Lecture 29, 8 Dec 2020

5-qubit code $M_0, M_1, M_2 M_3$

± 1

7-qubit code N_0, N_1, N_2 M_0, M_1, M_2

"stabilizers"

Surface code

Arbitrarily many stabilizers of the form $Z_a Z_b Z_c Z_d$

$X_a X_b X_c X_d$

$|0000\rangle$ $|1111\rangle$ $|0011\rangle$ $|0101\rangle$

± 1

$X_a X_b X_c X_d$

$|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$

$X|\pm\rangle = \pm|\pm\rangle$

$|++++\rangle$ $|----\rangle$

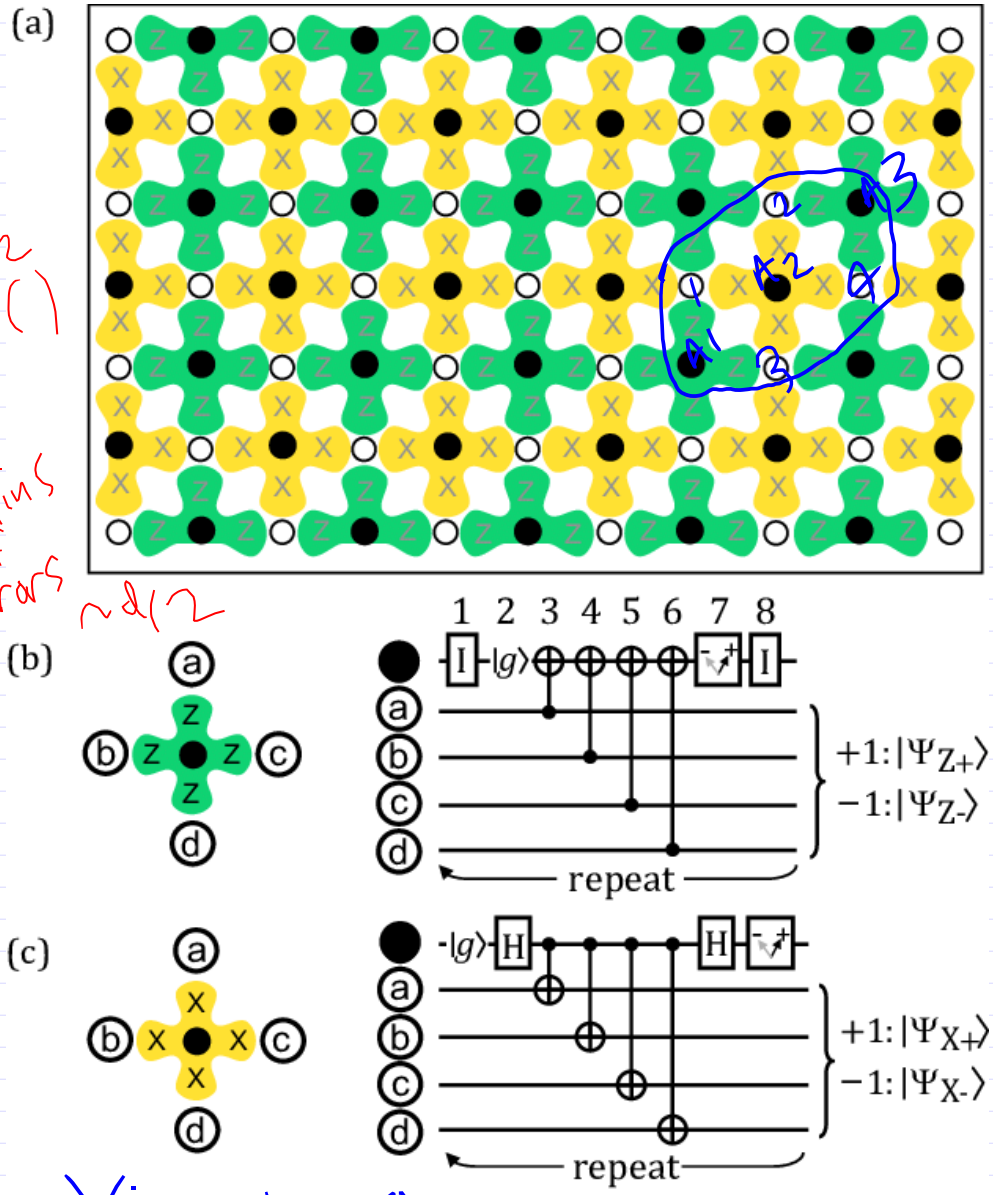
$(+1)$ (-1) $|+-+-\rangle$

need X_L Z_L

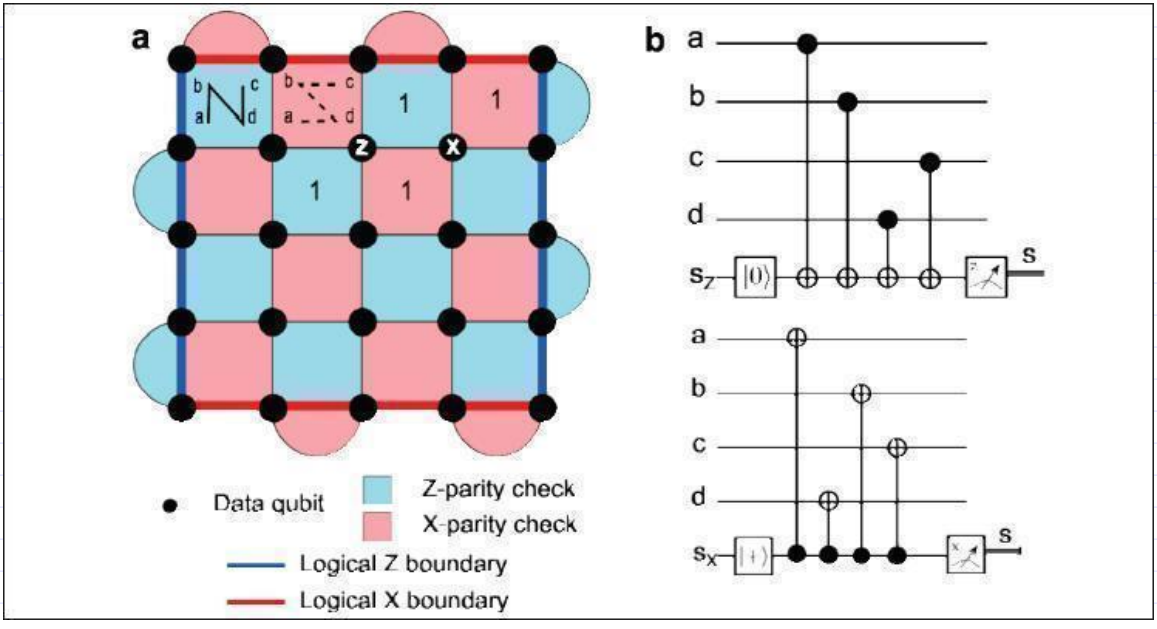
$X_L^2 = Z_L^2 = 1$ $X_L Z_L = -Z_L X_L$

$|\bar{0}\rangle = \bar{Z}_L|\bar{0}\rangle$ $\bar{Z}_L|\bar{1}\rangle$

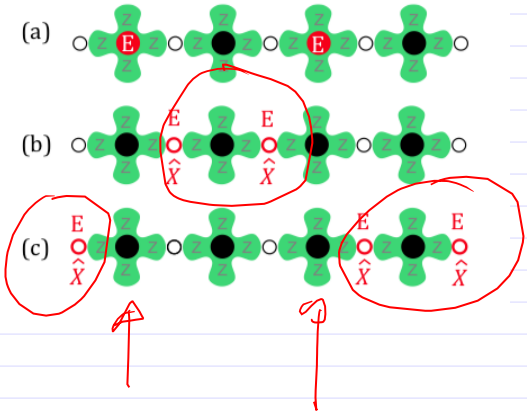
$\bar{X}_L|\bar{0}\rangle = |\bar{1}\rangle$ $= -|\bar{1}\rangle$



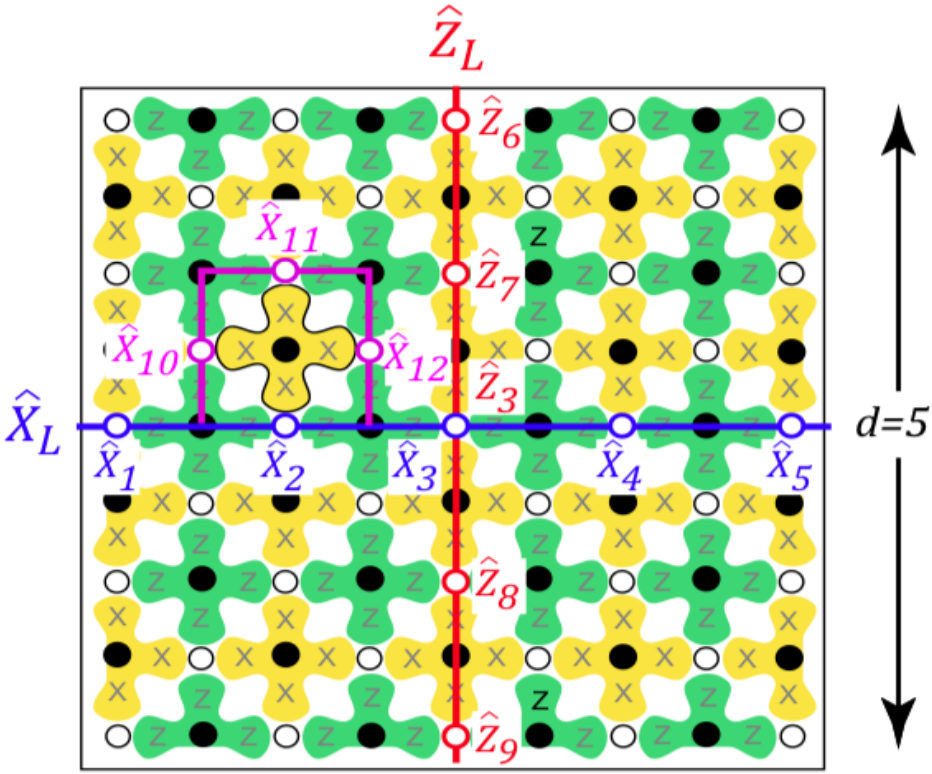
arXiv: 1208.0928

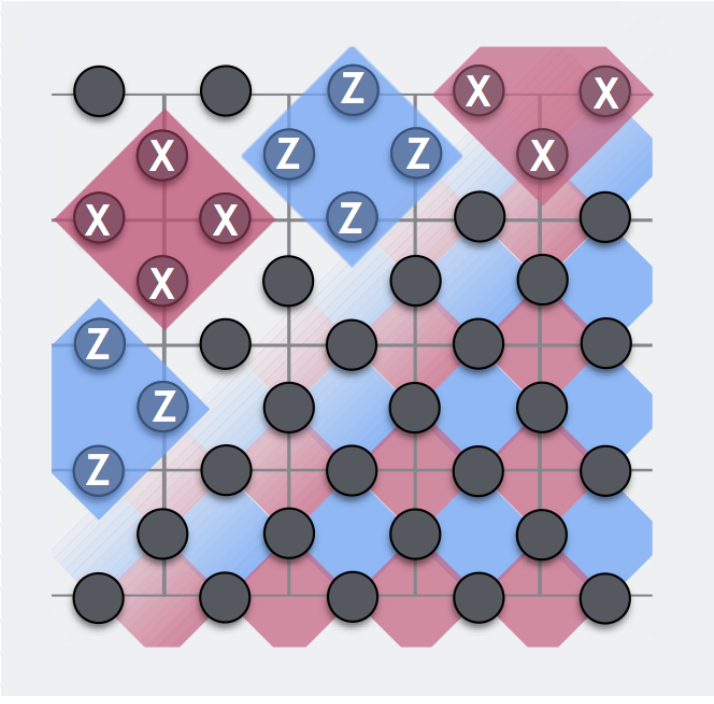

a
b
c
d
1
1
1
1
Z
X
Data qubit
Z-parity check
X-parity check
Logical Z boundary
Logical X boundary
b
a
b
c
d
s_Z
$|0\rangle$
s
a
b
c
d
s_X
$|+\rangle$
s

(IBM group)

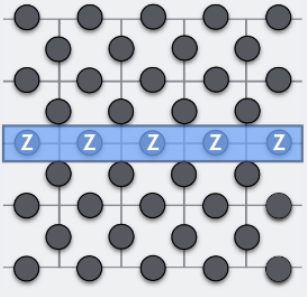


[12] Actually the surface code does not need to completely identify errors; it is sufficient that it identifies errors or chains of errors that are topologically equivalent to the actual errors, meaning any differences can be written as products of stabilizers.

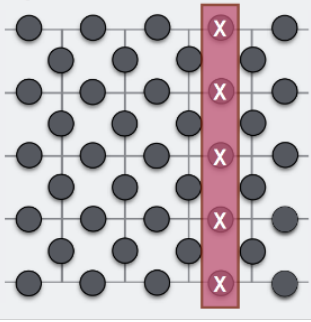

$\hat{Z}_L$
$\hat{Z}_6$
$\hat{X}_{11}$
$\hat{Z}_7$
$\hat{X}_{10}$
$\hat{X}_{12}$
$\hat{Z}_3$
$\hat{X}_L$
$\hat{X}_1$
$\hat{X}_2$
$\hat{X}_3$
$\hat{X}_4$
$\hat{X}_5$
$\hat{Z}_8$
$\hat{Z}_9$
d=5

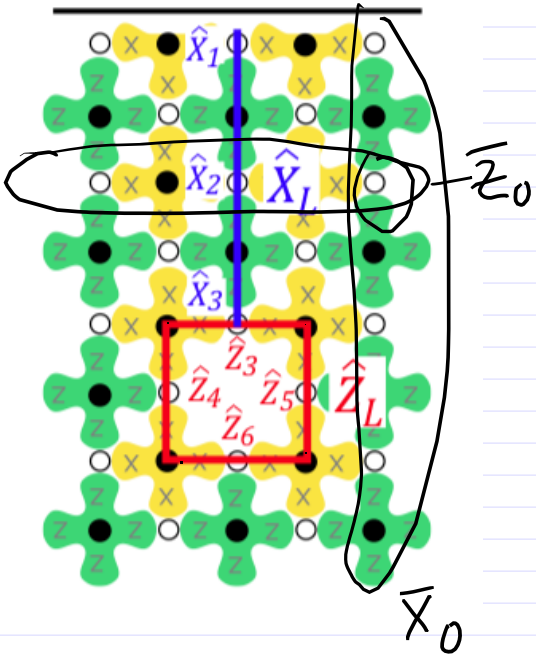


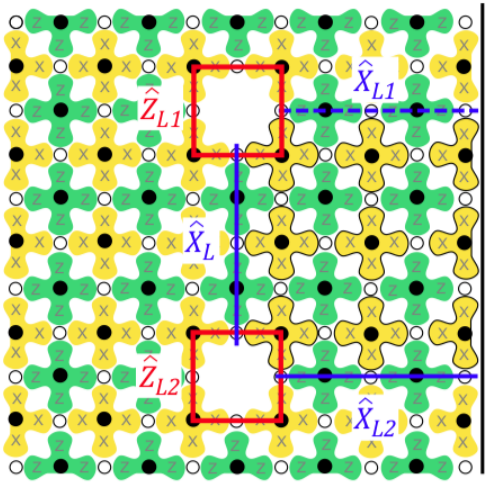
- logical **Z** operator:

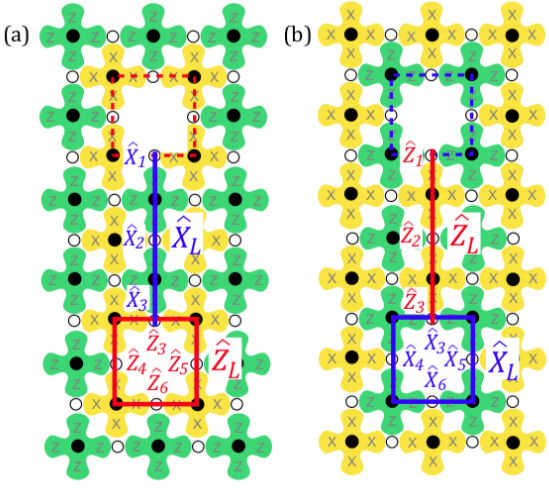


- logical **X** operator:




$\hat{X}_1$
$\hat{X}_2$
$\hat{X}_L$
$\hat{X}_3$
$\hat{Z}_3$
$\hat{Z}_4$
$\hat{Z}_5$
$\hat{Z}_6$
$\hat{Z}_L$
$\bar{Z}_0$
$\bar{X}_0$


$\hat{Z}_{L1}$
$\hat{X}_{L1}$
$\hat{X}_L$
$\hat{Z}_{L2}$
$\hat{X}_{L2}$


(a)
$\hat{X}_1$
$\hat{X}_2$
$\hat{X}_L$
$\hat{X}_3$
$\hat{Z}_3$
$\hat{Z}_4$
$\hat{Z}_5$
$\hat{Z}_6$
$\hat{Z}_L$
(b)
$\hat{Z}_1$
$\hat{Z}_2$
$\hat{Z}_L$
$\hat{Z}_3$
$\hat{X}_3$
$\hat{X}_4$
$\hat{X}_5$
$\hat{X}_6$
$\hat{X}_L$

Repeated Quantum Error Detection in a Surface Code

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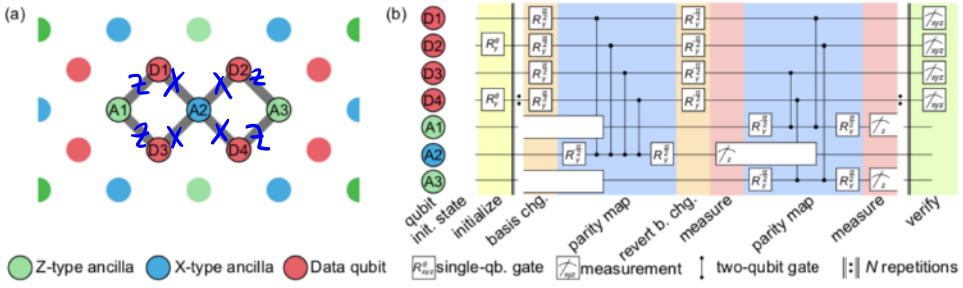
(Dated: December 20, 2019)

The realization of quantum error correction is an essential ingredient for reaching the full potential of fault-tolerant universal quantum computation. Using a range of different schemes, logical qubits can be redundantly encoded in a set of physical qubits. One such scalable approach is based on the surface code. Here we experimentally implement its smallest viable instance, capable of repeatedly detecting any single error using seven superconducting qubits, four data qubits and three ancilla qubits. Using high-fidelity ancilla-based stabilizer measurements we initialize the cardinal states of the encoded logical qubit with an average logical fidelity of 96.1%. We then repeatedly check for errors using the stabilizer readout and observe that the logical quantum state is preserved with a lifetime and coherence time longer than those of any of the constituent qubits when no errors are detected. Our demonstration of error detection with its resulting enhancement of the conditioned logical qubit coherence times in a 7-qubit surface code is an important step indicating a promising route towards the realization of quantum error correction in the surface code.



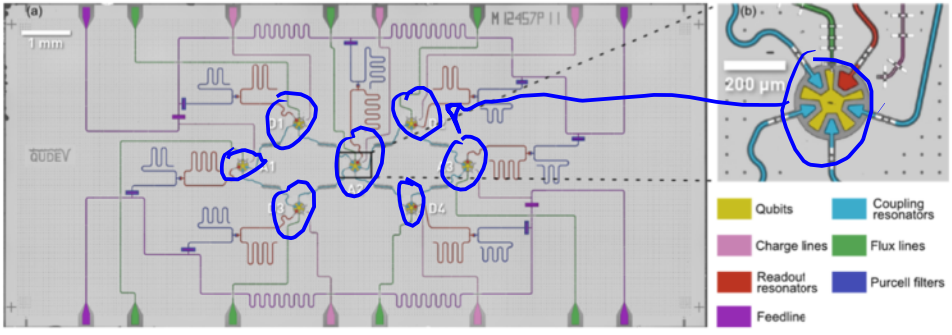


FIG. 2. Seven-qubit device. (a) False colored micrograph of the seven-qubit device used in this work. Transmon qubits are shown in yellow, coupling resonators in cyan, flux lines for single-qubit tuning and two-qubit gates in green, charge lines for single-qubit drive in pink, the two feedlines for readout in purple, transmission line resonators for readout in red and Purcell filters for each qubit in blue. (b) Enlarged view of the center qubit (A2) which connects to four neighboring qubits.

In the surface code, as in any stabilizer code, errors are detected by observing changes in the stabilizer measurement outcomes. Such syndromes are typically measured by entangling the stabilizer operators with the state of ancilla qubits, which are then projectively measured to yield the stabilizer outcomes. The surface code consists of a $d \times d$ grid of data qubits with d^2-1 ancilla qubits, each connected to up to four data qubits [28]. The code can detect $d-1$ errors and correct up to $\lfloor (d-1)/2 \rfloor$ errors per cycle of stabilizer measurements. In particular, the stabilizers of the $d = 2$ surface code, see Fig. 1, are given by

$$X_{D1}X_{D2}X_{D3}X_{D4}, \qquad Z_{D1}Z_{D3}, \qquad Z_{D2}Z_{D4}. \tag{1}$$

For the code-distance $d = 2$, it is only possible to detect a single error per round of stabilizer measurements and once an error is detected, the error can not be unambiguously identified, e.g. one would obtain the same syndrome outcome for an X-error on D1 and on D3.

Here, we use the following logical qubit operators

$$Z_L = Z_{D1}Z_{D2}, \quad \text{or} \quad Z_L = Z_{D3}Z_{D4}, \tag{2}$$
$$X_L = X_{D1}X_{D3}, \quad \text{or} \quad X_L = X_{D2}X_{D4}, \tag{3}$$

such that the code space in terms of the physical qubit states is spanned by the logical qubit states

$$|0\rangle_L = \frac{1}{\sqrt{2}}(|0000\rangle + |1111\rangle), \tag{4}$$
$$|1\rangle_L = \frac{1}{\sqrt{2}}(|0101\rangle + |1010\rangle). \tag{5}$$

To encode quantum information in the logical subspace, we initialize the data qubits in a separable state, chosen such that after a single cycle of stabilizer measurements and conditioned on ancilla measurement outcomes being $|0\rangle$, the data qubits are encoded into the target logical qubit state. In this work, we demonstrate this probabilistic preparation scheme for the logical states $|0\rangle_L$, $|1\rangle_L$, $|+\rangle_L = (|0\rangle_L + |1\rangle_L)/\sqrt{2}$ and $|-\rangle_L = (|0\rangle_L - |1\rangle_L)/\sqrt{2}$ and we perform repeated error detection on these states.

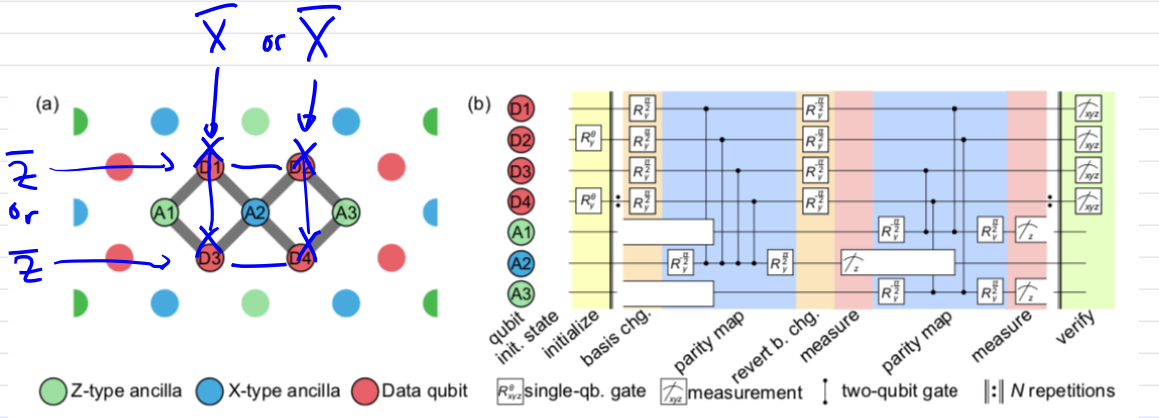


FIG. 1. Seven qubit surface code. (a) The surface code consists of a two-dimensional array of qubits. Here the data qubits are shown in red an the ancilla qubits for measuring X-type (Z-type) stabilizers in blue (green). The smallest surface code consists of seven qubits indicated by the data qubits D1-D4 and the ancilla qubits A1-A3. (b) Gate sequence for quantum error detection using the seven qubit surface code. Details of the gate sequence are discussed in the main text.

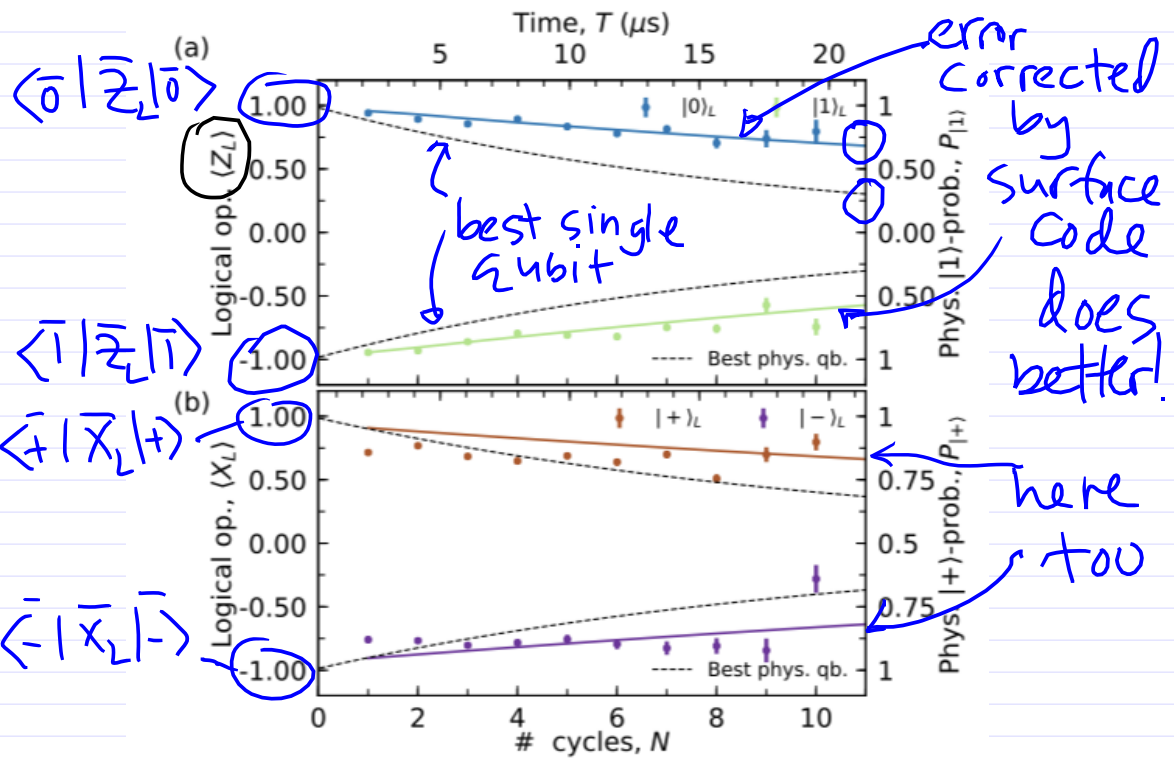


FIG. 5. Repeated quantum error detection. The expectation values of (a) the logical Z_L operator and (b) the logical X_L operator as a function of N, the number of stabilizer measurement cycles. The expectations values are shown for the prepared $|0\rangle_L$ (blue), $|1\rangle_L$ (green), $|+\rangle_L$ (brown) and $|-\rangle_L$ (purple) states. The solid lines indicate the corresponding values obtained from master equation simulations. Also shown (dashed lines, right axis) are the (a) qubit decay of the $|1\rangle$-state with the best measured T_1 value and (b) the physical qubit decay of the $|+\rangle$-state with the best measured T_2 value. (c) Total success probability p_s for detecting no errors during N cycles of stabilizer measurements for the $|0\rangle_L$ data shown in (a) and the corresponding values from numerical simulations. (d) Probability of observing k ancilla qubits in the $|1\rangle$ state for each measurement cycle and conditioned on having detected no error in any of the previous $N-1$ cycles. The data corresponds to the initial $|0\rangle_L$ state presented in (a).

Quantum Supremacy (Oct 2019)

What did they do?

53 qubits, initialized state, and measured...

The unitary to create the state can be specified with linear amount of data,

BUT classically we can't

Calculate (or simulate) the probability distribution of outcomes

53 bits

10110...0110

⋮

010...1101

Why not?

Consider "just" 50 qubits:

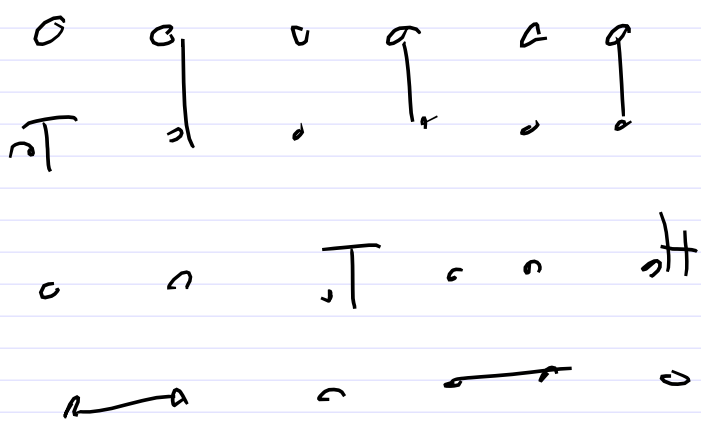
wave function has $2^{50} \sim 10^{15}$ complex components.

Takes order 1 petabyte just to store it.

(And a unitary operator is a matrix with $2^{50} \times 2^{50} \simeq 10^{30}$ entries.)

This "wave-function" sampling is what quantum computers are good at... Can be done without error correction. first example of a calculation where quantum outperforms classical... (though no practical applications)

Next time:
we'll see how they
set up the stereo



and confirm that it
actually works
as claimed.