CompF6 Report Summary

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Draft of the CF6 Report

• https://snowmass21.org/computational/start#report_drafts
Why is quantum computing interesting for HEP?

- A quantum computer is a programmable interface to quantum physics experiments.
  - *It is a tool for discovery, like a telescope, or a particle accelerator.*

- In HEP we face a set of *computational challenges* in where *the only practical path to solution requires the utilization of entanglement and superposition as algorithmic primitives.*

  - In particular, *scalable methods for accurately simulating quantum many-body systems are beyond the capabilities of classical computers.*
  
  - Additionally, quantum computers are anticipated to play a *strong role in future event generators*, speeding up matrix element calculations and even neutrino-nucleus cross section calculations.

  - Also, quantum computers may play an important role in *data analysis*, especially *in tandem with quantum sensors and networks.*

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Richard Feynman: the need for quantum computing (1981)

- First person to propose the idea of *quantum computers*
- Emphasized the idea of using quantum systems to simulate/solve quantum problems

Spentzouris | The Fermilab Quantum Science and Technology Program

Figure courtesy of H. Lamm
Simulating physics

• Quantum computing has the potential to revolutionize our ability to simulate physics. Quantum many-body simulation and lattice field theory in particular stand to gain.

• Daunting work program ahead though:
  - Need to understand interplay between theory errors and errors from the quantum computer, even as fault tolerance begins to come online. What is the “sweet spot” for ambitious applications?
  - Need to build error correction protocols into our calculations as well and progress calculations “up the ladder” of group complexity.
  - Need to fully understand how to leverage the capabilities of the hardware platforms available to us, including how to build specialized hardware for HEP calculations.
Quantum computers for data analysis & machine learning

- Classical data analyzed on a quantum computer is the most studied problem type.
  - Quantum computers may offer important benefits in data analysis, particularly in cases where combinatorics are a challenge (e.g., clustering, tracking).
  - Likely requires fault-tolerant quantum computers.

- Quantum data analysis on a quantum computer is another particularly exciting option - leverage quantum sensors or even the outputs of quantum computers running simulations where the data itself is naturally entangled and in a state of superposition.
NQIA Centers & SQMS

- H.R. 6227 authorized $625,000,000 over five years for five DOE and two NSF national quantum centers.
- HEP hosts one of the Centers at Fermilab - The Superconducting Quantum Materials and Systems Center (SQMS)
  - HEP is also involved at the Quantum Science Center (QSC) hosted at ORNL, as well as Q-NEXT and QSA.
- Leverage HEP expertise in large scale projects and cryogenic engineering to construct large testbeds.
- Leverage decades of research into SRF resonators to create 3D architectures in the quantum regime.
  - Highest coherence quantum resonators ever demonstrated.
  - Ambitious quantum sensing program as well.

Slide material courtesy of Anna Grassellino (FNAL)
Example Strategy @ QSC: Leverage HEP capabilities

Science targets: Topological quantum materials/computing, single photon detectors, microcalorimetry for dark matter searches. Engages condensed matter/materials capabilities of BES and ASCR.

highly multiplexed readout of cryogenic qubit/sensor arrays
Cryogenic qubit control systems
Low radiogenic background testing of quantum materials and sensors
We are in early days...

• There is an entire software stack to be built. Nobody reasons about classical algorithms using circuits anymore, but that is where we are in quantum.
  - Scientific applications will be a critical early driver in this process!
• There is a large diversity of hardware approaches and we don’t yet know what will scale best or be best suited to HEP problems - we need to have some exposure to all of them!

https://sqms.fnal.gov/research/
https://www.xanadu.ai/hardware