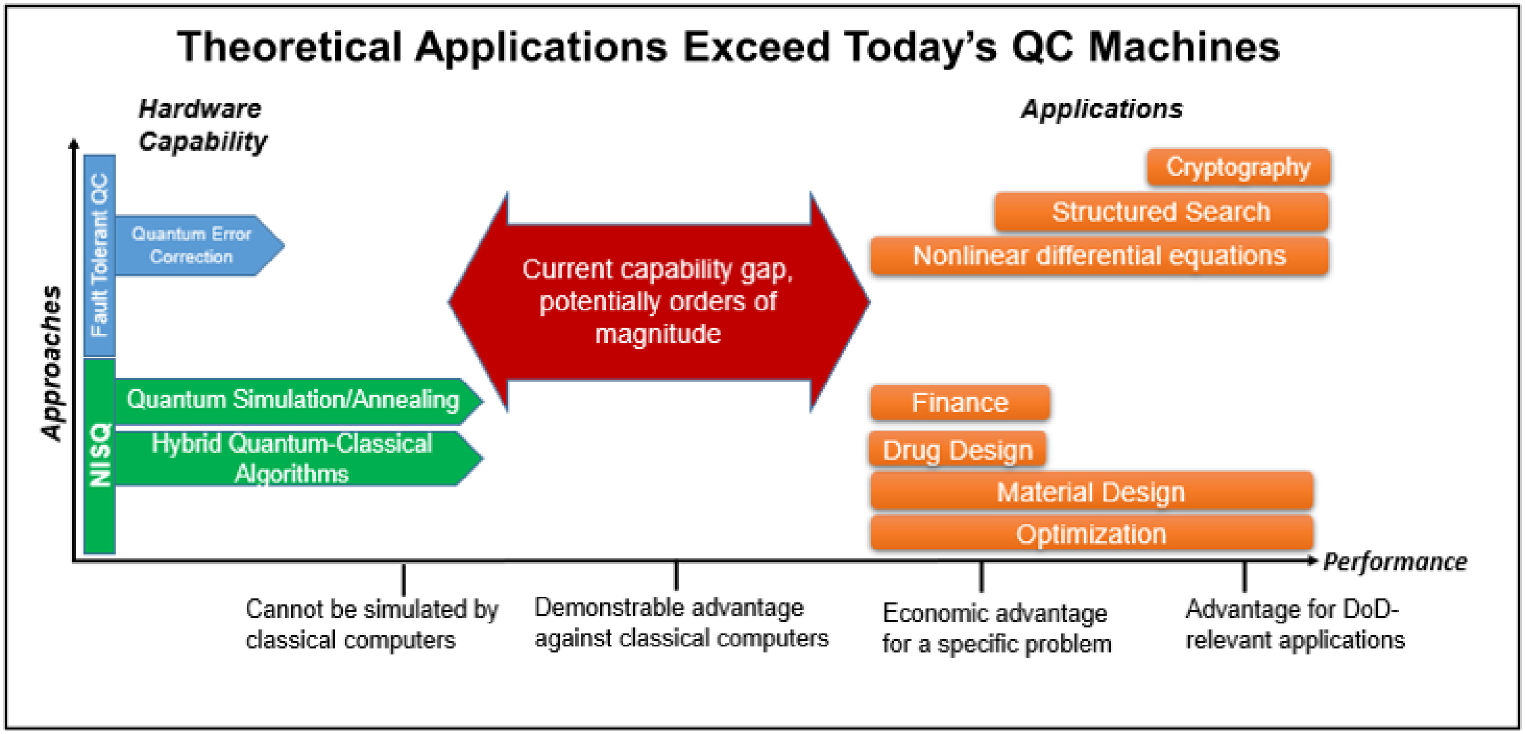
QC simulation has been proposed to optimize real-time battlefield logistics and improve the accuracy of artificial intelligence/machine (AI/ML) learning models.



QC Challenge: Current Capability Gap

Commercial uses of "quantum advantage" will arrive sooner than DoD applications.

- **Quantum advantage** will be achieved when QCs outpace classic computing to solve an otherwise incalculable problem in a feasible amount of time. Industry estimates are more optimistic than those of DoD, which will require stronger machines (potentially *millions* of qubits) for its own mission applications. The leading QC today has over 1,000 qubits.
- Noisy intermediate-scale quantum computing (NISQ), the current state of QC machines, is prone to high error rates.
- To achieve quantum advantage, QC systems must be *fault-tolerant*, either through error correction or inherent properties.
- QC machines with sufficient error correction for quantum advantage are expected by 2030 but may appear much sooner.



QC Challenge: Distributed Entanglement and Quantum Measurement

Distributed Entanglement

- Modular quantum computing—interconnecting multiple smaller quantum processors to function as one unified QC—is a strategy to overcome the current capability gap. This approach relies on the quantum principle of *distributed entanglement*.

For more on the opportunities and challenges associated with distributed entanglement, see slide 24.

Quantum Measurement

- Whether a QC has one quantum processor or is interconnected with several, the output format is the same regardless of computing power: traditional, binary data. This presents several constraints (*right*).

The Constraints of Quantum Measurement

- **Quantum information is very fragile.**
  - Measuring it reduces the output to classic binary information (1s and 0s).
  - Users must perform measurement to derive value—destroying quantum information in the process.
- **Quantum information cannot be cloned.**
  - The information is not a shared resource. It can only be created and used once by a single user.
- **Quantum data rates are slow, limiting achievable performance gains.**
  - Qubits (typically photons) are much slower to produce than classical photons from a laser. More research is needed to develop single-photon sources and generate entanglement faster.
- **Quantum information systems have limited capacity for optimization because feedback requires measurement.**

Competing Concerns: The Duality of Quantum Computing

The United States must continue to invest in quantum computing development while also countering its proliferation to adversaries and preparing for the inevitable arrival of codebreaking QCs.

Cryptographically relevant quantum computers (CRQC) may be possible in as soon as three years. CRQCs would break all current encryption keys—posing an existential threat to national security and the global economy.

Near-Term Threat

- CRQC

Long-Term Opportunity

- Powerful engine for GDP growth

Quantum computing may spur significant gross domestic product (GDP) growth, as other technology domains (e.g., railroads, automobiles, microelectronics) have done.

CRQC Mitigation

Deploy PQC

- Post-quantum cryptography (PQC) consists of new cryptology methods immune to CRQC that can operate on current computers.
- PQC is *not* a quantum capability.*

Protect Technology

- A technology protection plan with international support that acknowledges private-market impacts *(More on next slide.)*
- Targeted export controls that minimize unintended consequences for industry QC advancement

Build on Advantage

- Leading in most QC aspects and approaches, the United States should leverage its position to optimize investments and potential.
- Investment strategy needs to be nuanced and agile. The best strategy for today will be prone to disruption as QC technology matures.
- The total investment and time needed is likely large: billions of dollars and a decade or more.

** The National Security Agency (NSA), Cybersecurity and Infrastructure Security Agency (CISA) and National Institute of Standards and Technology (NIST) spearhead U.S. PQC deployment efforts.*

Priority: Maintain U.S. Leadership in Quantum

America's global leadership in quantum is fragile. To maintain it, the United States, led by DoD where appropriate, must meet three interrelated objectives:

1) protect its quantum technologies, supply chains, and intellectual property;
2) strengthen its industrial base and supply chains to achieve a comprehensive, integrated quantum manufacturing capability; and
3) develop a multidisciplinary workforce that advances both scientific research and manufacturing activities.

Technology Protection

Adversaries seek all means to advance their own quantum tech development, presenting grave security and economic risks to the United States and its allies.

DoD should promulgate its initial quantum technology plan to inform government and industry stakeholders on defending against and responding to intellectual property loss.

Manufacturing Capability

The foundations of U.S. quantum technology are neither robust nor resilient. Resource challenges abound, and many component suppliers are small businesses, inhibiting production at scale.

DoD should work toward an end-to-end quantum manufacturing capability, similar to the Microelectronics Commons, to strengthen its supply chain and industrial base.

Workforce Development

The U.S. quantum talent pipeline does not satisfy current or future workforce needs. DoD is disadvantaged in its talent competition by an attractive private sector and the significant percentage of foreign-born talent ineligible to serve the DoD mission.

DoD must devise new strategies to attract and retain talent (U.S.-born and otherwise), as well as reinforce STEM programs to attract the skill sets required for quantum manufacturing.

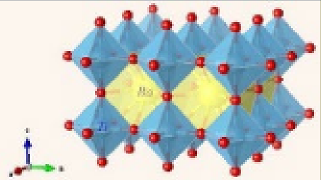
Quantum Supply Chain:
Fundamental Material and Component Needs

Thin-Film Insulators

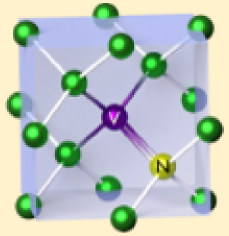
Lithium Niobate (TFLN and LNOI)

- Key material for photonic frequency control components—used in quantum, telecom, and radio frequency (RF) receivers

Barium titanate (high electro-optic coefficient) is of interest as a good switch or potential RF modulator



Nitrogen-Vacancy Center in Diamond



- Nitrogen-doped diamond (via chemical vapor deposition) is needed for vector quantum magnetic sensors
- Need diamond-on-insulator wafer solution

Isotopically Pure Bulk Materials

Cesium (cs) and rubidium (rb)

- Needed for atomic clocks
- Supplies of isotopically and chemically enriched alkali atoms are limited; Rb requires isotopic purity

Silicon (si)-28

- Necessary to improve qubit performance (si-29 causes spin decoherence, si-30 causes strain variability)

Helium (he)-3

- Tens of kiloliters needed for cold qubits
- Virtually all He-3 is produced from the decay of tritium via nuclear warhead manufacturing

Rare Earths

- Gallium, erbium, ytterbium, strontium, and barium

Wafer Bonding: Many technologies require bonding two materials (e.g., TFLN to silicon nitride). Wafer bonding can be hard to access for new prototyping.

Super/Semi-Conductors

Superconducting Qubits

- Popular materials used by commercial sector include aluminum, niobium, and tantalum

Cuprates Superconductors

- Yttrium barium copper oxide (YCBO) and others can achieve critical temperatures (+70°K) for use with liquid nitrogen–critical for high-transition temperature (T_c) SQUID array quantum sensors

Semiconductor Lasers and Photonics

- Boron-nitrogen compounds—especially gallium arsenide (GaAs) and nitride (GaN) needed for lasers and amplifiers
- Need reliable, low-defect, epiaxial wafers with good thickness for stability/accuracy
- Challenge: Fewer domestic suppliers of GaAs due to cost of facility maintenance (Arsenic byproduct is highly toxic.)

Quantum Supply Chain:
Current Activities Insufficient for All Materials and Component Needs

Current/Planned Activities (Fiscal Years 2026-2028)

OUSD(R&E) Manufacturing Technology Program

- Thin-film lithium niobate (TFLN)

Microelectronics Commons

- Semiconductor lasers fabrication architecture
- Laser systems for sensing
- Laser system components
- Superconducting qubit fabrication with novel materials

Outstanding Needs

- Diamond-on-insulator solution
- Systems-level laser architectures for sensors and qubits
- Super/semi-conducting circuits with cryo-complimentary metal oxide semiconductor (CMOS) fabrication and integration
- Superconducting cabling
- Cryogenic architectures for more efficient 10-millikelvin scaling
- Components such as vertical-cavity surface-emitting laser (VSCELs), GaAs processing, isolators, frequency combs, single-photon sources

Quantum Supply Chain:
Need for Full-Scale Integrated Technology Capability

The United States must grow its industrial capacity to improve the size, weight, and power of sensors.

Example: Miniaturization of Atomic Clock

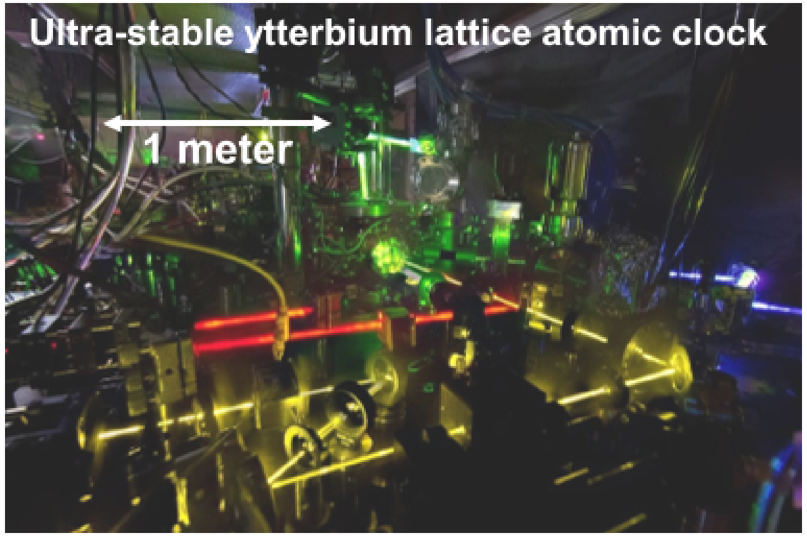


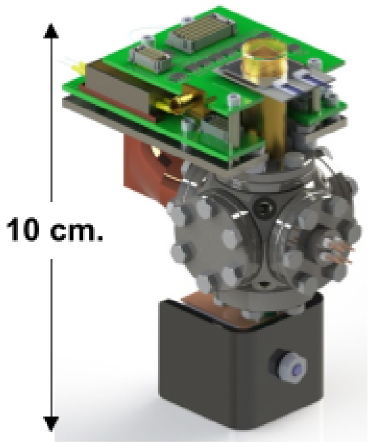
Photo: N. Phillips/National Institute of Standards & Technology (NIST), Boulder

Materials
- TFLN
- GaAS, GaN
- YCBO and NVD films
- He-3, Si-28, Rb-85, rb-87, cs-133

Components
- Lasers, laser systems, single-photon sources (laser systems on chip)
- Frequency control (low power on chip combs)
- Vacuum (vapor cells)
- Low-temperature tech (amplifiers)

Integration
- Multiple quantum technologies (logic, memory)
- Multiple classic technologies (photonics, CMOS, microwave)
- Interconnects

Conceptual Miniaturized Ion Clock*



* A conceptual solid model rendering of a 0.5-liter miniaturized ion clock based on trapping and detection of an ytterbium atom. The model demonstrated by Sandia National Laboratories (SNL) is a key step toward the realization of low-power, highly accurate, compact atomic clocks with important applications for future quantum computers and sensing systems based on trapped ions. Source: SNL

DoD Quantum Workforce Priority: Attract, Retain, Diversify

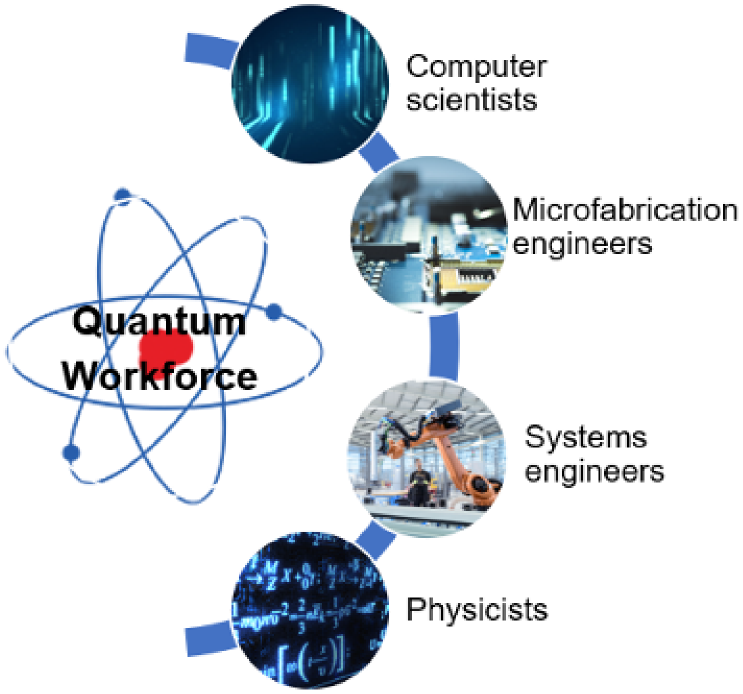
Current state: Like other science, technology, engineering and mathematics (STEM) disciplines, quantum expertise in the U.S. workforce is sparse overall, and within DoD especially. There are more DoD quantum research projects to be executed (~250) than personnel in the DoD quantum workforce (~200 Federal employees and contractors).

Despite STEM investments that have contributed to DoD's quantum S&T pipeline, a considerable amount of U.S.-trained talent remains inaccessible to DoD due to foreign-born students returning to home countries and competition from other Federal agencies as well as the private sector.

Needs:

- **Strategy**: In addition to continued funding and expansion of STEM initiatives, the DoD would benefit from a comprehensive strategy to recruit and retain quantum talent domestically and abroad to the DoD mission.
- **Quantum beyond physicists:** Beyond training more quantum information scientists and researchers, the United States must meet a steeply increasing need for quantum engineering and other highly specialized industrial skill sets. Doing so is critical to DoD's continued success and acceleration of quantum technology development and delivering enhanced warfighter capabilities.

Objective: A Multidisciplinary Workforce



41	DoD STEM education programs contributed to quantum workforce development from fiscal years 2019 through 2023.*

Potential initiatives to be initiated/expanded:

- Create quantum-designated opportunities within DoD Young Investigator and SMART Scholarship programs
- DOD-industry exchange program for quantum
- Expand University Affiliated Research Centers' efforts to encourage quantum outside of physics departments
- K-12 outreach (e.g., summer schools, camps)
- Partner with industry to prioritize outreach to socialize quantum careers outside of academia
- DoD study to better determine skill needs and talent development/recruitment methods

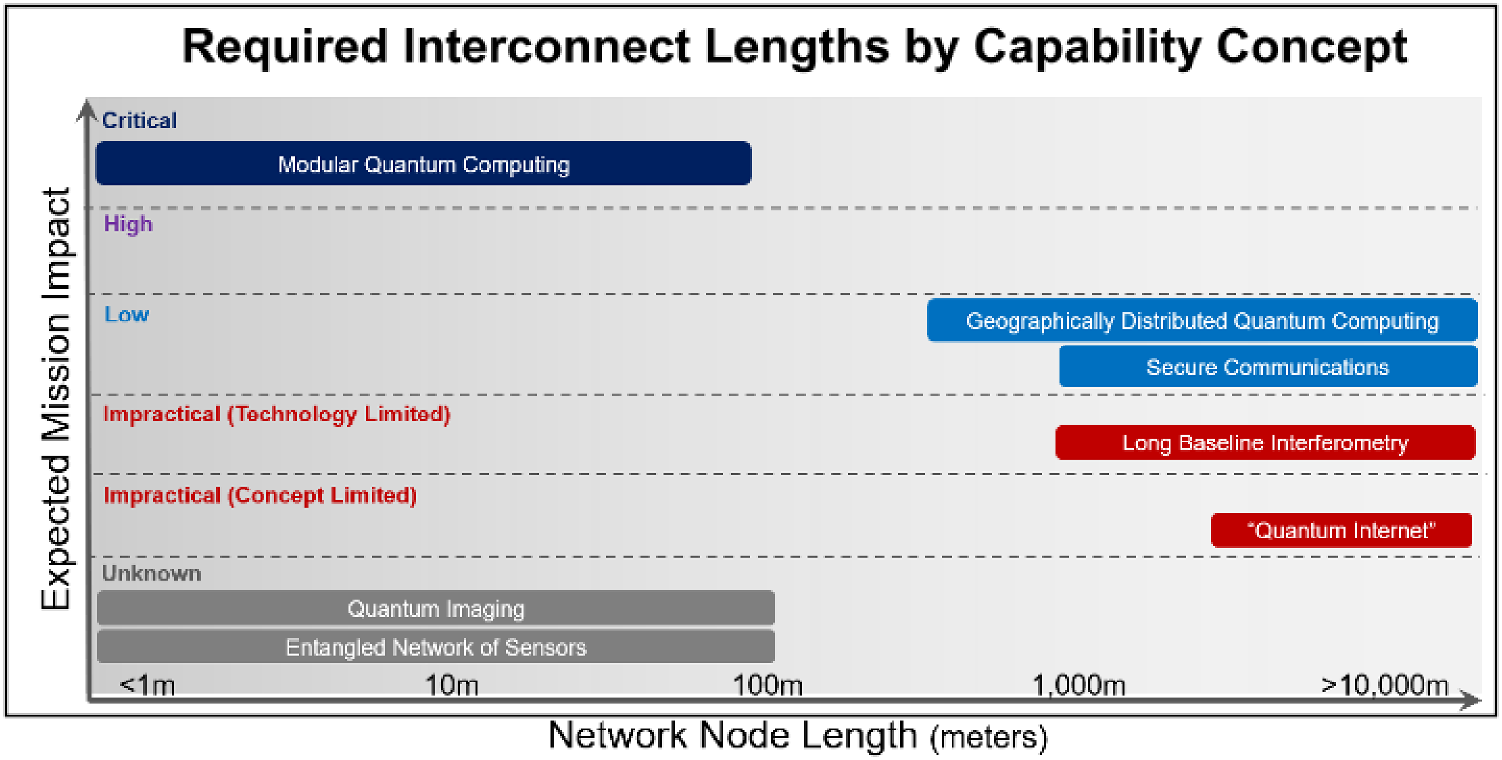
* "Quantum Technologies: Defense Laboratories Should Take Steps to Improve Workforce Planning," GAO-24-106284, December 2023

Quantum Areas of Interest with Uncertain DoD Rewards

Opportunities for Applied Research Projects

- **Information security based on existing quantum protocols**
  - Theoretical security benefit is difficult to realize in practice when considered with other security needs.
- **Large quantum-network infrastructure**
  - Aside from modular quantum computing, concepts that require distributed entanglement—such as quantum key distribution for secure communications*—are too immature to warrant infrastructure investment. *(See below.)*
- **Multi-user networks ("quantum internet")**
  - Multi-user networks of quantum computers offer low utility to DoD due to sensitivity to entangled-photon loss, data latency, and cost challenges.
- **Light detection and ranging (LiDAR)/ remote illumination**
  - Analysis shows that observation of distant objects with entangled light ("quantum radar") is impractical and unlikely to impact DoD.

* *China leads in quantum communications R&D, which is a low U.S. priority.*



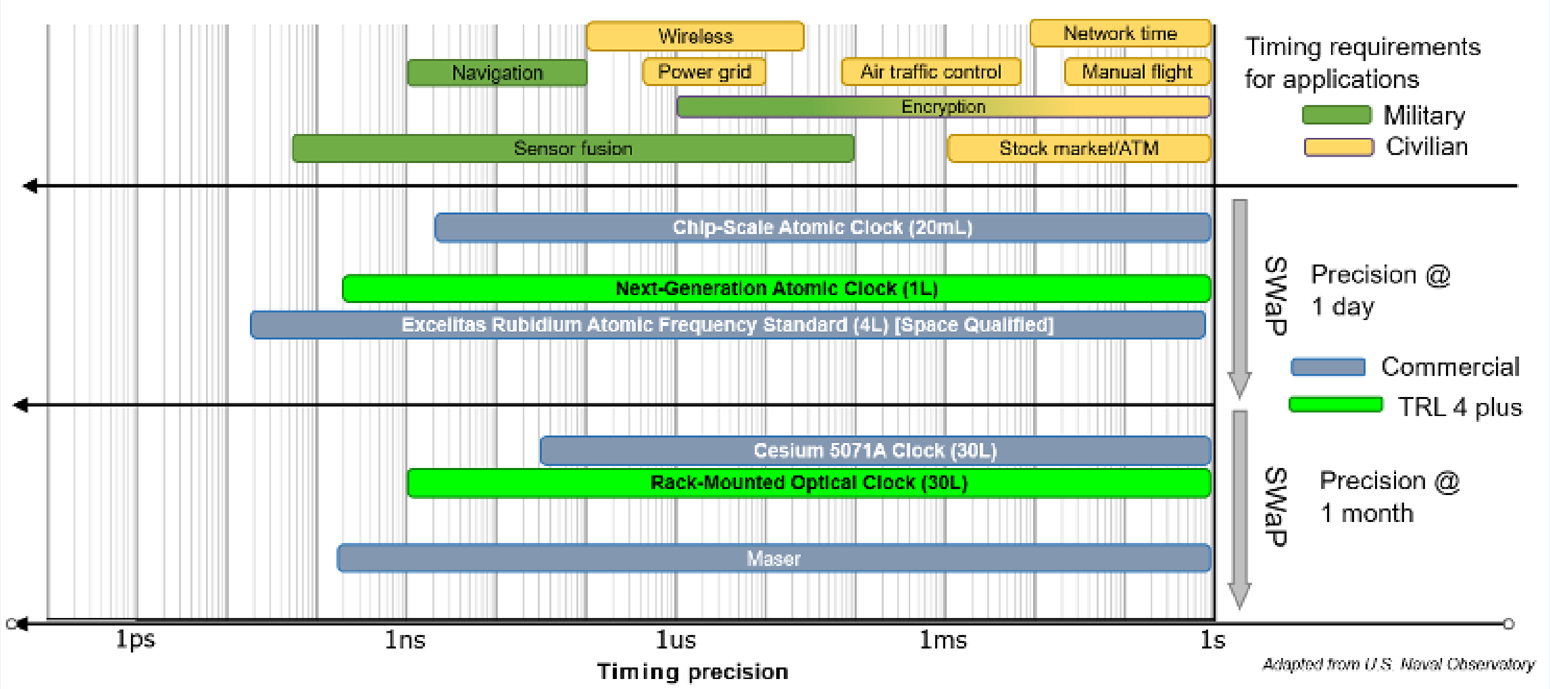
Basic Research Areas for DoD Quantum Tech Advancement

Opportunities for Basic Research Projects

Scientific research is needed to further investigate the fundamental limits of quantum measurements and information storage and transmission. These investigations would support the potential discovery of novel concepts for defense applications, including:

- Picosecond (ps)-level coordinated time (*See precision of current clocks, right*)
- Electromagnetic sensors in the spectrum
- Non-QC use cases for distributed entanglement
- Novel QC algorithms, architectures, or error-correction concepts
- Quantum systems, qubits, and materials that are more robust, offer higher performance, or could be controlled/ manipulated more easily
- Novel transduction, control, or distribution mechanisms

Precision of state-of-the-art clocks and key applications



Summary: Quantum Priorities and Expected Mission Impacts

Field Quantum Sensing

- Quantum sensors offer substantial improvement over current capabilities.
- GPS-independent PNT will enable freedom of operations and precision-strike capabilities.
- DoD programs of record are needed to support transition to the field.

Enhanced, Enduring Impact

Accelerate Quantum Computing

- DoD will experience costs before benefits, which may be 10+ years away.
- DoD-specific mission applications require further research.
- U.S. must balance QC advancement with protection from risks (e.g., codebreaking).

Uncertain, but Potentially Disruptive

Maintain American Advantage

- DoD must continue to develop and promulgate its quantum technology protection plan with U.S. Government (USG) and industry stakeholders.
- The United States should prioritize its quantum manufacturing capability to integrate processes from material source development to final system delivery.
- The United States must attract more quantum talent from a range of disciplines to DoD and USG/industry.

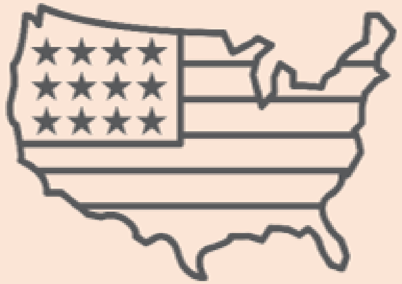


Image: Shutterstock