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Title: Programming Oscillators with the Jaynes–Cummings Interaction: From Universal Control to Quantum Chemistry

Abstract: My group builds quantum processors with random-access memory by coupling superconducting circuits to low-loss microwave cavities, realizing multimode cavity-QED systems with cooperativities approaching a billion. Separating processing from memory improves connectivity and reduces control complexity, while the bosonic nature of the cavity modes provides a hardware-efficient route to quantum error correction. I will describe our progress on multimode circuit-QED architectures and control protocols designed to be resilient to many-body and ancilla-induced errors. By harnessing the Josephson nonlinearity of the circuit, we use microwave drives to realize coherent exchange of photons between the circuit and any target cavity mode [1]. We experimentally demonstrate the first use of this tunable Jaynes–Cummings interaction to program *arbitrary* unitary operations on an oscillator, demonstrating a universal qudit gate set [2]. The same programmability makes multimode circuit QED a natural platform for hybrid continuous-variable–discrete-variable quantum simulation: cavity modes efficiently encode vibrational, rotational, and spin degrees of freedom, substantially reducing the overhead compared with qubit-only encodings. I will illustrate this with two directions in chemistry: simulating molecular rovibrational dynamics, and developing bosonic approaches to machine learning and constrained optimization for molecular design.

[1] J. Huang et al., “Fast Sideband Control of a Multimode Cavity Memory with Weak Dispersive Coupling to a Transmon,” *Phys. Rev. X* **16**, 011058 (2026).

[2] J. Huang, E. Kasaba, T. J. DiNapoli, T. Roy, and S. Chakram, “Universal Jaynes–Cummings Control of an Oscillator,” arXiv:2605.18658 (2026).