Carnegie Mellon University
Software Engineering Institute

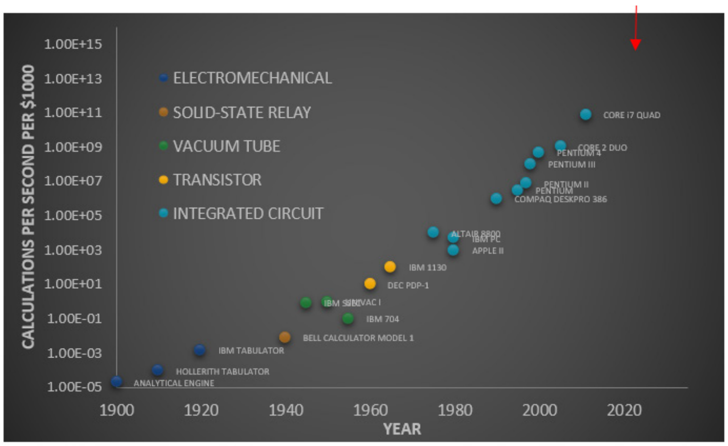
# Quantum Computing for Mission

## Performant Quantum Computing at the SEI

**AT THE SEI, WE ARE WORKING TO MAKE QUANTUM COMPUTING MISSION-CAPABLE** for important problems within the U.S. Department of Defense. Some of the most computationally challenging software engineering problems—for example, software verification and validation, and machine learning/artificial intelligence—are combinatorial optimization problems. For many combinatorial optimization problems, finding the exact optimal solution is NP-hard and could take billions of years to solve with classical computing paradigms. Our focus is on applying quantum computing to solve these problems in mission-critical time.

### Context for Our Work

At the SEI, we are working on performant quantum computation: quantum processing units (QPUs) and algorithms that can solve problems faster than classical computers, and in the ideal case, problems that no classical computer ever could solve in a reasonable amount of time (i.e., less than billions of years). The graph below, a plot of computational capacity per dollar each year, shows the progression through the first five computing paradigms, from electromechanical to integrated circuit.




**Is Quantum Computing the Next Major Paradigm?**
adapted from Ray Kurzweil "The Singularity Is Near: When Humans Transcend Biology"

Since the beginning of the post-Dennard scaling era and the end of Moore's law,[1] the integrated circuit computing paradigm has reached fundamental limits. To tackle the hardest problems in tasks and fields like software verification and validation (VV) and machine learning and AI (ML/AI), a new computing paradigm is needed.

### Achieving Quantum Advantage

Quantum computing is a candidate for this next computing paradigm. While much of the attention surrounding quantum computing has focused very generally on quantum supremacy, we are working toward quantum *advantage*: a clear demonstration of a quantum computer solving a problem of practical interest faster than a classical computer.

Some examples of these types of problems are the Lockheed Martin Challenge problems.[2] These problems involve complicated software components of aircraft flight controls that are challenging to verify and validate using classical computers. Software components like these require a new paradigm in optimization algorithms and computational capabilities to verify and validate in mission-critical time. We are investigating whether quantum algorithms and computers can serve as this next paradigm for optimization in applications like software VV.

Theoretically, quantum algorithms and computers promise polynomial and superpolynomial speedup for algorithms like Grover's and Shor's, but these algorithms require in excess of $O(10^{\wedge 5})$ qubits with quantum error correction.[3] While actual quantum computers are available from several different companies, we are currently in the Noisy Intermediate- Scale Quantum (NISQ) era. The number of qubits in current and near-term quantum computers is small ($O(10^2\text{-}10^3)$), and their operations are "noisy."[4] Because we don't have enough qubits to run quantum error correction, algorithms that can cope with this are necessary.

## Current Work

We are investigating near-term optimization algorithms that can run effectively on NISQ QPUs, like Variational Quantum Eigensolver (VQE) and Quantum Approximation Optimization Algorithm (QAOA).[5] We are investigating the following:

- Benchmarking Variational Quantum Optimization techniques, such as QAOA, and their ability to tolerate NISQ-era QPUs.
- Improving circuit generation for NISQ-era QPUs.
- Analyzing the hierarchy of the problems of interest and identifying which parts can be mapped effectively to QPUs.
- Addressing the challenges of scaling up to $O(10^2\text{-}10^3)$ qubits and predicting/projecting quantum advantage.
- Developing software tools to help data scientists and engineers use quantum computers.

## Future Work

We plan to build on this work and extend it to the following applications:

- Quantum machine learning: quantum algorithms to perform machine learning/artificial intelligence tasks
- Quantum interactive proof systems
- Using QPUs to form interactive proof systems
- Verifying/validating quantum computation

## SEI Quantum Team

Dr. Jason Larkin, jmlarkin@sei.cmu.edu
Daniel Justice, dljustice@sei.cmu.edu

### References:

[1] Tom Simonite. "Moore's Law Is Dead. Now What?" *MIT Technology Review*. May 13, 2016.

[2] Chris Elliott. "Cyber- Physical V&V Challenges for the Evaluation of State of the Art Model Checkers." *Research in Quantum Enabled V&V Technology*. 2016.

[3] M. Roetteler and K. M. Svore. "Quantum Computing: Codebreaking and Beyond." *IEEE Security & Privacy*. October 2018.

[4] John Preskill. "Quantum Computing in the NISQ Era and beyond." quantum-journal.org. 2018.

[5] Edward Farhi et al. "A Quantum Approximate Optimization Algorithm." quantum-journal.org. 2018.



## Contact Us

CARNEGIE MELLON UNIVERSITY
SOFTWARE ENGINEERING INSTITUTE
4500 FIFTH AVENUE; PITTSBURGH, PA 15213-2612

sei.cmu.edu
412.268.5800 | 888.201.4479
info@sei.cmu.edu