Quantum State Preparation

Quantum Computers, Quantum Circuits & Measurements

CRC183
ENTANGLED STATES OF MATTER

Simon Trebst
University of Cologne

ML4Q
MATTER AND LIGHT FOR
QUANTUM COMPUTING

Advanced School and Conference on Quantum Matter

Trieste, December 2025

mechanical computer

Inca quipu “device” (7th century), **knot** computing

today

mechanical computer

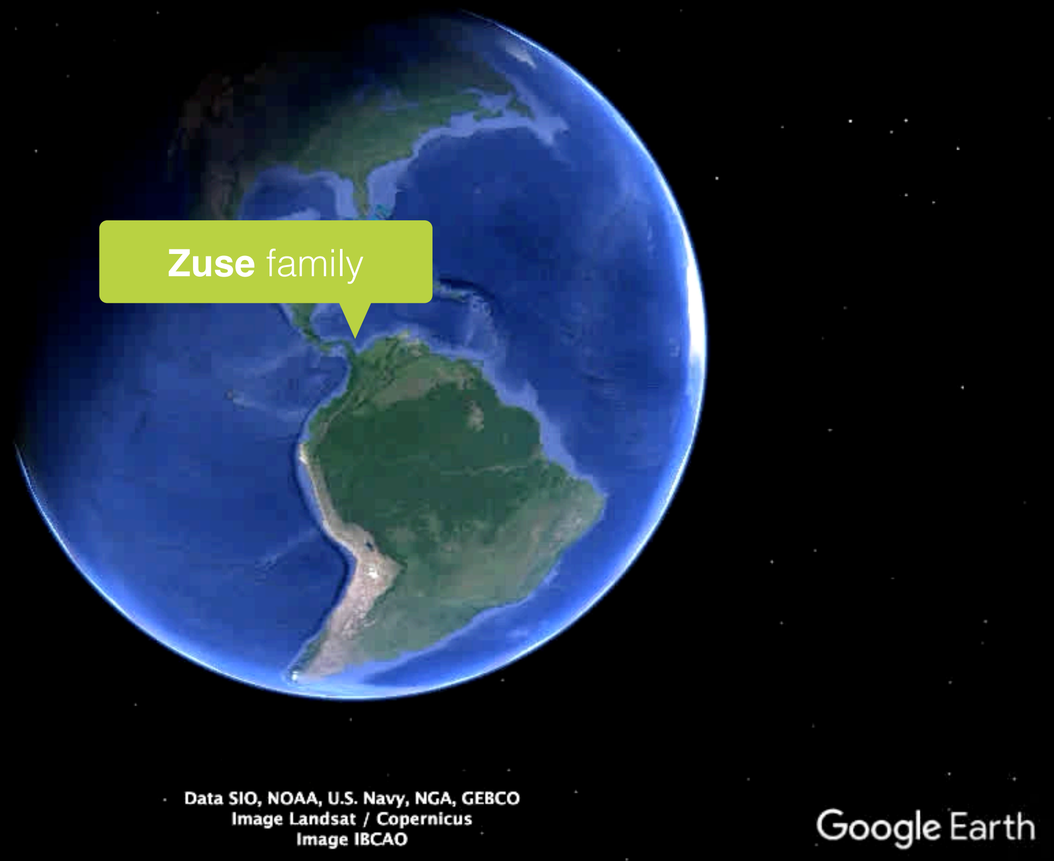
stepped reckoner

mechanical **multiplication** of numbers

Gottfried Wilhelm Leibniz, 1690

mechanical computer

digital computer

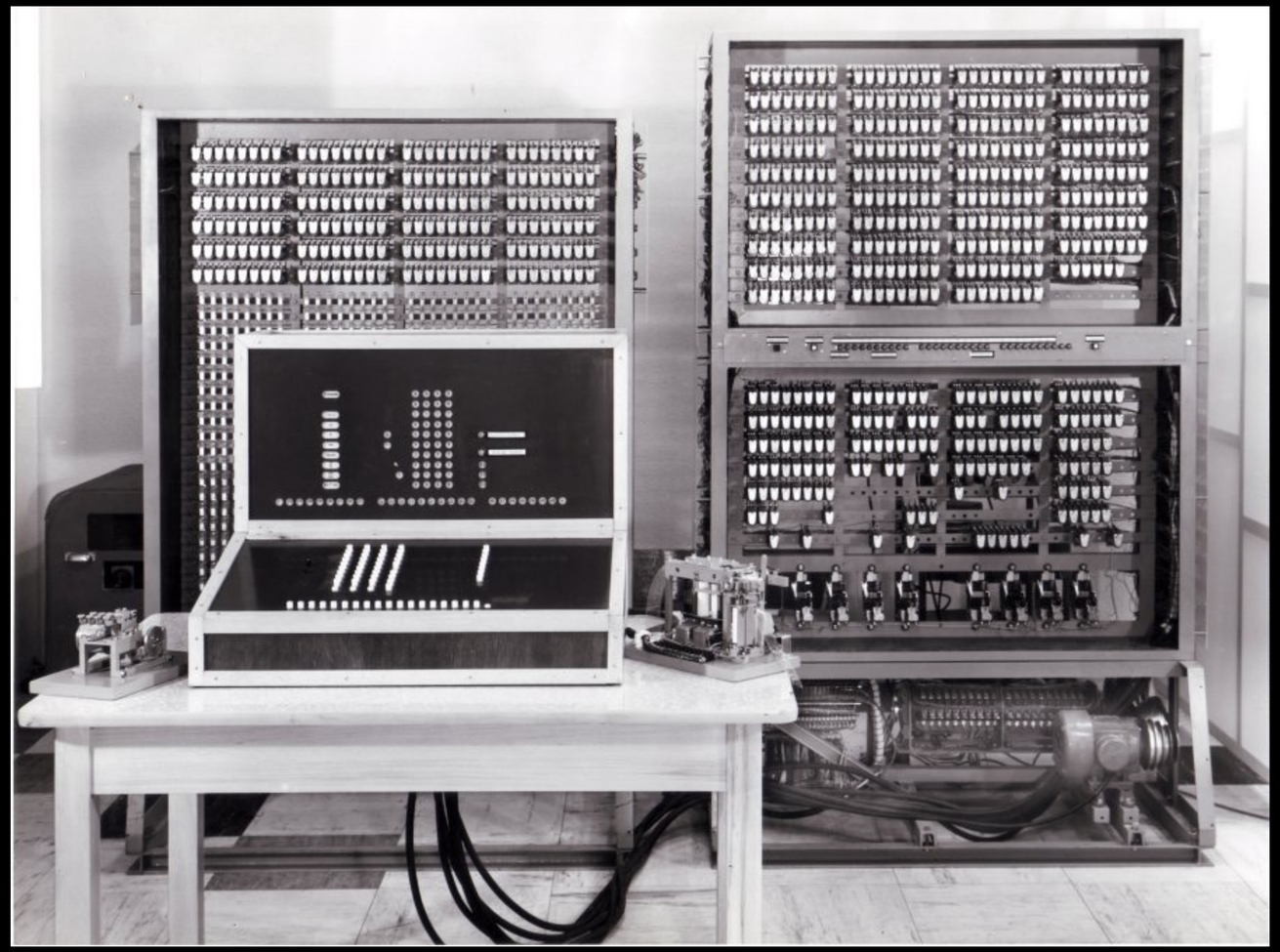


Methfesselstr. 7 in Berlin-Kreuzberg

mechanical computer

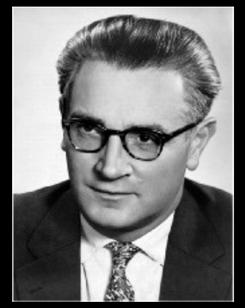
digital computer

Konrad Zuse
(1910-1995)

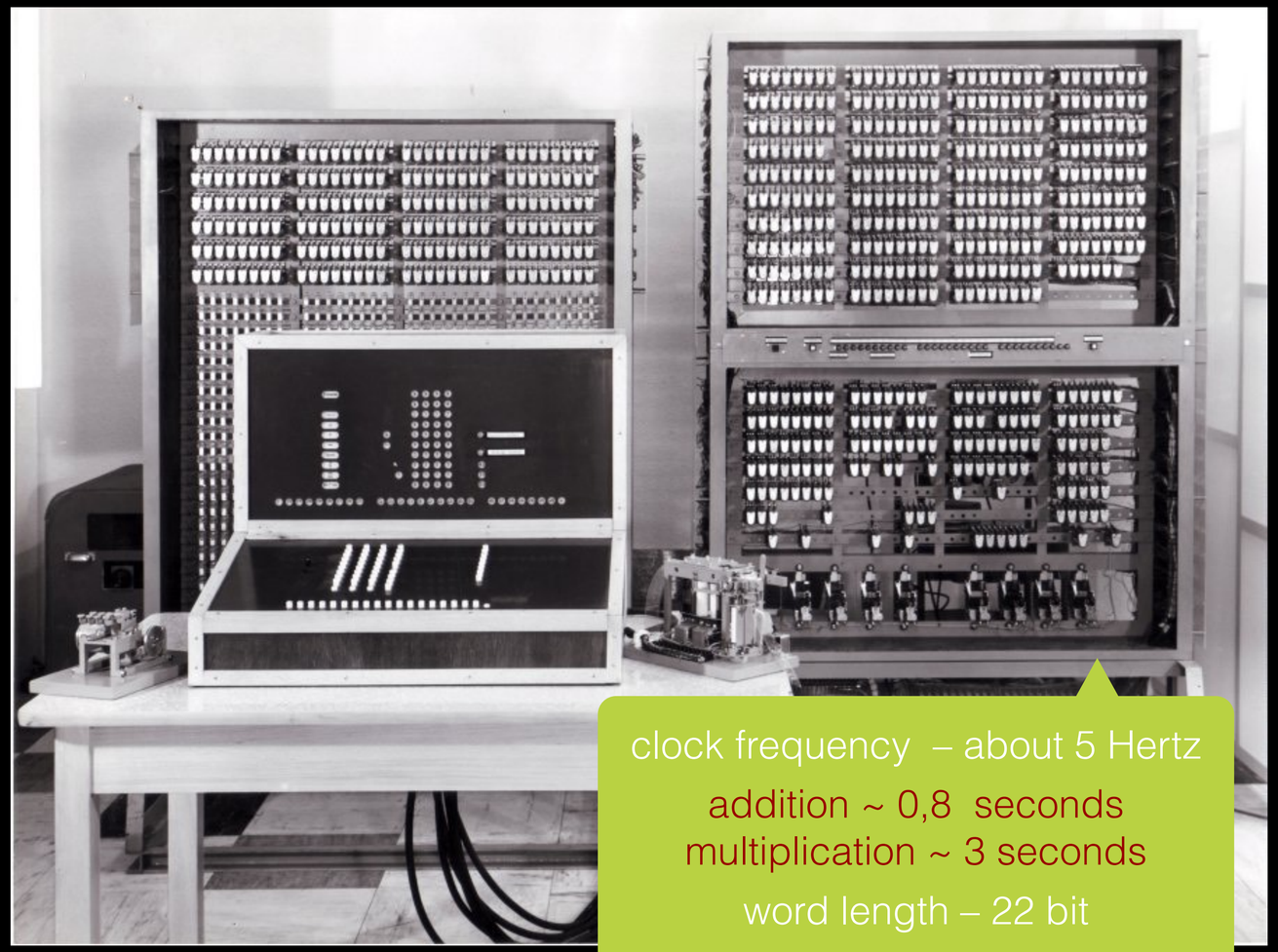


mechanical computer

digital computer



Konrad Zuse
(1910-1995)



clock frequency – about 5 Hertz

addition ~ 0,8 seconds
multiplication ~ 3 seconds

word length – 22 bit

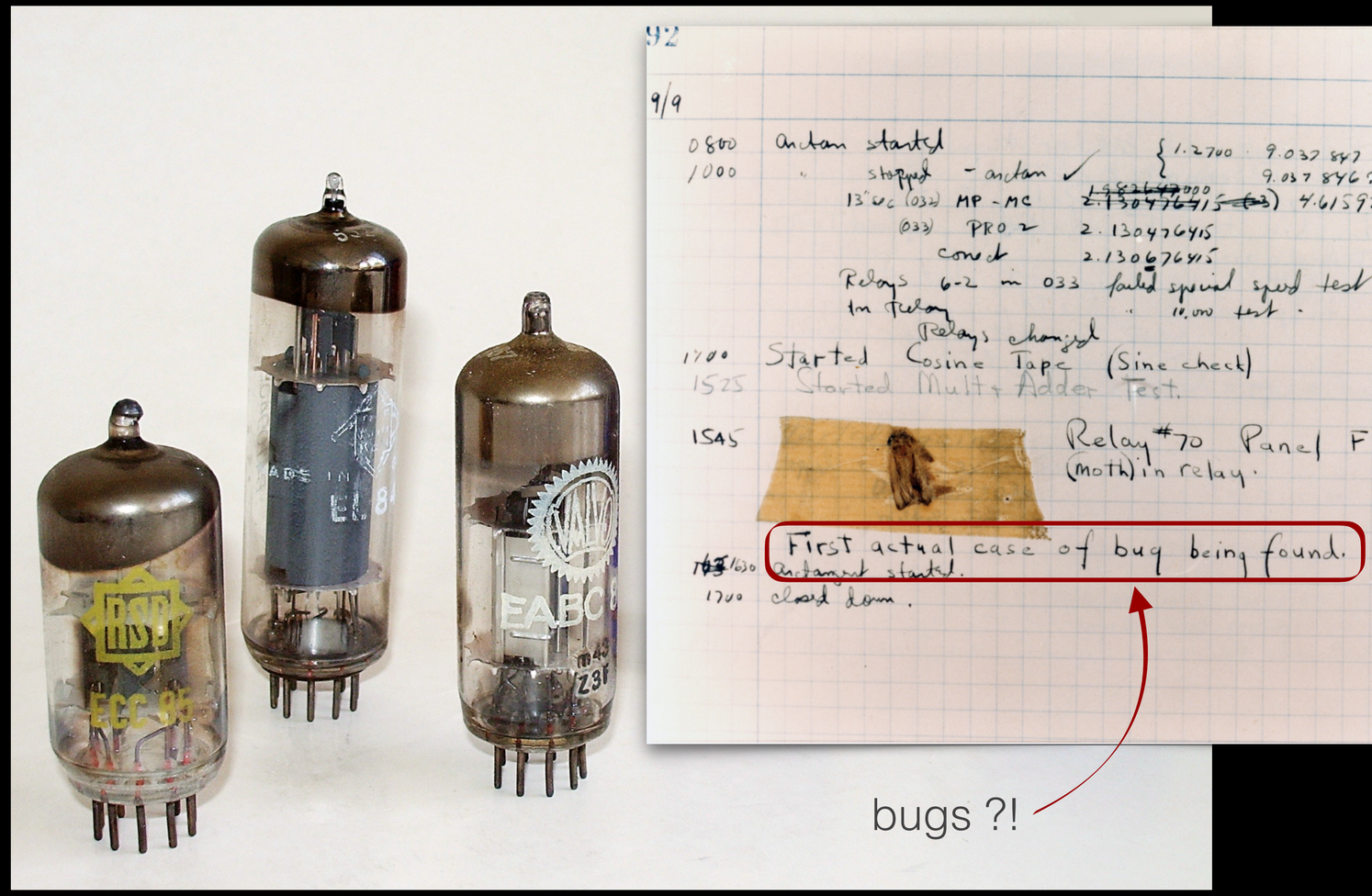
power intake – some 4000W

weight – about 1 ton

mechanical computer

digital computer

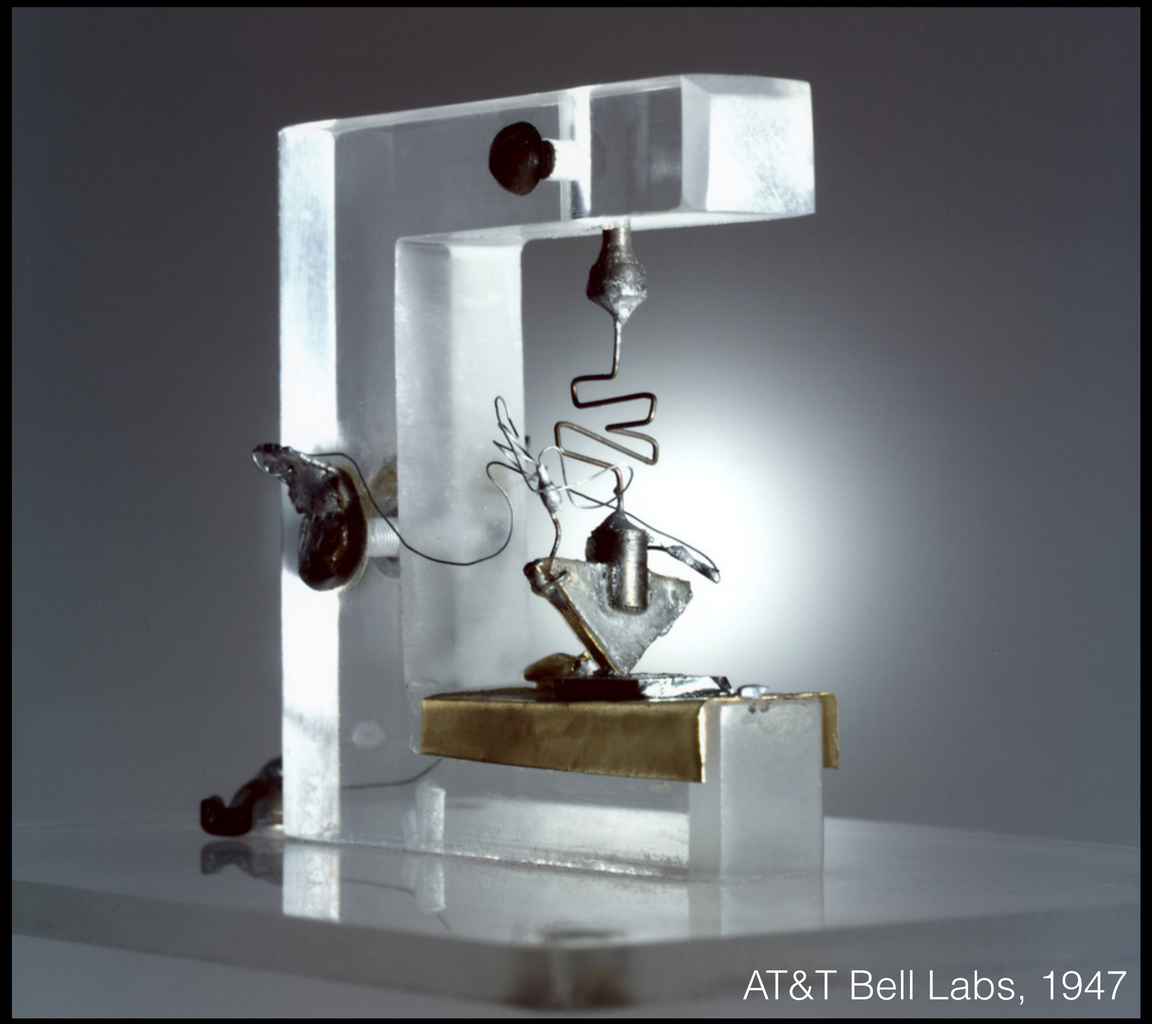
Konrad Zuse
(1910-1995)



vacuum tube computing

mechanical computer

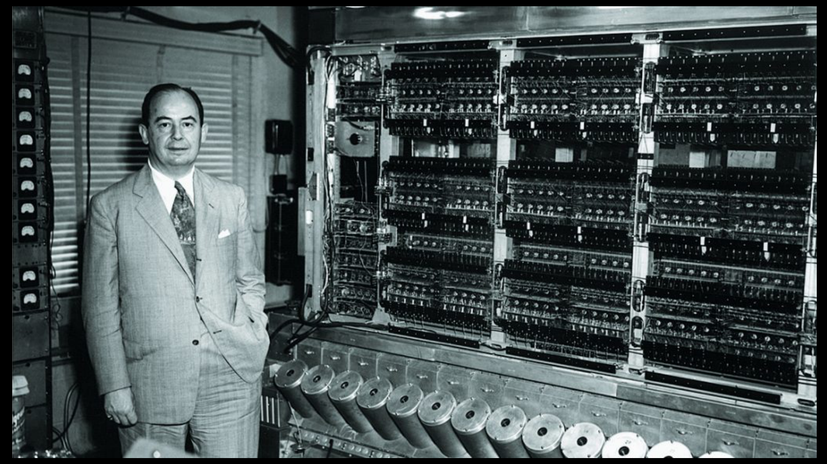
digital computer



transistor

mechanical computer

digital computer



John von Neumann & MANIAC, Los Alamos

Edward Teller & IBM mainframe, Berkeley

Cray X-MP/28 supercomputer, ETH Zürich

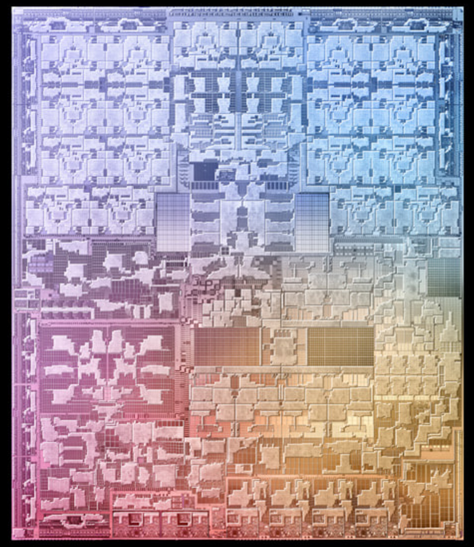
transistor computing

mechanical computer

digital computer

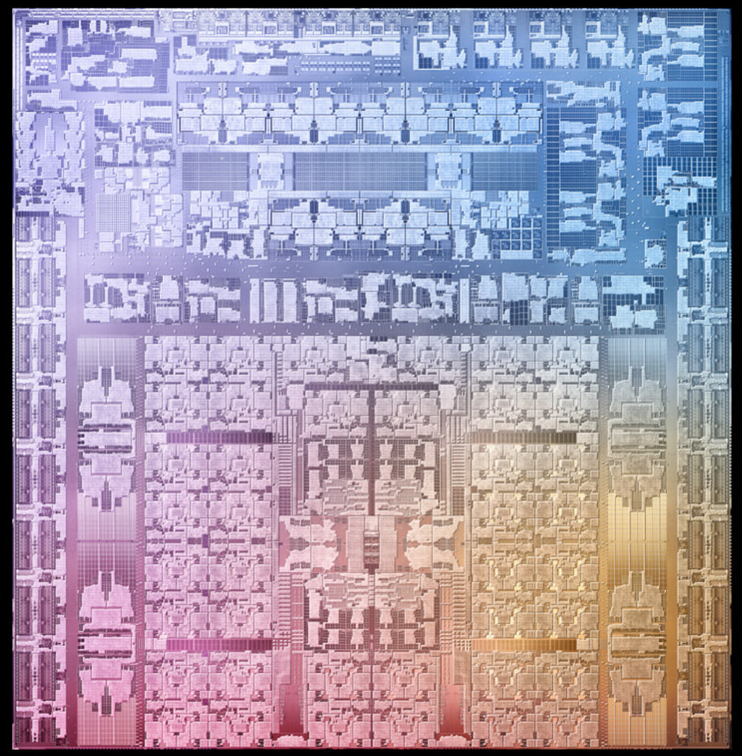
M3

25 billion
transistors



M3 Pro

37 billion
transistors



M3 Max

92 billion
transistors

transistor computing

mechanical computer

digital computer

November 2024, research center Jülich

supercomputer “off the shelf” – JUPITER

mechanical computer analog

digital computer digital

digital revolution

analog quantum simulators

digital quantum computers

mechanical computer

digital computer

analog quantum simulators

Max-Planck Institut for quantum optics, Munich

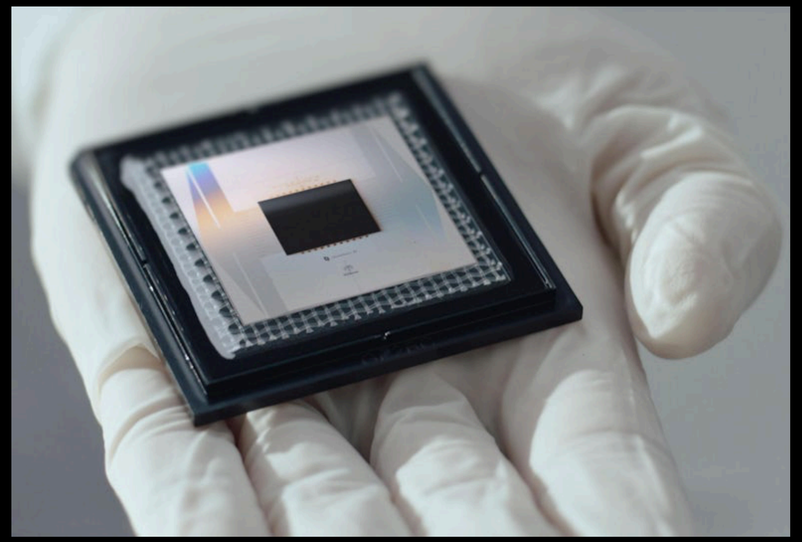
since about 2000

mechanical computer

digital computer

analog quantum simulators

digital quantum computers



Google's Willow chip (December 2024)

Microsoft's Majorana 1 chip (February 2025)

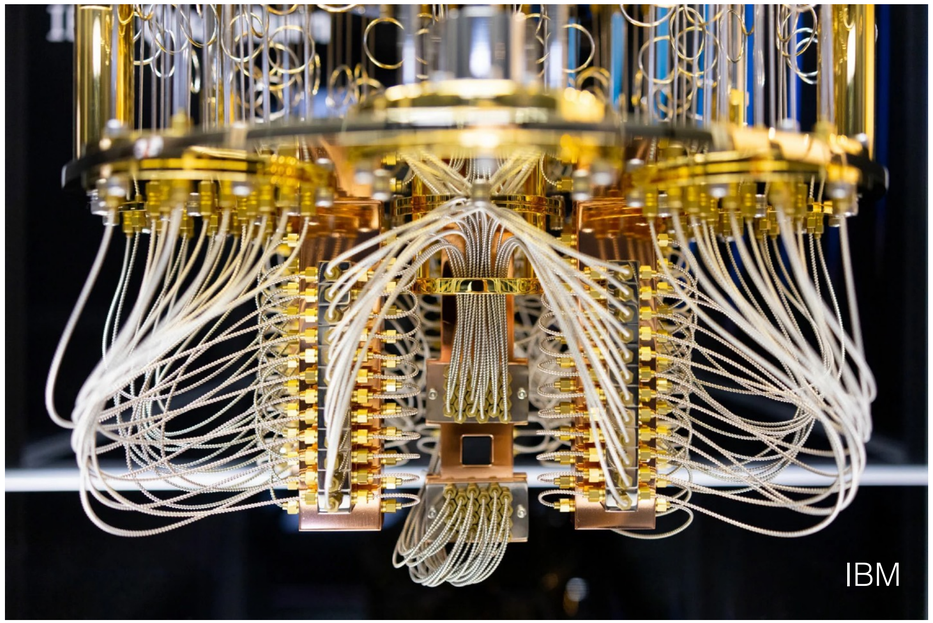
quantum computing today – “NISQ”

An experimental pivot from of a **few pristine qubits**

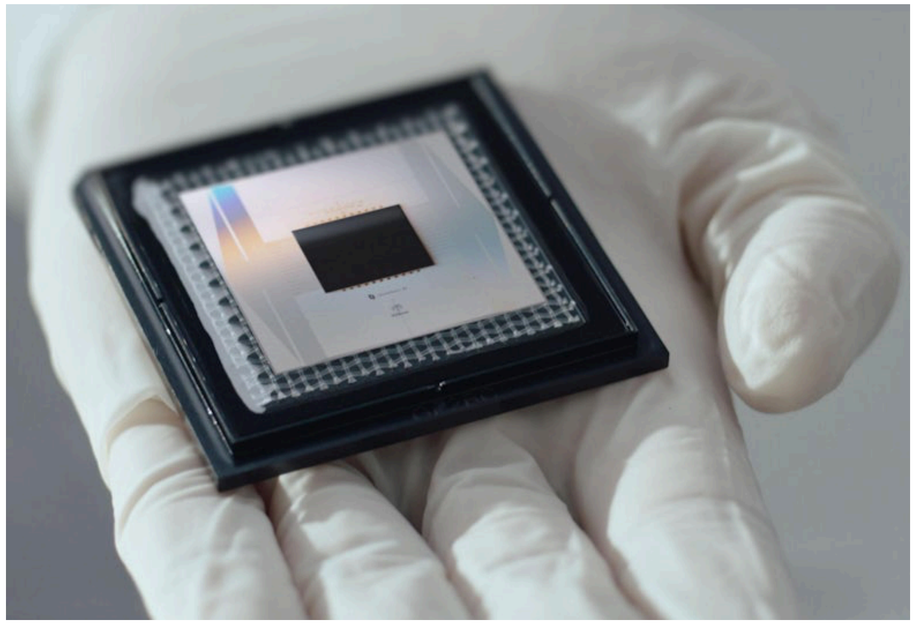
to the realization of circuit architectures of **50 … 1000 qubits**

but tolerating a significant level of **imperfections.**

noisy intermediate scale quantum devices



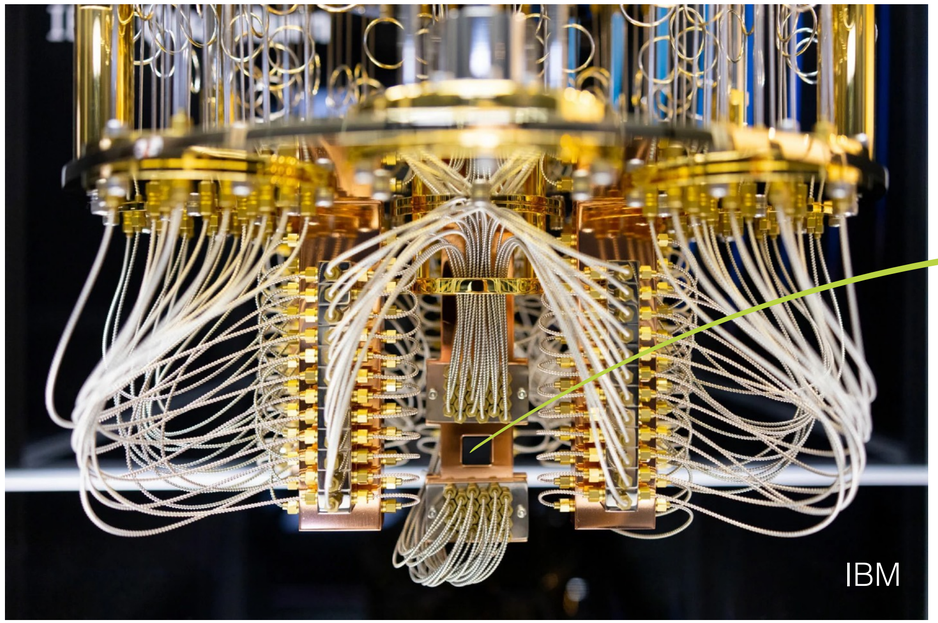
IBM’s Eagle generation — **127 qubits**



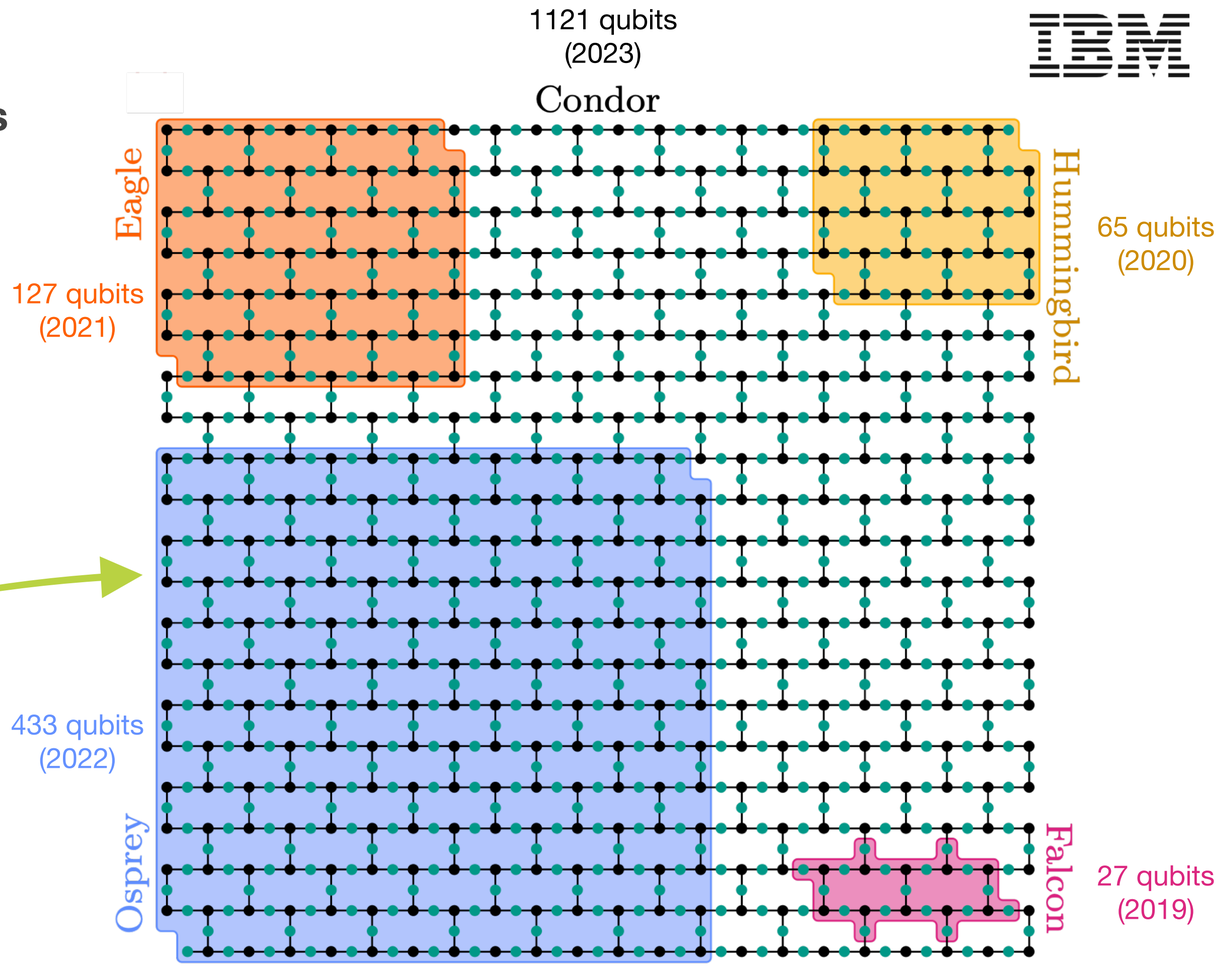
Google’s Willow chip — **105 qubits**

quantum computing today – “NISQ”

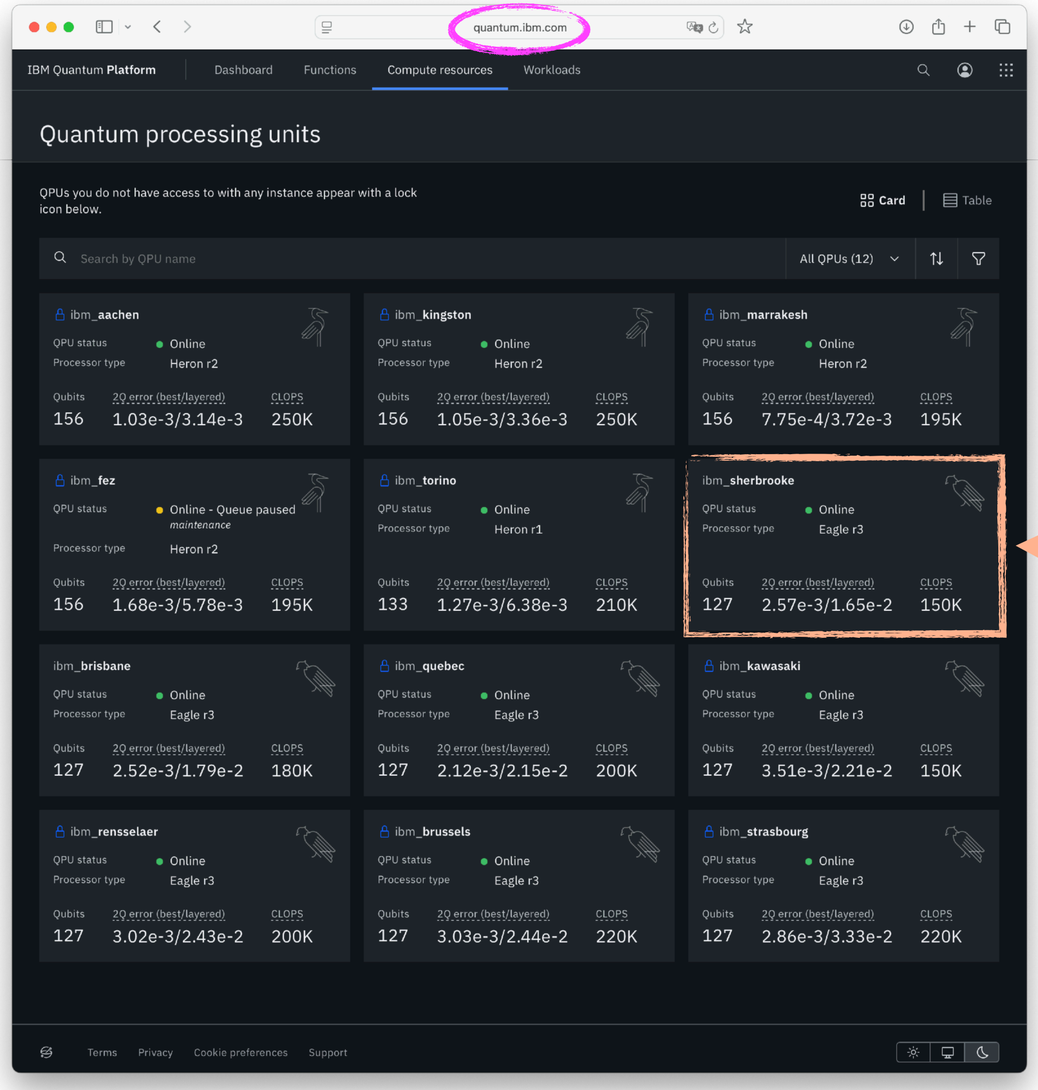
An experimental pivot from of a **few pristine qubits** to the realization of circuit architectures of **50 … 1000 qubits** but tolerating a significant level of **imperfections.**

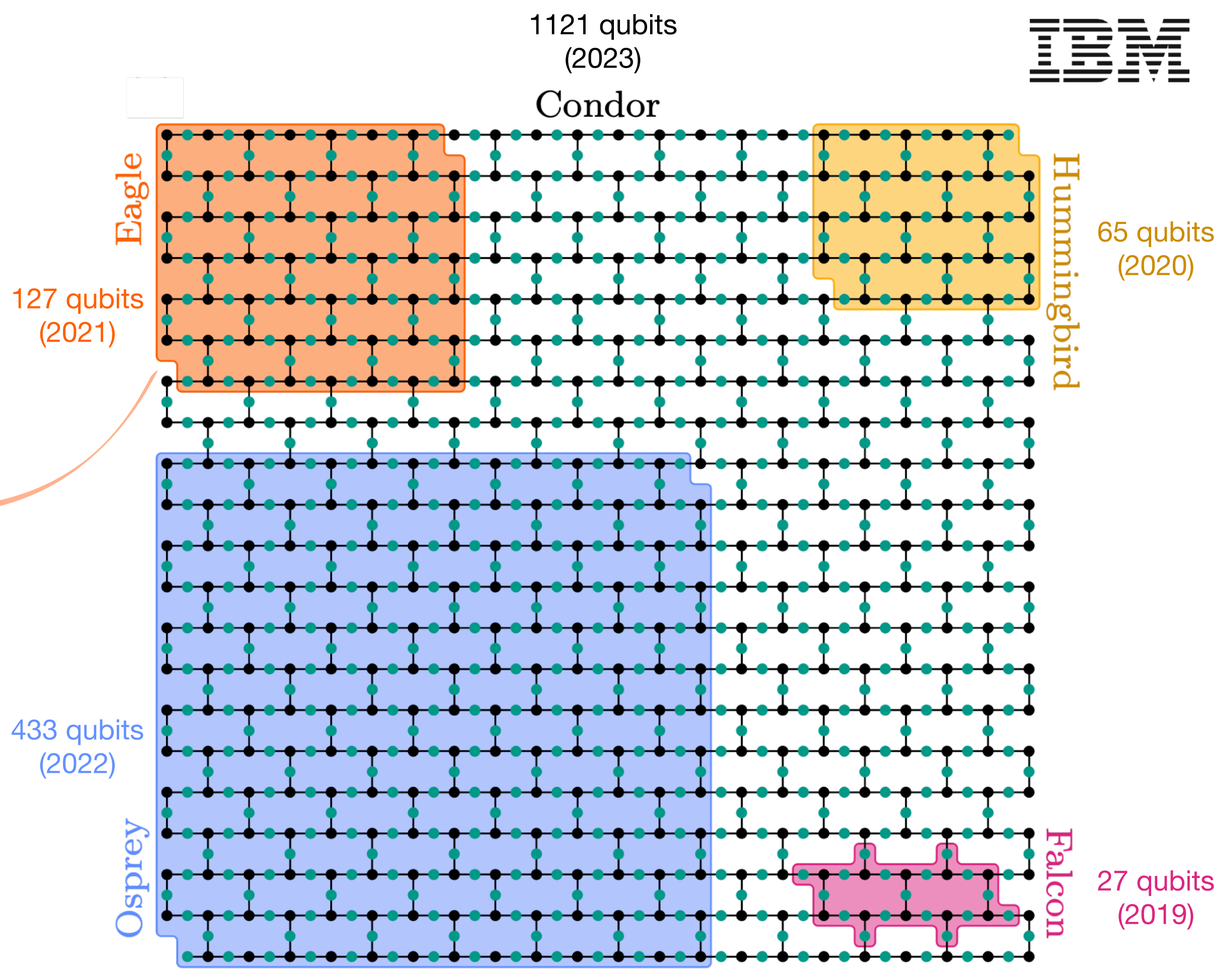


IBM’s Eagle generation — **127 qubits**



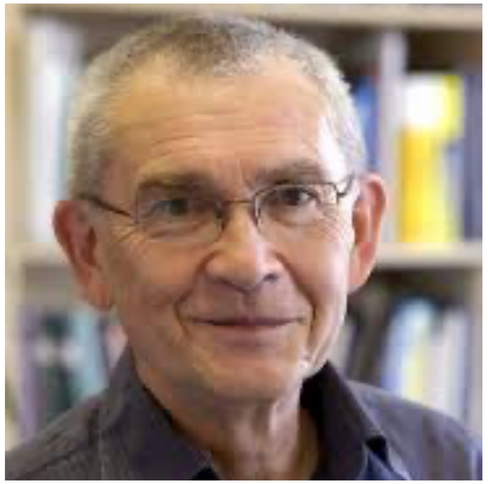
quantum computing today – cloud computing



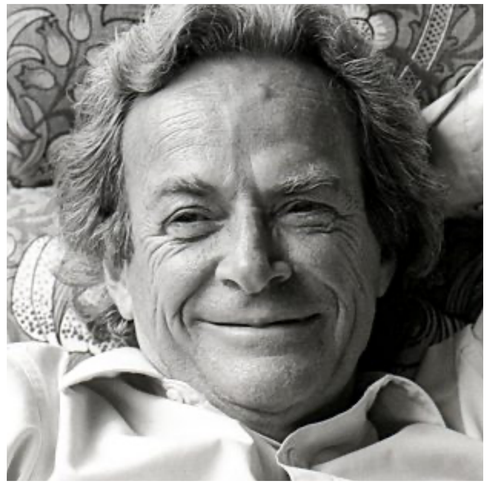


the **“killer app”** of quantum computing?

Paul Benioff, 1980
Quantum-Turing machine



Yuri Manin, 1980
Computable and Uncomputable



Richard Feynman, 1981
Quantum Computer

“ If you want to make a **simulation of nature**, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy. ”

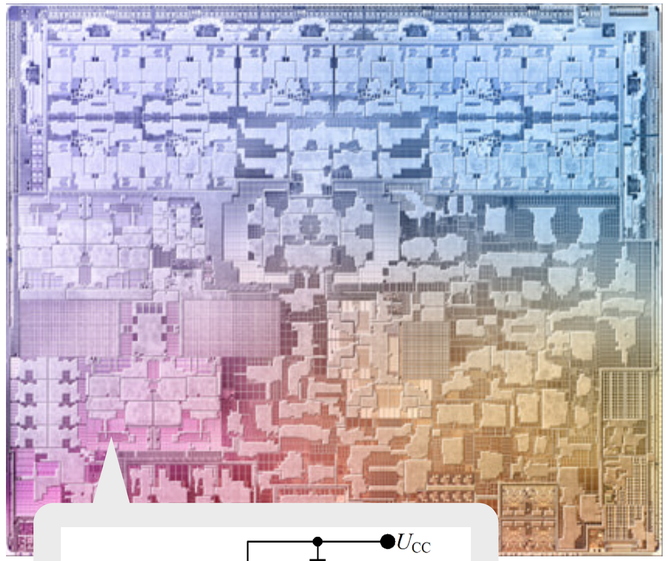
— Richard Feynman, 1981

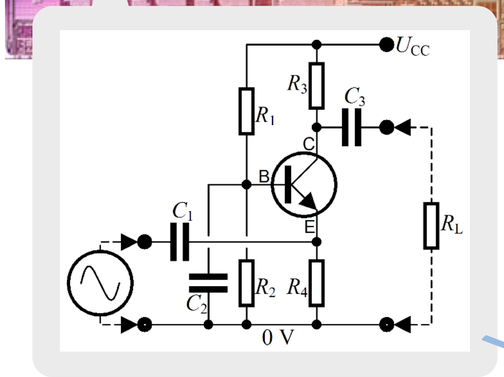
the basics of

quantum computers

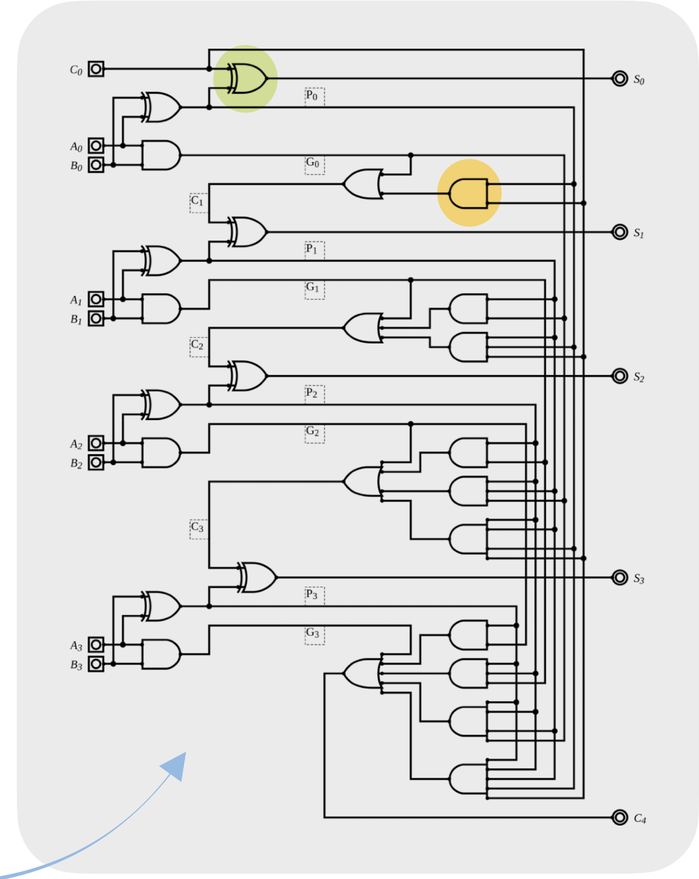
conventional computer & circuits

processor / computer chip

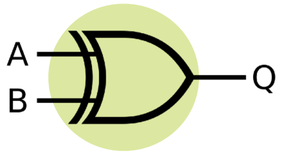




electrical **circuit**

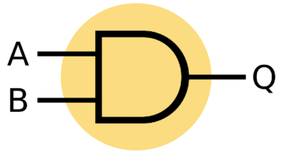


logical circuit



XOR

$A\ B$	Q
0 0	0
0 1	1
1 0	1
1 1	0



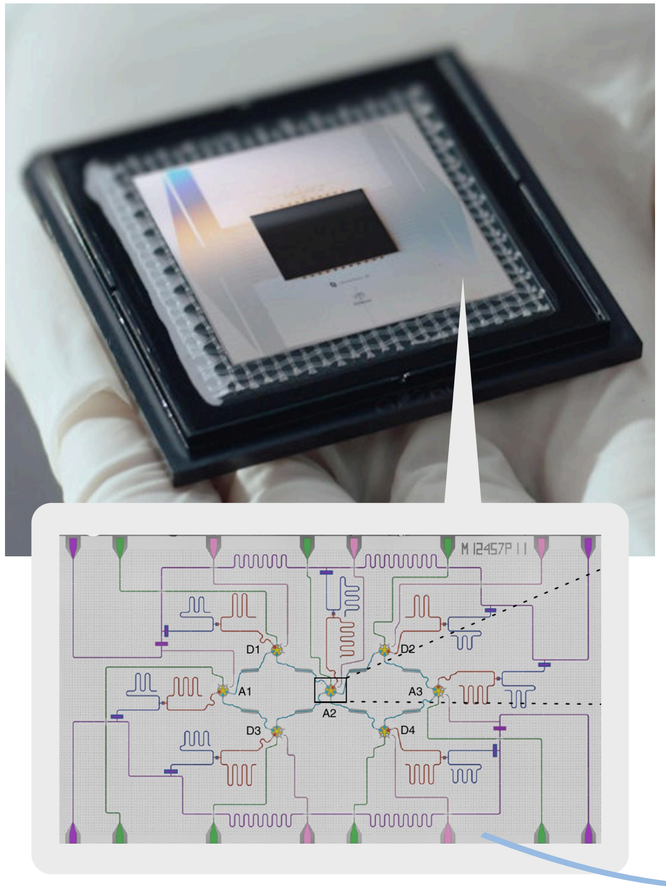
AND

$A\ B$	Q
0 0	0
0 1	0
1 0	0
1 1	1

logical gates

quantum computer & circuits

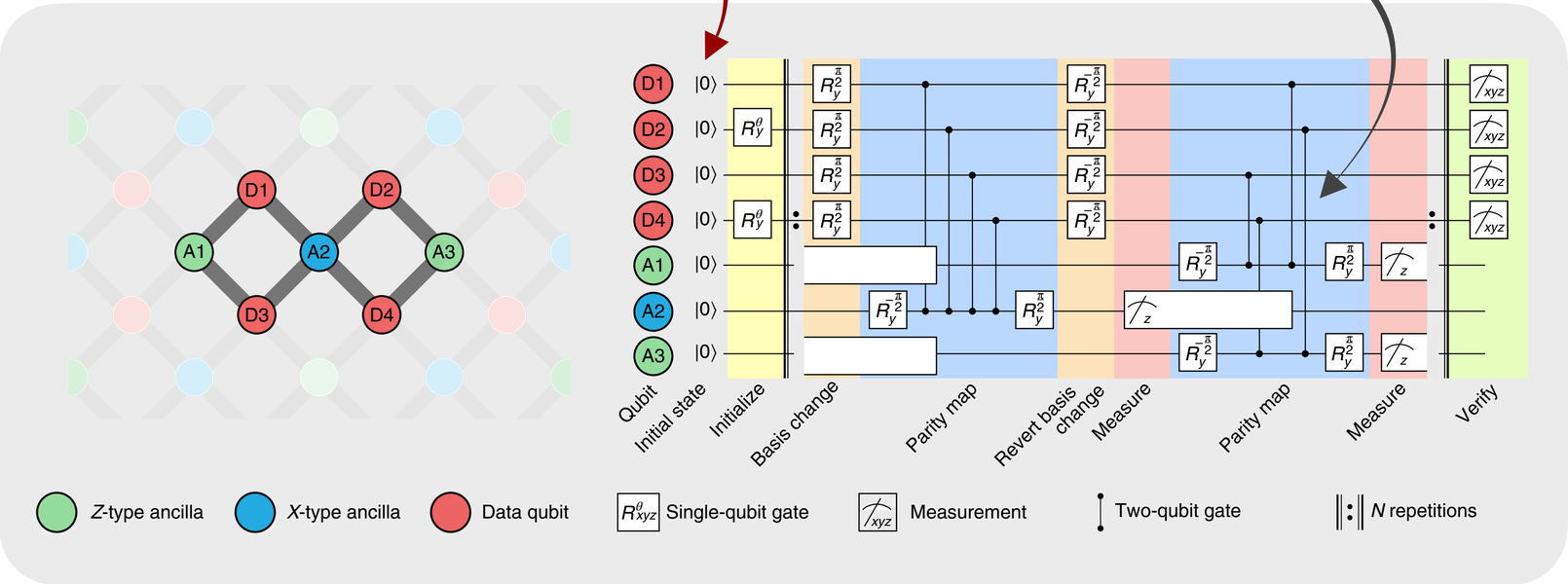
quantum processor



electrical **circuit**

logical bits = **quantum bits**

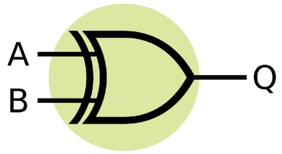
quantum gates



logical circuit = quantum circuit

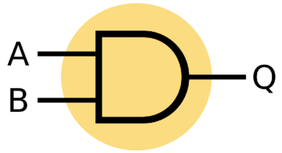
quantum circuits

conventional gates



XOR

$A\ B$	Q
$0\,0$	0
$0\,1$	1
$1\,0$	1
$1\,1$	0

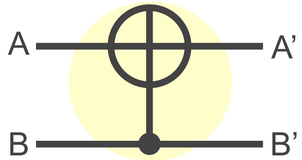


AND

$A\ B$	Q
$0\,0$	0
$0\,1$	0
$1\,0$	0
$1\,1$	1

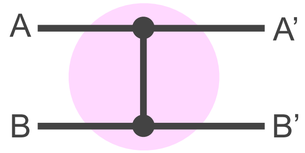
logical gates

quantum gates



CNOT

$A\ B$	$A'\ B'$
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$
$\lvert 1\,0\rangle$	$\lvert 1\,1\rangle$
$\lvert 1\,1\rangle$	$\lvert 1\,0\rangle$



ZZ parity

$A\ B$	$A'\ B'$
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$
$\lvert 1\,0\rangle$	$\lvert 1\,0\rangle$
$\lvert 1\,1\rangle$	$\lvert 1\,1\rangle$

HADAMARD

A	A'
$\lvert 0\rangle$	$\lvert 0\rangle + \lvert 1\rangle = \lvert +\rangle$
$\lvert 1\rangle$	$\lvert 0\rangle - \lvert 1\rangle = \lvert -\rangle$

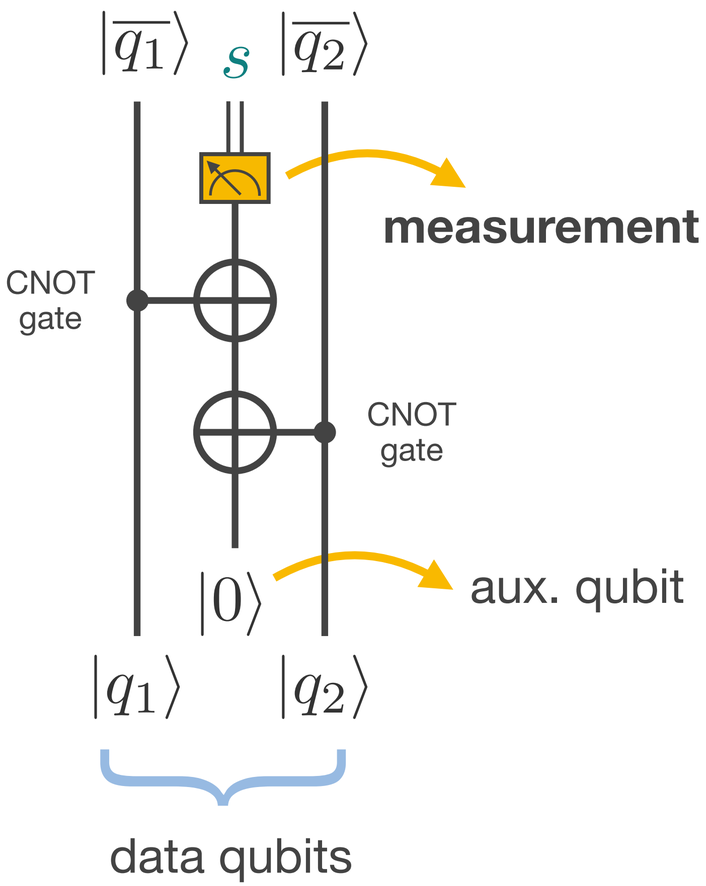
quantum **superposition**

$A\ B$	$A'\ B'$
$\lvert + +\rangle$	$\lvert 0\,0\rangle + \lvert 1\,1\rangle$ $\lvert 0\,1\rangle + \lvert 1\,0\rangle$

quantum **entanglement**

ZZ parity checks – **joint measurements**

quantum circuit for 2-qubit **joint measurement**



extract information

$\lvert q_1\rangle\lvert q_2\rangle$	$\lvert\overline{q_1}\rangle\lvert\overline{q_2}\rangle$	s
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$	0
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$	1
$\lvert 1\,0\rangle$	$\lvert 1\,0\rangle$	1
$\lvert 1\,1\rangle$	$\lvert 1\,1\rangle$	0

syndrome measurement

ZZ **parity check**

shape entanglement

product state

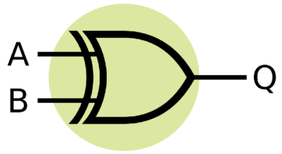
$\lvert q_1\rangle\lvert q_2\rangle$	$\lvert\overline{q_1}\rangle\lvert\overline{q_2}\rangle$	s
$\lvert ++\rangle$	p = 1/2: $(\lvert 00\rangle + \lvert 11\rangle)/\sqrt{2}$	0
	p = 1/2: $(\lvert 01\rangle + \lvert 10\rangle)/\sqrt{2}$	1

Bell state

$$|++\rangle = \frac{1}{2}\left(|00\rangle + |01\rangle + |10\rangle + |11\rangle\right)$$

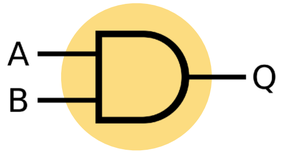
quantum circuits

conventional gates



XOR

$A\ B$	Q
$0\,0$	0
$0\,1$	1
$1\,0$	1
$1\,1$	0

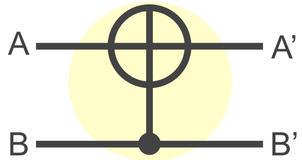


AND

$A\ B$	Q
$0\,0$	0
$0\,1$	0
$1\,0$	0
$1\,1$	1

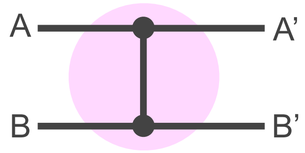
logical gates

quantum gates



CNOT

$A\ B$	$A'\ B'$
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$
$\lvert 1\,0\rangle$	$\lvert 1\,1\rangle$
$\lvert 1\,1\rangle$	$\lvert 1\,0\rangle$



ZZ parity

$A\ B$	$A'\ B'$
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$
$\lvert 1\,0\rangle$	$\lvert 1\,0\rangle$
$\lvert 1\,1\rangle$	$\lvert 1\,1\rangle$

HADAMARD

A	A'
$\lvert 0\rangle$	$\lvert 0\rangle + \lvert 1\rangle = \lvert +\rangle$
$\lvert 1\rangle$	$\lvert 0\rangle - \lvert 1\rangle = \lvert -\rangle$

quantum **superposition**

$A\ B$	$A'\ B'$
$\lvert + +\rangle$	$\lvert 0\,0\rangle + \lvert 1\,1\rangle$ $\lvert 0\,1\rangle + \lvert 1\,0\rangle$

quantum **entanglement**

quantum circuits

Z gate

A	A'
$\lvert 0\rangle$	$\lvert 0\rangle$
$\lvert 1\rangle$	$-\lvert 1\rangle$

S gate

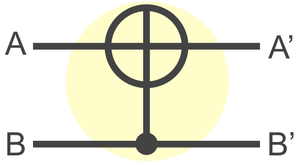
A	A'
$\lvert 0\rangle$	$\lvert 0\rangle$
$\lvert 1\rangle$	$i\lvert 1\rangle$

Clifford circuit

easy to simulate (Gottesman-Knill theorem)
but **not universal**

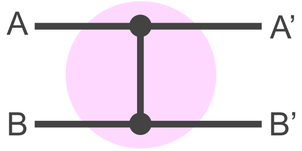
complex phases

quantum gates



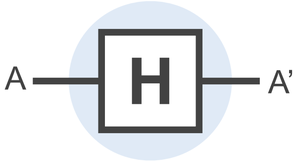
CNOT

$A\,B$	$A'\,B'$
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$
$\lvert 1\,0\rangle$	$\lvert 1\,1\rangle$
$\lvert 1\,1\rangle$	$\lvert 1\,0\rangle$



ZZ parity

$A\,B$	$A'\,B'$
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$
$\lvert 1\,0\rangle$	$\lvert 1\,0\rangle$
$\lvert 1\,1\rangle$	$\lvert 1\,1\rangle$



HADAMARD

A	A'
$\lvert 0\rangle$	$\lvert 0\rangle + \lvert 1\rangle = \lvert +\rangle$
$\lvert 1\rangle$	$\lvert 0\rangle - \lvert 1\rangle = \lvert -\rangle$

$A\,B$	$A'\,B'$
$\lvert + +\rangle$	$\lvert 0\,0\rangle + \lvert 1\,1\rangle$ $\lvert 0\,1\rangle + \lvert 1\,0\rangle$

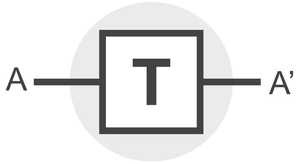
quantum **superposition**

quantum **entanglement**

quantum circuits

Z gate

A	A'
$\lvert 0\rangle$	$\lvert 0\rangle$
$\lvert 1\rangle$	$-\lvert 1\rangle$



T gate

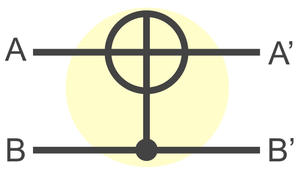
A	A'
$\lvert 0\rangle$	$\lvert 0\rangle$
$\lvert 1\rangle$	$e^{i\frac{\pi}{4}}\lvert 1\rangle$

non-Clifford circuit

universal and **hard** to simulate

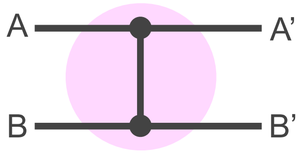
complex phases

quantum gates



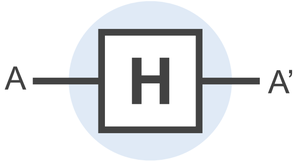
CNOT

$A\,B$	$A'\,B'$
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$
$\lvert 1\,0\rangle$	$\lvert 1\,1\rangle$
$\lvert 1\,1\rangle$	$\lvert 1\,0\rangle$



ZZ parity

$A\,B$	$A'\,B'$
$\lvert 0\,0\rangle$	$\lvert 0\,0\rangle$
$\lvert 0\,1\rangle$	$\lvert 0\,1\rangle$
$\lvert 1\,0\rangle$	$\lvert 1\,0\rangle$
$\lvert 1\,1\rangle$	$\lvert 1\,1\rangle$



HADAMARD

A	A'
$\lvert 0\rangle$	$\lvert 0\rangle + \lvert 1\rangle = \lvert +\rangle$
$\lvert 1\rangle$	$\lvert 0\rangle - \lvert 1\rangle = \lvert -\rangle$

$A\,B$	$A'\,B'$
$\lvert +\,+\rangle$	$\lvert 0\,0\rangle + \lvert 1\,1\rangle$ $\lvert 0\,1\rangle + \lvert 1\,0\rangle$

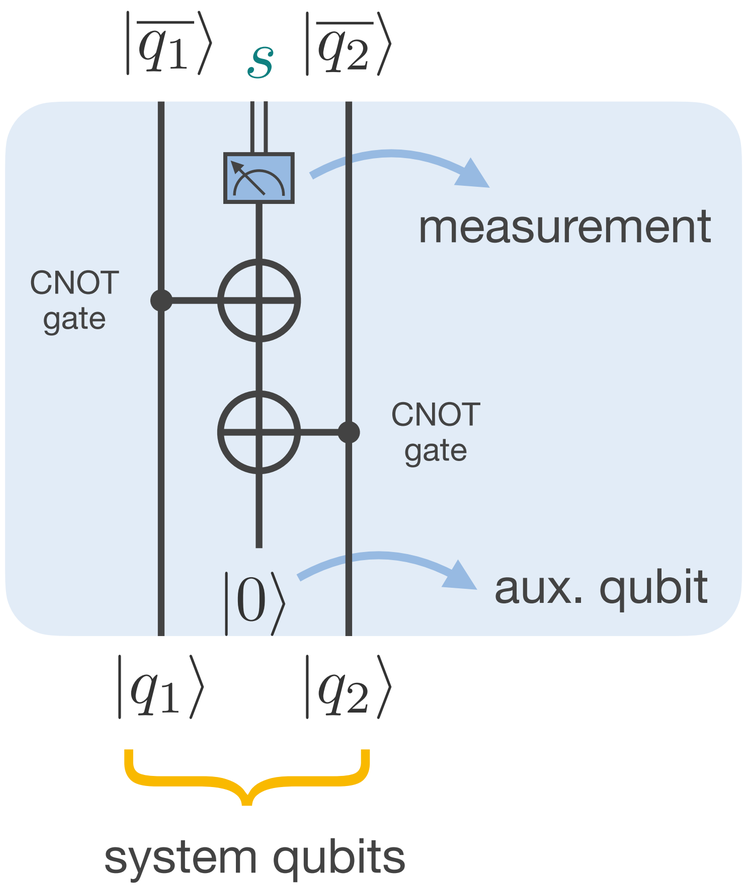
quantum **superposition**

quantum **entanglement**

shallow circuits

state preparation

joint measurements & **state preparation**

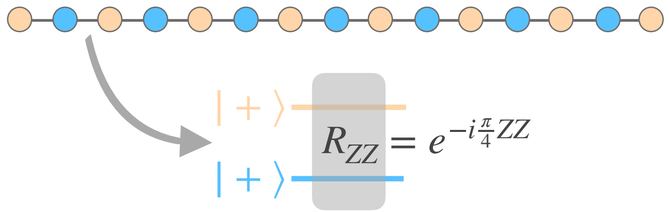


=

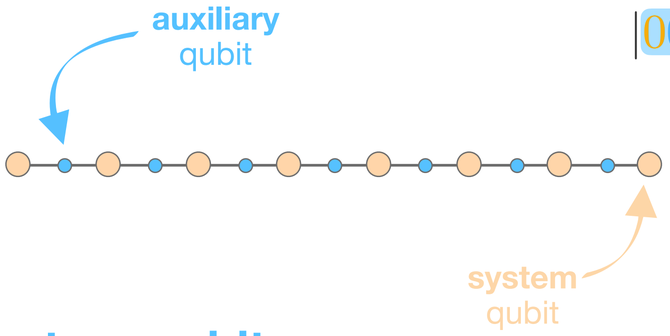
ZZ

parity check

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

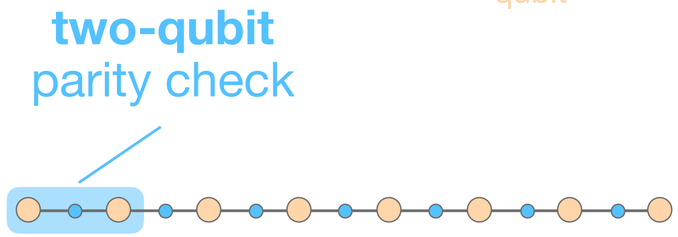


product state



$|0000\rangle + |0110\rangle + |1101\rangle - |1011\rangle$

cluster state



$|00110010\rangle + |11001101\rangle$

cat state

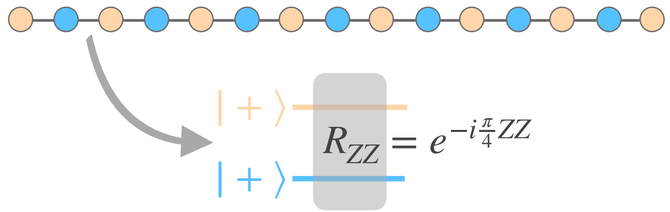
decode

GHZ state $|00000000\rangle + |11111111\rangle$

state preparation & **quantum circuit**

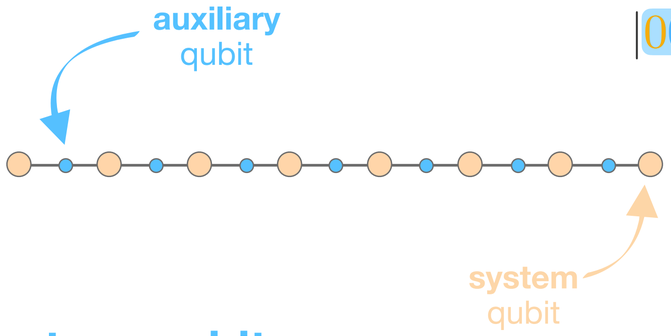
$|+++++++++\rangle$

product state

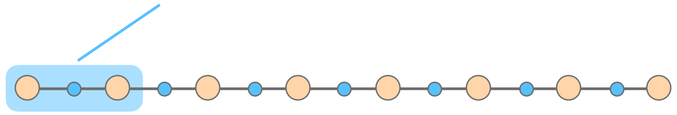


$|0000\rangle + |0110\rangle + |1101\rangle - |1011\rangle$

cluster state



two-qubit parity check



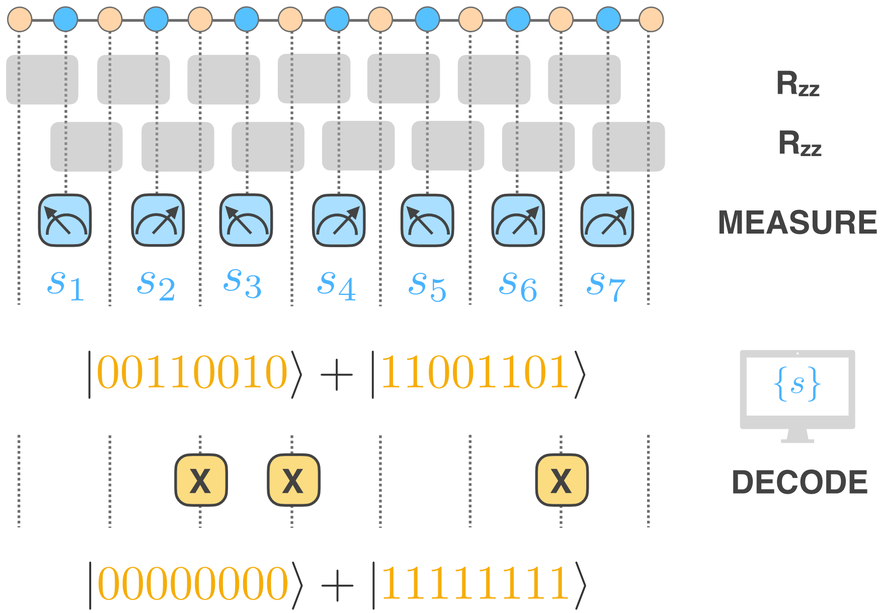
$|00110010\rangle + |11001101\rangle$

cat state

decode

$|00000000\rangle + |11111111\rangle$

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



$|00110010\rangle + |11001101\rangle$

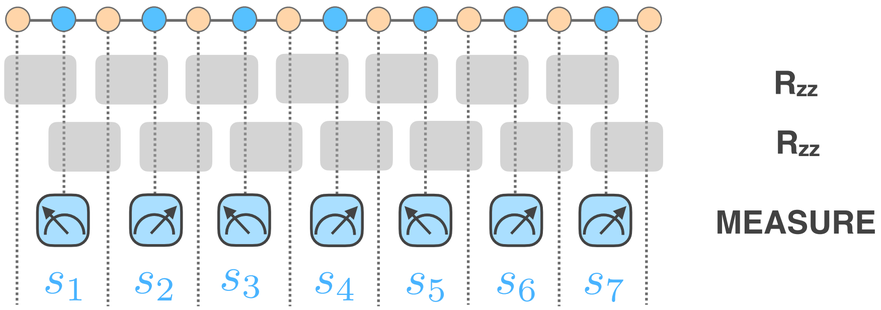
$|00000000\rangle + |11111111\rangle$

shallow circuit

The circuit **depth does not scale** with the number of qubits.

fast state preparation

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



R_{zz}

R_{zz}

MEASURE

$|00110010\rangle + |11001101\rangle$

DECODE

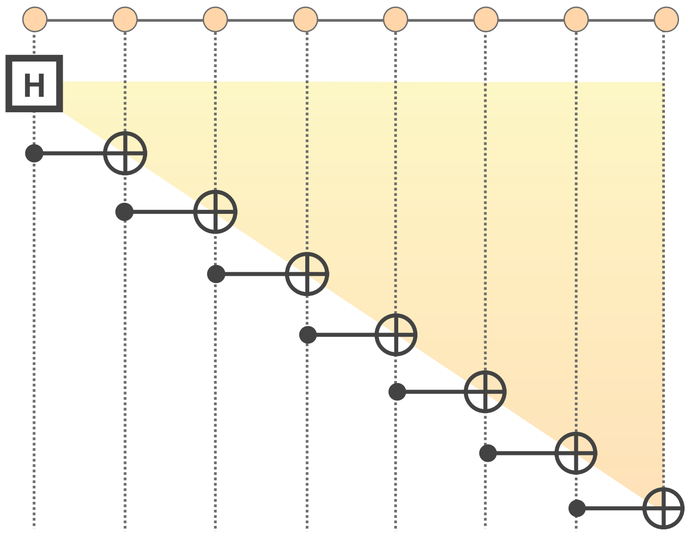
$|00000000\rangle + |11111111\rangle$

shallow circuit

The circuit **depth does not scale** with the number of qubits.

monitored dynamics

$|00000000\rangle$



HADAMARD

CNOT

CNOT

CNOT

CNOT

CNOT

CNOT

CNOT

$|00000000\rangle + |11111111\rangle$

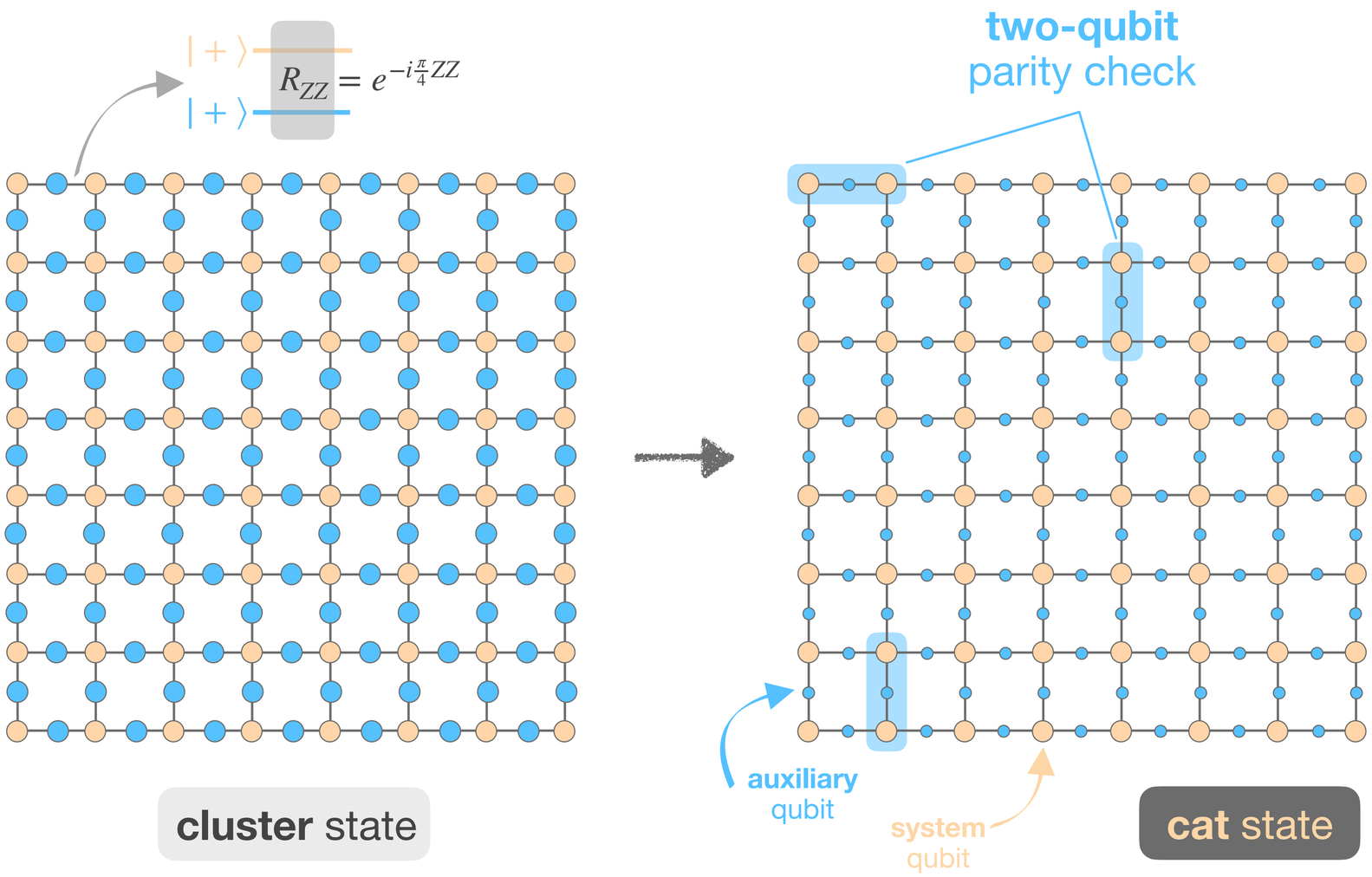
deep circuit

The circuit **depth scales** at least **logarithmically** with the number of qubits.

long-range entanglement

unitary dynamics

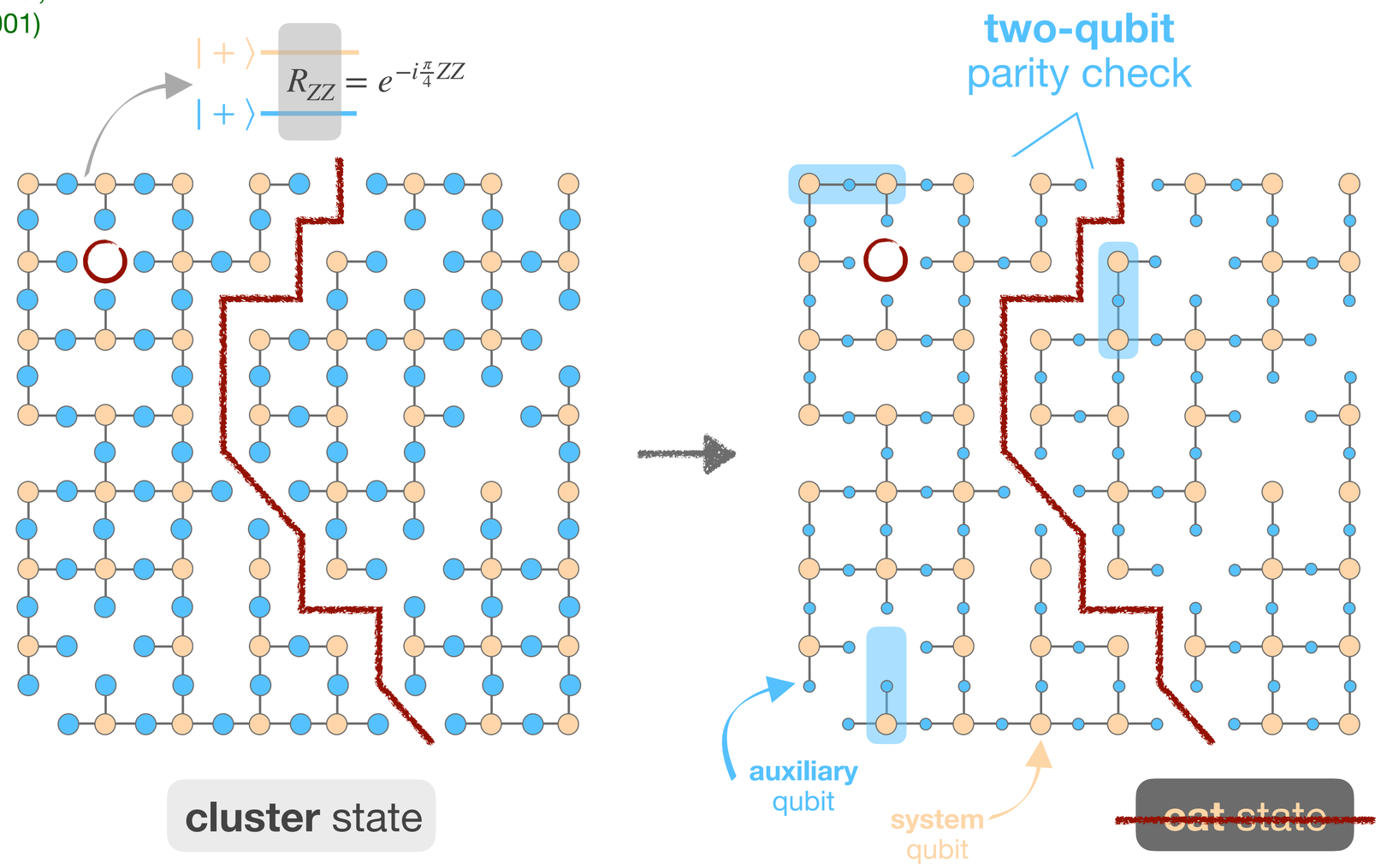
two-dimensional quantum states



two-dimensional quantum states

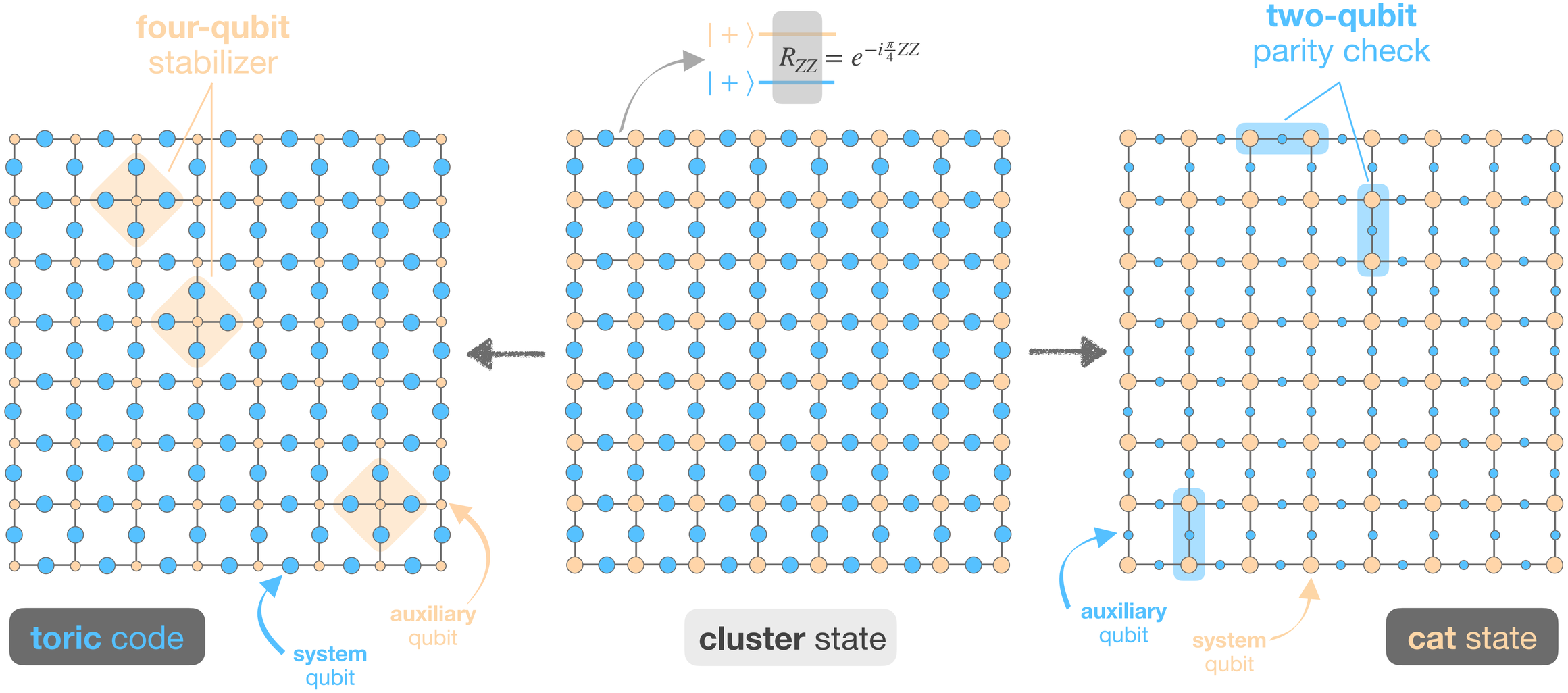
Robert Raussendorf and Hans J. Briegel,
A One-Way Quantum Computer,
Phys. Rev. Lett. **86**, 5188 (2001)

percolation
transition

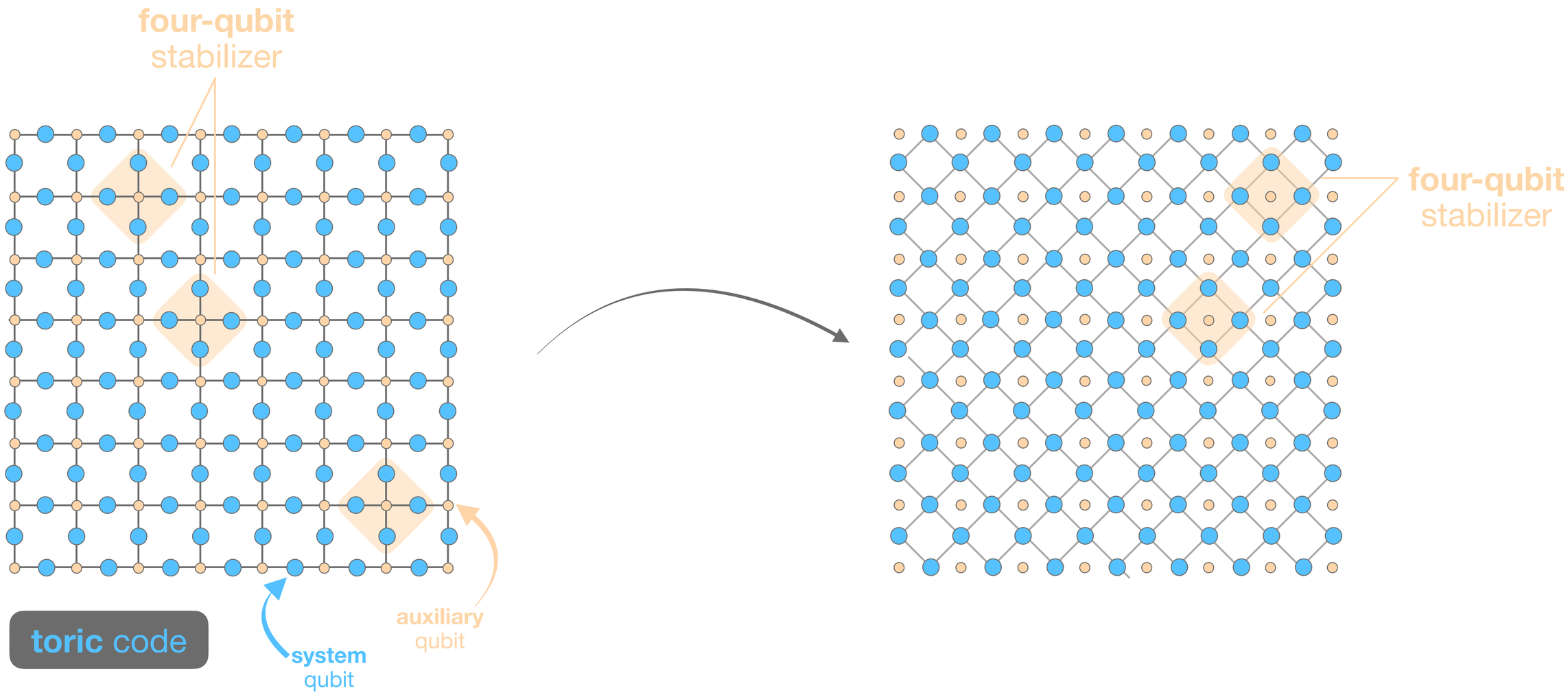


cluster state

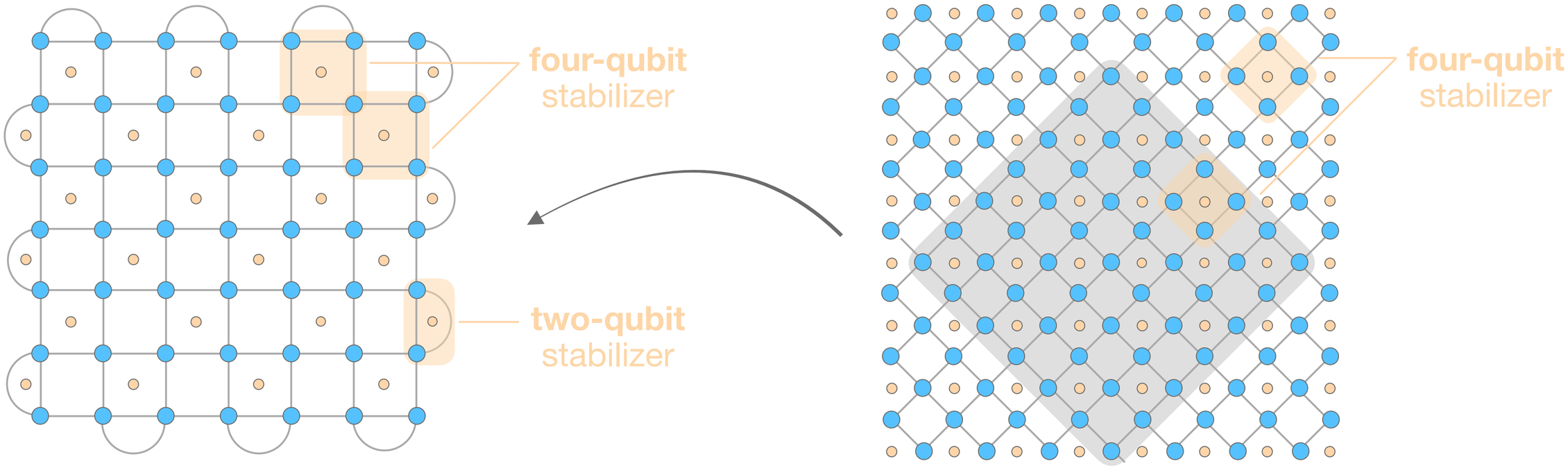
two-dimensional quantum states



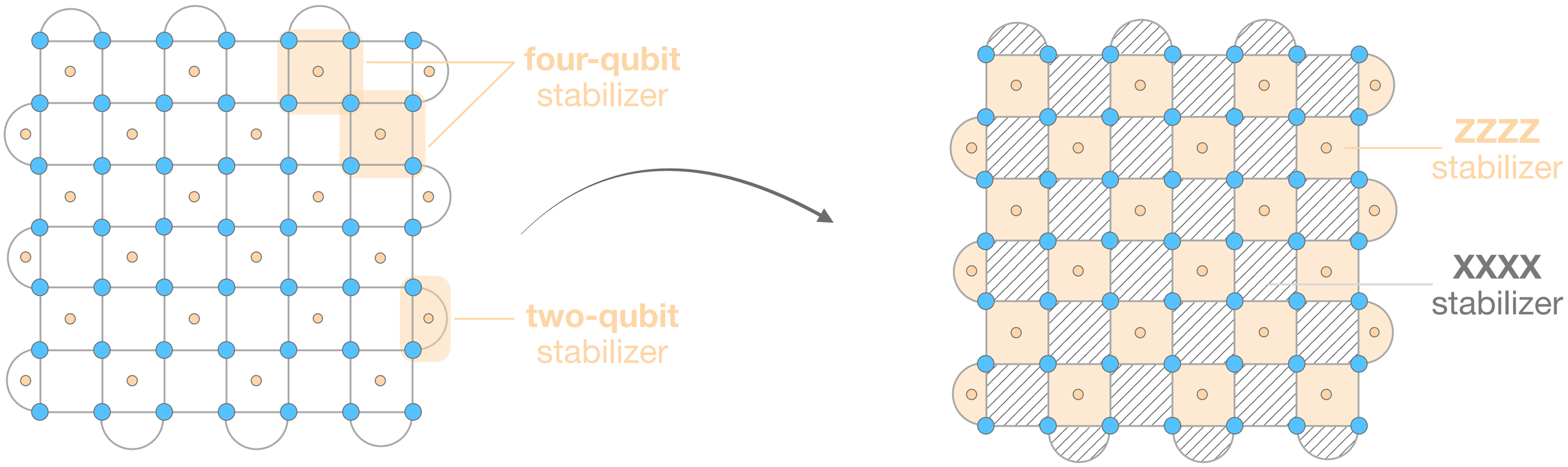
Why is this a toric code?



Why is this a toric code?



Why is this a toric code?

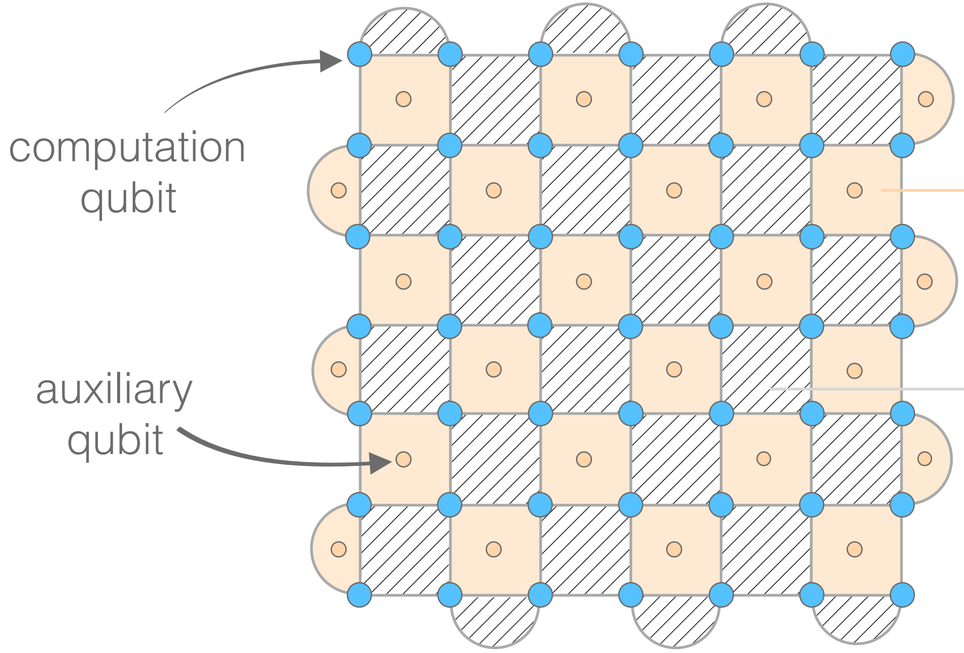


rotated surface code

rotated surface code

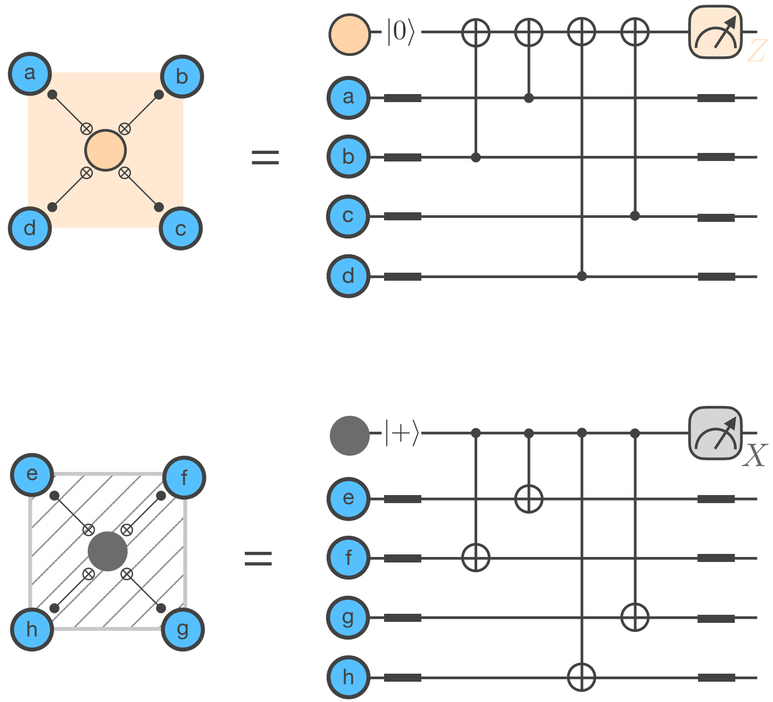
Kitaev (1997)

open boundaries
(rotated surface code)



ZZZZ stabilizer

XXXX stabilizer



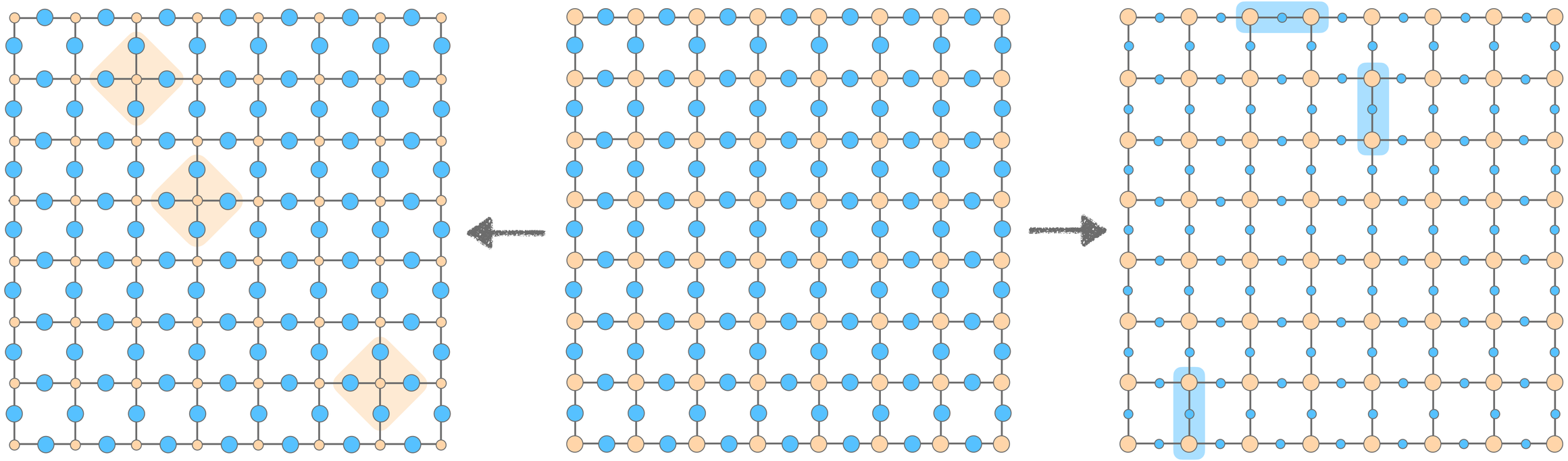
49 computational qubits
48 auxiliary qubits

d=7 code

The toric/surface code was conceived as a **measurement protocol.**

two-dimensional quantum states

N. Tantivasadakarn, R. Thorngren, A. Vishwanath, and R. Verresen, *Long-Range Entanglement from Measuring Symmetry-Protected Topological Phases,* PRX **14**, 021040 (2024)



toric code

$Z_2^{(1)}$

long-range entangled
topological order

cluster state

$Z_2 \times Z_2^{(1)}$

short-range entangled
SPT order

cat state

Z_2

long-range entangled
quantum order

perspectives

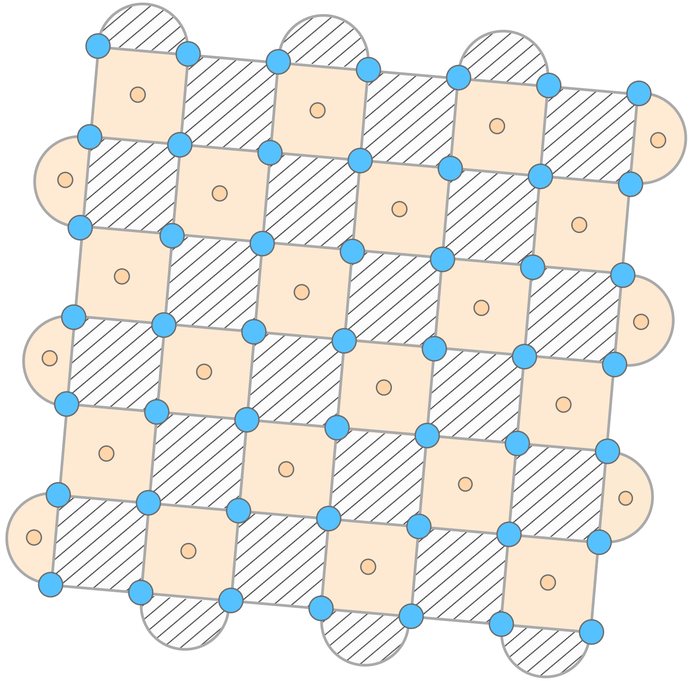
state preparation by measurement

Raussendorf & Briegel, PRL **86**, 5188 (2001)
Tantivasadakarn *et al.*, PRX **14**, 021040 (2024)

- **measurements** are a powerful tool to create entangled states
  - **shallow** circuit constructions for cat & toric code states
  - trade-off in form of **auxiliary qubits** and **decoding**
  - preparation of **non-Abelian** topological order also possible

    N. Tantivasadakarn, R. Verresen, and A. Vishwanath,
    Shortest Route to Non-Abelian Topological Order on a Quantum Processor,
    Phys. Rev. Lett. **131**, 060405 (2023)

Erez Berg's talk tomorrow



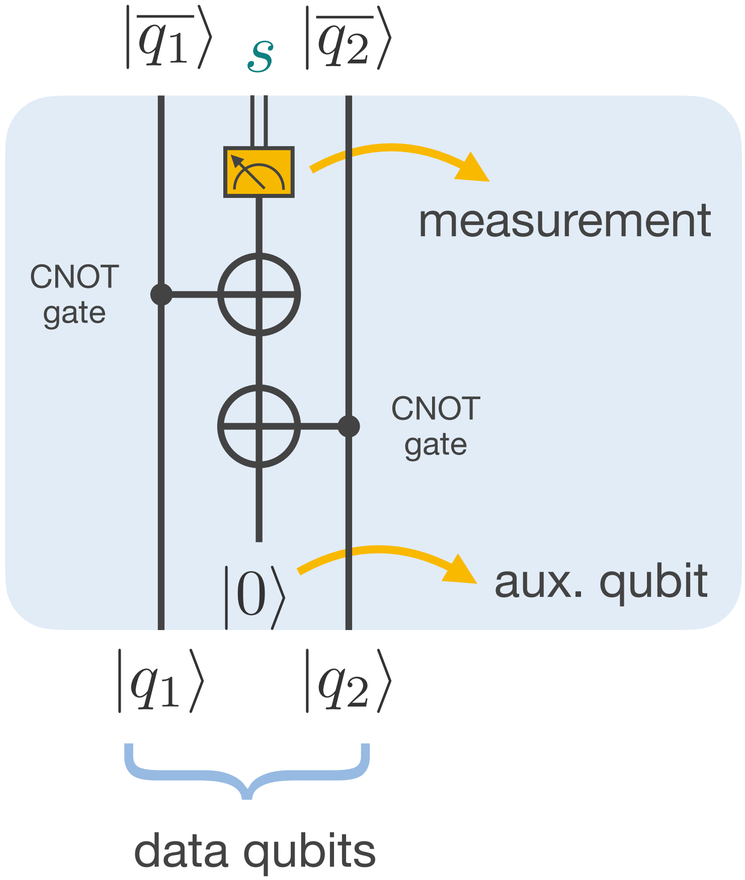
- **open** questions
  - **stability** of protocols
  - thresholds & **critical phenomenology**
- **implementation** on quantum processors

tomorrow's **lecture**

deep circuits

monitored dynamics

joint measurements & entanglement



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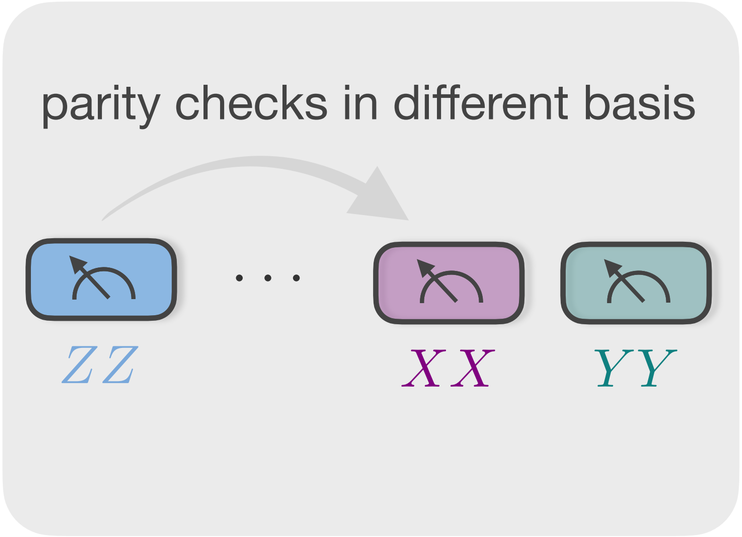
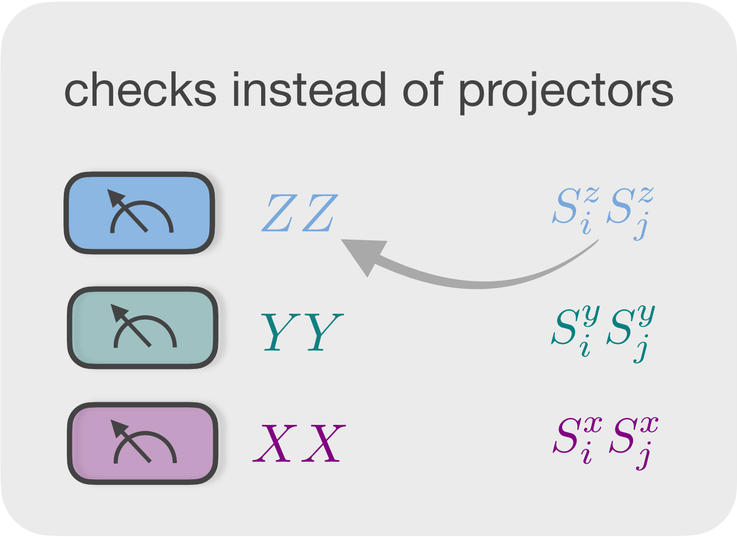




measurement dynamics

Hamiltonian dynamics

new toolbox for quantum many-body physics

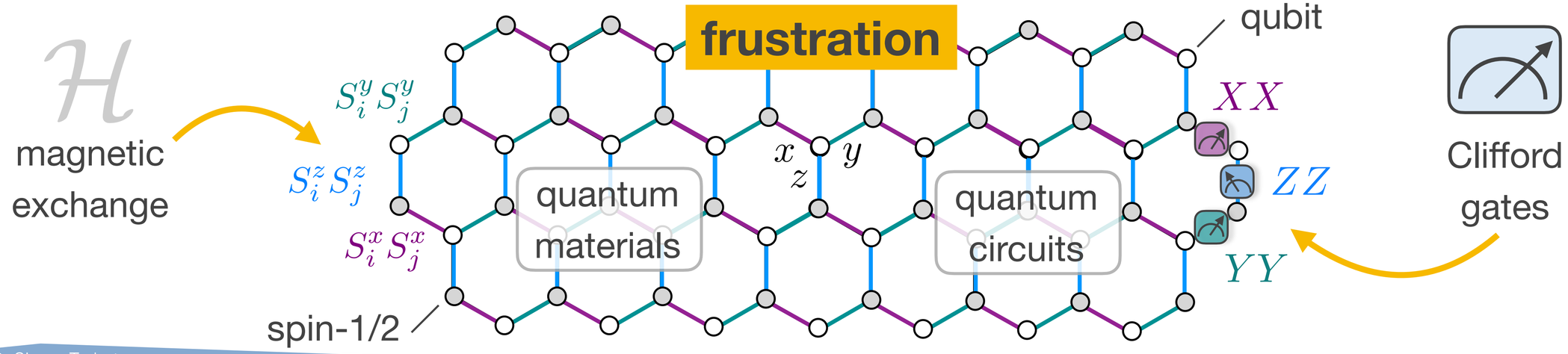
Hamiltonian vs. monitored dynamics

Hamiltonian dynamics

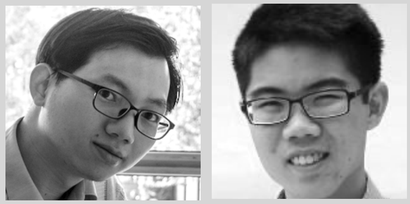
- **equilibrium** dynamics of **isolated** systems
- **unitary** evolution
- energy **conserved**
- quantum **ground states**
- **area-law entanglement** structures
- macroscopic entanglement (spin liquids)

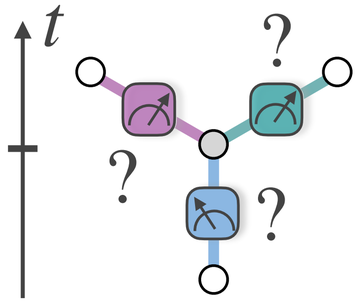
measurement dynamics

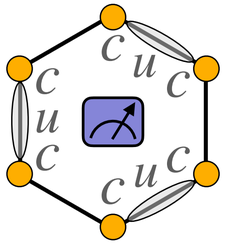
- **out-of-equilibrium** dynamics of **open** systems
- **non-unitary** evolution
- energy **not** conserved
- long-time **steady states**
- **plethora of entanglement** structures
- macroscopic entanglement (spin liquids)



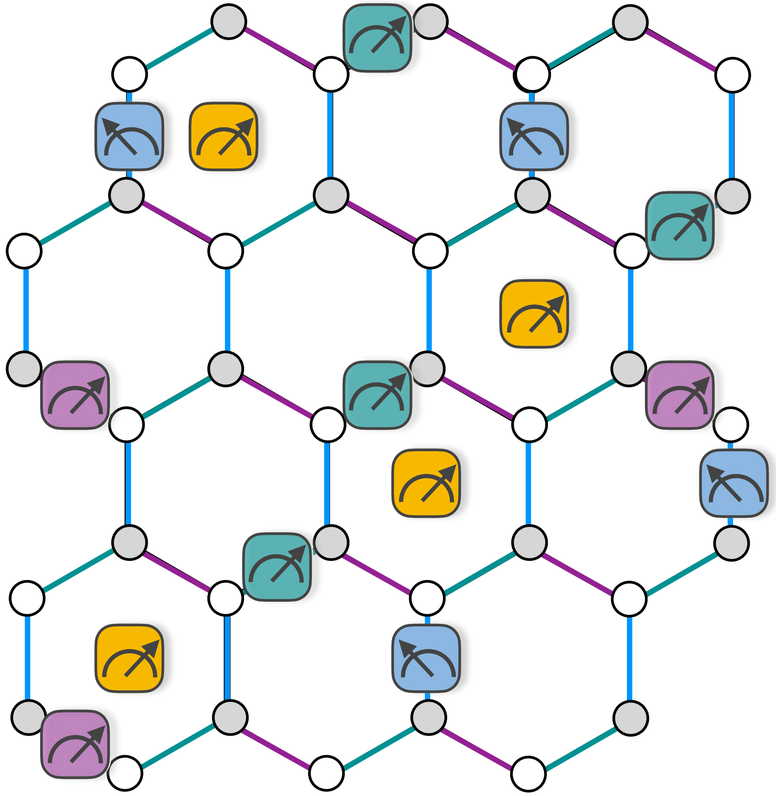
random projective Kitaev measurements







Majorana interaction
→ Majorana surface code



not (commuting) plaquette flux

Clifford circuit

even **interacting** problem can be simulated in polynomial time (in Heisenberg picture)

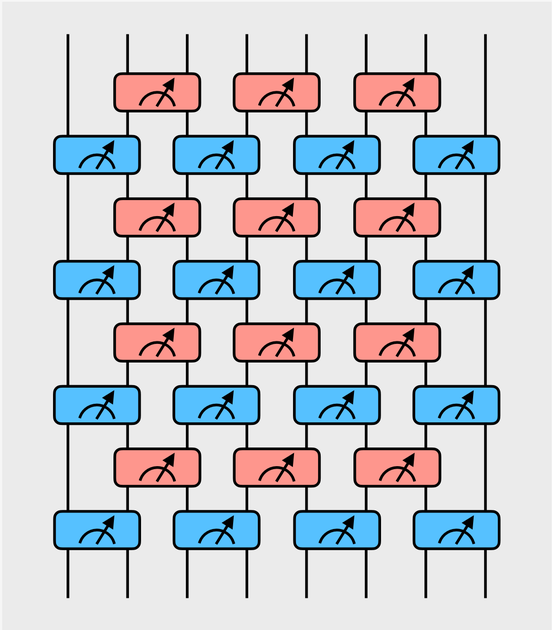
Nahum, Skinner 2020; Lavasani, Luo, Vijay 2023; Sriram, Rakovszky, Khemani, Ippoliti 2023; **Zhu, Tantivasadakarn, ST 2023: + Majorana interaction**

imaginary time vs. measurement-only dynamics

Hamiltonian ground state

$$e^{-\beta H}|\psi_0\rangle$$

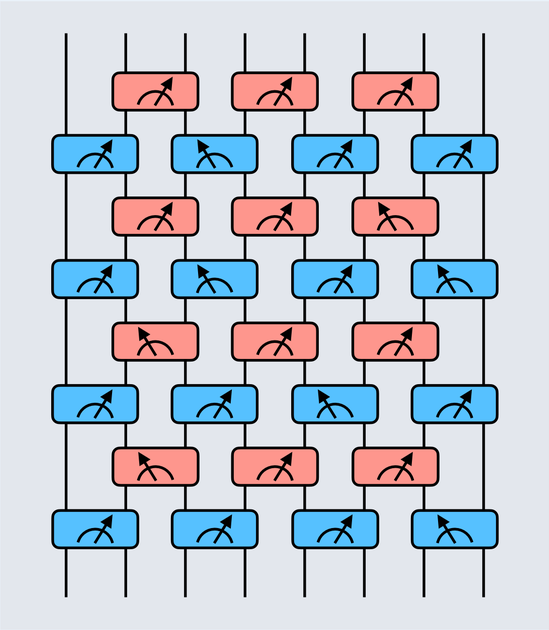
$e^{-\tau H_r}$



- **brickwall** circuit
- **no** disorder

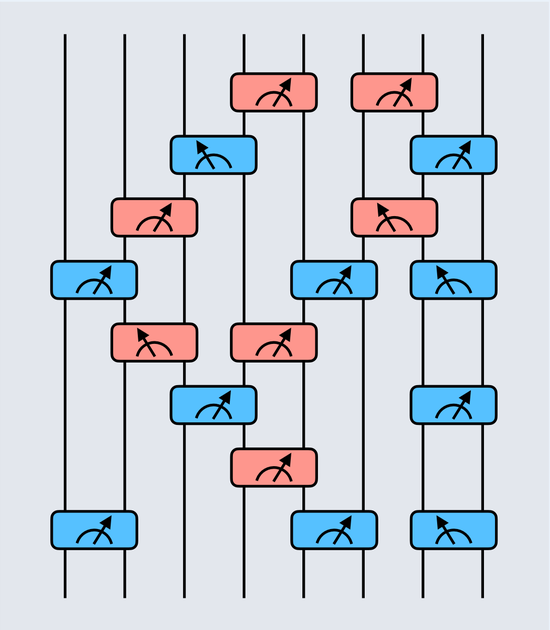
Floquet weak measurement

$$\left(e^{\mp\tau H_r}\cdots e^{\mp\tau H_0}\right)|\psi_0\rangle$$



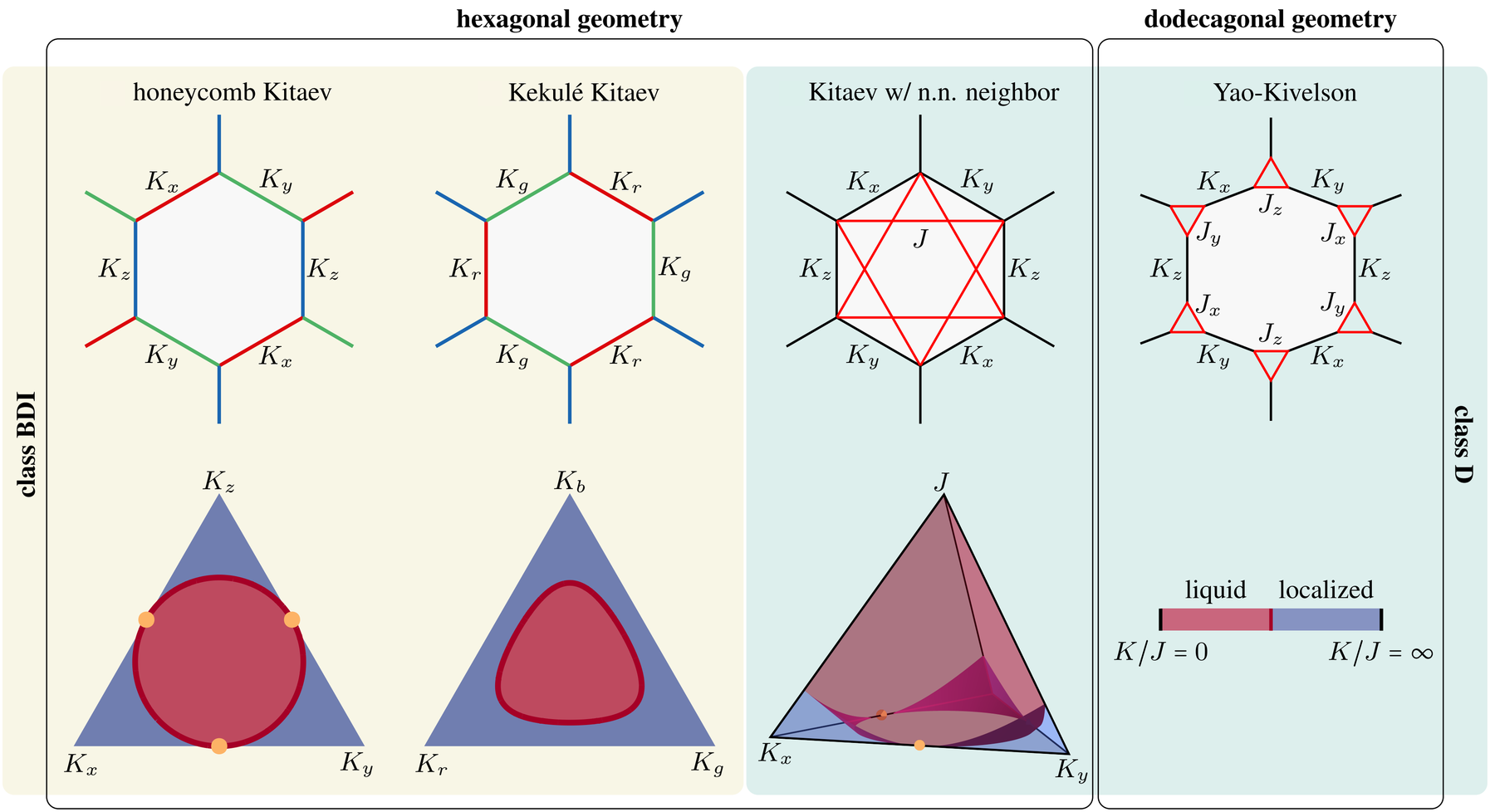
- **brickwall** circuit
- **Born** disorder

random weak/strong measurement



- **stochastic** circuit
- **Born** disorder

entanglement & circuit geometry



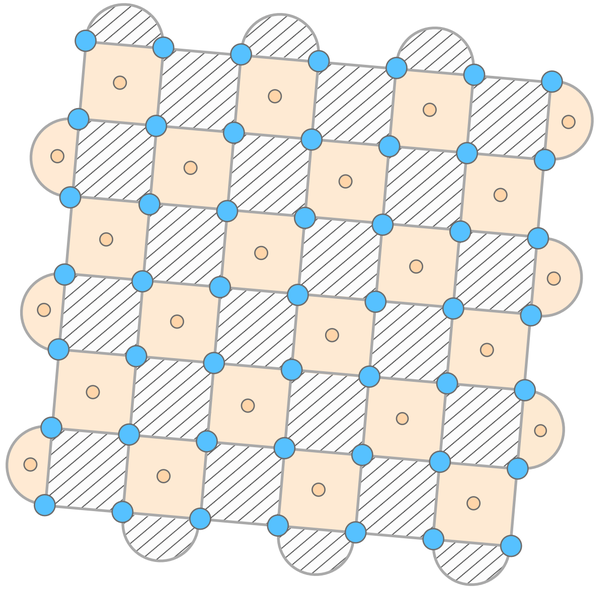
Nahum, Skinner 2020; Lavasani, Luo, Vijay 2023; Sriram, Rakovszky, Khemani, Ippoliti 2023
Klocke, Simm, Zhu, ST, Buchhold 2024: non-bipartite geometries

analytical connections to **loop models** and **NLσM models**
numerical simulations for 100,000,000 = **10^8 qubits**

perspectives

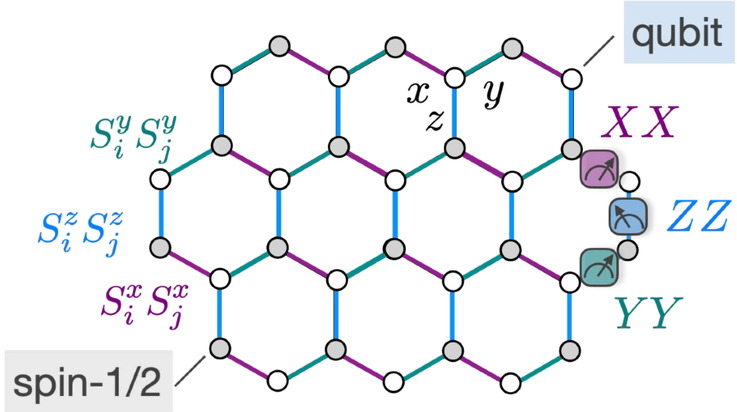
state preparation by measurement

- **measurements** are a powerful tool to create entangled states



- **shallow** circuits
  - **long-range entanglement** from short-range SPT order
  - trade-off in form of **auxiliary qubits** and **decoding**
  - preparation of **non-Abelian** topological order also possible

- **deep** circuits
  - **measurement-only** dynamics
  - **monitored Kitaev** models
  - fractionalization in **Floquet codes**



Thanks!