Quantum teleportation [11] is an exquisite example of the power of quantum information transfer. Teleportation has been demonstrated in many experimental quantum information processing platforms [16–21], and it is an essential tool for quantum error correction [22], measurement-based quantum computing [23], and quantum gate teleportation [14]. However, quantum teleportation has not previously been demonstrated in quantum-dot spin qubits. In this work, we present a quantum teleportation protocol for semiconductor quantum dot spin qubits. We implement this method in a four-qubit processor by conditionally teleporting single-spin eigenstates and entangled spin states between distant electrons, and we demonstrate conditional gate teleportation.

Separating entangled pairs of spins to remote locations, as required for quantum teleportation, has previously presented the main challenge to teleportation in quantum dots. Here, we overcome this challenge using a recently demonstrated technique to distribute entangled spin states via Heisenberg exchange [12]. This technique does not involve the motion of electrons, greatly simplifying the teleportation procedure. Our teleportation method also leverages Pauli spin blockade, a unique feature of electrons in quantum dots, to generate and measure entangled pairs of spins. We combine these concepts in a protocol that enables conditional teleportation, entanglement-swapping, and gate teleportation. We implement this technique in a four-qubit quantum processor, which consists of a quadruple quantum dot fabricated in a GaAs/AlGaAs heterostructure [Fig. 1(a)].

Because the ground state wavefunction of two electrons has the spin-singlet configuration, initialization of two spins in a single quantum dot automatically generates an entangled pair of spins [24, 25]. Furthermore, spin-to-charge conversion via Pauli spin blockade [24, 26] enables rapid single-shot measurement of pairs of electron spins in the $\{|S\rangle, |T\rangle\}$ basis, where $|T\rangle$ is any one of the triplet states $\frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle), |\downarrow\downarrow\rangle$. We therefore configure the quadruple quantum dot as two pairs of spins to

FIG. 1. Experimental setup. (a) Scanning electron micrograph of the quadruple quantum dot. The positions of the electron-spin qubits are overlaid. The scale bar is 200 nm. (b) Physical implementation of the teleportation protocol. Dots 3 and 4 are initialized in the singlet configuration via electron exchange with the reservoirs and then separated via tunneling. We implement the SWAP gate as a positive voltage pulse to the barrier gate between dots 2 and 3. Pairs of qubits are measured in the singlet/triplet basis via Pauli spin blockade. (c) Circuit diagram for the conditional quantum teleportation protocol. $|\psi\rangle$ represents the four-qubit wavefunction.
facilitate teleportation. Spins 1 and 2 form the left pair, and spins 3 and 4 form the right pair.

Quantum teleportation also requires the ability to transmit at least one member of an Einstein-Podolsky-Rosen (EPR) pair to a distant location. We achieve this through coherent spin-state transfer based on Heisenberg exchange [12]. To transfer a spin state from one electron to another, we induce exchange coupling between electrons by applying a voltage pulse to the barrier gate between them [Fig. 1(b)] 27 28. Because exchange coupling generates a SWAP operation, this procedure interchanges the two states. This procedure can be repeated for different pairs of spins to enable long-distance spin-state transfer. Importantly, exchange-based spin swaps preserve entangled states [12].

Figure 1(c) shows the quantum circuit for our procedure, which can conditionally teleport an arbitrary state $|\psi\rangle$ from dot 1 to dot 4. We prepare qubit 2 in the $|\uparrow\rangle$ state, and it is used later for readout, as discussed further below. We generate the EPR pair between qubits 3 and 4 by loading two electrons into the right-most dot via electrical exchange with reservoirs. We then separate the two electrons via tunneling. After a SWAP gate on qubits 2 and 3, the EPR pair resides in qubits 2 and 4. To teleport $|\psi\rangle$ from qubit 1 to qubit 4, we project the left pair of qubits onto the $\{S,T\}$ basis via diabatic charge transfer into the outer dots [12] [Fig. 1(b)]. Our measurements in the $\{S,T\}$ basis can only distinguish $|S\rangle = |\Psi^-\rangle$ from the other Bell states $|\Psi^+\rangle$, $|\Phi^+\rangle$, or $|\Phi^-\rangle$, which are linear combinations of the triplet states. In this case, therefore, successful teleportation requires obtaining a singlet in the left pair. To verify teleportation, we also project the right pair, using either diabatic or adiabatic charge transfer (see Methods).

The utility of quantum teleportation lies in its ability to transmit unknown quantum states. Usually, teleportation of unknown states is experimentally demonstrated by verifying teleportation of a complete set of single-qubit basis states [10] or through process tomography [19]. Because our four-qubit device does not incorporate a micromagnet or antenna for magnetic resonance, we are not able to prepare superposition states of single spins. Therefore, to illustrate the operation of the teleportation procedure, we first teleport a classical spin state from qubit 1 to qubit 4. Later, we demonstrate entanglement swapping in our four-qubit processor, which conclusively demonstrates non-local manipulation of quantum states via measurements.

To demonstrate the basic operation of our teleportation method using $|\phi\rangle = |\uparrow\rangle$, we prepare qubits 3 and 4 in a spin singlet [Fig. 2(a)]. Qubits 1 and 2 are prepared in the $|\psi\rangle_{12} = |\psi\rangle_1 |\psi\rangle_2 = |\uparrow\rangle_1 |\downarrow\rangle_2$ state by electrical exchange with the reservoirs (see Methods). After the SWAP operation, if the left pair projects onto $|S_{12}\rangle$, qubit 4 should be identically $|\uparrow\rangle$ [11]. Because qubit 3 has the $|\uparrow\rangle$ state (a result of the earlier SWAP operation), the right pair should be in the $|\psi_{34}\rangle = |\psi\rangle_3 |\phi\rangle_4 = |\uparrow\rangle_3 |\downarrow\rangle_4$ state, and measuring a singlet on the left pair should perfectly correlate with measuring a triplet on the right pair. Figure 2(b) displays a joint histogram of 65,536 single-shot measurements on both pairs of qubits for the teleportation operation discussed above. Figure 2(c) shows the extracted probabilities for the different outcomes. Our measurements closely match the predicted probabilities, as shown in Fig. 2(d) (see Methods). Figure 2(e) shows a prediction including known sources of experimental error, including readout fidelity, relaxation during readout, state preparation error, charge noise, and hyperfine fields, and this prediction matches the observed data closely. We discuss these errors further below.

To verify conditional teleportation of the classical state, we perform an exchange gate on qubits 3 and 4 following the teleport [Fig. 3(a)]. In the case of successful teleportation, qubits 3 and 4 should have the $|\psi_{34}\rangle = |\uparrow\rangle_3 |\uparrow\rangle_4$ state, and the exchange gate should have no effect. Indeed, after measuring a singlet on the left pair, we observe no exchange oscillations on the right pair, but after measuring a triplet on the left pair,
of quantum information using measurements [Fig. 4(a)]. Entanglement swapping \([19]\) uses teleportation to generate entanglement between pairs of qubits that never directly interact. In this case, we prepare the EPR state between qubits 1 and 2 via a \(\sqrt{\text{SWAP}}\) gate, starting from the \(\ket{|\uparrow\rangle_1 |\uparrow\rangle_2}\) state. This process generates the entangled state \(\frac{1}{\sqrt{2}} (|S_{12}\rangle - i |T_{0,12}\rangle)\), where \(|T_0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle + |\downarrow\rangle)\). At the same time, we prepare a separated singlet between qubits 3 and 4. Before teleportation, we evolve the separated singlet in its local hyperfine gradient \(\Delta B_{34}\) for a variable time \(t\). This evolution generates an effective \(z\)-rotation on qubit 4 relative to qubit 3 by an angle \(g \mu_B \Delta B_{34} t / \hbar\), where \(g\) is the electron \(g\) factor in GaAs, \(\mu_B\) is the Bohr magneton. The \(z\)-rotation on qubit 4 generates coherent evolution between the singlet and unpolarized triplet states of qubits 3 and 4 [24, 25]. During this evolution time, qubits 3 and 4 remain maximally entangled.

After a \(\sqrt{\text{SWAP}}\) gate between qubits 2 and 3, qubits 1 and 3 are entangled, and qubits 2 and 4 are entangled. After projection to a singlet on the right side, entanglements have been swapped, because the entangled state of qubit 4 is teleported to qubit 1. Qubits 1 and 2, which were not entangled immediately before the measurement, become entangled, provided qubits 3 and 4 project onto the singlet state. Moreover, the coherent singlet-triplet evolution that occurred on qubits 3 and 4 should appear on qubits 1 and 2, given a singlet outcome on the right pair. To verify entanglement swapping, we measure the left pair of qubits by adiabatic charge transfer [24, 25] (see Methods) following another \(\sqrt{\text{SWAP}}\) gate. In the case of successful entanglement swapping, the final \(\sqrt{\text{SWAP}}\) gate preserves the coherence of the teleported state against the effects of hyperfine fluctuations during readout.

To observe the anticipated oscillations, we sweep \(t\), which controls the \(z\) rotation on qubit 4, from 1 to 128 ns, in steps of 1 ns. For each time interval, we implement the quantum circuit shown in Fig. 4(a) and record a single-shot measurement of both pairs of qubits, and we average this set of measurements 256 times. Figure 4(b) shows the average of one such set of measurements. No oscillations are visible in the the unconditioned singlet probability of the left pair \(p(S_L)\). However, prominent oscillations are visible in the probability of a singlet on the left given a singlet on the right \(p(S_L|S_R)\) and also in \(p(S_L|T_R)\), in good agreement with our simulations [Fig. 4(b)]. These oscillations demonstrate conditional entanglement swapping.

Because the nuclear hyperfine fields fluctuate in time, we repeat this set of measurements 256 times, and the entire data set is shown in Extended Data Fig. 3. In between each set, we also perform additional measurements to determine the hyperfine gradients between dots 1 and 2 (\(\Delta B_{12}\)) and dots 3 and 4 (\(\Delta B_{34}\)) (Extended Data Fig. 3). In total, each repetition takes about one sec-
entanglement swapping using our four-qubit processor consisting of qubits 3 and 4. The oscillations appear on the left side of the EPR pair before teleportation, appears on qubit 4 after teleportation. The initial entangled state of qubits 1 and 2 is \( |\psi_{12}\rangle = \frac{1}{\sqrt{2}} (|S_{12}\rangle - i |T_{12}\rangle) \). Following the SWAP and conditional teleportation of qubit 1 to qubit 4, qubits 3 and 4 have the state \( |\psi_{34}\rangle = (\mathbb{1} \otimes U \cdot R_{z}(\pi/2)) |\psi_{12}\rangle \), and \( U \) has been applied to qubit 4. The added z rotation on qubit 4 occurs because of the additional SWAP and measurement via adiabatic charge transfer on the left side [Fig. 4(d)].

We measure the right pair of qubits in the via diabatic charge transfer to verify teleportation [Fig. 4(e)]. The unconditioned data show very weak oscillations, likely due to independent nuclear hyperfine gradients. (d) Circuit diagram for conditional gate teleportation. (e) \( p(S_R) \) shows only weak oscillations, but \( p(S_L|S_R) \) and \( p(S_R|T_L) \) show prominent singlet-triplet oscillations. Simulated predictions are shown in same color. (f) Comparison of the extracted oscillation frequency vs repetition number measured on qubits 1 and 2.

For each repetition, we extract the oscillation frequency by taking a fast Fourier transform of the data (see Methods and Extended Data Fig. 3). Figure 4(c) shows the extracted oscillation frequency that appears on qubits 1 and 2 after entanglement swapping in addition to the frequencies corresponding to \( \Delta B_{34} \) and \( \Delta B_{12} \), which were measured concurrently with the teleportation. The observed oscillation frequency measured on qubits 1 and 2 clearly matches the measured hyperfine gradient \( \Delta B_{34} \). Because \( \Delta B_{12} \) and \( \Delta B_{34} \) result from independent nuclear spin ensembles, they evolve differently in time. We note the good agreement between the time evolution of the oscillation frequency after entanglement swapping and the gradient \( \Delta B_{34} \).

The appearance of singlet-triplet oscillations on the left pair of qubits is direct evidence of entanglement swapping. The observed oscillations on qubits 1 and 2 originate entirely from the coherent evolution between entangled states of qubits 3 and 4. The oscillations appear on qubits 1 and 2 because of the SWAP gate and Bell-state measurement. This demonstration of entanglement swapping using our four-qubit processor confirms that we can perform non-local coherent manipulation of quantum information by quantum measurements. We also note that the combination of a unitary SWAP and Bell-state measurement demonstrates a non-local measurement-assisted procedure for transmitting states of encoded qubits, which may be useful for fault-tolerant quantum computing. Specifically, we have transferred a qubit state encoded in a decoherence-free subspace spanned by the singlet and unpolarized triplet states of qubits 3 and 4 to qubits 1 and 2.

A similar circuit [Fig. 4(d)] also implements a simple example of conditional quantum gate teleportation [14], provided that we post-select on the left-side measurements, instead of the right side. In this case, the EPR pair initially consists of qubits 3 and 4, and we teleport qubit 1 to qubit 4. A unitary gate \( U \) (the same \( z \)-rotation discussed above), which is applied to one member of the EPR pair before teleportation, appears on qubit 4 after teleportation. The initial entangled state of qubits 1 and 2 is \( |\psi_{12}\rangle = \frac{1}{\sqrt{2}} (|S_{12}\rangle - i |T_{12}\rangle) \). Following the SWAP and conditional teleportation of qubit 1 to qubit 4, qubits 3 and 4 have the state \( |\psi_{34}\rangle = (\mathbb{1} \otimes U \cdot R_{z}(\pi/2)) |\psi_{12}\rangle \), and \( U \) has been applied to qubit 4. The added \( z \) rotation on qubit 4 occurs because of the additional SWAP and measurement via adiabatic charge transfer on the left side [Fig. 4(d)].

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to an imperfect SWAP gate [12]. Post-selecting based on singlet outcomes on the left side yields prominent oscillations in time, consistent with our simulations. The extracted oscillation frequency versus repetition number agrees well with the data from Fig. 4(c), as shown in Fig. 4(f).

The fidelity of the teleport operation is limited by readout fidelity, relaxation during readout, state preparation, charge noise, and the hyperfine coupling between the electron spins and Ga and As nuclear spins in the substrate. Readout fidelity and relaxation both limit the probability that we will correctly measure the Bell state of one of the EPR pair and the qubit to be teleported. Readout fidelities due to noise are 0.99 for the left pair and 0.98 for the right pair (Extended Data Fig. 3), and losses due to relaxation are 0.06 for the left pair and 0.11 for the right pair (Extended Data Fig. 1) (see Methods). State preparation of the EPR pair also affects the teleport operation. We estimate the probability that we correctly prepare the singlet state in dots 3-4 is 0.89, based on our experimental characterization of the loading process [Extended Data Fig. 5(b)]. Charge noise causes dephasing of the SWAP operation, and the nuclear hyperfine field limits the fidelity of the SWAP operation that we use to transmit the entangled pair of electrons [12]. The simulations shown in Fig. 2, Fig. 4, and Extended Data Fig. 2 include all of these effects, in addition to the classical-state initialization error (see Methods) where appropriate.

To assess the fidelity of the teleport operation itself for classical states, we simulated the circuit shown in Fig. 2(a), assuming perfect state preparation of the left pair, but including all other sources of error. Based on our simulations, we expect that the spin in dot 4 will be in the $|\uparrow\rangle$ state after the teleport with a probability of about 0.9, given a singlet on the left pair. In the presence of realistic hyperfine gradients (tens of MHz) and exchange strengths (several hundred MHz), we estimate that readout errors contribute the majority of the error.

Assuming perfect state preparation of a separated singlet state, our simulations suggest that the fidelity of the entanglement swap [Fig. 1(a)] on a singlet state can be about 0.7, provided that the state is allowed to evolve in the presence of a quasi-static magnetic gradient to undo the coherent singlet-triplet evolution incurred during the SWAP operation in the presence of a gradient [12]. In this case, readout errors, state preparation errors, and errors in SWAP gate due to the magnetic gradient all contribute to the overall error.

This teleportation protocol will work best with small magnetic gradients, as can be achieved with silicon qubits. In large gradients, resonant approaches [5, 29] or dynamically corrected gates [8] can still generate high-fidelity SWAP operations. State preparation errors can be suppressed by improving the coupling between the quantum dots and the reservoirs, and readout errors can be minimized by optimizing the position of the sensor quantum dots.

As mentioned above, the conditional quantum teleportation protocol we have developed is compatible with arbitrary qubit states. Deterministic quantum teleportation of arbitrary quantum states can also be realized with measurements of each qubit in the computational basis, together with CNOT [3, 10] and single-qubit gates [7], which will enable complete measurements in the Bell-state basis [31]. Fast spin measurements together with real-time adaptive control [32] could be used to complete the deterministic state transfer process.

Our demonstration of conditional state teleportation, entanglement swapping, and gate teleportation adds time-honored capabilities to the library of quantum information processing techniques available to spin qubits in quantum dots. We envision that teleportation will be useful for the creation and manipulation of long-range entangled states and for error correction in quantum-dot spin qubits. As spin-based quantum information processors scale up, maintaining high-connectivity between spins will be critical, and quantum teleportation also opens an essential pathway toward achieving this goal. In many ways, spin qubits in quantum dots are an ideal platform for quantum teleportation, because they offer a straightforward means of generating and measuring entangled states of spins. As a result, we expect that quantum teleportation will find significant use in future spin-based quantum information processing efforts.

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AUTHOR CONTRIBUTIONS

S.K.M., A.N.J., and J.M.N conceptualized the experiment. Y.P.K, H.Q, and J.M.N conducted the investigation. S.F., G.C.G., and M.J.M provided resources and conducted investigation. All authors participated in writing. J.M.N supervised the effort.
METHODS

Device

The four-qubit processor is a quadruple quantum dot fabricated on a GaAs/AlGaAs heterostructure with a two-dimensional electron gas located 91 nm below the surface. The two-dimensional electron gas density $n = 1.5 \times 10^{11} \text{cm}^{-2}$ and mobility $\mu = 2.5 \times 10^6 \text{cm}^2/\text{Vs}$ were measured at $T = 4\text{K}$. Voltages applied to Al depletion gates define the quadrupole-dot potential. The quadruple dot is cooled in a dilution refrigerator to a base temperature of approximately 10 mK. An external magnetic field $B=0.5 \text{T}$ is applied in the plane of the semiconductor surface perpendicular to the axis connecting the quantum dots. Using virtual gates [33], we tune the device to the single-occupancy regime.

Initialization

To load the $|T_{+12}| = |\uparrow\rangle_1 |\uparrow\rangle_2$ state, we exchange electrons with the reservoirs in the $(1,1)$ charge configuration [25]. Both the magnetic field and temperature limit the fidelity of this process (Extended Data Fig. 5). We simulated this loading process using the methods described in Ref. [25], assuming an electron temperature of 75 mK and a magnetic field of 0.5 T [Extended Data Fig. 5(a)]. This is broadly consistent with the electron temperatures we have measured in our setup, which range from 50-100 mK. We estimate that this state preparation fidelity is about 0.7. The simulations presented here take this preparation error into account. In principle, increasing the magnetic field should improve the fidelity of the $|T_+|$ loading process. Empirically, however, we did not observe a substantial enhancement with fields up to 1T, as has previously been observed [33]. We suspect that unintentional dynamic nuclear polarization significantly modifies the magnetic field at the location of each dot.

To load a separated singlet state, we exchange electrons with the reservoirs in the $(0,2)$ charge configuration [25]. We initialize the right pair of electrons in dot 4 as a singlet with 0.89 probability for a load time of 2 $\mu$s [Extended Data Fig. 5(b)]. This could be improved in the future by optimizing the coupling of the electrons to the source and drain reservoirs. Based on simulations of the Landau-Zener tunneling process to separate the electrons, we estimate that separating the singlet state incurs only a few percent error.

We can initialize either pair of electrons as $|\downarrow\uparrow\rangle$ or $|\uparrow\downarrow\rangle$ by adiabatically separating a singlet state [25]. The orientation of the two spins in this product state depends on the orientation of the local hyperfine field.

Exchange

We induce exchange coupling gates between pairs of qubits by applying a voltage pulse to the barrier between the respective pair of dots [27, 28]. Exchange coupling generated in this way is first-order insensitive to charge noise associated with the plunger gates. Barrier-gate pulses are accompanied by compensation pulses on the plunger gates to keep the dot chemical potentials fixed. For the exchange gates used in this work, we used a combination of barrier- [27, 28], and tilt-controlled [24] exchange. We used this combination to boost the exchange coupling strength as much as possible above the gradient strength to maximize the fidelity of the SWAP operation.

Readout

Diabatic charge transfer into the outer dots projects the spin state of the separated pair onto the $\{|S\rangle, |T\rangle\}$ basis [24, 25]. Adiabatic charge transfer into the outer dots maps either $|\downarrow\uparrow\rangle$ or $|\uparrow\downarrow\rangle$ to $|S\rangle$, depending on the sign of the local magnetic gradient, and it maps all other spin states to triplets [24, 25]. Here, “diabatic” or “adiabatic” refer to the speed with which the electrons are recombined relative to the size of the hyperfine gradient. We represent readout by diabatic charge transfer with an “$ST$” in figures, and we represent readout by adiabatic charge transfer with an “$\downarrow\uparrow$” in figures. When used to verify teleportation, diabatic charge transfer can only verify teleportation when $|\phi\rangle = |\uparrow\rangle$. In principle, however, readout by adiabatic charge transfer could be used to measure qubit 4 in its computational basis. If $\Delta B_{34}$ were such that $|\uparrow\rangle_3 |\downarrow\rangle_4$ was the ground state, adiabatic charge transfer would map $|\uparrow\rangle_3 |\downarrow\rangle_4$ to a singlet, and $|\uparrow\rangle_3 |\uparrow\rangle_4$ to a triplet. Together with tomographic rotation pulses, such a measurement would enable verification of teleportation of arbitrary states.

In addition to conventional spin-blockade readout on both pairs of electrons, we use a shelving mechanism [30] to enhance the readout visibility. Using the two sensor quantum dots configured for rf-reflectometry (Fig. 1) [29], we achieve single-shot readout with integration times of 4$\mu$s on the left side and 6$\mu$s on the right side and fidelities of 0.99 and 0.98, respectively. Relaxation times during readout were 65 $\mu$s and 48 $\mu$s on the left and right sides. Extended Data Figs. 7(a)-(b) show the experimentally measured curves demonstrating the relaxation during readout for both pairs of electrons. Extended Data Figs. 8(a)-(b) show fits to the readout histograms using Equations (1) and (2) in Ref. [26] for each pair of qubits. In all teleportation measurements, both pairs of qubits are measured sequentially in the same single-shot sequence.

To determine the probabilities for the four different possibilities for joint measurements of both pairs, we fit
the total measurement histogram for each pair separately. We determine the threshold for each pair by choosing the signal level that maximizes the visibility [26]. We then use these two thresholds to divide the probability distribution into quadrants. The overall probability is normalized, and we calculate the net probability in each quadrant.

The idling configuration of both pairs of electrons is deep in the (1, 1) charge state, where both electrons in the pair are separated. This idling configuration largely eliminates any state-dependent crosstalk between pairs [12] by ensuring that each pair always has the (1,1) charge configuration when the other pair is manipulated or measured. We also reload the first pair of electrons that we measure as an |S⟩ before reading out the next pair.

Improvements to readout can be made by repositioning the sensor quantum dots for maximum differential charge sensitivity to achieve readout errors of < 0.01 in integration times of < 1 μs, as has previously been demonstrated in quantum dot spin qubits [32, 37].

Simulation

Our simulations include errors associated with state preparation, readout fidelity, relaxation during readout, charge noise, and the fluctuating magnetic gradient. We approximate singlet loading error by creating a two-electron state

$$|\tilde{S}\rangle = s_1 |S\rangle + s_2 |T_0\rangle + s_3 |T_+\rangle + s_4 |T_-\rangle,$$

(1)

where $|s_1|^2 = f_s$, and $|s_2|^2 = |s_3|^2 = |s_4|^2 = (1 - f_s)/3$. Also, $|T_-\rangle = |\downarrow\downarrow\rangle$, and $|T_+\rangle = |\uparrow\uparrow\rangle$. $f_s = 0.89$ is the singlet load fidelity. All coefficients are given random phases for each realization of the simulation. To simulate loading error during adiabatic separation of electrons, we set

$$|\tilde{G}\rangle = s_1 |\downarrow\uparrow\rangle + s_2 |\uparrow\downarrow\rangle + s_3 |T_+\rangle + s_4 |T_-\rangle,$$

(2)

where the coefficients are the same as described above. We use the same coefficients, because the singlet initialization error dominates the error in this process. We also allow the orientation of the spins in this state to change between runs of the simulation as the hyperfine gradient changes. We approximate the $|T_+\rangle$ loading error by simulating the loading process as described in Ref. [35]. We directly extract the population coefficients of the other three two-electron spin states. We create a state which is a sum of all two-electron spin states:

$$|\tilde{T}_+\rangle = t_1 |S\rangle + t_2 |T_0\rangle + t_3 |T_+\rangle + t_4 |T_-\rangle,$$

(3)

where $|t_i|^2$ is determined as discussed above. We assign random phases to each of the coefficients during each realization of the simulation.

To simulate the spin-eigenstate teleport operation, we set the initial state of the four qubit system as

$$|\psi_i\rangle = |\tilde{T}_{12}\rangle \otimes |\tilde{S}_{34}\rangle.$$

(4)

To simulate the entangled-state teleport operations, we set the initial state as

$$|\psi_i\rangle = |\tilde{G}_{12}\rangle \otimes |\tilde{S}_{34}\rangle.$$

(5)

We incorporate charge noise and the hyperfine magnetic field and their effects on the SWAP operation by directly solving the Schrödinger equation for a four spin system. We generated a simulated SWAP operation from the following Hamiltonian:

$$H_S = \frac{1}{2} J_{23} (\sigma_{x,2} \otimes \sigma_{x,3} + \sigma_{y,2} \otimes \sigma_{y,3} + \sigma_{z,2} \otimes \sigma_{z,3}) + \frac{g_{\mu_B}}{2} \sum_{k=1}^{4} B_k \sigma_{z,k}.$$

(6)

(7)

We assume a fixed exchange coupling of $J_{23}$ of 250 MHz between spins 2 and 3, and we adjust the time $T_S$ for the SWAP operation to give a π pulse. These parameters correspond closely to the actual experiments. To account for charge noise, we allow the value of $J_{23}$ to fluctuate by 1% between simulation runs. This level of noise corresponds with the measured quality factor of exchange oscillations, which is approximately 21. For the spin-eigenstate simulation, we set the local nuclear magnetic fields $B_k$ of spin $k$ to be $(-1, 6, -4, 0)$ MHz × $\frac{2h}{g_{\mu_B}}$ for the qubits. We also include for each qubit the overall background field of 0.5T. We allow the nuclear field at each site to fluctuate according to a normal distribution with standard deviation of 12 MHz for qubits 1 and 2 and 10 MHz for qubits 3 and 4. The field and fluctuations are adjusted to improve the agreement between the simulations in Extended Data Figs. 2 and 3. The overall evolution of the four-qubit system during the SWAP operation is given by the following propagator: $S_{23} = \exp \left(-i H_{SWAP}/T_S \right)$.

The voltage pulses in our setup have finite rise times, which cause the four-qubit system to evolve under the magnetic gradient in the absence of exchange. To simulate this effect, we define

$$H_B = \frac{g_{\mu_B}}{2} \sum_{k=1}^{4} B_k \sigma_{z,k}.$$

(8)

Under this Hamiltonian, the wavefunction evolves according to the following propagator: $U_B = \exp \left(-i H_B T_B \right)$. In the experiment, all pulses are convolved in software with a Gaussian of width 2 ns before delivery to the qubits, so we set $T_B = 2$ ns. To simulate the spin-eigenstate teleport experiment, the simulated final state after the teleport operation is thus $|\psi\rangle = U_B S_{23} U_B |\psi_i\rangle$.

To compute the expected probabilities in Fig. 2(d)-(e), we calculate all pairs of two-qubit correlators: $C_{\alpha,\beta} = \langle \psi | (\alpha \otimes \beta) (\alpha \otimes \beta) |\psi\rangle$, where $\alpha$ (qubits 1 and 2) and $\beta$ (qubits 3 and 4) can be any of $\{ |S\rangle, |T_+\rangle, |T_0\rangle, |T_-\rangle \}$. 

$$H_S = \frac{1}{2} J_{23} (\sigma_{x,2} \otimes \sigma_{x,3} + \sigma_{y,2} \otimes \sigma_{y,3} + \sigma_{z,2} \otimes \sigma_{z,3}) + \frac{g_{\mu_B}}{2} \sum_{k=1}^{4} B_k \sigma_{z,k}.$$

(6)

(7)
We calculate the probabilities in Fig. 2 as

\[ P_{SS} = C_{\{S\},\{S\}}, \]
\[ P_{TT} = \sum_{\beta \neq \{S\}} C_{\alpha,\beta}, \]
\[ P_{ST} = \sum_{\beta \neq \{S\}} C_{\{S\},\beta}, \]
\[ P_{TS} = \sum_{\alpha \neq \{S\}} C_{\alpha,\{S\}}. \]

To simulate readout errors, we define the \( g_{L(R)} = 1 - \exp(-r_{m}^{L(R)}/T_{1}^{L(R)}) \) to be the probabilities that the singlet state on the left (right) side will relax to the singlet during readout. Here \( T_{1}^{L(R)} \) is the measurement time, and \( T_{1}^{L(R)} \) is the relaxation time, as discussed above. We also set \( r_{L(R)} = 1 - f_{L(R)} \) as the probability that singlet or triplet on the left (right) side will be misidentified due to noise. Here \( f_{L(R)} \) is the measurement fidelity due to random noise on the left (right) pair. The experimentally measured probabilities are

\[
P'_{SS} = (1 - r_{L} - r_{R})P_{SS} + g_{L}P_{TS} + g_{R}P_{ST} + r_{L}P_{TS} + r_{R}P_{ST},
\]
\[
P'_{ST} = (1 - r_{L} - r_{R})P_{ST} + g_{L}P_{TT} - g_{R}P_{ST} + r_{L}P_{TT} + r_{R}P_{ST},
\]
\[
P'_{TS} = (1 - r_{L} - r_{R})P_{TS} - g_{L}P_{TT} + g_{R}P_{TT} + r_{L}P_{SS} + r_{R}P_{TT},
\]
\[
P'_{TT} = (1 - r_{L} - r_{R})P_{TT} - g_{L}P_{TT} - g_{R}P_{TT} + r_{L}P_{PS} + r_{R}P_{TT}.
\]

The displayed probabilities in Fig. 2(d) are \( P'_{SS}, P'_{ST}, P'_{TS}, \) and \( P'_{TT} \).

To simulate the data shown in Fig. 3 we generate variable exchange propagators \( U_{12} \) and \( U_{34} \) using Hamiltonians analogous to Eq. 7 for exchange between qubits 1-2 and qubits 3-4. Probabilities were calculated as described above. For example, to generate the simulations in Extended Data Fig. 2(b), the final state is computed as \( |\psi\rangle = U_{B}U_{34}U_{B}S_{23}U_{B}|\psi_{i}\rangle \). We compute all possible correlators \( C_{\alpha,\beta} \), where \( \alpha \) is any of \( \{ |S\rangle, |T_{+}\rangle, |T_{0}\rangle, |T_{-}\rangle \} \), and \( \beta \) is any of \( \{ |\downarrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle \} \) and extract probabilities as discussed above. The simulated data are averaged over 1000 realizations of magnetic and electrical noise and random state errors. We note that the ground state configuration (\( |\downarrow\uparrow\rangle \) or \( |\uparrow\downarrow\rangle \)) is allowed to change in the simulation if the gradient changes sign due to random noise. These results of these simulations are shown in Extended Data Fig. 2 which shows the operator sequences and initial states used to simulate the data.

To simulate the data in Fig. 4 we compute the final state as \( |\psi\rangle = S_{34}^{1/2}U_{B}S_{23}U_{B}S_{34}^{1/2}U_{B}(t)|\psi_{i}\rangle \). Here \( U_{B}(t) \) indicates that the right-pair of qubits evolves for a variable time \( t \) in their magnetic gradient \( \Delta B_{34} \). We compute all possible correlators \( C_{\alpha,\beta} \), where \( \alpha \) is any of \( \{ |\downarrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle \} \), and \( \beta \) is any of \( \{ |S\rangle, |T_{+}\rangle, |T_{0}\rangle, |T_{-}\rangle \} \). For this simulation, magnetic gradients were chosen to match the observed frequencies, and the width of the hyperfine distribution was reduced to mimic the effects of averaging for only a few seconds and to match the observed decay. For these data, exchange strengths were chosen to be 150 MHz.

**Estimated \( \Delta B \) Frequencies**

To extract the oscillation frequencies of the data in Fig. 4 and Extended Data Fig. 4 we zero-padded each line (corresponding to an average of up to 256 single-shot repetitions of each evolution time) by 256 points and took the absolute value of the fast Fourier transform of this averaged time series. We then found the frequency giving the peak value. To reduce the effects of noise, we rejected all repetitions giving frequencies larger than 100 MHz. To generate the displayed frequency vs repetition number traces, we smoothed the frequency vs repetition series with a moving 10-point average.

**Estimated Fidelity**

We simulate the fidelity of the conditional teleportation operation for spin eigenstates by starting with the initial state \( |\psi_{i}\rangle = |T_{+},1\rangle \otimes |S_{34}\rangle \), and we simulate the following operator sequence, as discussed above: \( |\psi\rangle = U_{B}S_{23}U_{B}|\psi_{i}\rangle \). We seek to compute the probability that a singlet outcome on the left pair coincides with qubit 4 having the \( |\uparrow\rangle \) state. To assess this probability, we compute all correlators \( C_{\alpha,\beta} \) as before. To incorporate readout errors and relaxation, we set

\[
C'_{\{S\},\beta} = (1 - r_{L})C_{\{S\},\beta} + (g_{L} + r_{L}) \sum_{\alpha \neq \{S\}} C_{\alpha,\beta}.
\]

The probability for qubit 4 to have the \( |\uparrow\rangle \) state, conditioned on the left pair yielding a singlet, is

\[
P_{\uparrow} = \frac{C'_{\{S\},\{T_{+}\}} + \frac{1}{2} \left( C'_{\{S\},\{T_{0}\}} + C'_{\{S\},\{T_{-}\}} \right)}{\sum_{\beta} C'_{\{S\},\beta}}.
\]
We averaged $P_1$ over 100 different realizations of the magnetic and electric noise and state preparation errors, as discussed above.

The fidelity of the combined teleport and SWAP operation for entangled states is determined through a simulation similar to that described above. We initialized the array in the $|\psi_i\rangle = |G_{12}\rangle \otimes |S_{34}\rangle$ state, and the final state is computed as $|\psi\rangle = S_{34}^{1/2}U_BS_{23}U_BS_{34}^{|S\rangle\langle S|}\psi_i\rangle$. We have assumed perfect state preparation on the right pair of qubits. Now, we compute all possible correlators that incorporate readout errors as above, and the fidelity was computed as the maximum value of $C_{|S\rangle\langle S|}$ as the evolution time $t$ varies in a quasi-static gradient. Choosing the maximum value in this way is equivalent to picking a single-qubit $z$ rotation to undo the effects of singlet-triplet evolution in a gradient.

**Entanglement swapping**

Here we derive the expected measurement dynamics for the entanglement swapping experiment. We label the quantum dots respectively 1, 2, 3, and 4. The electrons in dots 1 and 2 are initialized in the following two qubit entangled state,

$$|\psi_{12}\rangle = \frac{1}{\sqrt{2}} \left( e^{i\phi} |\uparrow\rangle_1 |\downarrow\rangle_2 - e^{-i\phi} |\downarrow\rangle_1 |\uparrow\rangle_2 \right), \quad (19)$$

where we take $\phi = \frac{-\pi}{4}$. The electrons in quantum dots 3 and 4 are also initialized in a two qubit entangled state,

$$|\psi_{34}\rangle = \frac{1}{\sqrt{2}} \left( e^{i\chi(t)} |\uparrow\rangle_3 |\downarrow\rangle_4 - e^{-i\chi(t)} |\downarrow\rangle_3 |\uparrow\rangle_4 \right), \quad (20)$$

where $\chi(t)$ is the time dependent phase generated by the magnetic field gradient $\Delta B_{34}$. The joint spin state of four qubits is,

$$|\psi_0\rangle = \frac{1}{\sqrt{2}} \left( e^{i[\phi+x(t)]} |\uparrow\rangle_1 |\downarrow\rangle_2 - e^{-i[\phi-x(t)]} |\downarrow\rangle_1 |\uparrow\rangle_2 \right) \otimes \frac{1}{\sqrt{2}} \left( e^{i\chi(t)} |\uparrow\rangle_3 |\downarrow\rangle_4 - e^{-i\chi(t)} |\downarrow\rangle_3 |\uparrow\rangle_4 \right)$$

$$= \frac{1}{2} \left( e^{i[\phi+x(t)]} |\uparrow\rangle_1 |\downarrow\rangle_2 |\uparrow\rangle_3 |\downarrow\rangle_4 - e^{-i[\phi-x(t)]} |\downarrow\rangle_1 |\uparrow\rangle_2 |\uparrow\rangle_3 |\downarrow\rangle_4 \right.
+ e^{-i[\phi+x(t)]} |\downarrow\rangle_1 |\uparrow\rangle_2 |\uparrow\rangle_3 |\downarrow\rangle_4 - e^{i[\phi-x(t)]} |\uparrow\rangle_1 |\downarrow\rangle_2 |\uparrow\rangle_3 |\downarrow\rangle_4 \right). \quad (21)$$

In principle, entanglement swapping via joint measurements can be demonstrated on this quantum state, by jointly measuring the qubits 2 and 3 (or 1 and 4), but for the ease of implementing the joint measurement in our four qubit processor, we apply a unitary SWAP operation between the qubits 2 and 3 that swaps the quantum states of electrons between quantum dots 2 and 3, yielding the modified quantum state,

$$|\psi_0\rangle = \frac{1}{2} \left( e^{i[\phi+x(t)]} |\uparrow\rangle_1 |\uparrow\rangle_2 |\downarrow\rangle_3 |\downarrow\rangle_4 - e^{-i[\phi-x(t)]} |\downarrow\rangle_1 |\uparrow\rangle_2 |\uparrow\rangle_3 |\downarrow\rangle_4 \right.
+ e^{-i[\phi+x(t)]} |\downarrow\rangle_1 |\uparrow\rangle_2 |\uparrow\rangle_3 |\downarrow\rangle_4 - e^{i[\phi-x(t)]} |\uparrow\rangle_1 |\downarrow\rangle_2 |\uparrow\rangle_3 |\downarrow\rangle_4 \right). \quad (22)$$

The electron in quantum dot 1 is now entangled to the electron in quantum dot 3, and the electron in quantum dot 2 is entangled to the electron in quantum dot 4. When we perform a joint measurements of the qubits 3 and 4 in the $\{|S\rangle, |T\rangle\}$ basis, and look at cases where the outcome is a singlet, we find that the conditional state of electrons in quantum dots 1 and 2 is,

$$\langle S_{34}|\psi_0\rangle = \frac{1}{2\sqrt{2}} \left( e^{i[\phi-x(t)]} |\uparrow\rangle_1 |\downarrow\rangle_2 - e^{-i[\phi-x(t)]} |\downarrow\rangle_1 |\uparrow\rangle_2 \right). \quad (23)$$

We find that, as a result of the joint measurement of electrons in the dots 3 and 4, and cases where the measurement outcome is a singlet entangled state, the reduced
state of electrons in dots 1 and 2 is maximally entangled. Also note that the coherent singlet-triplet evolution previously occurring between the qubits 3 and 4 now happens between qubits 1 and 2, provided a singlet is measured on qubits 3 and 4.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.
Extended Data Figure 1. Verification of conditional teleportation of a classical spin state. (a) We apply a variable exchange
gate to the right pair after measuring the left pair. Here, $\theta = 2\pi J_{34} t$, where $J_{34}$ is the exchange coupling between qubits 3 and
4, and $t$ is the evolution time given by the x-coordinate of each data point. ($\theta = \pi$ corresponds to a SWAP operation.) When
then left pair give a singlet, the right pair have the same spin, and no oscillations should be visible. The inset shows the same
data from 0-32 ns. (b) Control experiment with no SWAP operation. Residual oscillations result from errors in preparing the
EPR pair. (c) Control experiment with the EPR pair replaced by a product state. Oscillations occur because the fluctuating
hyperfine gradient between the right pair sometimes favors the $|\uparrow \downarrow\rangle$ orientation. (d) Applying an exchange gate to the left pair
after measuring the right pair generates exchange oscillations on the left pair only if the right pair yields a triplet. The inset shows the same
data from 0-32 ns. (e) Control experiment with no SWAP operation. No oscillations occur because qubits
1 and 2 are prepared in the $|\uparrow \uparrow\rangle$ state. (f) Control experiment with the EPR pair replaced by a product state. Here, the
oscillations are small because the hyperfine gradient between qubits 3 and 4 fluctuates around zero. Each data point represents
the average of 16,384 single shot measurements.
Extended Data Figure 2. Simulated variable-exchange experiments. Each panel presents a simulation of the corresponding panel in Extended Data Fig. 1. Above each panel is the operator sequence used in the simulation and the initial state used in the simulation. In panels (a)-(c), $p(S_R|S_L)$ indicates the the right-side singlet probability given a singlet on the left, and $p(S_R|T_L)$ indicates the right-side singlet probability given a triplet on the left. In (d)-(f), $p(S_L|S_R)$ indicates the left-side singlet probability given a singlet on the right, and $p(S_L|T_R)$ indicates the left-side singlet probability given a triplet on the right.
Extended Data Figure 3. Conditional teleportation of entangled states and conditional gate teleportation. (a) Averaged singlet probability on the left pair of qubits $p(S_L)$. (b) Averaged singlet probability on the right pair of qubits $p(S_R)$. (c) Averaged singlet probability on the left pair of qubits given a singlet on the right pair $p(S_L|S_R)$. (d) Averaged singlet probability on the right pair of qubits given a singlet on the left pair $p(S_R|S_L)$. (e) Absolute value of the fast Fourier transform of the data in (c). The extracted peak frequency is overlaid in green. (f) Absolute value of the fast Fourier transform of the data in (d). The extracted peak frequency is overlaid in green.
Extended Data Figure 4. Measurement of $\Delta B$. (a) Averaged measurements of $\Delta B_{12}$ oscillations [32]. Acquisition of each vertical line was interleaved with the data shown in Fig. [3]. (b) Absolute value of the fast Fourier transform of the data in (a), with the extracted frequency shown in green. (c) Averaged measurements of $\Delta B_{34}$ oscillations. Acquisition of these data were also interleaved with the data in Fig. [3]. (d) Absolute value of the fast Fourier transform of the data in (c), with the extracted frequency shown in green.

Extended Data Figure 5. State preparation fidelity. (a) Experimentally measured $|T_+\rangle$ loading curve, obtained by sweeping $\mu_1$, the electrochemical potential of dot 1, across the (1,1)-(2,1) charge transition, where $(m, n)$ indicates $m$ electrons in dot 1 and $n$ electrons in dot 2 [35, 38]. The peak in the data indicates where the value of $\mu_1$ where the $|T_+\rangle$ loading probability is highest. Inset: Simulated results of the loading process. The blue simulation gives the expected triplet signal, and the red simulation is probability of loading a $|T_+\rangle$. The simulation assumes a load time of 2$\mu$s, a ramp time of 200ns, a temperature of 75mK, and a magnetic field of 0.5 T. The $x$ axis represents the chemical potential $\alpha\mu_1$ in units of the magnetic field, where $\alpha$ is the effective lever-arm. (b) Singlet probability as a function of loading time. All experiments were conducted with a loading time of 2$\mu$s. The blue points are data, and the red line is a fit to an exponential decay.
Extended Data Figure 6. Readout fidelity. (a) Measurement histogram and fit for the left pair of qubits for the data shown in Fig. 2(b). The extracted average fidelity for singlets and triplets is 0.99. (b) Measurement histogram and fit for the right pair of qubits for the data shown in Fig. 2(a). The extracted average fidelity for both singlets and triplets is 0.98. In both panels, the red lines are fits to the equations (1) and (2) of Ref. [21]. The quoted fidelities do not include the effects of relaxation during readout. In both panels, the V_{RF} represents the raw voltage from our readout circuit. In both panels, the threshold which maximizes the visibility is indicated.

Extended Data Figure 7. Relaxation during readout. (a) Data and fit showing the relaxation of the left-pair of qubits during readout. (b) Data and relaxation of the right pair of qubits during readout. The data in both panels are obtained by subtracting the results of two measurements. The first involves preparing a mixed state and measuring it for 60 μs. Then, we prepare a singlet state and also measure it for 60 μs. We repeat this set of two measurements 10,000 times. For each repetition, we record the entire 60 μs measurement record. We plot the difference of the two experiments, averaged across all repetitions, as a function of integration time from 0-60 μs. We fit this difference to a decaying exponential and extract the relaxation time T_1. The fits give relaxation times of 65 μs and 48 μs.