Kerr quantum learning machine for bosonic modes

Deepesh Singh and G J Milburn*

Centre for Engineered Quantum Systems,

School of Mathematics and Physics, The University of Queensland.

(Dated: May 25, 2024)

Variational quantum circuits in the qubit-gate-circuit architecture have been discussed as routes to quantum machine learning[1]. We suggest a different path to learning that uses Kerr nonlinearities for bosonic modes in an analogue quantum device. Kerr nonlinearities are known to be a route to universal continuous variable (CV) quantum computation and may be able to play this role for quantum machine learning[2].

We describe a variational learning scheme based on using the training data to modulate Kerr non-linearities in a superconducting circuit. Superconducting quantum circuits are highly effective for studying Kerr nonlinear quantum dynamics, exhibiting Kerr effects up to 11 orders of magnitude stronger than in optical materials. This strong nonlinearity, originating from the Josephson effect, can be tuned via external controls. Quantum fields are confined in planar superconducting waveguides and measured using heterodyne detection and Josephson parametric amplifiers. Although direct photon counting at microwave frequencies is difficult, experimental demonstrations, including number-resolving detection, have been successful.

Entangled cat states were first demonstrated in superconducting circuits by Vlastakis et al[3]. The nonlinearity is due to the nonlinear inductance of a SQUID loop and can be tuned by adjusting the flux bias of a DC SQUID. Tunable cross-Kerr interactions can also be implemented. The Wigner function for a single-mode case describes the probability of detecting photons in a displaced state, and displacements are facilitated using beam splitter interactions. By keeping the mean photon number low, the sample size for experiments can be minimized.

The variational part of the scheme uses feedback from the measurement results to control randomly displaced parity operators on each mode (Figure 1). We numerically perform classification and regression tasks using the model specified in Figure 1 to motivate similar experiments on superconducting quantum circuits. The feedback is based on gradient descent in the complex plane of displacements. The cost function is shown to be the Wigner function (scaled) for the encoded states. The appearance of the Wigner function here is natural due to its role in Wigner state tomography. As the decision function must be bounded between ±1, we need the Wigner negativity function and non-classical bosonic states. Given Wigner functions for all classical states are positive, learning in the manner we describe here cannot be achieved without a quantum encoding. Such Wigner negative

---

* g.milburn@uq.edu.au

states can be generated by Kerr non-linearities. We include both spontaneous emission noise and phase diffusion to show the scheme is robust against these imperfections and might in fact perform better in the presence of noise.

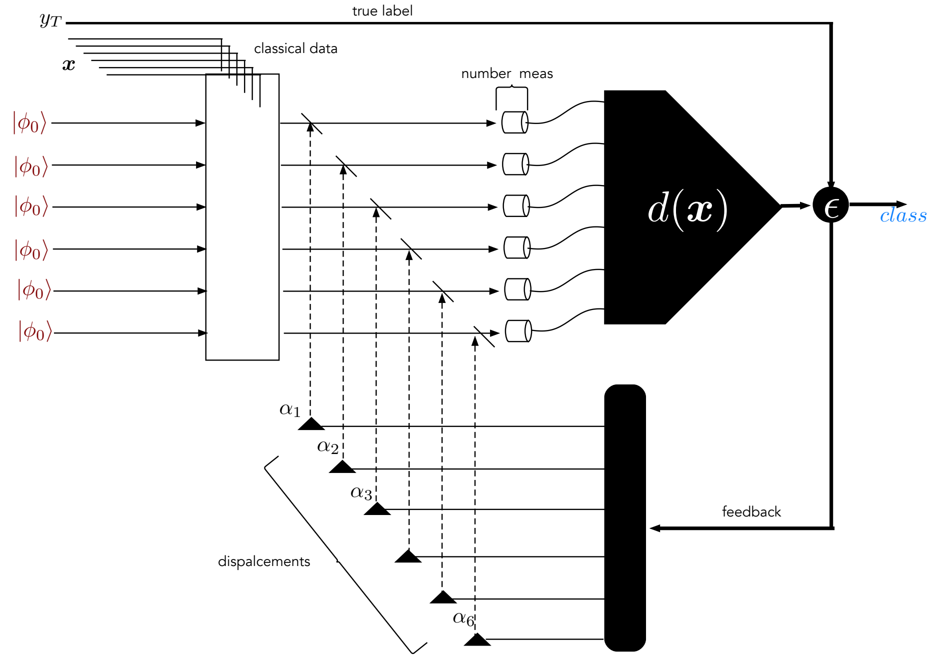

FIG. 1. A schematic representation of a Kerr bosonic quantum learning machine. The encoding is done using many modes interacting via cross-Kerr non-linear coupling. The data modulates the strength of the Kerr nonlinearity. The required displacements are implemented in the feedback loop using almost perfectly transmitting beam splitters. Finally, number-resolving detectors are required to implement the feedback loop.

[1] Kandala, A., Mezzacapo, A., Temme, K., Takita, M., Brink, M., Chow, J.M., Gambetta, J.M., Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets. nature 549(7671), 242–246 (2017)

[2] Alen Senanian, Sridhar Prabhu, Vladimir Kremenetski et al., Microwave signal processing using an analog quantum reservoir computer, arxiv2312.16166 (2023).

[3] Vlastakis, B., Kirchmair, G., Leghtas, Z. et al., Science 342, 607 (2013), https://www.science.org/doi/pdf/10.1126/science.1243289