Neural-network decoders for measurement induced phase transitions

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Open quantum systems have been shown to host a plethora of exotic dynamical phases. Measurement-induced entanglement phase transitions in monitored quantum systems are a striking example of this phenomena. However, naive realizations of such phase transitions requires an exponential number of repetitions of the experiment which is practically unfeasible on large systems. Recently, it has been proposed that these phase transitions can be probed locally via entangling reference qubits and studying their purification dynamics. In this work, we leverage modern machine learning tools to devise a neural network decoder to determine the state of the reference qubits conditioned on the measurement outcomes. We show that the entanglement phase transition manifests itself as a stark change in the learnability of the decoder function. We study the complexity and scalability of this approach in both Clifford and Haar random circuits and discuss how it can be utilized to detect entanglement phase transitions in generic experiments.
quantum error correction codes and quantum decoders\textsuperscript{40–48}, we provide a generic neural network (NN) approach that can efficiently find the aforementioned decoders. First, we sketch our physically motivated NN architecture. Although we use numerical simulations of Clifford circuits to show the efficacy of our NN decoder, we argue that in principle the same decoder with slight modifications should work for any generic circuit. We investigate the complexity of our learning task by studying the number of circuit runs required for training the neural network decoder. Importantly, we show that the learning task only needs measurement outcomes inside a rectangle encompassing the statistical light-cone\textsuperscript{49} of the reference qubit. Furthermore, we demonstrate that by studying the temporal behavior of the learnability of the quantum trajectories, one can estimate the critical properties of the phase transition. We also verify that for large circuits one can train the NN over smaller circuits which provides evidence for the scalability of our method. Finally, we explain how our method can be applied to generic circuits with Haar random gates, and we study the temporal behavior of the averaged entanglement entropy for two values of measurement rate in the area-law and volume-law phases for a small ensemble of such circuits.

**Results**

**Model**

The circuits that we study have a brickwork structure as in Fig. 1, with $L$ qubits. We consider time evolution with $T$ time steps with repetitive layers of two-qubit random unitary gates, followed by a round of single-site measurements of the Pauli $Z$ operators at each site with probability $p$. As one tune $p$ past some critical value $p_c$, there is a phase transition from a volume-law entanglement behavior ($p < p_c$) to an area-law behavior ($p > p_c$) and a logarithmic scaling at the critical point ($p = p_c$). Crucially for this work, this phase transition is also manifested in the time dependence of the entanglement entropy of a reference qubit entangled with the system $S_2(T)$\textsuperscript{49}. $S_2(T)$, averaged over many circuit runs, is known as the coherent quantum information and plays a crucial role in the fundamental theory of quantum error correction\textsuperscript{49}. For polynomials in system-size circuit depths, $S_2(T)$ maintains a finite value in the volume-law phase and vanishes in the area-law phase. The protocol we use to probe $S_2(T)$ is illustrated in Fig. 1a. Starting from a pure product state, we make a Bell pair out of the qubit in the middle and an ancilla reference qubit. Throughout the paper, we use periodic boundary conditions for the circuit.

**Decoder**

To find $S_2(T)$ in the experiment, we need to find the density matrix of the reference qubit at time $T$, which is a vector inside the Bloch sphere and can be specified by its three components $\langle \sigma_X \rangle$, $\langle \sigma_Y \rangle$ and $\langle \sigma_Z \rangle$. Therefore, probing the phase transition can be viewed as the task of finding a decoder function $F_\gamma$ for a given circuit $\mathcal{C}$, such that

$$F_\gamma(M_T) = (\langle \sigma_X \rangle, \langle \sigma_Y \rangle, \langle \sigma_Z \rangle)$$ (1)

where $M_T$ is the set of circuit measurement outcomes. Let $p_T(m|M_T)$ for $P \in \{X,Y,Z\}$ denote the probability of getting reference qubit outcome $m = \pm 1$ when measuring $\sigma_P$ of the reference qubit after time $t = T$, conditioned on the measurement outcomes $M_T$. Since $\langle \sigma_P \rangle = \sum_m m p_T(m|M_T)$, the problem of finding the decoder $F_\gamma$ is equivalent to finding the probability distributions $p_T(m|M_T)$ for $P \in \{X,Y,Z\}$.

**Deep learning algorithm**

Instead of finding $p_T(m|M_T)$ analytically for a given circuit $\mathcal{C}$, we plan to use ML methods to learn these functions from a set of sampled data points which in principle could be obtained from experiments. The task of learning conditional probability distributions is known as the probabilistic classification task in ML literature.\textsuperscript{50–52} Let us fix the circuit $\mathcal{C}$ and the Pauli $P$. A sample data point is a pair of $(M_T, m)$ for a single run of the circuit where $M_T$ is the circuit measurement outcomes and $m$ is the outcome of measuring the reference qubit in the $\sigma_P$ basis at the end of the circuit. By repeating the experiment $N_t$ times, we can generate a training set of $N_t$ data points. By training a neural network using this data set, we obtain a neural network representation of the function $p_T(m|M_T)$.

Framing the problem as a probabilistic classification task does not necessarily mean that the learning task would be efficient. Indeed, given that the number of different possible $M_T$ outcomes scales exponentially with the system size, one would naively expect that the minimum required $N_t$ should also scale exponentially for the learning task to succeed, i.e., we need to run the circuit exponential number of times to generate the required training data set. However, the crucial point made in ref. \textsuperscript{38} is that, when the reference qubit is initially entangled locally to the system, its density matrix at the end of the circuit only depends on the measurement outcomes that lie inside a statistical light cone, and up to a depth bounded by the correlation time that is finite in the system size away from the critical point. Hence, for a typical circuit away from the critical point, the function $p_T(m|M_T)$ depends only on a finite number of elements in $M_T$ and that makes the learning task feasible.

To show the effectiveness of this method, we test our decoder using data points gathered from numerical simulation of Clifford circuits with $p_c = 0.160(1)$, which enables us to study circuits of large enough sizes. Due to Clifford dynamics, the reference qubit either remains completely mixed at $T = T_\text{for}$ or it is purified along one of the Pauli axis. This means the measurement outcome of $\sigma_P$ at the end of the circuit is either deterministic or completely random. Therefore, it is more natural to view the problem as a hard classification task (rather than probabilistic) where we train the neural network to determine the measurement outcome of $\sigma_P$ (see the “Methods” section). Note, if the reference qubit is purified at the end of the circuit, then the decoder can in principle learn the decoding function while, if it is not, then the measurement outcomes are completely random, leading to an inevitable failure of the hard classification. Thus, the purification phase
transition shows itself as a learnability phase transition. It is worth noting that we are only changing how we interpret the output of the NN, i.e., we pick the label with the highest probability, so the same NN architecture can be used for more generic gate sets. For simplicity, we also only look at the data points corresponding to the basis $P$ in which the reference qubit is purified. In an experiment, the purification axis is not known, so one needs to train the NN for each of the three choices of $P$. If the learning task fails for all of them, it means the qubit is totally mixed. Otherwise, the learning task will succeed for one axis and fail for the other two (Note, for a fixed Clifford circuit, the purification axis does not depend on $M_L$), which means the reference qubit is purified.

Since locality plays an important role in purification dynamics, we employ a particular deep learning architecture called convolutional neural networks (CNN) that are efficient in detecting local features in image recognition applications. In utilizing these networks the input data is treated as a snapshot as in Fig. 1b with each pixel treated as a feature of the NN and the label of each image is the measurement outcome of $\Phi_l$.

Learning complexity

For a fixed circuit $C$, we start the training procedure by training the NN with a given number of labeled quantum trajectory measurements and then evaluate its performance in predicting the labels of newly generated trajectories produced by the same circuit $C$. The learning accuracy $1 - \epsilon_l$ is the probability that the NN predicts the right label. The minimum number of training samples denoted by $M(\epsilon_l)$ to reach a specified learning error $\epsilon_l$ can provide an empirical measure of the learning complexity of the decoder function $F_{G_{\Phi_l}}$. In what follows, we fix the learning error of each circuit to be $\epsilon_l = 0.02$.

In performing this analysis, different learning settings can be considered. Intuitively, for a fixed circuit, we expect the purification time of the reference qubit, $t_p$, after which the reference qubit's state does not alter any further, to play an important role in determining $M$. Therefore, in our first learning setup, we consider a conditional learning scheme where for a given measurement rate, we select quantum circuits based on their purification time $t_p$, which allows us to study the effect of the system size on the learning complexity. Moreover, we discard measurement outcomes corresponding to measurements performed after $t_p$. This is to say that for each $t_p$, measurement outcomes outside a mask with width $L$ and height $t_p$ will be masked. Here, we note that given $N_c$ circuits with the same purification time, in addition to the learning efficiency of each circuit, we need to fix the learning accuracy averaged over $N_c$ circuits, $\delta_l$, which we fix to be $\delta_l = 20\%$. We remark that this number is larger than $\epsilon_l$ since some of the conditionally selected circuits have not been learned.

In the second setting, we remove the conditioning constraint and only consider the overall complexity of the learning task when we randomly generate circuits for a given $p$ in a completely unconditional manner. The two schemes can be related using the probability distribution $r_p$ of the purification time as shown in Fig. 2a and explained more concretely in the methods section. We should emphasize that a conditional learning scheme is only a tool for studying the complexity of the learning problem for Clifford circuits. For probing the phases and phase transitions in both Clifford and Haar circuits, we use the unconditional learning scheme. Note that since the reference qubit is entangled locally at the beginning, there is always a finite probability that it will be purified in early times. In the mixed phase, the distribution has an exponentially small tail until exponentially long times (both in system size) whereas, in the pure phase, the ancilla purifies in a constant time independent of system size. Inspired by the approximate locality structure of hybrid circuits, we also consider a light-cone learning scheme, where we train the NN using only the measurement outcomes inside a box centered in the middle (see below). In Fig. 2b, we compare the complexity of the conditional learning task in

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**Fig. 2** Statistical analysis of the learning complexity and its relation with the purification time. a Distribution of purified circuits as a function of the purification time for different measurement rates $p = 0.05$ (mixed phase), $p = 0.15$ (critical value), $p = 0.5$ (pure phase) with $L = 16$ qubits and $N_c = 10^3$ random circuits. b and c Averaged number of quantum trajectories required for learning the reference qubit after conditioning on the purification time $t_p$, for $p = 0.1$ (mixed phase) and $p = 0.3$ (pure phase). Averaging is performed over $N_c = 20$ circuits for each $t_p$ and error bars are set according to the standard deviation. In b we have circuits with $L = 128$ qubits. In the main plot measurement outcomes from inside the fixed light-cone box are used for training while for the inset we use the measurement outcomes from the whole circuit. In c we have circuits with $L = 128$ qubits (solid line) and $L = 64$ qubits (dashed line) with $p = 0.1$ in the main plot and $p = 0.3$ in the inset. d Ratio of learned circuits as a function of a number of quantum trajectories with $L = 64$ and for different $p$ without conditioning on the purification time with $N_c = 10^3$ circuits for each $p$.
the pure and mixed phases both by using the light-cone box (main) and whole circuit (inset) measurement data. For each purification time and $p$, we consider $N_c = 20$ different circuits and we average over their minimum required training numbers to calculate $M(c, \delta)$, and show the standard deviation as the error bar. Here, for all the curves, we observe an approximate exponential growth of $M(c, \delta)$ as a function of the purification time $\tau_p$. By comparing the mixed and pure phases, we notice that the conditional learning task is more complicated in the pure phase than the mixed phase, which is expected since, all else being equal, there are more measurements in the pure phase. Additionally, as shown in the inset, we find that learning with light-cone data is less complicated than using all the measurement outcomes. These behaviors can be understood by recognizing that to learn the decoder we need to explore the domain of the mapping in Eq. (1) whose size scales exponentially with $2^n$.

In Fig. 2c we compare the system size dependence of the complexity in the two phases with $L = 64, 128$ where we train our networks with the light-cone data. We note that since the size of the light-cone box for a fixed $\tau_p$ is independent of the system size, we expect the asymptotic complexity to be independent of the system size. Our numerical observation is partially in agreement with this theoretical expectation. In the “Methods” section, this point has been studied further where we explicitly depict the system size dependence of the complexity for circuits with experimentally relevant system sizes $L = [16, 32, 64, 128]$. In the “Methods” section, we also obtain similar complexity results for circuits with initial states scrambled by a high-depth random Clifford circuit.

In the final step, we consider the unconditional learning task. Figure 2d shows the ratio of circuits that can be learned, denoted by $R_t$, as a function of $N_c$ with the circuit depth fixed at $T = 10$. After an initial fast growth in $R_t$, the learning procedure slows down. This can be understood by noting that exponentially more samples are required to learn the decoder for circuits with longer purification time. Moreover, the saturation value for each $p$ is bounded by the ratio of circuits that are purified by time $T$, which can be expressed as

$$R_t(T) = \int_0^T r_p \, dt$$

where $r_p$ is the purification rate plotted in Fig. 2a.

### Dynamics of coherent information

We can utilize the NN decoder to study the critical properties of the phase transition. For a fixed circuit configuration c with a given $p$, let $\rho_c$ and $s_c(t) = -\text{tr}(\rho_c \log_2 \rho_c)$ denote its density matrix and von Neumann entropy of the reference qubit after time $t$, respectively. Based on this definition, we let $S_c(t) = -\sum_{c=1}^{N_c} \frac{1}{N_c} \text{tr}(\rho_c \log_2 \rho_c)$ denote the average entropy of the reference qubit after time $t$, i.e., the coherent quantum information of the system with 1 encoded qubit. We may assume on general grounds that $S_c(t)$ follows an early-time exponential decay $e^{-\lambda t}$ with $\lambda$ following the scaling form:

$$\lambda = \frac{d}{C_0} \frac{\ln S_c(t)}{d t}$$

when it is plotted for different system sizes. Here, $\tau_p = t_d/L$ is the differentiation time which should be sufficiently large. In Fig. 3b, we evaluate the decay rate obtained by learning $\lambda_{tr}$ for three different system sizes, $L = [32, 48, 64]$, at $t_d = 1/16$ using $S_c(t)$. The corresponding times are $\tau_p = [2, 3, 4]$ for which the deviation of the learned and simulated coherent information is negligible. Here, we notice an approximate crossing in the region $0.1 \leq p_c \leq 0.15$ signaling a phase transition in this region.

More systematically, we may find the best-estimated values of the critical data by collapsing the decay rate curves according to the scaling ansatz in Eq. (3). In particular after fixing $z = 1$, we can search simultaneously for $p_c$ and $\nu$ so that the fitting error of the regression curve would be minimized (see the “Methods” section). The inverse error has been plotted as a function of $p_c$ and $\nu$ in Fig. 3c where we observe that the lowest error corresponds to the region $p_c \approx 0.13, \nu \approx 1.5$. Similarly, we can examine our assumption about the conformal symmetry of the transition, by fixing $p_c = 0.13$, and allowing $\nu$ and $z$ to vary as in Fig. 3d. Here, we observe that the lowest error corresponds to the region $p_c \approx 0.13, \nu \approx 1.5$. Finally, we can examine our assumption about the conformal symmetry of the transition, by fixing $p_c = 0.13$, and allowing $\nu$ and $z$ to vary as in Fig. 3d. Here, we observe that the lowest error corresponds to the region $p_c \approx 0.13, \nu \approx 1.5$. Moreover, we can examine our assumption about the conformal symmetry of the transition, by fixing $p_c = 0.13$, and allowing $\nu$ and $z$ to vary as in Fig. 3d. Here, we observe that the lowest error corresponds to the region $p_c \approx 0.13, \nu \approx 1.5$. Using the obtained estimates, namely, $\nu \approx 1.5, z \approx 1$, and $p_c \approx 0.13$, in the inset of Fig. 3b we collapse the three curves of $L^2 \lambda$ as a function of $p = (p - p_0) L^{- \nu z}$. In the “Methods” section, we search simultaneously over all three parameters and find that the best estimates for the critical data are in the region $p_c \approx 0.14 \pm 0.03, z \approx 0.9 \pm 0.15$, and $\nu \approx 1.5 \pm 0.3$. Once the error margins are considered, these results are consistent with the results obtained from the half-chain entanglement entropy, $z = 1, p_c = 0.16$, and $\nu \approx 1.3 - 1.5$. However, in order to differentiate this phase transition from the percolation phase transition, more precise results for the critical exponents are required. Additionally, we verify our learning results by comparing them with the results obtained from exact simulations of $S_c(t)$, where we demonstrate that by increasing $L, t_d$ and $N_c$, the phase transition parameters can be determined more accurately.

### Scalability of learning

An important feature of a practical decoder is the possibility of training it on small circuits and then utilizing it for decoding larger circuits. Here, due to the approximate locality of the temporal evolution of the random hybrid circuits, one can examine the scalability of the decoders in a concrete manner. For a given circuit with $L$ qubits, we
generate smaller circuits with \( L_B < L \) number of qubits which have identical gates as the original circuit in a rectangular narrow strip around the middle qubit which is entangled to the reference qubit. The geometry of the two sets of circuits is displayed in Fig. 4a where the depth of the two sets of circuits is chosen to be equal. Here, for each \( p \) we generate \( N_c \) large circuits with \( L = \{32, 64\} \) and \( T = 10 \)-time steps. We also only consider those circuits that are learnable using measurement outcomes from the original circuit. Each point in these curves has a statistical error <2%. b Predicting the decoder function of a circuit using the neural network trained by the measurement outcomes inside the small circuit in the orange box. c Inverse fitting error as a function of \( \nu \) and \( p_c \) for \( z = 1 \). d Inverse fitting error as a function of \( \nu \) and \( z \) for \( p_c = 0.13 \). In c and d yellow areas show the best parameter estimates for the phase transition.

**Fig. 4 | Scalability analysis of the learning procedure.** a Predicting the decoder function of a circuit using the neural network trained by the measurement outcomes inside the small circuit in the orange box. b Fraction of experiments that can be learned using smaller circuits of width \( L_B \). When the ratio is 1, that means that there is no benefit in the training from increasing \( L_B \). Main: \( L = 64 \) and \( N_c = 100 \). Inset: \( L = 32 \) and \( N_c = 200 \).

In Fig. 4b, by increasing \( L_B \) the ratio of the circuits that can be learned by the smaller circuits’ NNS increases. Also, consistent with the effective light-cone picture, we see that for both system sizes, \( L = \{32, 64\} \), the largest required \( L_B \) to reach almost full efficiency, according to the light cone condition can be determined by \( L_B \geq 2T \) which in our case corresponds to \( L_B = 20 \). This demonstration provides evidence that independent of the system size, the light-cone-trained NNS can be used for learning larger circuits.

**Generalization to Haar random circuits**

To benchmark the methods, we have focused on Clifford circuits, which have two important simplifications for our learning procedure. First, the purification axis is independent of the measurement outcomes and the learning only needs to be performed along one of the
Quantum dynamics

The dynamics of hybrid circuits considered in this work in general can be described using the quantum channel formalism. The wave function of the circuit, denoted by $|\psi_t\rangle$ at the beginning of time evolution is entangled to a reference qubit. Formally, the time evolution of the system under this setting can be modeled using Kraus operators:\(^{64-66}\)

$$K_m = U_t P_{m_t} \cdots U_1 P_{m_1}$$

where $m_t, U_t$ and $P_{m_t}$ denote the measurement outcomes, unitary gates, and projective measurements at the $t$th layer of the circuit, respectively. We also denote the set of all measurement outcomes in different layers via $\mathcal{T}$. The corresponding expectation of the density matrix, $\rho$, can be described via the following quantum channel:

$$\mathcal{N} (\rho) = \sum_m K_m \rho K_m^\dagger \otimes |m\rangle \langle m|.$$  

(6)

For our purpose, to generate the quantum trajectories we need to consider the time evolution of the system at the level of the wave functions. Under an arbitrary unitary operator $U$, the wave function evolves as

$$|\psi\rangle \rightarrow U |\psi\rangle.$$  

(7)

For projective measurements, we consider a complete set of orthogonal projectors with eigenvalues labeled by $m$ satisfying $\sum_m P_{m_t} = 1$ and $P_{m_t}^2 = \delta_{nm} P_{n_t}$ under which the wave function evolves as

$$|\psi\rangle \rightarrow \frac{P_{m_t} |\psi\rangle}{||P_{m_t} |\psi\rangle||}.$$  

(8)

In simulating the time evolution of the wave functions, we use random unitaries sampled from the Clifford group where, under any conjugation operation, the Pauli group is mapped to itself.\(^{67}\) Such circuits, according to the Gottesman–Knill theorem, can be classically simulated in polynomial times in the system size\(^{68,69}\).

Implementation of deep learning algorithms

In this work, we mainly used convolutional neural networks for learning the decoder function. These networks are composed of several interconnected convolutional and pooling layers. The convolutional layer uses the locality of the input data to create new features from a linear combination of adjacent features through a convolution process. These layers are followed by pooling layers which reduce the number of features. Finally, a fully connected layer is used to associate a label to the newly generated features, thus classifying the data. These layers can be repeated a number of times for more complicated input
data. Our neural network architecture symbolically displayed in Fig. 1b consists of eight layers whose hyperparameters are chosen by an empirical parametric search to optimize the performance accuracy when the number of training samples are smaller than $5 \times 10^5$. From left to right these layers include: (1) a convolutional layer with $L_q/2$ filters where $L_q$ is the number of qubits with a kernel size of $4 \times 4$, and a stride size of $1 \times 1$ with a rectified linear unit (ReLU) activation function, (2) a convolutional layer with a $L_d/2$ filters where $L_d$ is the number of qubits with a kernel size of $3 \times 3$, and a stride size of $1 \times 1$ with a ReLU activation function, (3) a maximum pooling layer with a window size of $2 \times 2$ to decrease the dimension of the input data, (4) a dropout layer with a dropping rate of $r_\delta = 0.2$ to prevent overfitting, (5) a flattening layer to convert the data into a one-dimensional vector, (6) a dense fully connected layer with a sigmoid activation function which dictates the prediction for the spin of the reference qubit. Finally, since we have a classification problem, the loss function for comparing the predicted labels and the actual labels is a binary cross-entropy function. Using this loss function, for training our neural network model, we use the Adam optimization algorithm with a learning rate $\eta = 0.001$. The implementation of our neural network layers and their parameters is done by the Python deep-learning packages TensorFlow and Keras.

**Scaling analysis and estimation of critical exponents**

The critical exponents of this measurement-induced phase transition can be investigated from the decay rate of the reference qubit’s entanglement entropy denoted by $\lambda$, which has the scaling (see Eq. (3))

$$\lambda = f(p - p_c)L^{-v/z}.$$  \hspace{1cm} (9)

While in the main text, we fixed $z=1$ based on the assumption of conformal invariance, here, we perform the analysis with $z$ allowed to vary. To find the best combination of the critical data that collapses our data according to this ansatz, we compare the normalized mean squared errors (NMSE), $\varepsilon_{\text{NMSE}}$ such that the best fit is obtained when $\varepsilon_{\text{NMSE}}$ is maximized. In particular, for a given $p_c$, $v$, and $z$, using cubic polynomials we first find the regression curve of $y = L\lambda$ as a function of $(p-p_c)\ell^z$, and then we evaluate the corresponding value of the mean squared error between $y$ and the best-fitted value of $y$. We point out that in order to compare mean squared errors for different combinations of $(p_c, v, \ell)$, we have to normalize the data by defining dimensionless deviations and then evaluate the NMSE for different combinations of critical data according to $\varepsilon_{\text{NMSE}} = \sum L^{-1}c_{p_c}/C_0$ where the summation is performed over data for all the measurement rates and system sizes.

The results of this analysis are displayed in Fig. 6, where we have plotted $\varepsilon_{\text{NMSE}}^{-1}$ as a function of $v$ and $p_c$ for six different values of $z$ ranging from 0.75 to 1.25. Based on the subplots in this figure, we observe that the highest values for $\varepsilon_{\text{NMSE}}$ are obtained for $z = 0.85 \pm 0.05$ which is quite close to the value expected from theoretical results based on conformal symmetry $z = 1$. Allowing $\varepsilon_{\text{NMSE}}^{-1}$ to vary within almost 10% of its maximum value, we obtain following range for the best fits of the critical data, $\lambda_c = 0.14 \pm 0.03$, $v = 1.5 \pm 0.3$, and $z = 0.9 \pm 0.15$.

Finally, we compare our results with the results obtained directly from exact numerical simulations of Clifford circuits without employing our learning scheme. The results of such simulations for the decay rates for different system sizes have been displayed in Fig. 7. In the left subplot we have shown the results for the same system sizes as used for our learning simulations where we observe a crossing of the curves at $p_c \approx 0.13$ which supports our results obtained from the learning scheme. Furthermore, in the right subplot we observe that for larger system sizes, the obtained crossing of the curves is around $p_c \approx 0.16$ which is very close to the results obtained from half-chain entanglement entropy$^{55}$. Accordingly, we expect that by increasing $L$ and $N_c$, the estimates obtained from our learning scheme should improve.

**Key measurements in Clifford circuits**

Consider a hybrid Clifford circuit $\mathcal{C}$ which has $M$ Pauli measurements. Imagine applying this circuit on an initial stabilizer state which is...
entangled to a reference qubit. Assume that as a result of this, the reference qubit disentangles and purifies into the $|P; p_R\rangle$ state, where $P$ is one of the Paulis and $p_R = \pm 1$ determines which eigenvector of $P$ the reference qubit has been purified into. Let $s_1, \ldots, s_M = \pm 1$ denote the measurement outcomes for a single run of the circuit. If we run the same circuit again, the ancilla will purify in the same basis $P$, but we may get different $p_R$ as well as different $s_i$. The goal is to understand the relation between the value of $p_R$ and the measurement outcomes $|s_j\rangle_{j=1}^M$.

When a Pauli string is measured on a stabilizer state, the result is either predetermined (in case the Pauli string is already a member of the stabilizer group up to a phase) or it is $\pm 1$ with equal probability. We call the former determined measurements and the latter undetermined measurements. Note that in a stabilizer circuit, whether a measurement is determined or undetermined is independent of previous measurement outcomes. Therefore, for a given circuit $c$ and a fixed ordering of performing measurements, it is well-defined to label measurements as either determined or undetermined without referring to a specific circuit run.

The following is a straightforward result of the Gottesmann–Knill theorem:

**Corollary.** There exists a unique subset of undetermined measurement results $\{s_{j_1}, \ldots, s_{j_M}\}$ (which we call key measurements) such that,

$$p_R \times s_1 \times s_2 \times \cdots \times s_m = c$$

(10)

where $c = \pm 1$ is the same for all circuit runs. We call this set the key measurements set.

Note that since key measurements are undetermined measurements, their value are independent of each other. Hence, to predict $p_R$ from undetermined measurement outcomes with any accuracy better than $1/2$, one needs to have access to all key measurement results.

Each determined measurement can be seen as a constraint between previous undetermined measurement outcomes. Specifically, if $s_j$ is a determined measurement result for some $j$ it means that there is some fixed $c' = \pm 1$ (independent of circuit run) and a subset of undetermined measurements $\{s_{j_1}, \ldots, s_{j_M}\}$ such that

$$s_j \times s_{j_1} \times \cdots \times s_{j_M} = c'$$

(11)

The similarity to the Corollary is not accidental: if the reference qubit is purified in the $P$ Pauli basis, it means that measuring it in the $P$ basis would be a determined measurement.

The existence of these constraints then means that if we relax the condition of the measurements being undetermined in Corollary, then the set of key measurements is no longer unique; we may be able to

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**Fig. 7** | Simulated (not learned) entanglement entropy rate $\lambda$. Entanglement entropy rate calculated by exact stabilizer simulation of Clifford circuits is obtained for different system sizes as a function of the measurement rate. The crossing point of the scaled decay rates represents the critical measurement rate. (Left) The reference qubit disentangles and purifies into the $|P; p_R\rangle$ state, where $P$ is one of the Paulis and $p_R = \pm 1$ determines which eigenvector of $P$ the reference qubit has been purified into. Let $s_1, \ldots, s_M = \pm 1$ denote the measurement outcomes for a single run of the circuit. If we run the same circuit again, the ancilla will purify in the same basis $P$, but we may get different $p_R$ as well as different $s_i$. The goal is to understand the relation between the value of $p_R$ and the measurement outcomes $|s_j\rangle_{j=1}^M$.

**Fig. 8** | Sampling complexity for scrambled initial states using all mid-circuit measurements. Average of the minimum number of training samples required for learning the reference qubit’s state when using circuits with scrambled initial states is plotted after conditioning on the purification time $t_p$, for $p = 0.1$ (mixed phase) and $p = 0.3$ (pure phase). Averaging is performed over $N_c = 20$ circuits for each $t_p$ and error bars are set according to the standard deviation. We have circuits with $L = 128$ qubits. In the main plot measurement outcomes from inside the fixed light-cone box are used for training while for the inset we use the measurement outcomes from the whole circuit.
although we do not have the explicit form of $\eta$ averaged minimum number of training samples in Fig. 2b. Therefore, by integrating the information in Fig. 2a and b plus $M$, we employ a simplifying assumption that is approximately consistent with the exponential behaviors of the complexity as a function of the learning efficiency for the learnability of our decoder, we expect that during the initial fast growth of the curves in Fig. 2a, learned circuits mostly require more training samples than the circuits with product state initial conditions. However, this quantity can be evaluated by inverting the function $M(t)$ according to $r^\text{max}(N_t) = M^{-1}(t)$ where $M^t(N_t)$ is the inverse function of $M(t)$. Now, we notice that $M(t)$ after averaging over different circuits, can be read from the averaged minimum number of training samples in Fig. 2b. Therefore, by integrating the information in Fig. 2a and b plus $\eta(t, N_t)$, one can explain the behavior of $R(N_t)$ in Fig. 2d. Here, although we do not have the explicit form of $\eta(t, N_t)$, we use the step-like behavior as an approximation which is justifiable due to the exponential behaviors of the complexity as a function of the purification time. Thus, using Eq. (12) as a plausible approximation for the learnability of our decoder, we expect that during the initial fast growth of the curves in Fig. 2a, learned circuits mostly belong to the circuits with short purification times. However, since for longer purification times, an exponentially large number of training samples is required, the initial exponential growth is followed by a slow learning curve. Therefore, in Fig. 2d, we observe that deep in the pure phase where the majority of circuits have a short purification time, $R_t$ asymptotically approaches one.

**Relation between conditional and unconditional learning schemes**

Here, under certain conditions, we argue that the results of the two learning schemes as displayed in Fig. 2 are related to each other. In particular, using the purification-time distribution of the circuits in Fig. 2a, learnability $R_t(N_t)$ is related to the purification ratio $r_p(t_p)$. In what follows to make our analysis more intelligible, we assume that the learning error is nearly vanishing, $e_l \approx 0$. Next, we need to study the averaged learning efficiency of our decoder which for a given $t_p$ and $N_t$ we denote by $\eta(t_p, N_t)$. For a given $t_p$ and $N_t$, this quantity is related to the averaged inaccuracy introduced in the text by $\eta = 1 - e_l$. To proceed, we employ a simplifying assumption that is approximately consistent with our numerical results. More concretely, we imagine a decoder with a sharp step-like behavior for $\eta(t_p, N_t)$ as a function of $N_t$. Using the Heaviside theta function $\delta(t)$, we suppose $\eta(t_p, N_t) = \theta(t_p - M(t_p))$ where $M(t_p)$ is the minimum number of training samples to reach full efficiency for $t \leq t_p$. From the definitions, it follows straightforwardly that

$$R_t(N_t) = \sum_{t_p=1}^{r^\text{max}(N_t)} r_p(t_p), \quad (12)$$

where $r^\text{max}(N_t)$ is the maximum purification time that can be learned for a given $N_t$. However, this quantity can be evaluated by inverting the function $M(t)$ according to $r^\text{max}(N_t) = M^{-1}(t)$ where $M^t(N_t)$ is the inverse function of $M(t)$. Now, we notice that $M(t)$ after averaging over different circuits, can be read from the averaged minimum number of training samples in Fig. 2b. Therefore, by integrating the information in Fig. 2a and b plus $\eta(t_p, N_t)$, one can explain the behavior of $R_t(N_t)$ in Fig. 2d. Here, although we do not have the explicit form of $\eta(t_p, N_t)$, we use the step-like behavior as an approximation which is justifiable due to the exponential behaviors of the complexity as a function of the purification time. Thus, using Eq. (12) as a plausible approximation for the learnability of our decoder, we expect that during the initial fast growth of the curves in Fig. 2a, learned circuits mostly belong to the circuits with short purification times. However, since for longer purification times, an exponentially large number of training samples is required, the initial exponential growth is followed by a slow learning curve. Therefore, in Fig. 2d, we observe that deep in the pure phase where the majority of circuits have a short purification time, $R_t$ asymptotically approaches one.
4 on the tails. For more definitive results, we need to consider larger ensembles of circuits with larger $N$, and also increase the system size, which would be beyond the scope of this work.

**Data availability**

Source data for figures in the main text are provided with this paper. Data that support the plots within this paper and other findings of this study are generated and protected by the Extreme Science and Engineering Discovery Environment (XSEDE), at the Pittsburgh Supercomputing Center and are available from the corresponding author upon request. Source data are provided with this paper.

**Code availability**

The code used for this study is available on [https://github.com/Hossein-D/BrickwallCliffordCircuit](https://github.com/Hossein-D/BrickwallCliffordCircuit).

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Author contributions

All authors contributed to this work extensively and to the writing of the manuscript. The computational analysis and simulations have been conducted by the corresponding author.

Competing interests

The authors declare no competing interests.

Additional information

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