Packaging Challenges in Quantum Computing

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i. Quantum Computing
ii. Quantum Computing Landscape
iii. Challenges to Overcome
iv. IEEE Quantum Initiative
v. Technology & Packaging Commonalities
vi. Standalone QC Chapter in HIR

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What Keeps You Up At Night ?

"Well, your quantum computer is broken in every way possible simultaneously."

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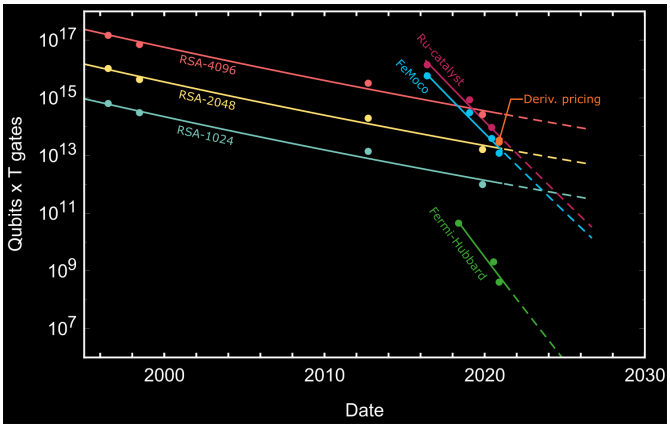
Quantum Computing

Quantum Computing is a profoundly world-changing technology that can solve otherwise impossible computational tasks

- ***Finance***: **risk management**
- ***Healthcare***: **personalized medicine, drug development**
- ***Materials***: **novel superconductors, new solar cells**
- ***Transportation***: **new fuels, new battery cells**
- ***Security***: **cryptanalysis**

It takes billions of gates to do something useful



RSA: C. Gidney and M. Ekera,, arXiv:1905.09749 (2019)
FeMoco / Ru-catalyst: J. Lee et al., arXiv:2011.03494 (2020)
Fermi-Hubbard: E. Campbell, arXiv:2021.09238 (2020)
Derivative pricing: S. Chakrabarti et al., arXiv:2012.03819 (2020)

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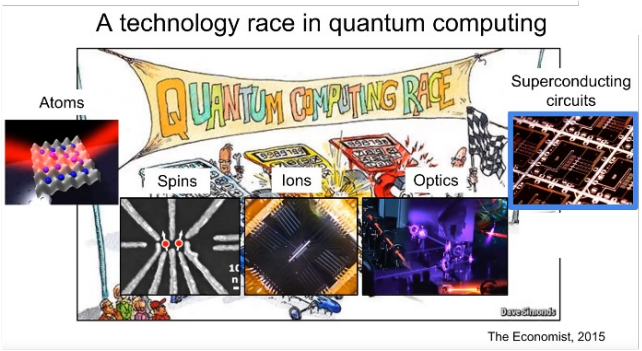
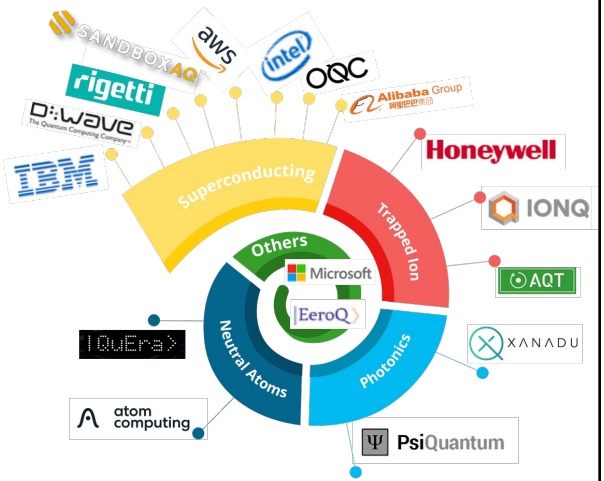
Quantum Computing Landscape





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Comparison of QC Technologies

Qubit	*Control Signal*	*Temperature*	*Challenges*	*Companies*
Superconducting Circuit	▪ Microwave current ▪ DC current ▪ RF control	~ 10 mK	▪ Noise shielding, filtering ▪ Cryo-electronics ▪ Entanglement with neighboring qubits only	IBM, Google
Ion Trap	▪ Laser ▪ RF ▪ DC voltage	< 1 K	▪ Off-chip light alignment with ions ▪ Flexible interconnection ▪ Electronics and photonics fab node difference	IonQ, Quantinuum
Silicon Spin	▪ AC & DC magnetic fields ▪ DC voltage ▪ RF control	< 1 K	▪ Noise shielding, filtering ▪ Cryo-electronics ▪ Complex electrodes layout	Intel
Photonics	▪ Laser ▪ RF ▪ DC voltage	> 4K	▪ High efficiency single photon source and detector ▪ Integration & alignment with waveguide circuit	PsiQuantum, Xanadu

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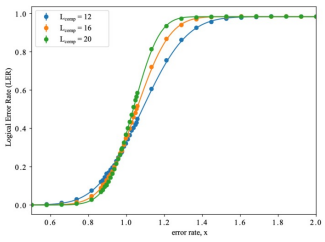
Challenges to Overcome

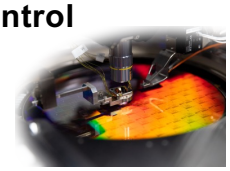
Performance

- Fault-tolerant architectures with a high threshold
- Low physical error rates



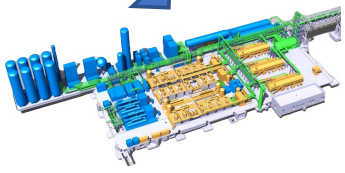
Scaling

- Modularized hardware architecture
- Manufacturability at large scale
- Reliable interconnects
- Fast and structured control



Infrastructure

- Feasible power consumption
- Realistic run times



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IEEE Quantum Initiative

Mission Statement

Our mission is to build a sustainable community within IEEE for advancing learning, innovation, and understanding in quantum science and engineering.

Vision Statement

Our vision is to be the world's leading professional community for the field of quantum computing and engineering.

Launched in 2019 by IEEE Future Directions; serving as IEEE's leading community for all projects & activities on quantum technologies
Supported by leadership and representation across multiple IEEE Societies and Organizational Units

Contact: **Terence Martinez, IEEE FDC Quantum Initiative Program Director**
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Quantum Initiative Leadership

Travis Humble
ORNL, Director
DOE Quantum Science Center

Candace Culhane
LANL, Program Director
Quantum Simulation & Computation

Hausi Müller
University of Victoria, Professor
Steering Committee Chair, IEEE Quantum Week

Luu Nguyen
Director, PsiQuantum
EPS Rep
IEEE Future Directions

IEEE Electronics Packaging Society · IEEE Photonics Society · IEEE ComSoc IEEE Communications Society · IEEE computer society · IEEE Educational Activities

MTT-S · IEEE Signal Processing Society · IEEE SA Standards Association · IEEE CSC Council on Superconductivity

https://quantum.ieee.org/about

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Quantum Initiative Strategic Goals

For the fields of quantum computing and engineering:

1. ***Raise Awareness***

   We will establish broad awareness within IEEE and external stakeholders

2. ***Grow Our Global Technical Community***

   We will form a diverse, inclusive, and equitable technical community

3. ***Build Our Organization***

   We will organize the technical community to be effective and transparent

4. ***Establish & Demonstrate Our Sustainability***

   We will become a sustainable technical community

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IEEE Quantum Initiative – Raise Global Awareness

QED-C: Quantum Economic Development Consortium
WEF: World Economic Forum

QI leverages the World Economic Forum to engage the political, business, cultural and other leaders of society to shape global, regional, and industry agendas

- **QI contributes to "Quantum Computing Governance Principles," January 2022**
- **QI participates in "Global Technology Governance Summit," June 2022**
- **QI supports "State of Quantum Computing: Building a Quantum Economy," September 2022**

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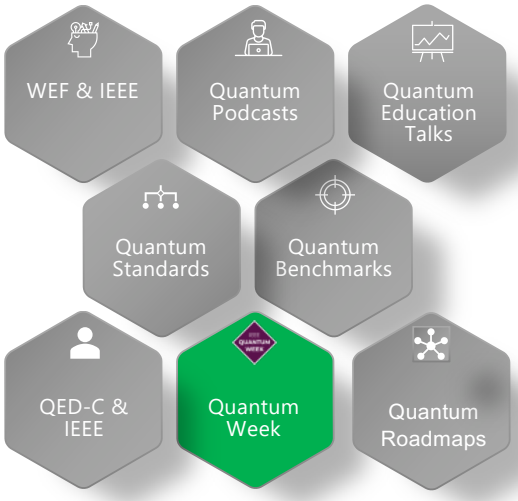
IEEE Quantum Initiative – Quantum Week



QED-C: Quantum Economic Development Consortium
WEF: World Economic Forum

IEEE International Conference on Quantum Computing & Engineering

- **Sun-Fri, Sep 17-22 at Hyatt Regency Bellevue on Seattle's Eastside**
- **35-45 Exhibits**
- **9-10 Keynotes**
- **18-22 Tutorials**
- **18-22 Workshops**
- **70-100 Technical Papers**
- **10-12 Panels**
- **50-70 Posters**
- **5-10 BoFs**
- **Prestigious Computer Society Annual Awards**

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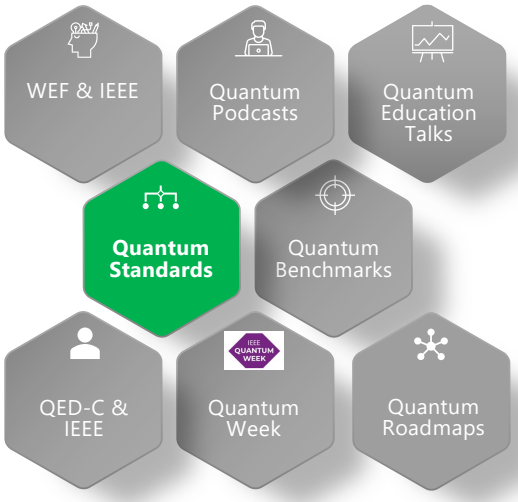
IEEE Quantum Initiative – Standards



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P3172 - Recommended Practice for Post-Quantum Cryptography Migration
- This recommended practice describes multi-step processes that can be used to implement hybrid mechanisms (combinations of classical quantum-vulnerable and quantum-resistant public-key algorithms).

P7130 - Standard for Quantum Computing Definitions
- This standard addresses quantum technologies specific terminology and establishes definitions necessary to facilitate clarity of understanding to enable compatibility and interoperability.

P7131 - Standard for Quantum Computing Performance Metrics & Performance Benchmarking
- The standard covers quantum computing performance metrics for standardizing performance benchmarking of quantum computing hardware and software.

ISO/IEC JTC1 WG 14 - Quantum Computing
- WG 14 was established by JTC 1 at its plenary meeting. It serves as a systems integration entity to focus on JTC 1's standardization program on Quantum Computing and maintain relationships with other related ISO and IEC/TCs and other organizations.

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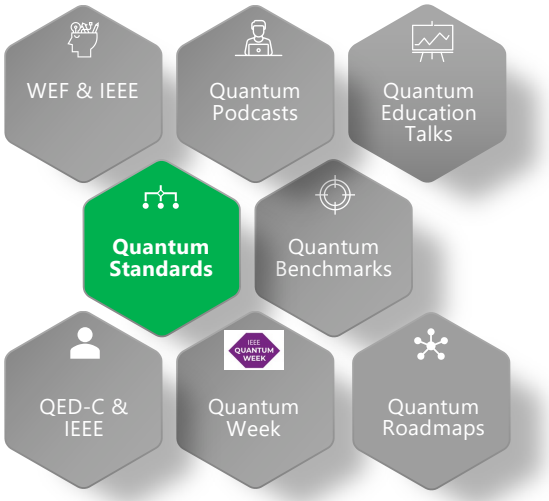
IEEE Quantum Initiative – Standards



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Quantum Standards in Process

P1913 - Software-Defined Quantum Communication
- This standard defines the Software-Defined Quantum Communication (SDQC) protocol that enables configuration of quantum endpoints in a communication network in order to dynamically create, modify, or remove quantum protocols or applications.

P2995 - Trial-Use Standard for a Quantum Algorithm Design and Development
- This trial-use standard defines a standardized method for the design of quantum algorithms.

P3120 - Standard for Quantum Computing Architecture
- This standard defines technical architectures for a quantum computers based on the technological type (e.g., fault-tolerant universal quantum computing) and one or more qubit modalities (e.g., superconducting quantum processor).

P3155 - Standard for Programmable Quantum Simulator
- This standard defines programming methods of quantum simulators according to analog digital and hybrid devices for the simulation of quantum phenomena beyond classical computing applications.

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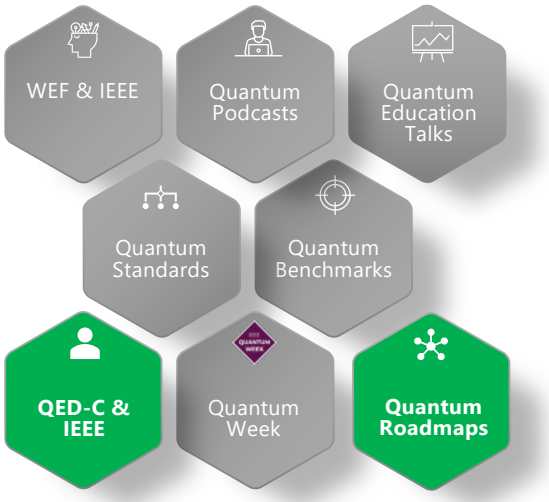
IEEE Quantum Initiative – Roadmaps



QED-C: Quantum Economic Development Consortium
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QED-C & IEEE

- **QTMR (Quantum Technology Manufacturing Roadmap) led by SRI under NIST funding**
- **Objective: Identify barriers to advanced manufacturing of quantum-related devices, components, and systems in the US**
- **Opportunity for IEEE and IEEE QI to participate — MOU signed with QED-C**
- **Kick-off meeting held in September 2022**
- **3 meetings in 2023 (APS (March), Semicon West (July), QED-C Plenary (Dec.))**

About QED-C:

*"QED-C is a consortium of stakeholders that aims to enable and **grow the U.S. quantum industry.** QED-C was established with support from the National Institute of Standards and Technology (NIST) as part of the Federal strategy for advancing quantum information science and as called for by the National Quantum Initiative Act enacted in 2018." https://quantumconsortium.org/*

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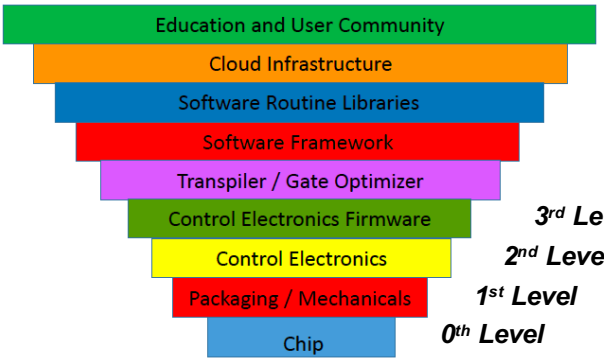
Packaging Role in Quantum Computing



3rd Level
2nd Level
1st Level
0th Level

Role of EPS

Packaging & Interconnect

Example of Ecosystem for Quantum Computing

It takes a village to build a quantum industry!

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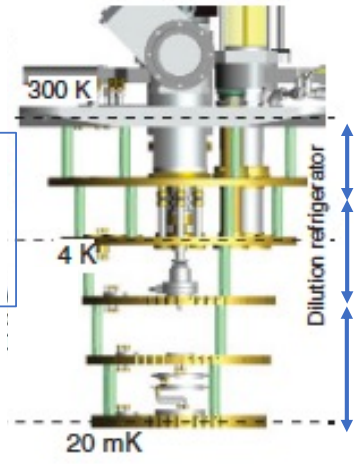
Technology Commonalities

Different Stages of the Dilution Refrigeration



Temperature Range

Cold Electronics 10K – 77K

Cryo Electronics 1K – 10K

Dilution Refrigeration < 1K

QC Technology

Superconducting, Ion Trap, Neutral Atom

Photonics

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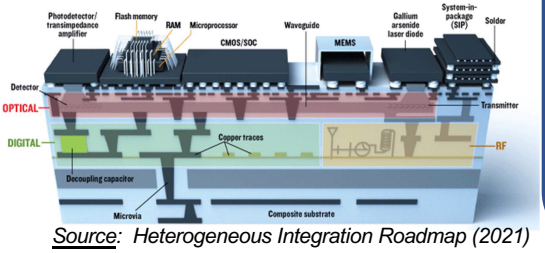
Commonalities in Packaging Challenges

Heterogeneous Integration Stack-up for Scalability



Source: *Heterogeneous Integration Roadmap (2021)*

Component/Module/Sub-system/System reliability
- Failure modes due to multiple thermal cycling?
- Reliability models?
- Cryo test standards? Acceleration factors? Prediction models?
- Database of material properties at cryogenic conditions?
- Design-for-Reliability (DfR), Design-for-Manufacturing (DfM), Design-for-Test (DfT) for cryo applications ?

New materials for enhanced cryo performance
- Substrates?
- Interconnects (0th / 1st / 2nd / 3rd level)?
- Adhesives (underfill, die attach, coating, optical glue)?
- Connectors?

Scalability → High density
- Packaging form factor?
- Interconnects (TSVs, solder bumps, Cu pillars?)
- Thermal management schemes?

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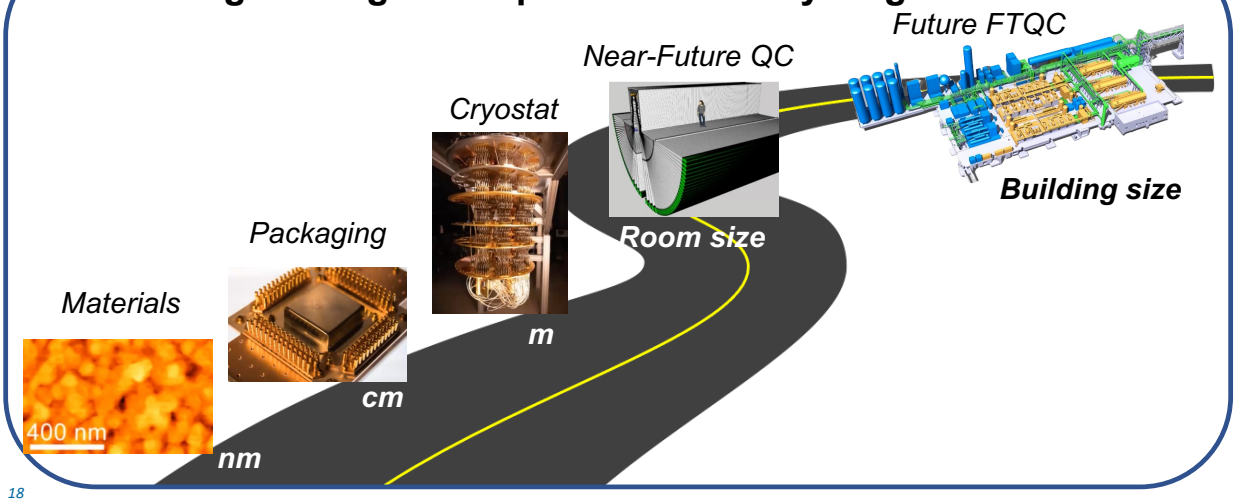
A Path for Scaling

Engineering development over many length scales



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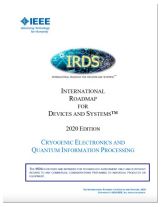
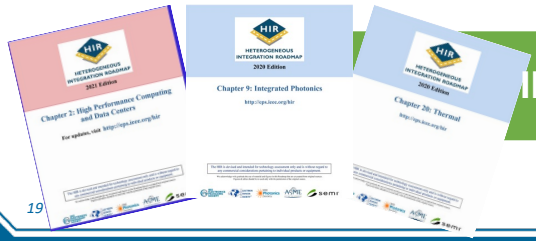
Standalone QC Chapter in HIR

QTMR Quantum Technology Manufacturing Roadmap
Scaling Up Quantum

QED-C → Manufacturing technologies



IEEE → Device-level; *lobsided focus on SC technology!*



IEEE

- Sub-section in HIR Ch 2
- Discussion with TWGs for Integrated Photonics & Thermal
- Standalone chapter?

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Potential Topics To Cover in QC Chapter

- QC technologies
- Commonalities in enabling technologies
  - Form factor (custom and commercial parts)
  - Thermal (scale-up requirements)
  - Materials
  - Assembly (linkage to HI; cryo testing)
  - Modeling
  - Reliability (accelerated testing, test standards)

More success in attracting folks from academia than from industry!

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