

# Random access quantum information processors

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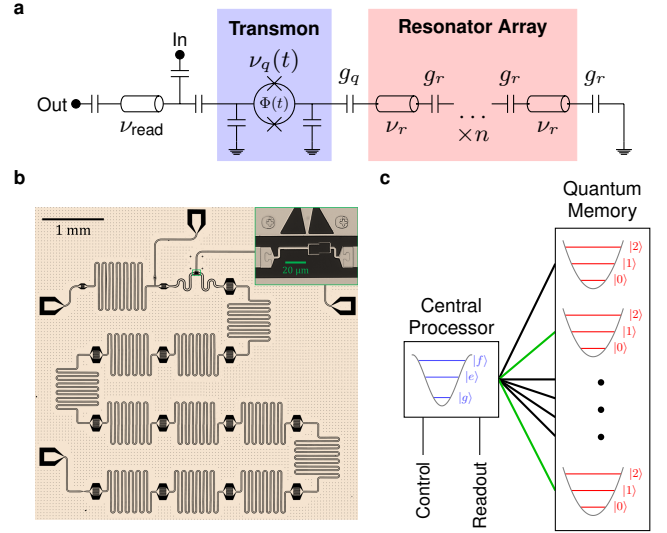
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Qubit connectivity is an important property of a quantum processor, with an ideal processor having random access – the ability of arbitrary qubit pairs to interact directly. Here, we implement a random access superconducting quantum information processor, demonstrating universal operations on a nine-bit quantum memory, with a single transmon serving as the central processor. The quantum memory uses the eigenmodes of a linear array of coupled superconducting resonators. The memory bits are superpositions of vacuum and single-photon states, controlled by a single superconducting transmon coupled to the edge of the array. We selectively stimulate single-photon vacuum Rabi oscillations between the transmon and individual eigenmodes through parametric flux modulation of the transmon frequency, producing sidebands resonant with the modes. Utilizing these oscillations for state transfer, we perform a universal set of single- and two-qubit gates between arbitrary pairs of modes, using only the charge and flux bias of the transmon. Further, we prepare multimode entangled Bell and GHZ states of arbitrary modes. The fast and flexible control, achieved with efficient use of cryogenic resources and control electronics, in a scalable architecture compatible with state-of-the-art quantum memories is promising for quantum computation and simulation.

Superconducting circuit quantum electrodynamics (cQED) is rapidly progressing towards small and medium-scale quantum computation [1]. Superconducting circuits consisting of lattices of Josephson junction qubits [2, 3] have been used to realize quantum information processors relying on nearest-neighbor interactions for entanglement. An outstanding challenge in cQED is the realization of architectures with high qubit connectivity, the advantages of which have been demonstrated in ion trap quantum computers [4–6]. Classical computation architectures typically address this challenge by using a central processor which can randomly access a large memory, with the two elements often comprising distinct physical systems. We implement a quantum analog of this architecture, realizing a random access quantum information processor using cQED.

As in the classical case, quantum logic elements, such as superconducting qubits, are expensive in terms of control resources and have limited coherence times. Quantum memories based on harmonic oscillators, instead, can have coherence times two orders of magnitude longer than the best qubits [7–9], but are incapable of logic operations on their own. This observation suggests supporting each logic-capable processor qubit with many bits of quantum memory. In the near term, this architecture provides a means of controlling tens of bits of highly coherent quantum memory with minimal cryogenic and electronic-control overhead, and is therefore a promising route to achieve quantum supremacy [10]. To build larger systems compatible with existing quantum error



**Figure 1 | Random access superconducting quantum information processor.** **a** and **b**, Schematic and optical image, respectively, of the superconducting microwave circuit. The circuit comprises an array of 11 identically designed, co-planar waveguide (CPW) half-wave resonators, coupled strongly to each other with interdigitated capacitors. The top end of the array is capacitively coupled to a tunable transmon qubit. The transmon is measured with a separate resonator, whose input line doubles as a charge bias for the transmon. The inset shows the tunable SQUID of the transmon, as well as its flux bias above it. **c**, Random access with multiplexed control. The quantum memory consists of the eigenmodes of the array, with each mode accessible to the transmon. This allows for quantum operations between two arbitrary memory modes (such as those highlighted in green) via the central processing transmon and its control lines.

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correction architectures [11–14], one can connect individual modules consisting of a single processor qubit and a number of bits of memory while still accessing each module in parallel.

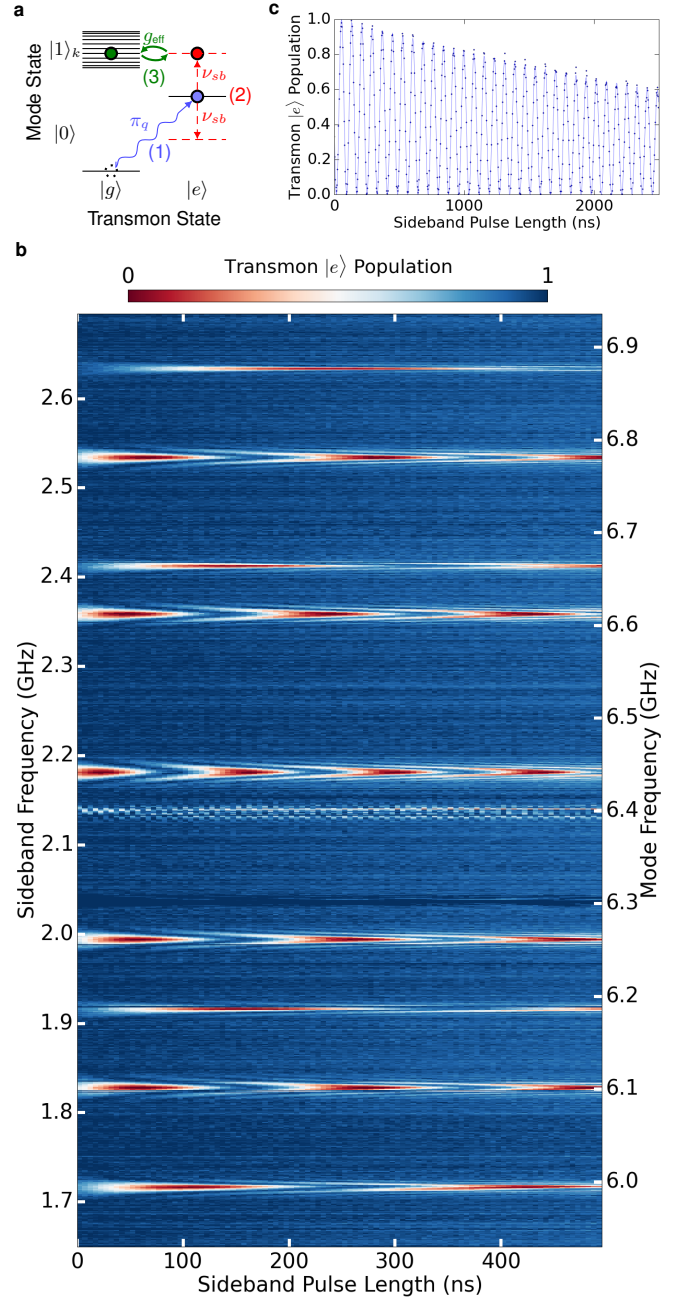
Here, we describe and experimentally demonstrate the use of a single non-linear element to enable universal quantum logic with random access on a collection of harmonic oscillators. We store information in distributed, readily accessible, and spectrally distinct resonator modes. We show how to perform single qubit gates on arbitrary modes by using frequency-selective parametric control [15–20] to exchange information between a superconducting transmon qubit [21] and individual resonator modes. Next, using higher levels of the transmon, we realize controlled-phase (CZ) and controlled-NOT (CX) gates on arbitrary pairs of modes. Therefore, we demonstrate all the ingredients necessary for universal quantum computation with harmonic modes. Finally, we use these tools to prepare multi-mode entangled states as an important step towards quantum error correction.

To build a multimode quantum memory we use the eigenmodes of a linear array of  $n = 11$  identical, strongly coupled superconducting resonators [22] (see Figure 1). For a linear array, the eigenmodes correspond to distributed “momentum” states. Importantly, every mode has non-zero amplitude at the edge, allowing the transmon to couple to each mode. The Hamiltonian of the combined system is:

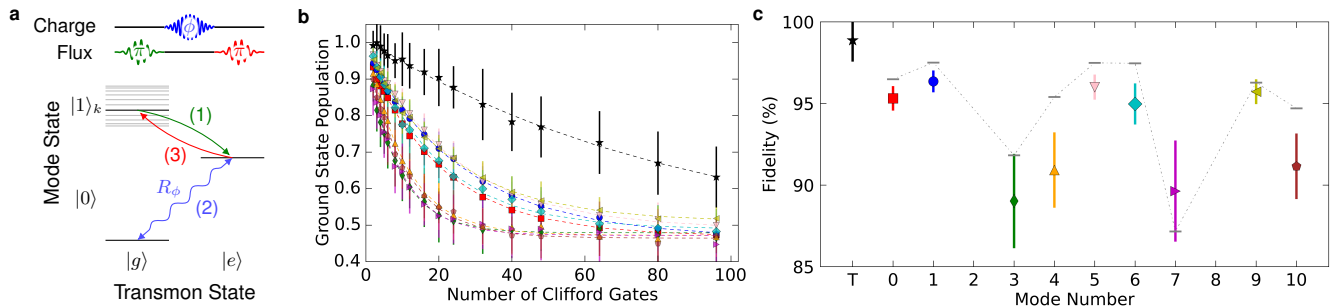
$$\hat{H} = h\nu_q(t)\hat{a}^\dagger\hat{a} + \frac{1}{2}h\alpha\hat{a}^\dagger\hat{a}(\hat{a}^\dagger\hat{a} - 1) + \sum_{k=1}^n h\nu_k\hat{b}_k^\dagger\hat{b}_k + \sum_{k=1}^n hg_k(\hat{b}_k + \hat{b}_k^\dagger)(\hat{a} + \hat{a}^\dagger), \quad (1)$$

where the transmon is treated as a Duffing oscillator [21] with anharmonicity  $\alpha$ , coupled to the modes with frequency  $\nu_k$  (6–7 GHz) and coupling strength  $g_k$  (50–200 MHz). The operators  $\hat{a}^\dagger$  ( $\hat{a}$ ) and  $\hat{b}_k^\dagger$  ( $\hat{b}_k$ ) create (annihilate) photons in the transmon and in eigenmode  $k$ , respectively. While this implementation is straightforward, the idea of a multimode memory also applies to related systems with many harmonic degrees of freedom, including long transmission-line [23] or 3D waveguide cavities. We limit ourselves to the zero- and one-photon Fock states of the eigenmodes. It is also possible to use more of the oscillator Hilbert space, allowing logical encoding in terms of cat [24] and binomial code [25] states.

Given access to the multimode memory via the transmon, we demonstrate methods to address each mode individually. In many circuit QED schemes, excitations are loaded into modes by adiabatically tuning the qubit frequency through or near a mode resonance [27]. This works well for single modes, but for a multimode manifold, one must carefully manage Landau-Zener transitions through several modes [22], to avoid leaving residual excitations elsewhere in the manifold. Also, the qubit must be returned to the far-dispersive regime to minimize



**Figure 2 | Stimulated vacuum Rabi oscillations.** **a**, Generation of stimulated vacuum Rabi oscillations.  $|1\rangle_k$  is the state with a single photon in mode  $k$ ; all other modes are in the ground state. (1) An excitation is loaded into the transmon via its charge bias. (2) The transmon frequency is flux-modulated to create sidebands. (3) When a sideband is resonant with a mode, single-photon vacuum Rabi oscillations occur between transmon and the mode. **b**, Experimental results obtained from this protocol for a range of sideband modulation frequencies, with the transmon biased at  $\nu_q = 4.28$  GHz. The length of the flux modulation pulse is swept for each frequency and the excited state population of the transmon is measured after the pulse ends. Chevron patterns indicate parametrically induced resonant oscillations with each of the memory modes. The distribution of the modes can be understood through Hamiltonian tomography [26] (Supplementary Information). **c**, Resonant oscillations between transmon and mode 6.



**Figure 3 | Single-mode gate protocol and benchmarking.** **a**, The sequence for generating arbitrary single-qubit gates of a memory mode: (1) The mode’s initial state, consisting of a superposition of 0 and 1 photon Fock states, is swapped to the transmon (initially in its ground state), using a transmon-mode iSWAP (see text). (2) The transmon is rotated by the desired amount ( $R_\phi$ ) via its charge control line. (3) The rotated state is swapped back to the mode, by reversing the iSWAP gate in (1). Segments of this sequence are used to achieve state preparation [steps (2) and (3)] and measurement [steps (1) and (2)] of each mode. **b**, Single-mode randomized benchmarking. We apply sequences of varying numbers of consecutive Clifford gates, then invert each sequence with a unique Clifford gate. We measure the transmon ground-state population after inversion and average over 32 different random sequences. **c**, From fitting the resulting data, we find single-mode gate fidelities from  $89.0 \pm 2.9\%$  to  $96.3 \pm 0.7\%$  and a transmon (T in the figure) gate fidelity of  $98.9 \pm 1.3\%$ . These are consistent with the expected coherence-limited fidelities, plotted as gray bars.

spurious unwanted interactions, requiring longer gate durations.

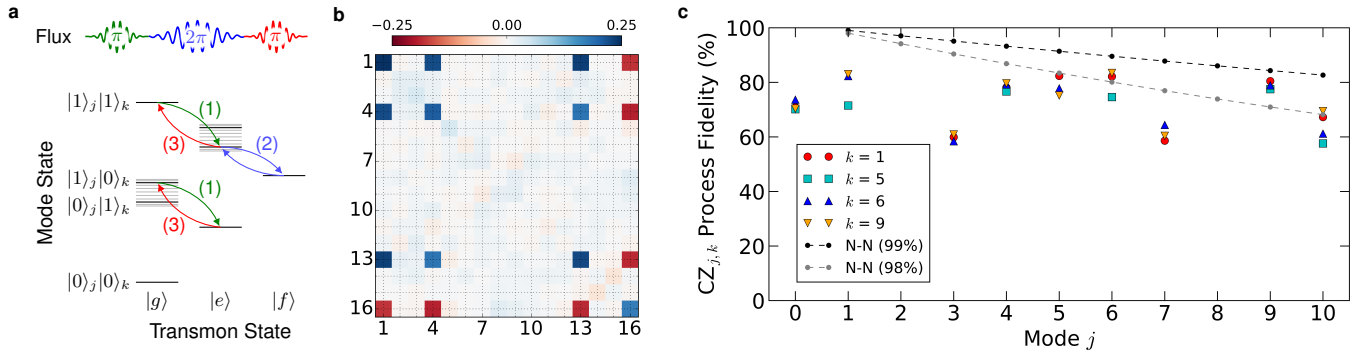
Instead, we induce resonant interactions between the transmon and an individual mode by modulating the transmon excitation energy via its flux bias. The modulation creates sidebands of the transmon excited state, detuned from the original resonance by the frequency of the applied flux tone. When one of these sidebands is resonant with a mode of the memory, the system experiences *stimulated vacuum Rabi oscillations*: parametrically induced exchange of a single photon between the transmon and the selected mode. These are similar to resonant vacuum Rabi oscillations [28], but occur at a rate that is controlled by the modulation amplitude [15, 16]  $g_{\text{eff},k} = g_k J_1(\epsilon/2\nu_{sb})$ , where  $J_1$  is the first Bessel function,  $\epsilon$  and  $\nu_{sb}$  are the amplitude and frequency of the modulation, respectively, and  $g_k$  is the bare coupling rate to eigenmode  $k$ . The rate of photon exchange is linear to lowest order in  $\epsilon$  and can be as large as  $g_k/2$ .

To illustrate the application of parametric control for addressing the multimode memory, we employ the experimental sequence shown in Figure 2a. First, the transmon is excited via its charge bias. Subsequently, we modulate the flux to create sidebands of the transmon excited state at the modulation frequency. This is repeated for different flux pulse durations and frequencies, with the population of the transmon excited state measured at the end of each sequence. When the frequency matches the detuning between the transmon and a given eigenmode, we observe full-contrast stimulated vacuum Rabi oscillations. In Figure 2b, we see the resulting characteristic chevron patterns [16] as the modulation frequency approaches the detuning between the transmon and each of the modes. For long modulation times, the excited state population approaches zero. This is evident in the stimulated vacuum Rabi oscillation between the trans-

mon and mode 6 shown in Figure 2c. This indicates that the original photon is being exchanged between the transmon and the mode and no other photons are being pumped into the system. We achieve photon exchange between the transmon and individual modes in 20-100 ns, depending on the mode. This rate is limited by spectral crowding arising from neighboring modes and sideband transitions involving the transmon  $|f\rangle$  level. This operation is coherent and can be used to transfer arbitrary qubit states between the transmon and the memory mode, corresponding to a transmon-mode iSWAP [29] in the single-excitation subspace.

The transmon-mode iSWAP and arbitrary rotations of the transmon state via its charge bias provide a toolbox for universal state preparation, manipulation, and measurement of each mode of the quantum memory. In Figure 3, we illustrate how to perform these operations. To characterize the quality of our single-mode operations, we perform randomized benchmarking (RB) [30, 31]. We generate single-mode Clifford operations by sandwiching single-qubit Clifford rotations of the transmon with transmon-mode iSWAPs. We achieve RB fidelities ranging from  $89.0 \pm 2.9\%$  to  $96.3 \pm 0.7\%$ . These fidelities approach the expected coherence limit, indicated by the gray bars in the figure. The coherence limits are estimated based on the qubit RB fidelity, the iSWAP times (20-100 ns) and the coherence times ( $T_1 = 1 - 5 \mu\text{s}$ ,  $T_2^* = 1 - 8.5 \mu\text{s}$ ) of individual modes (Supplementary Information). Each single-mode gate consists of two transmon-mode iSWAPs, and a single transmon gate. From the error in the single-mode and transmon RB, we estimate the fidelities of the individual transmon-mode iSWAP operations to range from 95 to 98.6%.

To achieve universal control of the quantum memory, we extend our parametric protocols to realize two-mode gates. We perform conditional operations between the



**Figure 4 | Controlled-phase gate between two arbitrary modes.** **a**, Protocol for controlled-phase (CZ) gate between an arbitrary pair of modes, with  $j$  indicating the control mode and  $k$  indicating the target mode of the gate: (1) The state of mode  $k$  is swapped to the transmon via a transmon-mode iSWAP pulse at the frequency difference between the transmon  $|g\rangle$ - $|e\rangle$  transition and mode  $k$ . (2) A CZ gate is performed between mode  $j$  and the transmon, by applying two frequency-selective iSWAPs from energy level  $|e1\rangle$  to level  $|f0\rangle$  and back, mapping the state  $|e1\rangle$  to  $-|e1\rangle$ . (3) The state of the transmon is swapped back to mode  $k$ , reversing the iSWAP in (1). **b**, Process matrix for the CZ gate between modes  $j = 6$  and  $k = 9$ , corresponding to a process fidelity of 82% (see Supplementary Information for details on state preparation and measurement.) **c**, Fidelities from process tomography for 38 pairs of memory modes with  $k = 1, 5, 6, 9$ . The process fidelities are extracted from sequences that include SPAM errors, and are conservative estimates of the gate fidelities. For comparison, the dashed black and gray lines show the decay in fidelity for a two-qubit gate between qubit 0 and qubit  $j$  in a corresponding linear array comprising only nearest-neighbor gates with fidelities of 99 and 98%, respectively.

transmon and individual modes by utilizing the  $|e\rangle$ - $|f\rangle$  transition of the transmon. A controlled-phase (CZ) gate between the transmon and an individual mode consists of two sideband iSWAPs resonant to the  $|e1\rangle$ - $|f0\rangle$  transition, selectively mapping the state  $|e1\rangle$  to  $-|e1\rangle$ , leaving all other states unchanged due to the anharmonicity of the transmon. To enact a CZ gate between two arbitrary modes, the control mode is swapped into the transmon, a transmon-mode CZ is performed, and the mode is swapped back as illustrated in Figure 4a. In our device, gate speeds (250-400 ns) are primarily limited by crosstalk between iSWAP operations on the  $|g\rangle$ - $|e\rangle$  and  $|e\rangle$ - $|f\rangle$  transitions of modes with difference frequencies approaching the anharmonicity of the transmon. This crosstalk can be reduced by tailoring the frequency spacing of the memory modes and the anharmonicity of the transmon. In addition to the CZ gate, we obtain controlled-X and Y gates (CX, CY) between modes by swapping  $|e\rangle$  and  $|f\rangle$  transmon state populations in the middle of the pulse sequence for the CZ gate. These gate protocols can be extended to realize two-mode SWAP gates (Supplementary Information), as well as multi-qubit gates such as Toffoli and controlled-controlled-phase (CCZ) gates [32] between arbitrary modes.

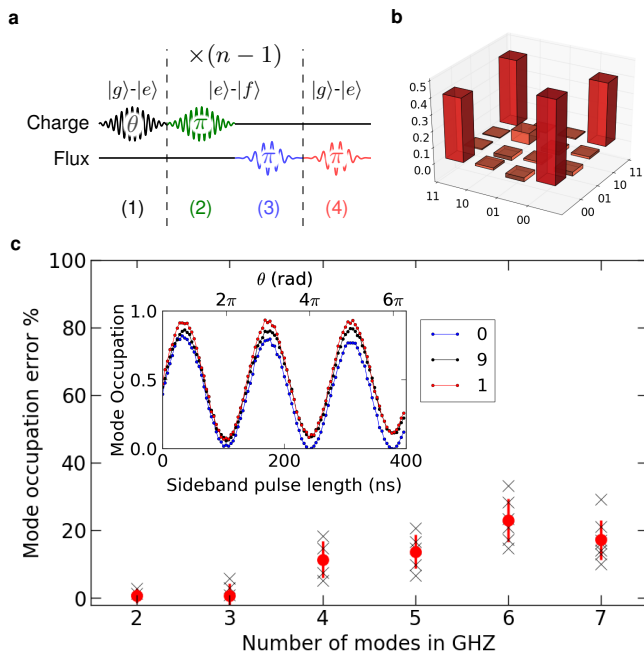
To perform high-fidelity gates between modes, several issues must be considered. These include: (1) DC shifts of the transmon frequency during iSWAP pulses ( $\sim 10$  MHz), (2) dispersive shift of the  $|e1\rangle$  state ( $\sim 1$  MHz), and (3) stimulated dispersive shifts of non-targeted modes during iSWAP pulses ( $\sim 10 - 100$  kHz). We fully compensate effect (1) and correct the phase error arising from (2) by calibrating the phase errors and suitably adjusting the relative phases of the iSWAP pulses

(Supplementary Information). The error from (3) is relatively small and currently adds to the gate error.

Our multimode architecture allows for straightforward measurements of arbitrary multi-bit correlators, forming a basis for tomography, and for the stabilizer measurements required for error correction. An arbitrary correlator comprises products of Pauli operators applied to each of the memory bits, and corresponds to a generalized parity measurement. This is exactly the back-action on the phase measurement of a transmon while serving as the control of a CZ (CX) gate targeting a memory mode [33]. The value of an arbitrary stabilizer can thus be measured by performing Ramsey interferometry of the transmon with a series of CZ (CX) gates applied to the desired memory modes.

We use correlator measurements to characterize a CZ gate between a given pair of modes via process tomography. We perform process tomography by applying the gate on 16 linearly independent input states that form a basis for an arbitrary two-qubit density matrix [34]. The resulting density matrices are reconstructed through state tomography. For two-qubit state tomography, we map all correlators to individual measurements of the transmon, using combinations of single- and two-mode gates.

In order to obtain a fair estimate of the gate fidelity, each of the process tomography sequences has a single two-mode gate. Additional gates required for tomography are combined with the characterized CZ gate (Supplementary Information). The process matrix obtained using this protocol for a CZ gate between modes 6 and 9 is shown in Figure 4b. We use this protocol to characterize the fidelities for gates between 38 mode pairs, as shown in Figure 4c. The fidelities from full process



**Figure 5 | Multimode Entanglement.** **a**, Pulse sequence for generating  $n$ -mode maximally-entangled states. Step (1) creates a superposition of the transmon  $|g\rangle$  and  $|e\rangle$  states, with the relative amplitudes of the superposition controlled by the rotation angle  $\theta$ . Steps (2) and (3) load photons into modes of the memory, conditioned on the transmon state by utilizing the transmon  $|f\rangle$  state. These steps are repeated  $n - 1$  times to entangle additional modes. Step (4) performs a  $|g\rangle\text{-}|e\rangle$  iSWAP to the last mode, disentangling the transmon from the modes. **b**, The real part of the density matrix of the  $|\Phi^+\rangle$  Bell state of mode 6 and 9, obtained from tomography. **c**, (inset) Correlated oscillations resulting from sweeping  $\theta$  and measuring each mode individually. This demonstrates control of the relative amplitudes of the entangled state superposition. **c**, Deviation from expected mean populations of each of the modes, upon preparation of the GHZ state ( $\theta = \pi/2$ ). The red filled circles indicate the average over individual mode measurements (black crosses).

tomography range approximately from 60 – 80% for the CZ gates between the mode pairs indicated. These fidelities incorporate state preparation and measurement (SPAM) errors, with the SPAM sequences being of similar duration as the gates. Conservative estimates from single-mode and transmon RB (see Figure 3c) give SPAM errors of 5 – 10%, depending on the modes addressed. The gate fidelities are largely limited by the coherence times of the modes ( $\sim 5 - 15\%$  error). Future devices based on 3D superconducting cavities [7] may have up to three orders of magnitude enhancement in memory mode coherence times. The process fidelities are additionally limited by dephasing of the transmon ( $\sim 5\%$  error), and residual coherent errors arising from bare and stimulated dispersive shifts. Many of these errors can be reduced or eliminated by coupling a flux-insensitive transmon to the multimode memory using a tunable coupler [18, 35].

Figure 4c highlights the advantages of random access in a quantum computing architecture. An entangling gate between the first and the  $j$ th qubit of an array with only nearest-neighbor coupling would require  $2j - 3$  gates (such as CXs or iSWAPs). This results in an exponential decay of the fidelity with increasing distance between the corresponding qubits, even with high-fidelity gates. Conversely, in a random access quantum information processor, there is no additional computational cost to perform gates between arbitrary pairs of qubits. Even without considering potential improvements in the coherence times, we see (Figure 4c) that the processor performs competitively for gates between what would otherwise be distant qubits in a nearest-neighbor architecture.

We use universal control of the quantum memory to build maximally entangled states spanning several modes, using the protocol described in Figure 5a. First, we create a superposition of the transmon ground and excited states. Next, we add a photon to the desired mode, conditioned on the transmon state. This is repeated for each mode in the entangled state. Finally, we disentangle the transmon from the memory modes, transferring the remaining population into the final mode. In Figure 5b, we show full state tomography for a Bell state [36] with state fidelity  $F = 0.75$ . In the inset of Figure 5c, we apply the protocol to three modes and show populations of each of the modes as a function of the initial qubit rotation angle,  $\theta$ . Finally, in Figure 5c, we show the population error from the target state at  $\theta = \pi/2$ , corresponding to a photonic Greenberger-Horne-Zeilinger (GHZ) state [37] of up to seven modes. These experiments demonstrate access to the full computational subspace of the quantum memory and illustrate generation of states useful for quantum optics and sensing [38]. Variants of this sequence can be used to create other classes of multimode entangled states, including W states, Dicke states [39] and cluster states [40], that are valuable resources in several quantum error correction schemes.

With minimal control-hardware overhead, we perform universal quantum operations between arbitrary modes of a nine-bit quantum memory using a single transmon as the central processor. The methods described in this work extend beyond this particular implementation of a multimode memory and in particular are compatible with the use of 3D superconducting cavities, which are naturally multimodal and have demonstrated the longest coherence times currently available in cQED [7], with the potential for even further improvements [41]. This architecture is compatible with the error-correcting codes that use higher Fock states of a single oscillator, such as the cat [9, 42] and binomial [25] codes, as well as distributed qubit codes [43, 44], and is ideally suited to explore the potentially rich space of multi-qudit error-correcting codes that lie in between the two regimes [45, 46]. This makes cQED-based random access quantum information processors a promising new module for quantum computation and simulation.

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## AUTHOR CONTRIBUTIONS

N.L., R.K.N., and S.C designed the device. R.K.N and N.L fabricated the device. S.C., R.K.N., and N.L. designed the experimental protocols, performed the experiments, and analyzed the data. P.G. and J.K. provided theoretical support. Y.L. and N.E. provided fabrication and experimental support. R.K.N., D.C.M., N.L., S.C., and D.I.S. conceived the experiment and all authors co-wrote the paper.

## COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.

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