Snowmass 2021 CompF6: Quantum Simulation of Quantum Field Theories

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Opportunities in quantum simulation of quantum field theories

Exascale classical computers will advance our knowledge of quantum chromodynamics (QCD), but some challenges will remain, especially concerning real-time evolution (e.g. scattering) and properties of nuclear matter and quark-gluon plasma as a function of both temperature and chemical potential.

Classical computers may never be able to address these (and other) problems; quantum computers will solve them eventually, though we’re not sure when. The big physics payoff may still be far away, but today’s research can hasten the arrival of a new era in which quantum simulation fuels progress in fundamental physics. Even in the near term, studies of dynamics in strongly-coupled many-particle systems can provide revealing insights.

Quantum simulation of quantum field theories.

Beyond Euclidean Monte Carlo on classical computers

-- Improved predictions for QCD backgrounds in collider experiments

-- Equation of state for nuclear matter, quark gluon plasma, early universe

-- Electroweak response of hadronic matter, e.g. intensity frontier

-- Simulation of nuclear reactions, e.g. astrophysical modeling

-- Exploration of other strongly-coupled theories, beyond-standard-model physics

-- Stepping stone to quantum gravity, e.g. through holographic duality

-- New insights!

What quantum simulators can do

-- Sample accurately from outgoing states in simulation of scattering event.

-- Real-time correlation functions, including at nonzero temp and chem potential.

-- Transport properties, far from equilibrium phenomena.

Quantum simulators

A variety of platforms

-- Superconducting circuits
-- Trapped ions
-- Ultracold atoms in optical lattices
-- Rydberg atoms
-- Potentially others (spins, photons, etc.)

Analog vs. digital

-- Analog quantum simulators are becoming increasingly programmable
-- Digital (circuit based) quantum simulators: less mature, more flexible
-- Both are noisy (now)
-- Both are important to pursue

Near term vs. long term

-- Today's NISQ devices are already hard to simulate classically
-- Noise seriously limits the reach of both digital and analog simulators
-- Long run: scalable error-corrected digital platforms, large overhead cost
-- Near term: better noise mitigation methods short of full blown QEC.

Quantum simulation of quantum field theories.

Where are we now?

-- Resource scaling estimates (number of qubits and gates) for scattering simulations in scalar and Yukawa theories.
-- *Classical* tensor-network simulation of massive 1D QED.
Static and dynamic studies of strings and string breaking.
-- Few-site *quantum* simulations of 1D QED with trapped ions and superconducting circuits.
-- Binding energies of deuteron, ^{3}He, ^{4}He in (pionless) effective field theory.
-- Proposals for analog simulation using ultracold atoms, etc.
-- In progress: Classical and quantum simulations of nonabelian gauge symmetry, higher dimensions.

Where to seek quantum advantage?

-- How to outperform classical tensor network calculations?
-- Classical simulation methods fail for highly entangled states.
-- High-energy scattering with multiple particle production.
-- Dynamics after a quench, or many successive scattering events.

Quantum simulation of quantum field theories: What next?

-- More qubits, better precision, greater programmability

-- Access to a variety of platforms, for exploration and benchmarking

-- Stepping stones toward QFT simulators, for both analog and digital approaches

-- Hybrid quantum / classical methods (focusing quantum resources where they are most needed)

-- Protocols for state preparation, evolution, readout, classical post-processing

-- Hamiltonian simulation theory: gauge invariance, errors, renormalization, scaling

-- Clarify the hardware / software requirements for a special-purpose QFT/QCD quantum machine

-- Exploit quantum advantage in sampling, matrix inversion, semidefinite programs

-- Elucidate the path forward, both near term and long term