Toward Practical Quantum Advantage in Scientific Computing

Hybrid Variational Methods for Differential Equations

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Outline

Quantum Computing Reading Group (QCRG)

Mission & Community

- Build a foundational understanding of quantum computing
- Engage in non-hyped scientific discussion
- Foster collaborative learning and decode research papers

Myths & Topics

- Quantum is not universally faster; it complements classical HPC
- Qubits obey physics, they don’t defy it
- Upcoming: algorithms, hardware toolkits, hackathons & community events

Quantum Advantage: Concept & Current State

- Quantum computing promises speedups for selected linear algebraic tasks
- NISQ devices: hundreds to ~1000 qubits; prone to decoherence and lack error correction
- Hybrid algorithms (VQE, QAOA) couple classical optimisation with quantum state preparation
- Variational PDE solvers use parameterised circuits with classical feedback

Road to Practical Quantum Advantage

NISQ era limitations

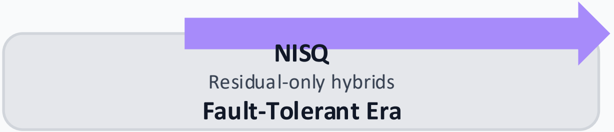
– Devices are noisy and have limited qubit counts; circuit depths must be shallow

Goal of current research

– Demonstrate feasible hybrid workflows combining classical discretisation with quantum residual minimisation instead of outperforming classical solvers

Towards fault-tolerant devices

– Increase qubit counts and implement error correction
– Develop mature, verifiable algorithms and mitigate errors
– Address communication overhead between classical and quantum components



Hybrid Variational Solver Overview

Classical Side

- Spectral Chebyshev discretisation
- Enforce boundary conditions

Residual →

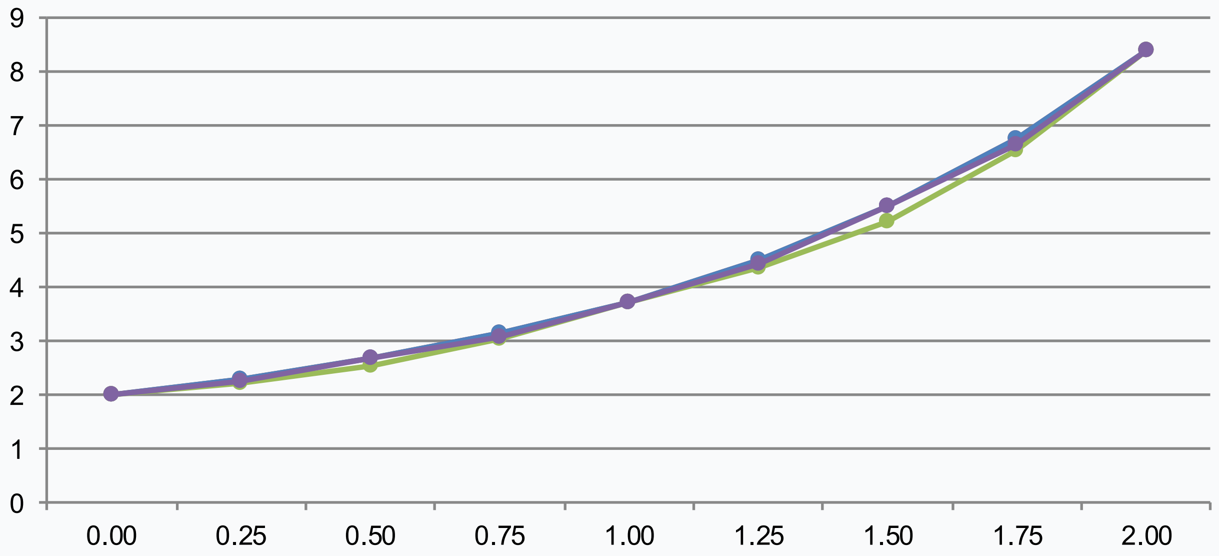
Quantum Side

- Residual minimisation
- Gate-based CUBO or QUBO annealer

Design Principles

– Offload only the residual norm to the quantum backend
– Enforce boundary conditions and operators classically
– CUBO: continuous cost on gate-based devices
– QUBO: discrete optimisation on annealers

Results: Nonlinear Boundary Value Problem



- Classical solver and exact solution are indistinguishable
- CUBO approximation deviates due to limited circuit depth and ansatz expressivity
- QUBO annealer achieves closer agreement across the domain
- Shallow circuits with fewer qubits improve convergence and reduce barren plateaus

Comparison & Discussion

Method	Approximation Quality	Resources / Complexity	Observations
Classical Spectral Solver	Matches exact solution	Low: CPU-based spectral chebyshev discretisation	Exponential convergence for smooth solutions
CUBO Gate-Based	Deviates slightly with interior bias	Medium: few qubits and shallow circuits	Improves over variational baseline but limited by ansatz expressivity & noise
QUBO Annealer	Close to exact solution across domain	Low–Medium: binary encoding suitable for annealers	Stable convergence; natural fit for quadratic optimisation

Key Insights

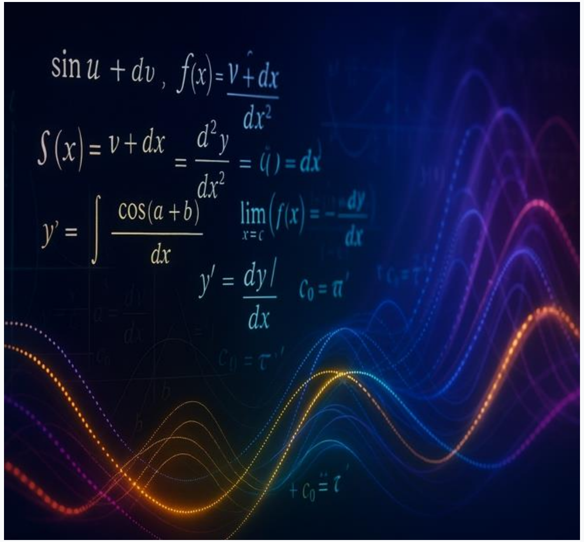
- Classical and exact solutions are essentially indistinguishable
- Annealers deliver accurate approximations today; Gate-based methods improve over variational baselines but remain limited
- Variational solvers without residual splitting struggle on NISQ devices

Outlook & Future Work

Advancing Hardware
– Increase qubit counts and improve coherence times
– Implement error correction and mitigation techniques

Enhancing Algorithms
– Design deeper yet trainable ansätze, warm-start strategies
– Develop unified hybrid schemes combining annealers and variational circuits

Expanding Applications
– Benchmark across a range of nonlinear ODEs/PDEs
– Explore higher-dimensional problems and new physics domains



Conclusion

- Practical quantum advantage remains a future goal, but hybrid solvers demonstrate a concrete path forward
- Residual-only offloading preserves the maturity of classical algorithms while tapping into quantum capabilities
- Annealer-based QUBO methods provide promising accuracy today; gate-based CUBO methods are positioned to benefit from hardware advances
- Continued collaboration between mathematics, HPC and quantum communities is essential to unlock practical scientific advantage

Let’s bridge today’s algorithms with tomorrow’s quantum machines!

References

1. J. Eisert and J. Preskill, "Mind the gaps: The fraught road to quantum advantage," arXiv:2510.19928v2 (2025).
2. S. K. et al. (Google Quantum AI), "Quantum Supremacy Using a Programmable Superconducting Processor," Nature 574, 505–510 (2019).
3. A. K. et al., "Error Corrected Quantum Supremacy," arXiv:2310.12345 (2023).
4. IBM, "IBM Quantum Heron Processor," IBM Research Blog (Dec. 2023).
5. S. A. Aseeri, "A Hybrid Quantum–Classical Spectral Solver for Nonlinear Differential Equations," Algorithms 2025, 18, 678.
6. S. Aseeri, "Quantum Computing Reading Group: Exploring Frontiers of Computation," lecture slides (Apr. 30, 2025).

Thank You!

Questions & Discussion

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