With great power comes great fidelity

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With great power comes great fidelity

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Many quantum applications require the careful preparation of quantum harmonic oscillators. The combination of a high-power microwave drive and weak nonlinearity enables fast control of such systems, with implications for quantum computing and metrology.

A perfect quantum harmonic oscillator is a desired ingredient in many modern quantum technologies. Here 'perfect' means without nonlinear interactions, which may lead to losses and distortions of the quantum state of the harmonic oscillator. However, many preparation procedures, such as creating squeezed states for quantum sensing or specific qubit encodings for quantum information processing, need some degree of nonlinearity. Therefore, a contradiction arises — to make these states faster than any loss rate of the system, one requires a large nonlinear interaction, which may introduce new imperfections in turn. As they report in *Nature Physics*, Alec Eickbusch and colleagues have now demonstrated that a strong microwave drive enables universal control of a quantum harmonic oscillator with a nonlinearity much smaller than any loss rate in the system[1].

Their experiment employed a three-dimensional superconducting cavity made out of aluminium and operated below 20 mK. The cavity could host microwave photons and acted as a harmonic oscillator initialized in its quantum mechanical ground state. Additionally, by coupling the cavity to a superconducting qubit, Eickbusch and collaborators realized a circuit quantum electrodynamics (QED) platform, which is a very widespread testbed for quantum optics and quantum computing experiments[2].

Traditionally, circuit QED experiments operate in a regime where nonlinear effects dominate over losses in the system. Specifically, it is common to couple a superconducting qubit to a harmonic oscillator via a dispersive interaction, which amounts to a resonance frequency of the cavity that depends on the state of the qubit. If the strength of the dispersive interaction is much larger than the loss rates of the cavity, any quantum state can be generated on demand[3,4].

A strong coupling between a cavity and a qubit, however, often reduces the quality of the cavity. Eickbusch and collaborators dispersively coupled the qubit to the cavity, but with a relatively weak coupling strength when compared with similar set-ups. Critically, the nonlinearity was smaller than the loss rates of the system. Despite this weak coupling, the team demonstrated universal control over the cavity field.

The authors used a computer simulation to optimize a series of strong microwave pulses impinging on the cavity interleaved between precise pulses impinging on the weakly coupled qubit. This sequence of pulses enabled, in principle, the generation of any unitary operators, which are necessary elements for arbitrary state preparation. To demonstrate the power of this method, Eickbusch et al. first prepared quantum states with specific photon numbers and then — approaching

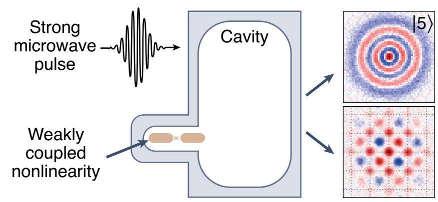

Fig. 1 | Universal control of quantum harmonic oscillator through strong driving. A superconducting 3D cavity weakly coupled to a superconducting qubit. Driving the cavity with a strong microwave pulse enhances the weak nonlinearity inherited from the qubit. This enables the preparation of any desired states of the cavity, such as specific photon number states (top) or Gottesman–Kitaev–Preskill states (bottom), useful for quantum error correction. Plots reproduced from ref. [1], Springer Nature Ltd.

specific applications — squeezed states, binomial code states and Gottesman–Kitaev–Preskill states[5] (Fig. 1).

Squeezed states are quantum states where the quantum fluctuations along one field axis are suppressed below the quantum fluctuation level of vacuum. Reduced fluctuations have advantages in metrology, and squeezed states in superconducting cavities may prove important in the hunt for dark matter[6]. Binomial code states and Gottesman–Kitaev–Preskill states, however, are states that may be critical in the realization of quantum computers[7]. A key aspect in bringing quantum computers to perform calculations beyond the powers of conventional computers is to achieve fault-tolerance, that is, ensuring that errors do not propagate through the system beyond a certain critical rate. The states prepared by Eickbusch and colleagues are designed in a way that, if an error occurs (such as a microwave photon is lost from the cavity) then that error can be detected and corrected, providing a path towards fault-tolerant quantum computing.

For quantum computing applications, a critical next step will be to demonstrate the scalability of the methods presented by Eickbusch et al. to large-scale devices with many cavities. For example, an interesting direction would be to show if similar techniques can successfully create entangled states of multiple cavities, which would provide a multi-cavity universal gate set — a set of quantum gates that can implement all possible logical quantum operations.

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References

1. Eickbusch, A. et al. *Nat. Phys.* https://doi.org/10.1038/s41567-022-01776-9 (2022).
2. Blais, A., Grimsmo, A. L., Girvin, S. M. & Wallraff, A. *Rev. Mod. Phys.* **93**, 025005 (2021).
3. Vlastakis, B. et al. *Science* **342**, 607–610 (2013).
4. Heeres, R. W. et al. *Phys. Rev. Lett.* **115**, 137002 (2015).
5. Gottesman, D., Kitaev, A. & Preskill, J. *Phys. Rev. A* **64**, 012310 (2001).

https://doi.org/10.1038/s41567-022-01749-y

6. Backes, K. M. et al. *Nature* **590**, 238–242 (2021).
7. Joshi, A., Noh, K. & Gao, Y. Y. *Quantum Sci. Technol.* **6**, 033001 (2021).

Competing interests
The author declares no competing interests.