<u>**Graduate Research Plan Statement**</u>

Background: Since Dr. John Preskill first introduced the concept of "Quantum Supremacy"—the point at which a quantum computer outperforms a classical computer on a specific task—many have viewed quantum and classical computing as competing paradigms, each striving to outperform the other on specific computational tasks. However, this viewpoint overlooks the potential for these approaches to work in tandem, leveraging their respective strengths to tackle problems more efficiently. Quantum solutions have been proposed and executed with varying degrees of success, but research results show that all steps in the quantum workflow could benefit from incorporating classical computational power **[1]**. While quantum-classical (Q-C) integration has been explored, existing techniques primarily focus on specific methods such as circuit simplification **[2]**, CNOT commutation **[3],** and adaptive variational algorithms **[4]**. These approaches aim to reduce quantum resource usage but don't fully tap into the potential of classical computing. However, my proposed graduate research focuses on more recent advancements in Q-C computing that **focus on finding ways to share the computational load of calculation by using quantum computing and classical simulation in tandem to run the quantum circuits.** Recent works in the Schrödinger-Heisenberg variational quantum algorithm (SH-VQA), a combination of a classical Heisenberg circuit and quantum Schrodinger circuit, that has been used to significantly reduce the number qubits needed to run to determine a solution, resulting in a more efficient algorithm **[5]**. Building on these results, **my goal is to develop techniques that optimize quantum algorithms by integrating classical simulation at each stage of the quantum workflow; problem encoding, circuit compilation, and execution**. Ultimately my project framework will benefit a wide range of algorithms for both Noisy Intermediate Scale Quantum Computers (NISQ) and Fault Tolerant Quantum Computers (FTQC), pushing the boundary of computation to new heights and allowing for more advanced research across all fields of study.

Broad Research Overview: I will integrate classical methods at each stage of the quantum workflow, beginning with improving Circuit Compilation, which transforms a high-level algorithm into a sequence of executable steps for a computer. My approach to enhancing this process involves designing a Q-C ansatz that efficiently merges quantum and classical circuits. Creating the Q-C ansatz is divided into three phases: **Phase (1)** My **focus will be on conducting preliminary research to determine** ***A.)*** which circuit operations are difficult for classical computers but can be handled efficiently by quantum computers, and the cost of separating those operations from the rest of the circuit. ***B.)*** How tradeoffs in quantum add additional cost of classical resources. ***C.)*** Once the research is complete, I'll Use the results from A and B to establish clear benchmarks for determining when and how operations should be split between classical and quantum systems for optimal efficiency. Once I complete Phase (1), **Phase (2)** Will focus on using the benchmarks established in Phase (1) to **identify the best methods for separating classically simulatable operations from those that require quantum processing**. This step will focus on exploring how standard quantum and classical optimization techniques such as Adapt-QAOA **[6]** can be integrated. My research will draw from my studies with my mentor Dr. Ji Liu at Argonne where I learned how to design a recursive algorithm designed to efficiently commute the classically simulated operations to the end of our quantum circuits for processing for the QAOA algorithm. I will also draw from a recent work that explores combining classical and quantum circuits for the subset of problems that fall under Variational Quantum algorithms. The paper explores combining a virtual Heisenberg circuit, which acts effectively on the measurement observables, to a Schrodinger circuit, enabling accurate quantum computation of otherwise intractable problems **[7].**

Once the benchmarks for efficiency are established and methods for effectively separating quantum and classical operations are developed, **Phase (3) will focus on how best to integrate previous optimization methods to be used in tandem with the created ansatz** as this will likely result in the best outcome. Following the completion of my work in **Circuit Compilation**, my research will extend as time allows, to **Problem Encoding**, where I will examine how a contextual subspace for Variational Quantum Eigensolvers, which approximates the ground state energy as the sum of contributions from both a classical circuit and a quantum circuit, can be extended to other NISQ algorithms such as QAOA and FTQC algorithms [8], and **Circuit Execution** where in addition to exploring the use of classical optimizers to improve the running of quantum circuits such as those used in Quantum Approximate Optimization Algorithm (QAOA) and Variational Quantum Eigensolver (VQE), I will investigate how field-programmable gate arrays (FPGAs) and tensor networks could be used to reduce the memory footprint and speed up these simulations, making them more efficient for high-qubit systems **[9]. Possible struggles**: I am likely to encounter difficulties when **defining benchmarks** for the Q-C ansatz as determining when exactly the Q-C methods will outperform classical methods alone is challenging due to the ever-advancing capabilities of quantum hardware. I aim to address this by drawing from my experience using Quantum Resource estimates algorithms to define the future markers of success in addition to current capabilities. **Additionally, ensuring scalability of my work will be key to the applicability of the research.** I anticipate the need for further training in classical algorithm development and formal education in quantum hardware to design hardware-sensitive algorithms to properly address such constraints. I have already **begun to learn more about hardware-sensitive algorithms through my research at Argonne** and I am confident that completing a Ph.D. in computer science at an exceptional department will provide me with the additional training I need. Both the Kate Smith group at Northwestern and the Galli group at UChicago, which have collaborated with my mentor Ji Liu over the past year, specialize in Quantum Optimization Algorithms. I look forward to the possibility of joining one of these groups or another similarly outstanding department as a Ph.D. student in Fall 2025.

Intellectual Merit: By necessity, most research in quantum computing today relies heavily on classical simulations due to the limited capabilities of existing quantum hardware. I seek to draw from the current literature and my own research experience integrating classical simulation and quantum processing of QAOA, to leverage classical simulation as a fundamental advantage, pushing the frontier of hybrid algorithms and developing scalable and resource-efficient quantum-classical computations techniques that improve both efficiency and scalability of current works. My work will advance the theory of how quantum and classical systems interact and provide a practical framework that will improve the performance of quantum algorithms across a wide range of applications.

Broader Impacts: Developing quantum-classical algorithms for NISQ and FTQC devices that offload portions of computations to classical systems can significantly extend the capabilities of current quantum hardware, allowing more complex problems to be tackled with fewer qubits and reduced error rates. My research in this field will not only accelerate progress in practical quantum applications but also help pave the way for hybrid computing solutions as the norm, allowing for immediate impact in chemistry simulation, machine learning calculations, and numerical optimization. Vital to the mission of advancing scientific progress is the willingness of diverse minds to collaborate and consider the problem. To this end, I will strive to share my knowledge as much as possible through mentorship of underrepresented groups including first generation and female undergraduates and graduate students, as well as through publications and presentations at quantum computing conferences such as the Institute of Electrical and Electronics Engineers (IEEE), and the Quantum Information Processing (QIP) conference.

References: [1] Cranganore, S. et al. (2024) Paving the way to hybrid quantum-classical workflows. arXiv; **[2]** Sriluckshmy, P. V. et al. (2023). Optimal decomposition of parameterized multi-qubit Pauli gates. Quantum Sci. Technol., 8(4), 045029; **[3]** Cole, B. R. (2021). Commuting compositions for quantum circuit reduction. Theses and Dissertations, 4889; **[4]** Grimsley, H. R. et al. (2019). An adaptive variational algorithm for molecular simulations. Nat Commun, 10, 3007; **[5]** Shang, Z.-X. et al. (2023). Schrödinger-Heisenberg variational quantum algorithms. arXiv:2112.07881; **[6]** Yanakiev, N. et al. (2023). Dynamic-ADAPT-QAOA: An algorithm with shallow and noise-resilient circuits. ArXiv; **[7]** Grimsley, H. R. et al. (2019). An adaptive variational algorithm for molecular simulations. Nat Commun, 10, 3007. **[8]** Kirby, W. M. et al. (2021). Contextual subspace variational quantum eigensolver. Quantum, 5, 456; **[9]** Levental, M. (2021). Tensor networks for simulating quantum circuits on FPGAs. arXiv