Resonant microwave-mediated interactions between distant electron spins

The devices studied in this work consist of two double quantum dots (DQDs), denoted L-DQD (left DQD) and R-DQD (right DQD), that are fabricated on a Si/SiGe heterostructure and positioned at the left and right antinodes, respectively, of a half-wavelength Nb superconducting cavity (Fig. 1a). Device 1 is fabricated on a natural-silicon quantum well and has a cavity centre frequency of \( f_c = 6.745 \text{ GHz} \) and a decay rate of \( \kappa/(2\pi) = 1.98 \text{ MHz} \). Device 2 uses an enriched \(^{28}\text{Si}\) quantum well with a \(^{29}\text{Si}\) residual concentration of 800 ppm. A single electron is isolated in each DQD\(^{29}\) and interacts with the electric field of the cavity through the electric dipole interaction. Our device design uses a split-gate cavity coupler (labelled 'CP' in Fig. 1b) that is galvanically connected to the central pin of the superconducting cavity\(^{22}\).

We first demonstrate the strong coupling of a spin trapped in each DQD to a cavity photon. In our device architecture, a large electric dipole coupling rate of \( g_d/(2\pi) = 40 \text{ MHz} \) is combined with an artificial spin–orbit interaction generated by a micromagnet to achieve spin–photon coupling\(^{22,23}\). To probe the spin–photon coupling, the cavity transmission is isolated in each DQD\(^{29}\) and interacts with the electric field of the cavity through the electric dipole interaction. Our device design uses a split-gate cavity coupler (labelled 'CP' in Fig. 1b) that is galvanically connected to the central pin of the superconducting cavity\(^{22}\).

We now demonstrate control over the difference between the spin resonance conditions of the two DQDs, denoted \( \chi_{\text{L}} \) and \( \chi_{\text{R}} \), and the cavity resonance condition \( \chi_c \). The field-tuning parameters are the external magnetic field \( B_{\text{ext}} \) and the angle \( \phi \) of \( B_{\text{ext}} \) relative to the interdot axis of the DQDs (Fig. 1b). Because of the intentional asymmetry, adjusting the angle \( \phi \) of the in-plane magnetic field relative to the DQD axes provides an additional degree of freedom for simultaneous tuning of both spins into resonance with the cavity. Qualitatively, the high-permeability Co micromagnet concentrates the magnetic-field lines, leading to a maximum total field when \( B_{\text{ext}} \) is aligned with the long axis of the micromagnet\(^{22}\). We show that this technique is suitable for controlling the spin resonance frequencies in Fig. 1d, where we set the magnetic-field angle at \( \theta = 2^\circ \). Here, the \( R \) spin resonance condition shifts up to \( B_{\text{ext}} = 104.7 \text{ mT} \) and the \( L \) spin resonance condition shifts down to \( B_{\text{ext}} = 107.4 \text{ mT} \).

We now demonstrate control over the difference between the spin resonance frequencies by fixing the magnitude of the external magnetic field \( B_{\text{ext}} \) and varying the angle \( \varphi \) of \( B_{\text{ext}} \) in the plane of the sample. The expected spin resonance frequencies are plotted in Fig. 2a as a function of \( \varphi \) with \( B_{\text{ext}} = 106.3 \text{ mT} \) (upper panel) and \( B_{\text{ext}} = 110 \text{ mT} \) (lower panel), confirming that these two control parameters will bring the
two spins into resonance with the cavity and with each other. On the basis of microwave spectroscopy measurements of the spins, we expect resonance to occur around $\phi = 6^\circ$ and $B_{\text{ext}} = 106.3$ mT. Figure 2b maps out the field angle dependence of the spin resonance frequencies over the range $\phi = 3^\circ$–$8^\circ$ with $B_{\text{ext}} = 106.3$ mT. The resonance frequency of the R spin monotonically moves to lower $f$ values as $\phi$ is increased, whereas the L spin shows the opposite dependence. With $\phi = 5.6^\circ$ both spins are tuned into resonance with the cavity. These results are well captured by the theoretical prediction of transmission through the cavity shown in Fig. 2c.

The spectrum of the Jaynes–Cummings model for a single spin and a single photon in the cavity is shown in Fig. 3a. With the L spin tuned into resonance with the cavity, the spin and cavity photon hybridize, leading to a vacuum Rabi splitting of magnitude $2g_{s,L}$ in the cavity transmission. By contrast, when both spins are simultaneously tuned into resonance with the cavity, the excited-state spectrum of the

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**Fig. 1** Cavity coupler for spins. *a*, Optical micrograph of the superconducting cavity containing two single-electron DQDs. The electron spin in each DQD is coupled to the cavity through a combination of electric-dipole and artificial spin–orbit interactions. $\hat{z}$ indicates the direction of the DQD interdot axis. *b*, False-colour scanning electron microscope image of L-DQD. A double-well potential is formed beneath the plunger gates P1L and P2L, and the barrier gate B2L is used to adjust interdot tunnel coupling. Spin–orbit coupling is induced by a Co micromagnet (dashed lines). CP, cavity coupler. S1L, S2L, S, D denote other gates used to define the DQD. *c*, Cavity transmission $A/A_0$ as a function of $B_{\text{ext}}$ and $f$. Vacuum Rabi splitting, a hallmark of strong coupling, is observed for each spin. For a field angle of $\phi = 0^\circ$ the R spin and L spin resonance conditions are separated by $\Delta B_{\text{ext}} = 6$ mT. *d*, Increasing the field angle to $\phi = 2.8^\circ$ reduces the field separation drastically.

**Fig. 2** Tuning two spatially separated spins into resonance. *a*, Expected spin resonance frequencies as a function of $\phi$ for $B_{\text{ext}} = 106.3$ mT (top panel) and $B_{\text{ext}} = 110$ mT (bottom panel). $B_{\text{ext}}$ allows control over both spin frequencies with respect to the cavity, whereas $\phi$ allows control over the spin frequencies with respect to each other. The frequency of the L (R) spin is plotted in blue (purple). *b*, $A/A_0$ as a function of $f$ and $\phi$, demonstrating simultaneous tuning of both spins into resonance with the cavity at $\phi = 5.6^\circ$ and $B_{\text{ext}} = 106.3$ mT. Dashed lines indicate L spin and R spin transition frequencies. *c*, Theoretical prediction for $A/A_0$. 196 | Nature | Vol 577 | 9 January 2020
Fig. 3 | Resonant coupling of the two spins via a cavity photon. a, Tuning the L spin into resonance with the cavity results in vacuum Rabi splitting with magnitude $2g_{\text{LR}}$. A vacuum Rabi splitting of magnitude $2g_{\text{LR}} = 2\sqrt{g_{\text{L}}^2 + g_{\text{R}}^2}$ is expected when both spins are tuned into resonance with the cavity. b, $A/A_0$ as a function of $f$ and $B^{\text{ext}}$ with $\varphi = 5.6^\circ$, indicating an enhanced vacuum Rabi splitting when the L spin and R spin are tuned into resonance with the cavity. c, $A/A_0$ as a function of $f$ for the R spin in resonance (upper curve), the L spin in resonance (middle curve) and both spins in resonance (bottom curve). The enhancement of the vacuum Rabi splitting with both spins in resonance with the cavity is indicative of coupling between the two spins via the cavity mode. d, Cavity-assisted spin coupling is also observed in a second device with a different gate pattern. Dashed lines in c, d are fits to a master-equation simulation. Insets in c, d are scanning electron microscope images of the devices, with scale bars of 200 nm.

Jaynes–Cummings model splits into a sub-radiant state and two bright states. For identical spins, the Jaynes–Cummings model predicts a collective $\sqrt{N}$ enhancement of the coupling rate. In our device geometry, the sub-radiant state is the spin triplet $|0, S_0 \rangle = \{ |0, \uparrow, \downarrow \rangle + |0, \downarrow, \uparrow \rangle \}$ because the DQDs are located at opposite ends of the cavity, where the electric fields are 180° out of phase. Here, the spin states of the L/R spin are quantized along the axis of their local total magnetic field. The bright states are hybridizations between the singlet state $|0, S_0 \rangle = \{ |0, \uparrow, \downarrow \rangle - |0, \downarrow, \uparrow \rangle \}$ and the state with a single photon $|1, \uparrow, \downarrow \rangle$, which are separated in energy by twice the collectively enhanced vacuum Rabi coupling, $2g_{\text{LR}} = 2\sqrt{g_{\text{L}}^2 + g_{\text{R}}^2}$. We now search for evidence of cavity-mediated single-spin coupling.

Figure 3b shows $A/A_0$ as a function of $f$ and $B^{\text{ext}}$ with $\varphi = 5.6^\circ$, where both spins are in resonance with the cavity. As $B^{\text{ext}}$ is increased, both spins are simultaneously tuned into resonance with the cavity at $B^{\text{ext}} = 106.3$ mT and we observe an enhancement in the vacuum Rabi splitting relative to the datasets shown in Fig. 1c, d. The vacuum Rabi splitting is quantitatively analysed for device 1 in Fig. 3c and for device 2 in Fig. 3d. These devices have slight differences in gate geometry, and the micromagnets in device 2 are cant at angles of $\theta = \pm 10^\circ$. In device 1, we extract $g_{\text{LR}}$ by measuring $A/A_0$ at $\varphi = 5.6^\circ$ by decoupling the R/L spin from the cavity. This is achieved by increasing the charge level detuning ($eU/e_C$) in the respective DQD to localize the electron in a single quantum dot. In device 2, we extract $g_{\text{LR}}$ by measuring $A/A_0$ at an off-resonance angle, at the now separated resonant fields (see Supplementary Fig. 1). For device 1, we observe a vacuum Rabi splitting of $2g_{\text{LR}}/(2\pi) = 21.4 \pm 0.2$ MHz when the L spin is in resonance with the cavity, $2g_{\text{LR}}/(2\pi) = 24.0 \pm 0.4$ MHz when the R spin is in resonance with the cavity, and $2g_{\text{LR}}/(2\pi) = 30.2 \pm 0.2$ MHz when both spins are in resonance with the cavity. Device 2 shows similar behaviour and again exhibits an enhanced vacuum Rabi splitting of $2g_{\text{LR}}/(2\pi) = 18.4 \pm 0.4$ MHz when both spins are tuned into resonance with the cavity, compared to the individual splittings $2g_{\text{LR}}/(2\pi) = 13.2 \pm 0.2$ MHz and $2g_{\text{LR}}/(2\pi) = 12.4 \pm 0.2$ MHz. Combining these two datasets give strong evidence for microwave-assisted interactions between two spins across a length scale of 4 nm, which is many orders of magnitude larger than what can be achieved using direct wavefunction overlap. Moreover, these measurements show that both the field angle and DQD-level detuning can be used to modulate the strength of the interactions between the two spins.

The data in Fig. 3c, d are fitted using a master-equation description of the spin–cavity system (see Supplementary Information). We independently measure the linewidths $\gamma_{\text{LR}}$ using microwave spectroscopy. The cavity linewidth $\kappa$ and the complex Fano factor $\eta$ are obtained by fitting the bare cavity response with the spins detuned from resonance. The spin–photon coupling rates $g_{\text{LR}}$ for each device are obtained by fitting the data obtained with the spins individually tuned into resonance with the cavity, as shown in Fig. 3c, d. From the Jaynes–Cummings model we expect the bright states to split with the enhanced collective coupling rate $2g_{\text{LR}} = 2\sqrt{g_{\text{L}}^2 + g_{\text{R}}^2}$. The extracted splittings agree with the theoretical predictions of $2g_{\text{LR}}/(2\pi) = 32.1$ MHz for device 1 and $2g_{\text{LR}}/(2\pi) = 18.1$ MHz for device 2 to within 6%.

The observation of enhanced vacuum Rabi splitting when the separated spins are simultaneously in resonance with the cavity is evidence of a long-range interaction between the two spins and a cavity photon. The nonlocal interaction of two spins marks an important milestone for all-to-all qubit connectivity and scalability in silicon-based quantum circuits. With further improvements in cavity quality factors and spin–photon coupling rates, time-domain demonstrations of cavity-assisted spin–spin coupling should be within experimental reach. The spin–photon coupling rate could be considerably increased by using high-impedance superconducting cavities, potentially enabling...
spin–spin coupling in the dispersive regime, where the spins are detuned from the cavity and the photonic degree of freedom can be effectively eliminated. High-fidelity long-range spin–spin coupling in the dispersive regime would allow the implementation of modular qubit architectures in silicon, where nearest-neighbour coupled registers of spin qubits can be interfaced with other sparsely distributed registers via microwave photons.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-019-1867-y.

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Data availability
The data that support the findings of this study are available from the corresponding author on reasonable request.

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Author contributions
F.B. and X.G.C. carried out the measurements with input from X.M. and J.R.P.; F.B. and X.M. fabricated the device. M.J.G. provided theory support. F.B., X.G.C., M.J.G. and J.R.P. wrote the manuscript. All authors discussed the results and commented on the manuscript.

Competing interests
X.M., J.R.P. and Princeton University have filed a non-provisional patent application related to spin–photon transduction (US patent application number 16534431).

Additional information
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