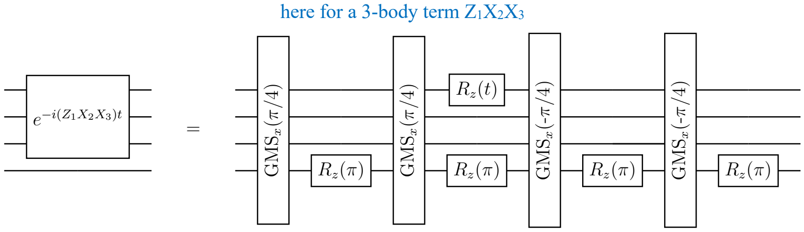
Analog Quantum Hardware: At the core of the proposed research is the quantum simulator in co-PI Richerme's lab. The Richerme experiments will provide a blueprint for developing the next generation of ion-trap analog quantum computers. The existing Richerme apparatus[4] has demonstrated the traditional ion-trap strengths of full control at the single-particle level, site-resolved measurement and readout, and long coherence times. In this system, the quantum bits are represented by the $^2S_{1/2}$ $|F=0,m_F=0\rangle$ and $|F=1,m_F=0\rangle$ hyperfine 'clock' states of $^{171}Yb^+$ ions. These states are well-isolated from sources of decoherence and operate at effectively zero spin temperature; the Richerme lab has observed T_2 coherence times of greater than one second and T_1 coherence times which are effectively infinite. Local rotations of this qubit state may be accomplished by applying microwaves at the hyperfine splitting frequency of 12.6 GHz, or by using a pair of phase-coherent laser beams to drive a stimulated Raman transition at this same frequency. Single- and multi-qubit interactions are programmed using laser light, with typical fidelities of 99.8% and 97% for one- and two-qubit gates, respectively. The current apparatus can trap ions in both one- and two-dimensional lattice arrays, with system sizes up to 30 ions.

In 4-6 years, an upgraded version of this analog quantum computer will be ready to implement advanced models of QM, NP, and CMP using 50-100+ qubits. This machine will serve as a universal quantum platform with local single-qubit rotations and global entangling operations as its hardware primitives. During the design stage, small-scale compiled algorithms for quantum simulations will be run on this device to validate the system design. During this phase, we will work with our industry partner IonQ to engineer upgrades to our analog quantum simulator to prepare it for large-scale use. Two specific hardware improvements will be required. First, we will expand our apparatus to implement targeted qubit addressing, enabling all necessary state preparation and local gates for simulating the model systems described above. This will be accomplished using a far-detuned laser beam to induce local rotations around the z-axis of the Bloch sphere, R_z, by a programmable angle. For instance, using a tightly focused beam, an R_z gate may be implemented by irradiating an ion with only 50 mW of optical power for ~1 microsecond. The second essential hardware upgrade will be the realization of multi-qubit gates to reduce the runtime of our quantum algorithms and improve their fidelity. Using global Molmer-Sorensen (GMS) interactions between qubits, in concert with the locally applied rotations described above, we will be able to emulate the time dynamics of systems evolving under arbitrary *N*-body Hamiltonians. For instance, we may express targeted unitary evolution under the 3-body term $Z_1X_2X_3$ embedded within a larger qubit array using the circuit below (Fig. 1):

Fig. 1. Local rotations and global entangling operations may encode targeted multi-qubit unitary evolutions shown here for a 3-body term $Z_1X_2X_3$



In Fig. 1, and for any *N*-body term, time evolution may be elegantly implemented using only small numbers of GMS gates. Only two GMS gates are required for the simulation of systems where all qubits interact simultaneously. Compared to traditional gate-model approaches which are limited to 2-body interactions, this approach leads to quadratically-smaller circuit depths and avoids additional errors arising from Suzuki-Trotter-type expansions. Such multi-qubit gates are not available on general commercial quantum computing platforms; they require purpose-built hardware and will be a unique feature of our apparatus.

Our quantum simulation hardware will be optimized to study problems arising in the domains of QM, NP, and CMP. Our system does not seek to replicate one-and two-qubit gates as found in the traditional circuit model of quantum computation. Rather, our approach is to implement time-dependent Hamiltonians that give rise to complex phenomena and allow them to evolve in a quantum system where the coherence time

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is long compared to the interaction times. This technique of tailored hardware for analog quantum simulation offers the possibility for higher-fidelity characterizations of physically inspired quantum systems when compared with gate-model approaches.

We will use our analog quantum simulator to implement the time dynamics of quantum systems much more efficiently than digital gate-model approaches. This potential advantage of analog simulators arises from (1) the inherent all-to-all connectivity of the ions, coupled with (2) the ability to drive simultaneous multi-qubit interactions during the simulation as opposed to standard two-qubit gates. Multi-qubit operations are known to greatly reduce the circuit depth of certain quantum algorithms compared to those with only 1- or 2-qubit operations; recent work in the Richerme group showed that incorporating multi-qubit gates into quantum algorithms leads to an exponential reduction in circuit depth for simulating the kinetic energy of quantum wavepackets. For instance, the simulation of a 16-lattice site (4-qubit) chemical dynamics problem would require the application of only 10 multi-qubit interaction pulses in an analog quantum simulator, compared to 200+ in standard two-qubit gates. This analog simulator approach, combined with local qubit addressing, will enable scaling to larger system sizes at higher fidelity than is otherwise possible.