Quantum Information Science and Computing

• QIS: the nature, acquisition, storage, manipulation, computing, transmission, and interpretation of information.

• Entanglement and superposition distinguish quantum information from classical information.

• Improving control of superposition and entanglement over macroscopic space-time volumes has produced first devices for quantum computation and quantum sensing. Defining the Quantum-2 era.
The Potential of Quantum Computing

~ 100 qubit devices can address problems in chemistry that are beyond classical computing

50 qubits : ~ 20 petabytes ~ Leadership-Class HPC facility

300 qubits : more states $[10^{90}]$ than atoms in universe $[10^{86}]$
Where a quantum advantage may be achieved

Quantum Field Theories and Fundamental Symmetries
- indefinite particle number
- gauge symmetries and constraints
- entangled ground states

Real-Time Dynamics
- parton showers
- fragmentation
- neutrino-nucleus interactions
- neutrinos in matter
- early universe
- phase transitions - matter?
- non-equilibrium

Dense Matter
- neutron stars
- gravity waves
- > medium nuclei
- chemical potentials
Where a quantum advantage may be achieved - 2

Classical Computing
- Euclidean space
- high-lying states difficult
- Signal-to-noise
- Severe limitations for real-time or inelastic collisions or fragmentation

Quantum Computing
- real-time Minkowski space evolution
- exponentially-large Hilbert spaces
- S-matrix
- mitigated sign problem(s) (naively)
- integrals over phases
“First Qubits” for Scientific Applications

NISQ-era quantum devices for applications

Analog, Digital and Hybrid Simulation

**analog simulations**
- H : native to system
  - e.g. atoms in optical lattices
  - SRF cavities
  - BECs

**digital computations**
- e.g. trapped-ions, superconducting qubits
- H : universal gate sets
- NISQ, a while before error-corrected

**Hybrid**
- QPU “like” a GPU for the intrinsically quantum parts of the computation
  - Scaling?
Analog Simulation (classic) examples

Elliptic flow
cold atom simulation
Analog Simulation examples
SRF cavities

LLNL and FermiLab

Toward nuclear reactions and field theory
Analog Simulation: dense matter example

Selection of different experimental systems/atoms, controls, (number of) species and accessible observables

New Frontier
non-equilibrium dynamics of strongly-interacting systems
e.g. evolution of domain walls

One example: Dilute neutron matter

Short-range correlations
The "Contact"
Unitary Fermi Gas
Analog Simulation: Quantum Field Theory - ideas

Quantum Link Models
(see Schladaming lectures by Uwe-Jens Wiese, 2015)

Hauke et al
Unitary operations implemented through quantum circuits using a set of gates

e.g., entangling gate
\[ \text{CNOT}(1;2) = \Lambda_0 \otimes I + \Lambda_1 \otimes \sigma_x \]

https://www.extremetech.com/extreme/204553-ibm-gate-closer-to-real-quantum-computing
https://medium.com/@jonathan_hui/qc-how-to-build-a-quantum-computer-with-superconducting-circuit-4c30b1b296cd
Digital Simulation

First Steps being taken to understand our problems

Generically, 3 “workflow phases”

1. **state preparation** - generally, entangled
2. **time-evolution** - Trotterized evolution operator
3. **measurement**

- Minimal or no error correction
- Few hundred qubits with modest gate depth
- Imperfect quantum gates/operations - like "running experiments"
- Different "flavors"
- NISQ-era is the next decade of quantum simulation
  - much to be gained during this period
  - learn by doing - just like all experiments
- Searching to find Quantum Advantage(s) in scientific applications
Scalar Field Theory
The Gold Standard - Jordan, Lee, Preskill

- Discretize 3-d Space
- Define Hamiltonian on grid
- Trotterized time evolution
- Technology transfer from Lattice QCD
- Digitize field(s)

\[ \hat{H} = \hat{H}_\Pi + \hat{H}_\phi \]
\[ \hat{H}_\Pi = \frac{1}{2} \Pi^2 \quad \hat{H}_\phi = \frac{1}{2} (\nabla \phi)^2 + \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4!} \phi^4 \]
\[ \hat{H}_\phi = b \sum_x \left( \frac{1}{2} \phi_j \phi_{j+1} + \frac{1}{2} \phi_j \phi_{j-1} - \phi_j^2 + \frac{1}{2} m^2 \phi_j^2 + \frac{\lambda}{4!} \phi_j^4 \right) \]
Scattering Wavepackets in Scalar Field Theory

Quantum Computation of Scattering in Scalar Quantum Field Theories

Stephen P. Jordan,† Keith S. M. Lee,‡ and John Preskill § *

1. Create wavepackets of free theory
2. Adiabatically evolve the system to interacting system
3. Evolve the prepared state forward
4. Adiabatically evolve systems to free theory OR introduce localized detectors into the simulation
Digital Simulation
Dynamics in the Schwinger Model
Baby steps using small, 1dim systems

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer
Esteban A. Martinez,1,2 Christine Muschik,2,3 Philipp Schindler,1 Daniel Nigg,1 Alexander Erhard,1 Markus Heyl2,4 Philipp Hauke,2,3 Marcello Dalmonte,2,3 Thomas Monz,3 Peter Zoller,2,3 and Rainer Blatt1,3

(2016) 1+1 dim QED

Innesbruck
ORNL-Washington-Basque
Innesbruck
Maryland
BNL-Stonybrook
BNL-Oxford

Quantum Algorithms for Simulating the Lattice Schwinger Model
Shaw, Alexander F.1, Lougovski, Pavel1, Stryker, Jesse R.2, and Wiebe, Nathan3,4
Digital Simulation Examples

Towards fragmentation and hadronic structure

A quantum algorithm for high energy physics simulations

\[ L = \bar{f}_1(i\partial + m_1)f_1 + \bar{f}_2(i\partial + m_2)f_2 + (\partial_\mu \phi)^2 + g_1\bar{f}_1f_1\phi + g_2\bar{f}_2f_2\phi + g_{12} [\bar{f}_1f_2 + \bar{f}_2f_1] \phi. \]

Parton Physics on a Quantum Computer
Henry Lamm, Scott Lawrence, and Yukari Yamauchi
(1) Department of Physics, University of Maryland, College Park, Maryland 20742, USA
(Dated: February 18, 2020)
Digital Simulation
The role of spin models

Spin models are becoming nice sandboxes

Quantum simulation of scattering in the quantum Ising model

Erik Gustafson$^1$, Y. Meurice$^1$, and Judah Unmuth-Yockey$^2$

$^1$ Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242, USA and
$^2$ Department of Physics, Syracuse University, Syracuse, NY 13244 USA
(Dated: February 5, 2019)

$$H_{obs} = -J \sum_{i=1}^{N_s-1} \hat{\sigma}_i^x \hat{\sigma}_{i+1}^x - \hbar \sum_{i=1}^{N_s} \hat{\sigma}_i^z.$$
Matrix Elements
Toward Inelastic Neutrino Nucleus Interactions

Linear Response on a Quantum Computer
Alessandro Roggero* and Joseph Carlson†
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, L
(Dated: April 13, 2018)

- a unitary $\hat{U}_G$ which prepares the ground-state of the Hamiltonian of interest
- a unitary $\hat{U}_O$ which implements time evolution under $\hat{O}$ for a short time $\gamma < \text{poly}(\delta_S)$
- a unitary $\hat{U}_t$ which implements time evolution under the system Hamiltonian for time $t$

Short-depth circuits for efficient expectation value estimation
A. Roggero*
Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA
(Dated: May 22, 2019)

A. Baron†
Department of Physics and Astronomy University of South Carolina,
712 Main Street, Columbia, South Carolina 29208, USA

2D Hubbard Model

\[
\begin{align*}
|0\rangle & \quad H \quad S \quad H \\
|\Psi\rangle & \quad e^{i\tau O}
\end{align*}
\]
How to Digitize Scalar Fields

What is the optimal way to map field theories onto NISQ-era quantum computers?

Jordan, Lee and Preskill - several works
Rolanda Somma [LANL]
Macridin, Spentzouris, ... [FNAL]
Siopsis, Pooser, ...[ORNL/UTK]
Klco, MJS [UW]

e.g., Gray-encoding
Olivia diMatteo et al

Field basis
Harmonic Oscillator

e.g., 3 Qubits = 8 States
Localized State Preparation and the RG

Natalie Klco and MJS  
e-Print: 1912.03577 [quant-ph]  
e-Print: 2002.02018 [quant-ph]
Symmetric Exponentials on Poughkeepsie
3-spatial sites

Natalie Klco and MJS

IBM Poughkeepsie

ORNL-IBM

\[ n_Q=3 \otimes n_Q=3 \otimes n_Q=3 \mid \phi(0) \phi(1) \phi(2) > \]

Working with FermiLab to prepare entangled ground state
Digital Simulation
Lattice Theories: Logical Qubits and Error Correction

Kitaev (1997)

\[ H_T = -J_e \sum_s A_s - J_m \sum_p B_p \]

Energy

2^n - 4
Excited states

\[ \Delta E \neq 0 \]

| \psi \rangle

4-degenerate ground state (CODE SPACE)

Quantum Spin Liquids: a Review

Lucile Savary¹, Leon Balents²
Starting down the Path
Digitizing SU(2) Gauge Theory

Digitizing Gauge Fields: Lattice Monte Carlo Results for Future Quantum Computers

Daniel C. Hackett, 1,* Kiel Howe, 2,† Ciaran Hughes, 2,* William Jay, 1,2,# Ethan T. Neil, 1,3,*,† and James N. Simone 2,**

1 Department of Physics, University of Colorado, Boulder, Colorado 80309, USA
2 Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA
3 RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA

- Graphs showing L2 and APR results with various markers indicating different parameters like $\tilde{D}_{48}$, $v=88$, $\tilde{l}_{120}$, etc., plotted against $r/a$.
2+1, 3+1 Gauge Theories

Gauss's Law, Duality, and the Hamiltonian Formulation of U(1) Lattice Gauge Theory
David B. Kaplan, Jesse R. Stryker, arXiv:1806.08797 [hep-lat]

SU(2) lattice gauge theory: Local dynamics on nonintersecting electric flux loops

Digital quantum simulation of lattice gauge theories in three spatial dimensions

Quantum Simulation of Gauge Theories
NuQS Collaboration (Henry Lamm et al.). e-Print: arXiv:1903.08807 [hep-lat]
SU(2) Gauge Theory

$t=0 : 2$ plaquettes with $j_{\text{max}}=1/2$

SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers

Natalie Kico, Jesse R. Stryker and Martin J. Savage

1 Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-5250, USA

(Dated: August 10, 2019 - 13:7)

\[
\hat{H} = \frac{g^2}{2} \sum_{\text{links}} \hat{E}^2 - \frac{1}{2g^2} \sum_{\text{Q}} \left( \hat{\mathbb{Q}} + \hat{\mathbb{Q}}^\dagger \right)
\]
Digital Simulation
New ``Tricks’’

Together with new Trotter product formulae error bounds, and a novel low-weight fermionic encoding, this improves upon state-of-the-art results by over three orders of magnitude in circuit-depth-equivalent.

See also, Childs et al
Summary

• Quantum Simulations are expected to be able to address grand challenge problems that cannot be addressed with classical computing in the future.

• Next few years will allow us to “spin-up”, — develop algorithms, expertise and workforce to move toward solving beyond-classical problems. Start small but think big.

• Qualitative new understandings to feed back into classical?

• Sensors and simulators are intertwined

• Diverse collaboration are essential,
  • HEP, NP, BES, QIS, expt, theory
FIN