Quantum Application Survey:
Progress in Analog Quantum Computing

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QuIICS/UMD/AWS Braket
A major application of quantum computing with early feasibility
Amenable to both circuit-model and Hamiltonian-model implementation
Recent pulse-level control of quantum devices enables investigation of both
Circuit-based Digital Implementation is Expensive

Digital Quantum Computing Paradigm

Target Problem → Quantum algorithm → Discrete Circuits → Compiler → Continuous Pulses → Quantum devices with universal gates

Large constant factor
High expertise demand
Huge implementation overhead
Few supportive devices

On IBM devices:
10 \cdot T_{\text{CNOT}} \approx T_1 \approx T_2
T_{RXX(\theta)} \approx 2 \cdot T_{\text{CNOT}}

[1]: Childs et al., Toward the first quantum simulation with quantum speedup, PNAS, 2018.

• Circuit-model is a well-recognized theoretical model/interface between quantum applications and hardware, w/ merits in its mathematical elegance.
• Overheads w/ circuit abstraction. Resource-Efficient Quantum Computing by Breaking Abstractions [IEEE]
• Mismatch in quantum & classical hardware specs: clock rate, hardware acceleration
• Asymptotic theoretical speedup (circuit) \neq \text{speedup in practice} [CACM, May 2023; q. IPM]
Hamiltonian-based Analog Machines

Analog computing predates digital computing, and revives recently due to challenges in scaling up digital computing (e.g. Moore’s law).

- Energy Efficiency — low overhead
- Domain applications like analog AI chip

Wind Tunnels & Various Testbeds remain the standard solutions in practice for many domain applications.

Analog Quantum Simulators are not unfamiliar either.

The Analog Milestone for QC:
Understand unknown physics w/ help of analog/special-purpose quantum machines!

We believe analog thinking & tool-chain will be critical to achieve this milestone!
Conceptual Differences between circuit and Hamiltonian models

Quantum Applications

Infrastructure of Quantum Computing

DIGITAL

Parameterized Quantum Circuits

Variational Q. Methods

Circuits to describe everything

Algorithm & Complexity

ANALOG

Differentiable Quantum Physics

Variational Q. Methods

Hamiltonian Simulation

Algorithm & Complexity

Pulse-level control enables the investigation of the latter

problems from scientific computing, operation research, machine learning ……
Examples of Hamiltonian-based Demonstration

• Physical phenomena: quantum scar, phase transition, spin liquid, or so

• Neutral atoms (QuERA, Pasqal), Trapped Ions, Superconducting (IBM, Rigetti)

• Leverage native programmability of quantum devices, but w/ more complicated error models, lacks a fault-tolerant theory and a nontrivial use of native Hamiltonian (for now)

Simulation -> Differentiable Simulation / variational methods

• Leveraging pulse-ansatz for variational methods: 2008.04302, 2202.08908, 2208.01215, 2211.02584, 2211.02748, 2212.12911, 2304.09253, and so on....

• We developed an auto-differentiation training method for differentiable quantum physics (NeurIPS 2022), demonstrate orders of magnitude advantage on simulators.
Hamiltonian-oriented Algorithm Design: beyond naive cases

- Hamiltonian-oriented design: both (1) **new quantum algorithms** and (2) **more efficient implementation** of existing quantum algorithms
- Apply to both *near-term* and *long-term* quantum devices
- Key new technique in implementation is the **Hamiltonian embedding** scheme
## Hamiltonian-oriented Algorithm Design: Examples

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Hamiltonian-oriented Algorithm Design: Examples

**New Quantum Algorithm**

Quantum Hamiltonian Descent

derived from the *path integral* of continuous-time classical gradient flow

Superior Performance in TTS (Time-To-Solution) than *quantum adiabatic* and *five classical SOTA algs* on 75-dim quadratic programming instances

**New Implementation:** Hamiltonian Embedding

Hamming Encoding Quantum Ising Machine

**Platforms**

QHD Website

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**Continuous Optimization**

**Quantum PDE Solvers**

Quantum PDE Solver for First-order hyperbolic equations (e.g., Hamilton-Jacobi, Heat, Liouville’s)

Via embedding classical dynamics into Schrödinger equation

**Particle in real space & Dirac equation**

Unary encoding + Anti-Ferromagnetic (AF) Quantum Ising Machine

**Quantum Walk & Spatial Search**

Anti-Ferromagnetic (AF) + One-shot Encoding Quantum Ising Machine

Neutral Atoms Neutral Atoms/Trapped Ions

*Manuscript Under-Preparation*
1-D quantum walk example: early view on IonQ Aria

IonQ resource estimate for quantum walk

- Single qubit gate count
- Two qubit gate count
- Total gate count

Example:
- 12-vertices 1-D quantum walk
- Via one-shot encoding
- Accessed on 05-17-23
- 33 USD on Braket
Infrastructure for Hamiltonian-oriented Programming

Analog (Hamiltonian-oriented) Quantum Computing Paradigm

|\psi(0)\rangle \xrightarrow{\text{Evolve under } H(t) = tZ_1Z_2 + \cdots} |\psi(t)\rangle \xrightarrow{\text{Analogue Compiler}} \text{Continuous Pulses} \xrightarrow{} \text{Programmable quantum systems}

Natural model for many problems (etc., simulation)

Hardware-efficient compilation

Supports most modern quantum devices

SIMUQ

SIMULATION language for Quantum

ABSTRACTION & SOFTWARE?

GitHub repo: https://github.com/PicksPeng/SimuQ

Enhance your capability of harnessing the power of quantum devices

Project website: https://pickspeng.github.io/SimuQ/

arXiv: 2303.02775
All our Hamiltonian-oriented applications are now coded w/ SimuQ !!!

Currently support IBM (via Open-Pulse), Rigetti (Braket Pulse), QuERA as well as arbitrary-angle MS gates on Trapped Ions

GitHub repo: https://github.com/PicksPeng/SimuQ

arXiv: 2303.02775
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Thank You!