

Quantum Computing Approaches to Multi-Scale Modeling of

Coupled Thermal, Mechanical, and Electromagnetic Phenomena

Alara Onur

American Collegiate Institute

Abstract—Multi-scale modeling of coupled thermal, mechanical, and electromagnetic phenomena presents one of the most computationally demanding challenges in scientific simulation. These interactions often span quantum-level processes, mesoscopic transport behavior, and macroscopic material responses, requiring integrated frameworks capable of resolving complex nonlinearity, strong coupling, and multi-physics feedback loops. Quantum computing offers a transformative pathway toward more accurate and scalable simulations of such systems. This study investigates quantum-enhanced approaches for modeling heat transfer, stress evolution, electromagnetic field propagation, and their mutual interactions across scales. By integrating quantum algorithms for partial differential equations, quantum linear solvers, and quantum-accelerated spectral and tensor representations, the research explores how quantum models can capture high-dimensional dependencies and strong correlations that classical methods struggle to resolve. The analysis highlights the potential of hybrid quantum–classical workflows to accelerate multi-physics simulation, improve predictive fidelity, and support the design of advanced materials, energy devices, and engineering systems that rely on thermal–mechanical–electromagnetic coupling.

■ Many of today’s most advanced technologies rely on the intricate interplay of thermal, mechanical, and electromagnetic phenomena. Examples range from high-performance electronics and aerospace materials to fusion-energy components, photonic devices, and electromechanical systems [5]. These systems experience simultaneous heat generation, electromagnetic excitation, mechanical deformation, and complex feedback mechanisms that evolve across multiple spatial and temporal scales. Accurately representing such tightly coupled behaviors pushes the limits of classical computational methods [4].

Traditional multi-physics modeling frameworks must navigate a landscape filled with nonlinear partial differential equations, high-dimensional constitutive relationships, and coupling effects that often require iterative, resource-intensive solvers [2]. As systems grow in complexity—incorporating nanoscale thermal transport, dynamic electromagnetic fields, or stress-induced property changes—classical simulations face rapidly increasing computational demands. Capturing these interactions coherently across scales remains challenging even for the most advanced supercomputers [6].

Quantum computing introduces new opportunities to overcome these limitations. Quantum algorithms offer more efficient approaches for solving large

Digital Object Identifier 10.62802/ztb4ge27

Date of publication 19 11 2025; date of current version 19 11 2025