Quantum tensor networks on a trapped-ion QCCD quantum computer

Michael Foss-Feig
Quantinuum

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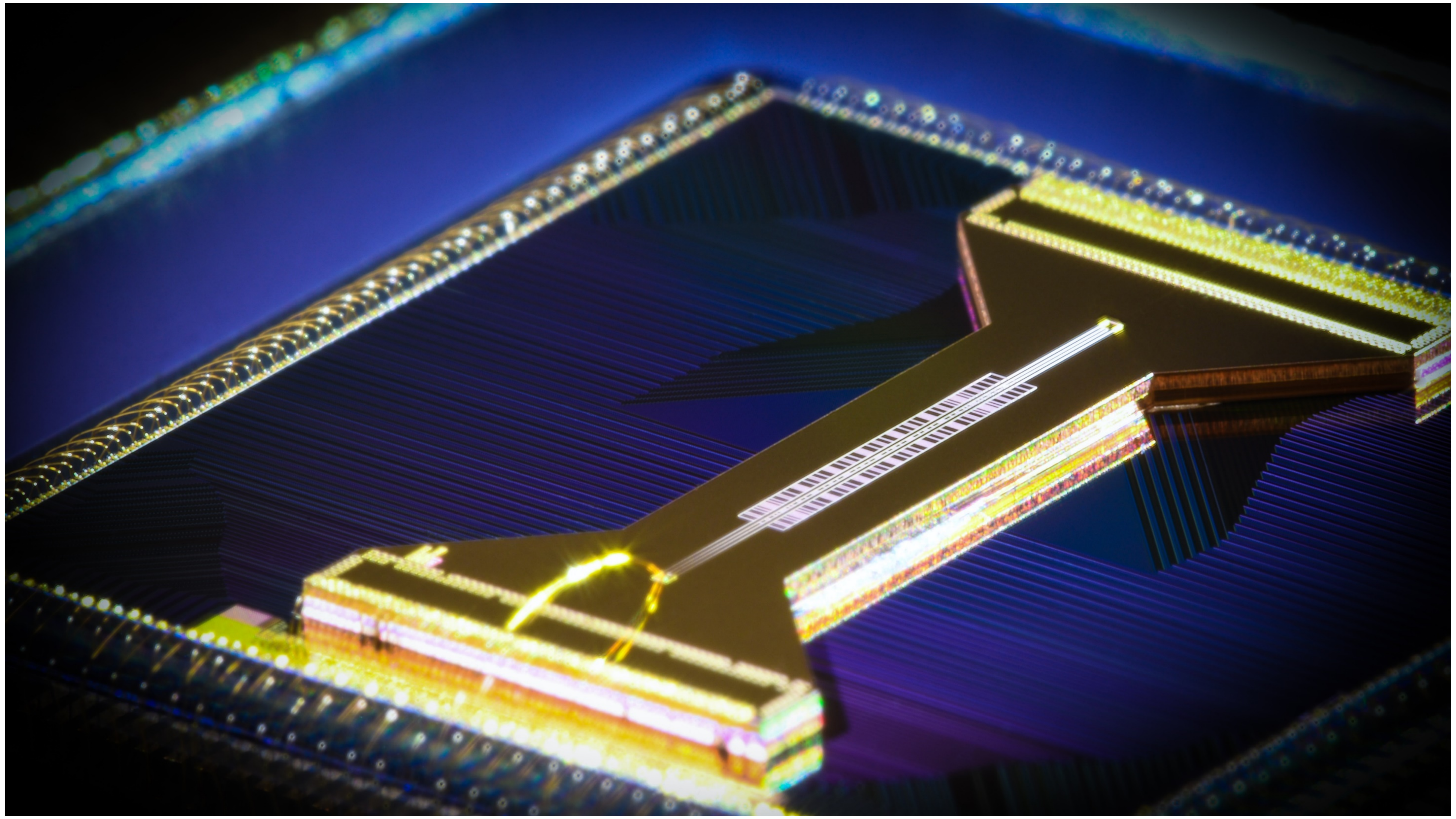
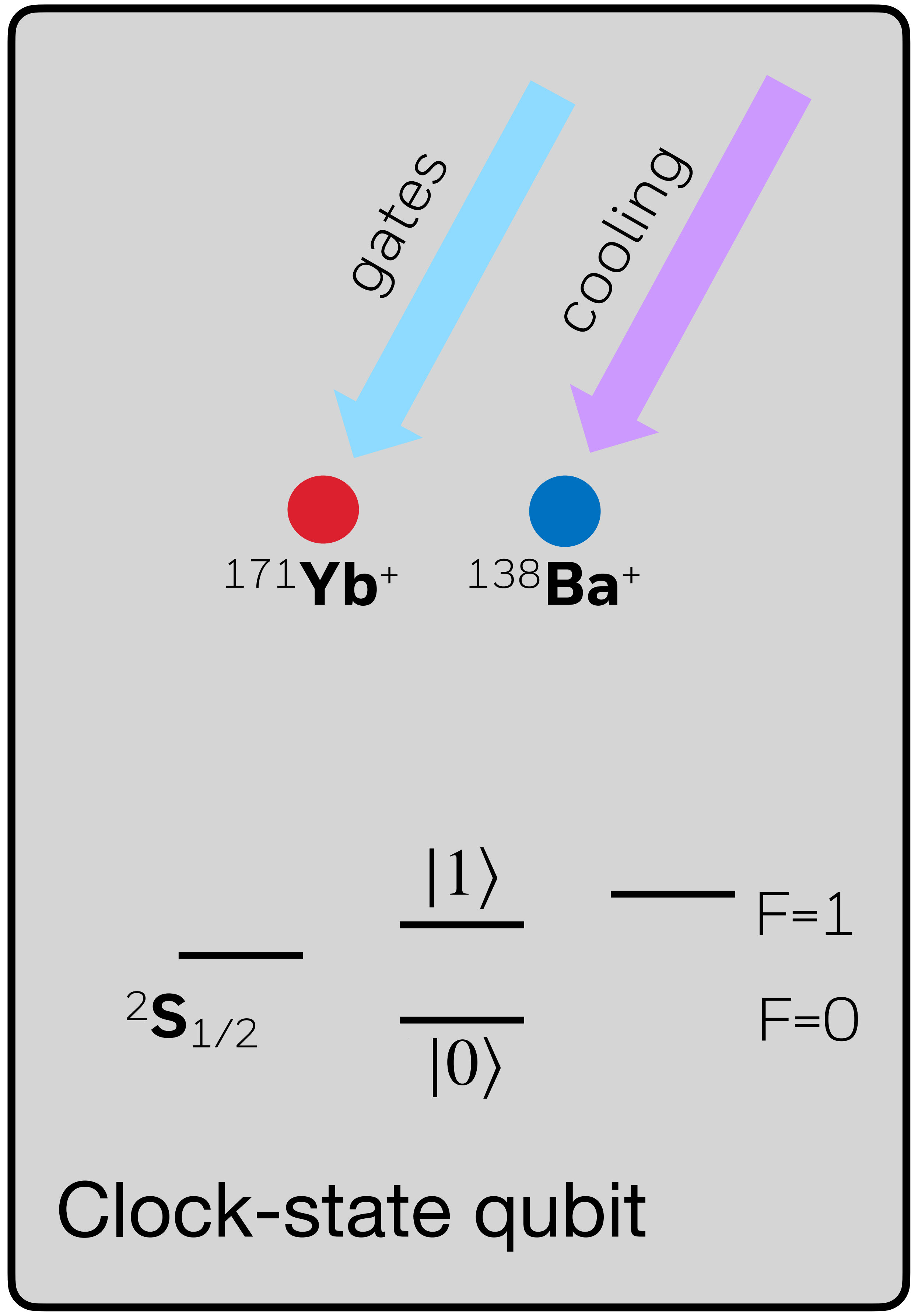
Quantinuum's H1 series quantum computers

QCCD approach [2], pioneered at NIST [1]

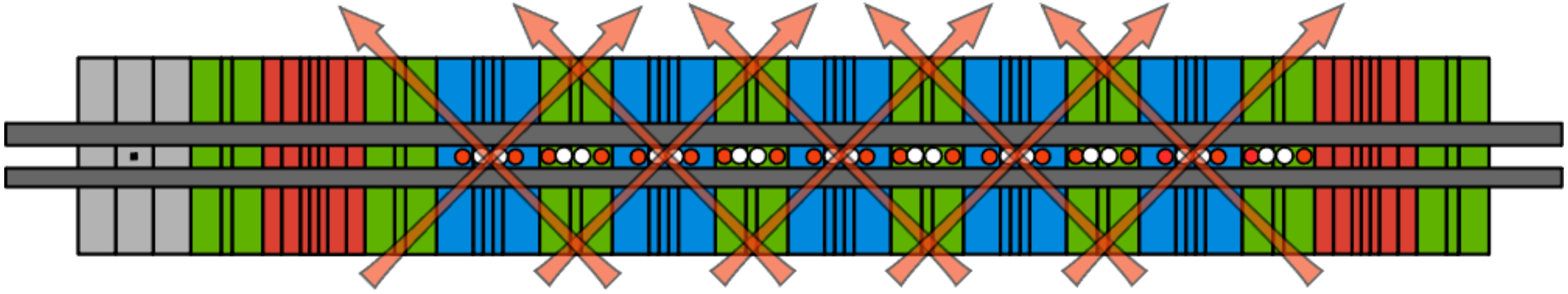


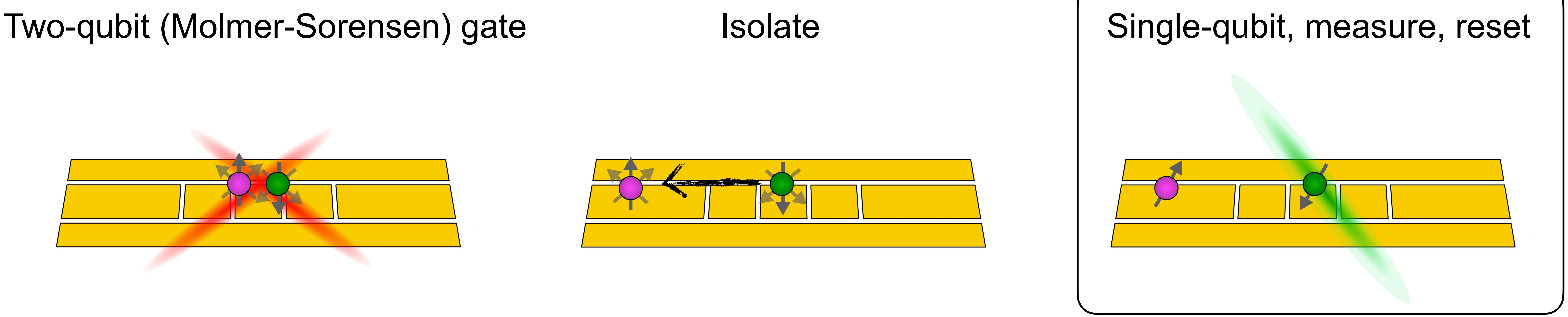


[1] Wineland, D.J., Monroe, C., Itano, W.M., Leibried, D., King, B.E., Meekhof, D.M., Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions, J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998)
[2] Pino, J.M., Dreiling, J.M., Figgatt, C. *et al.* Demonstration of the trapped-ion quantum CCD computer architecture. *Nature* **592,** 209–213 (2021).

Quantinuum's H1 series quantum computers

Despite 1D architecture, qubits can be arbitrarily rearranged/paired via physical swaps, shifts, and mergers

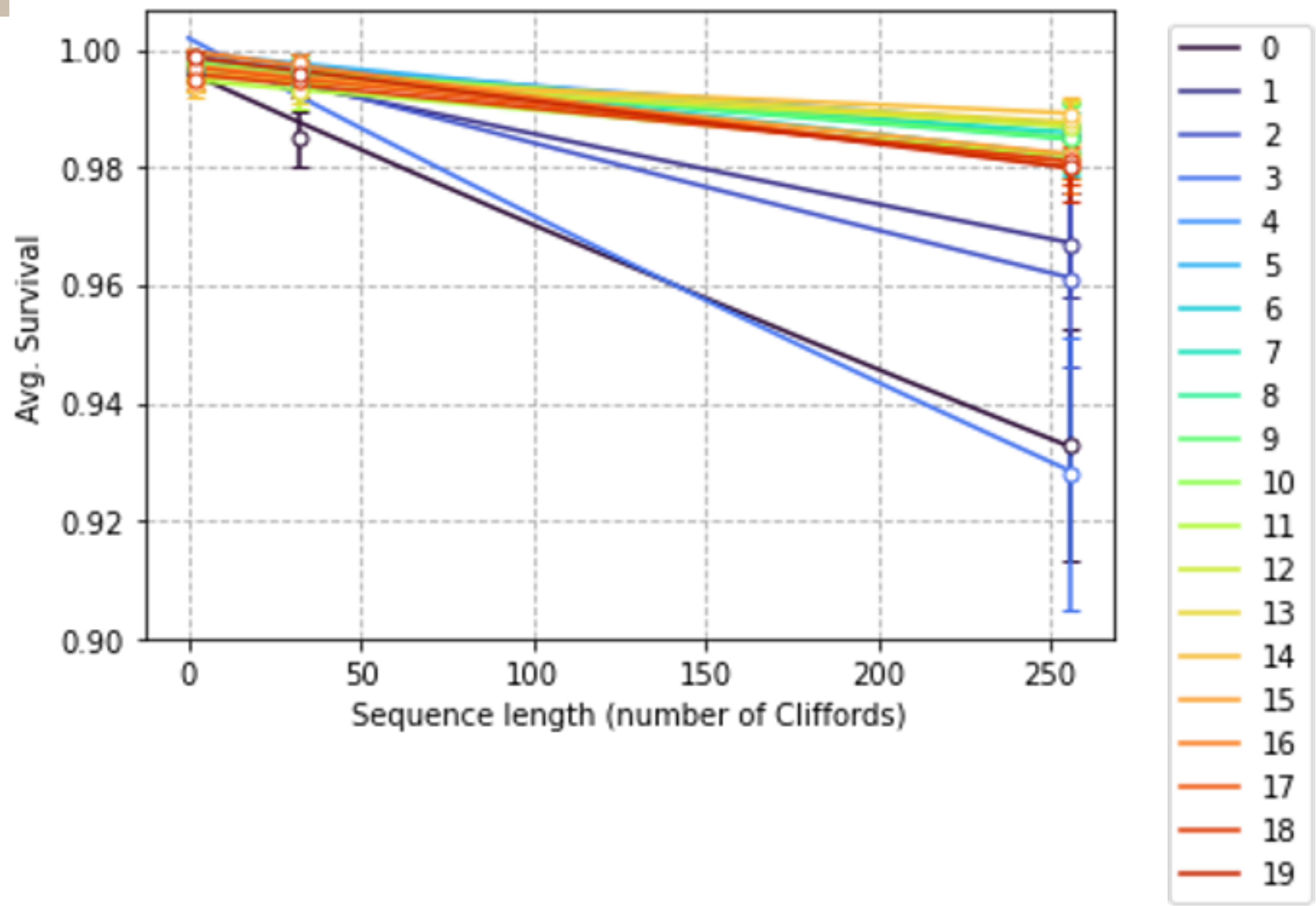




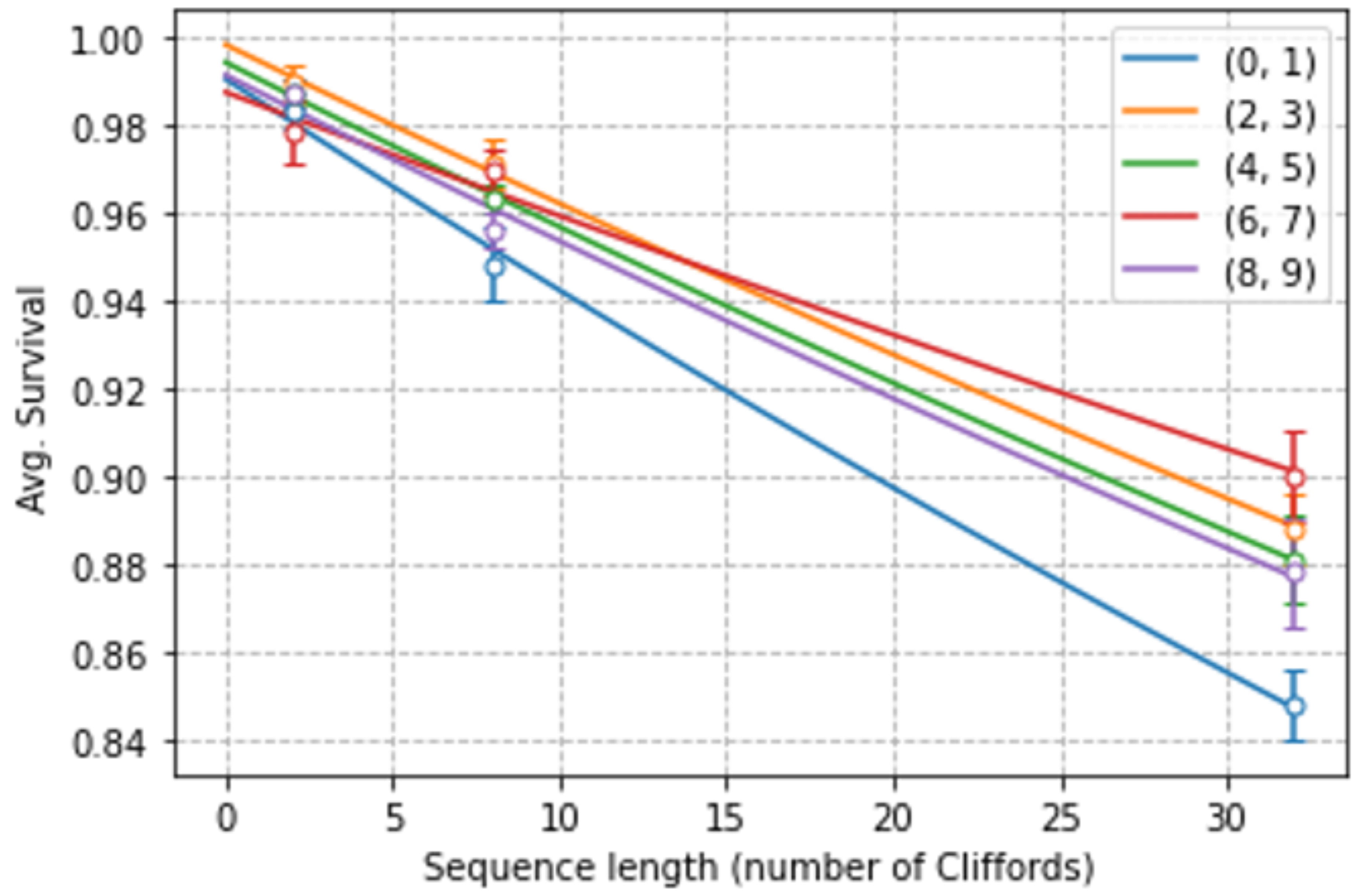
Low-crosstalk MCMR key to this work, and also recent demonstration of real-time QEC (C. Ryan- Anderson et al., arxiv:2107.07505)

Quantinuum's H1 series quantum computers

Single-qubit gates:



Two-qubit gates:



SQ fidelity: $(8.4 \pm 3.3) \times 10^{-5}$ SPAM fidelity: $(2.4 \pm 2.0) \times 10^{-3}$ TQ fidelity: $(2.6 \pm 0.4) \times 10^{-3}$

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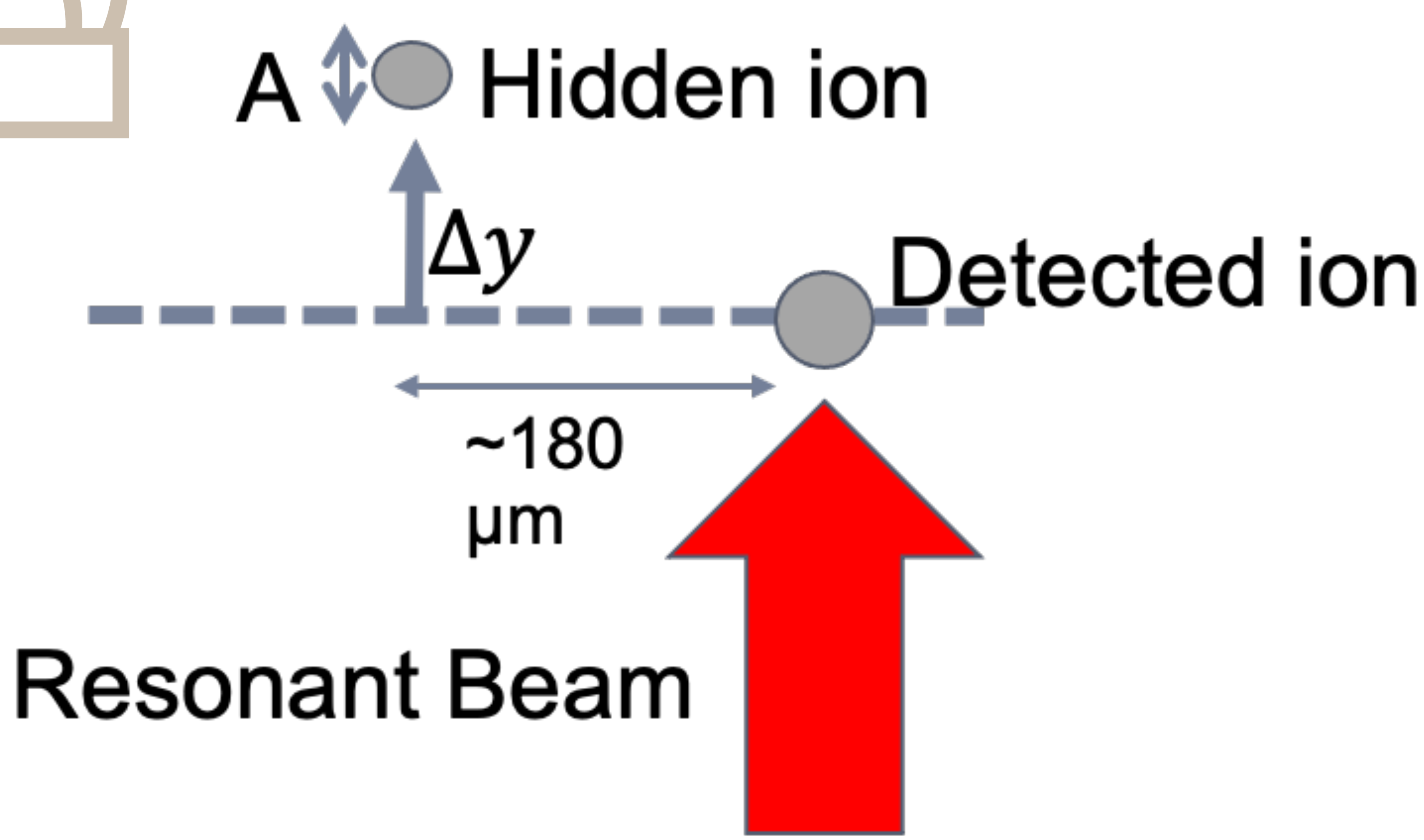
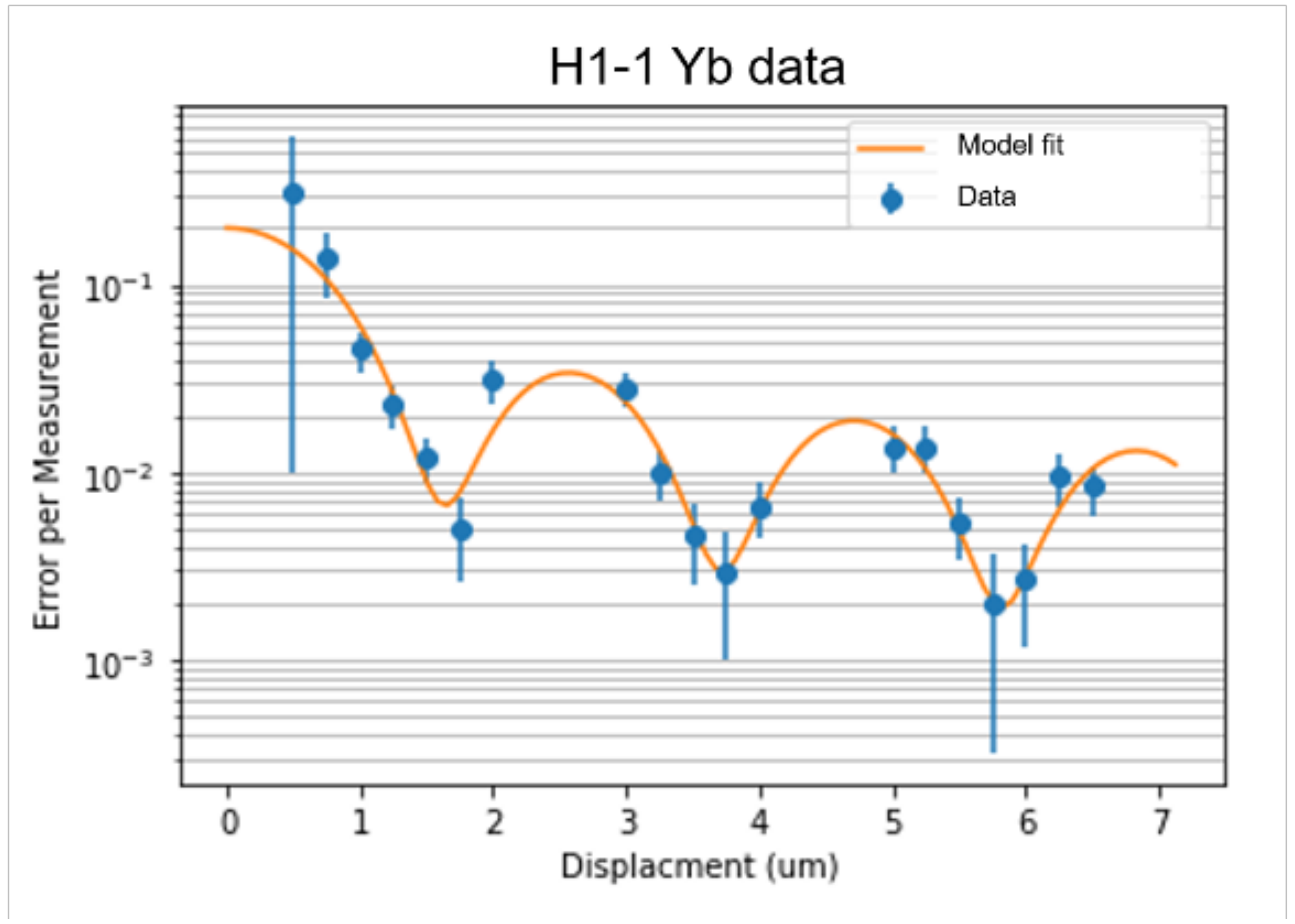
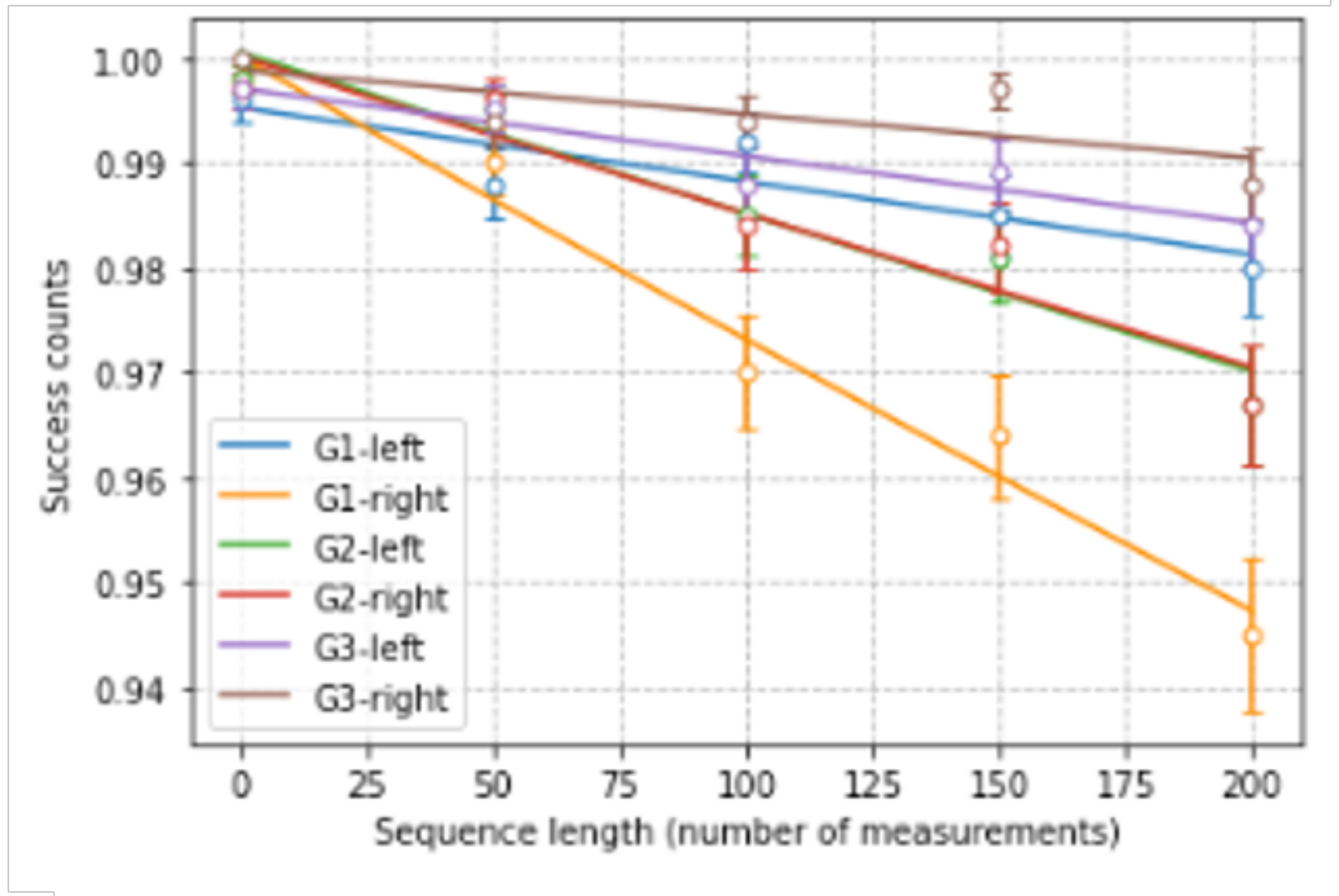
Quantinuum's H1 series quantum computers



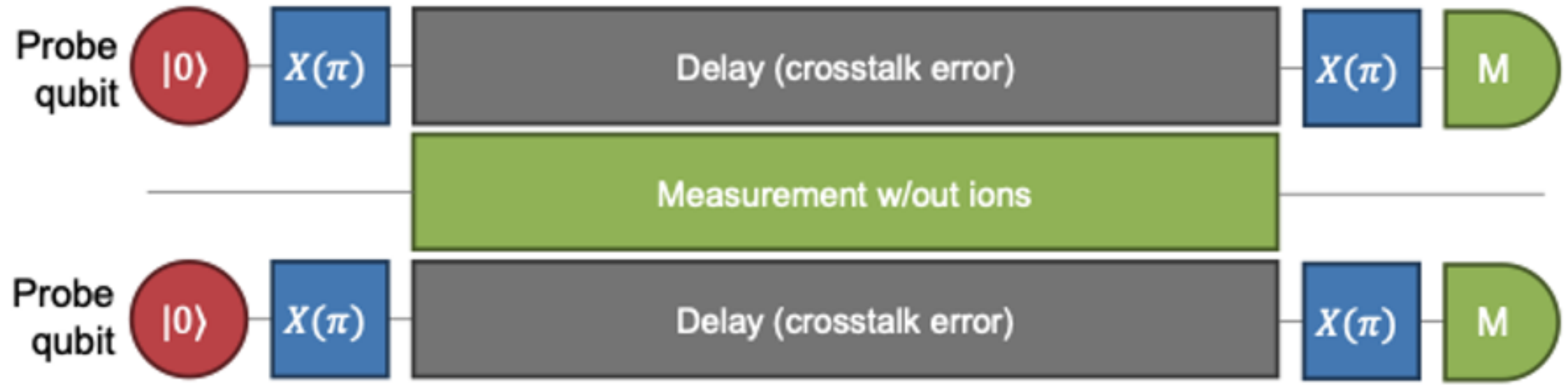


H1-2 Detection



	Avg. infidelity
G2-left	2.974E-05
G2-right	1.144E-04
G3-left	6.460E-05
G3-right	6.289E-05
G4-left	2.710E-05
G4-right	1.765E-05
Mean	5.273E-05

(a)



See J.P. Gaebler et al., arXiv: 2108.10932

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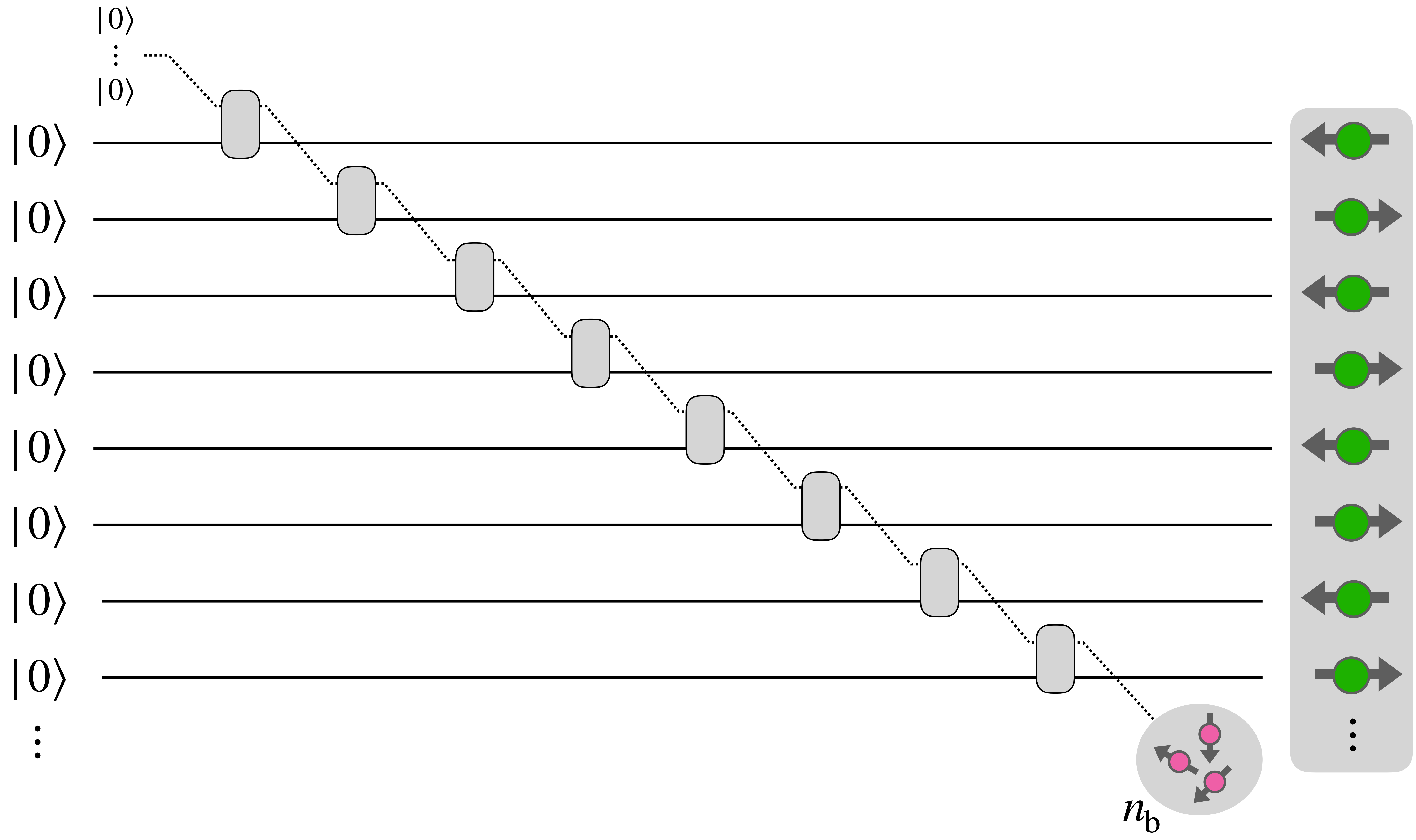
Quantum tensor networks with MCMR

Example: MPS as a quantum circuit



What have we gained? A nice circuit ansatz for generating some physically relevant state, but something else too…

Quantum tensor networks with MCMR

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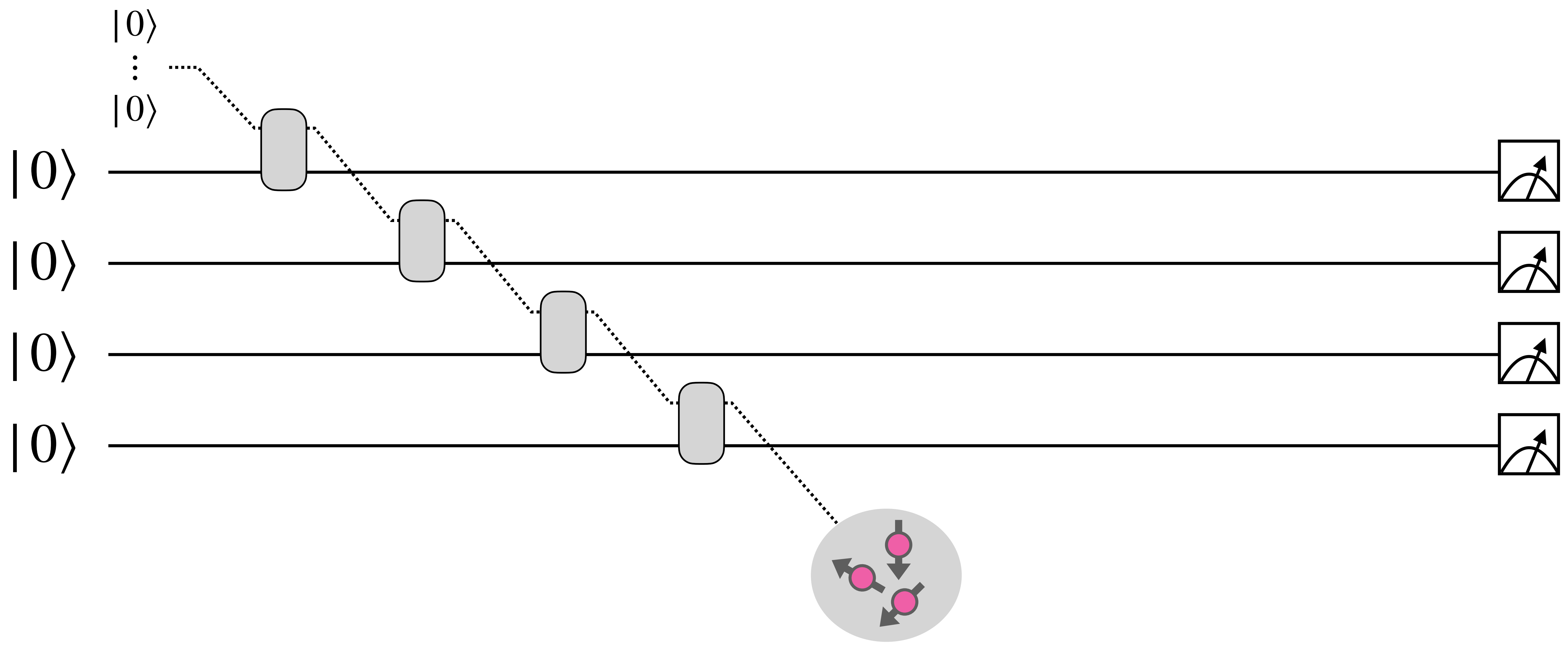

Quantum tensor networks with MCMR

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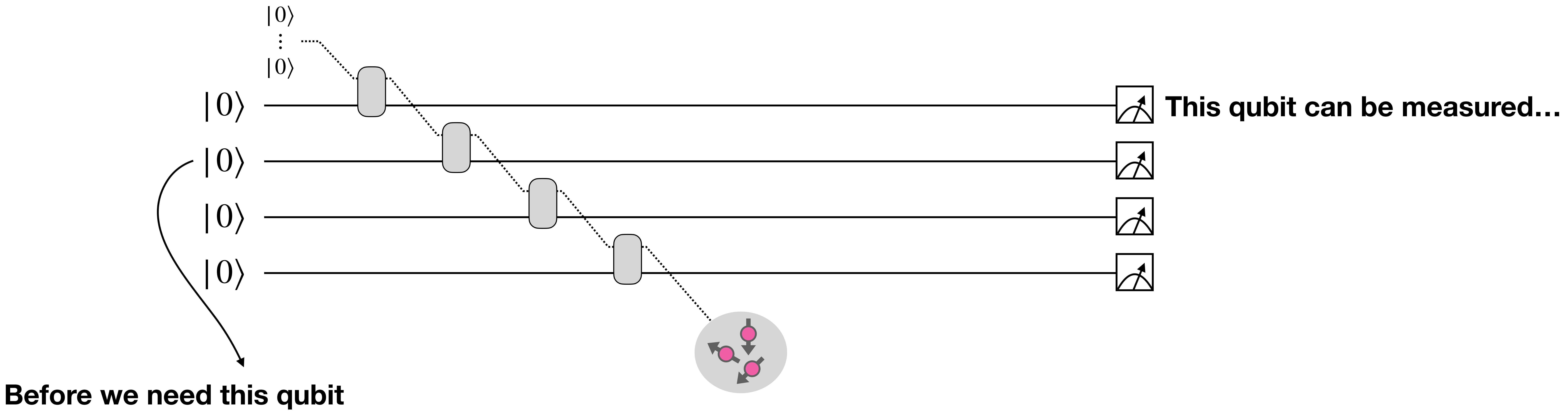

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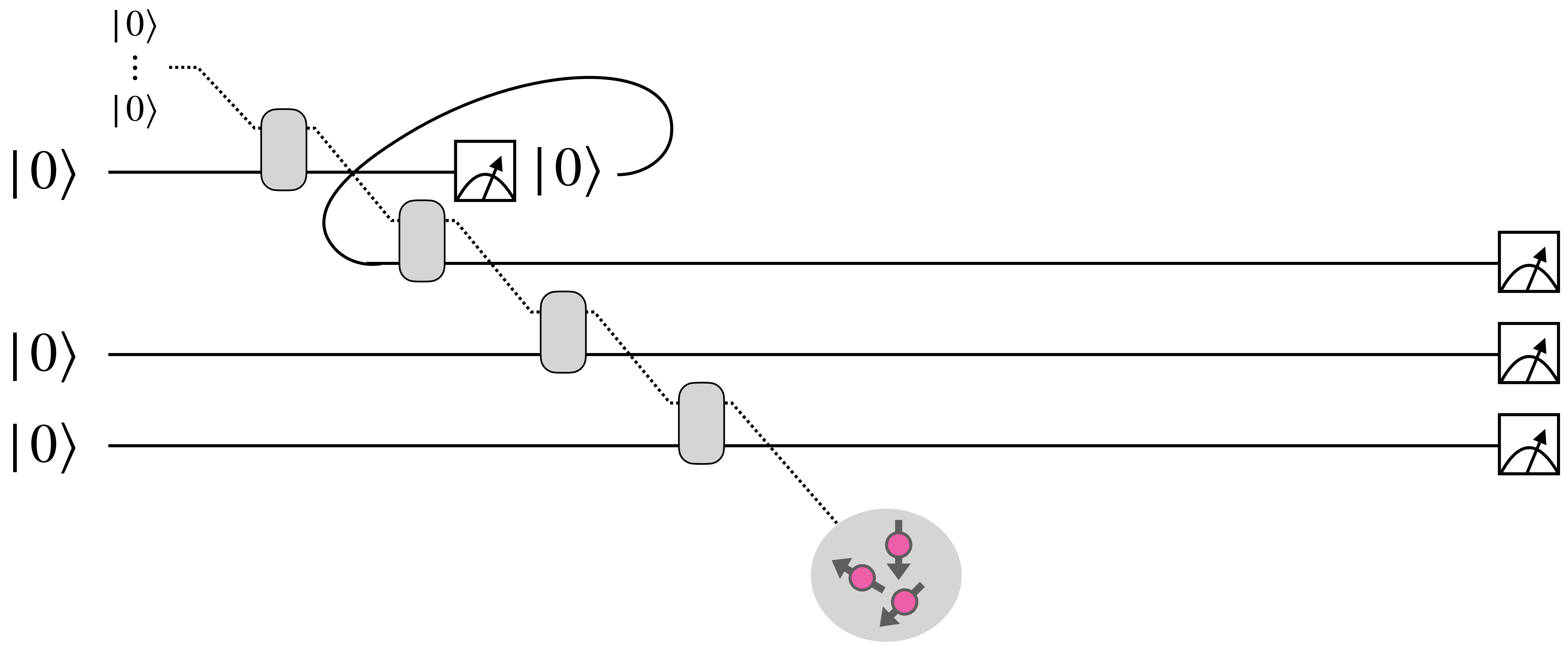

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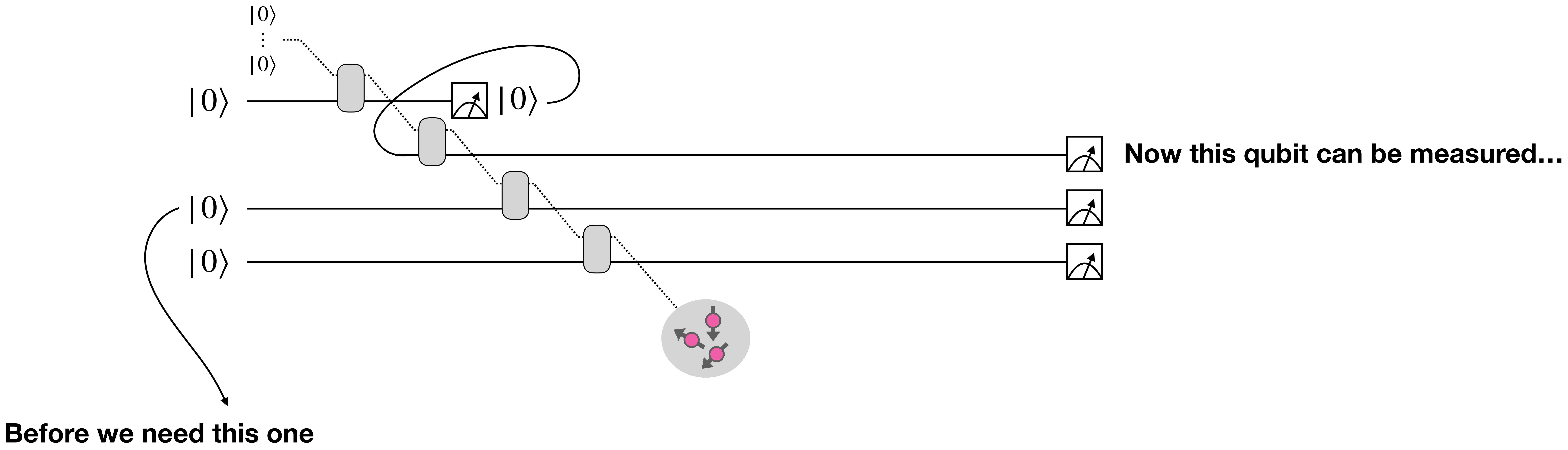

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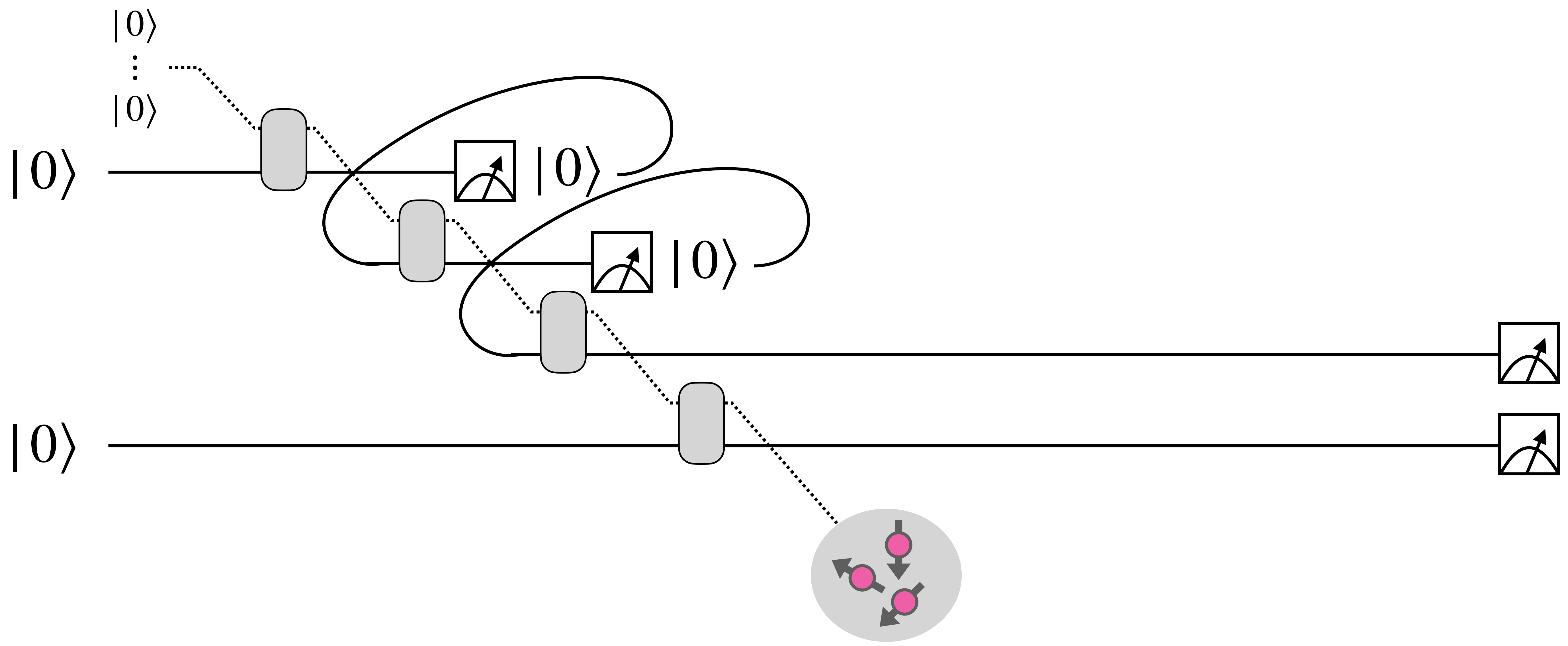

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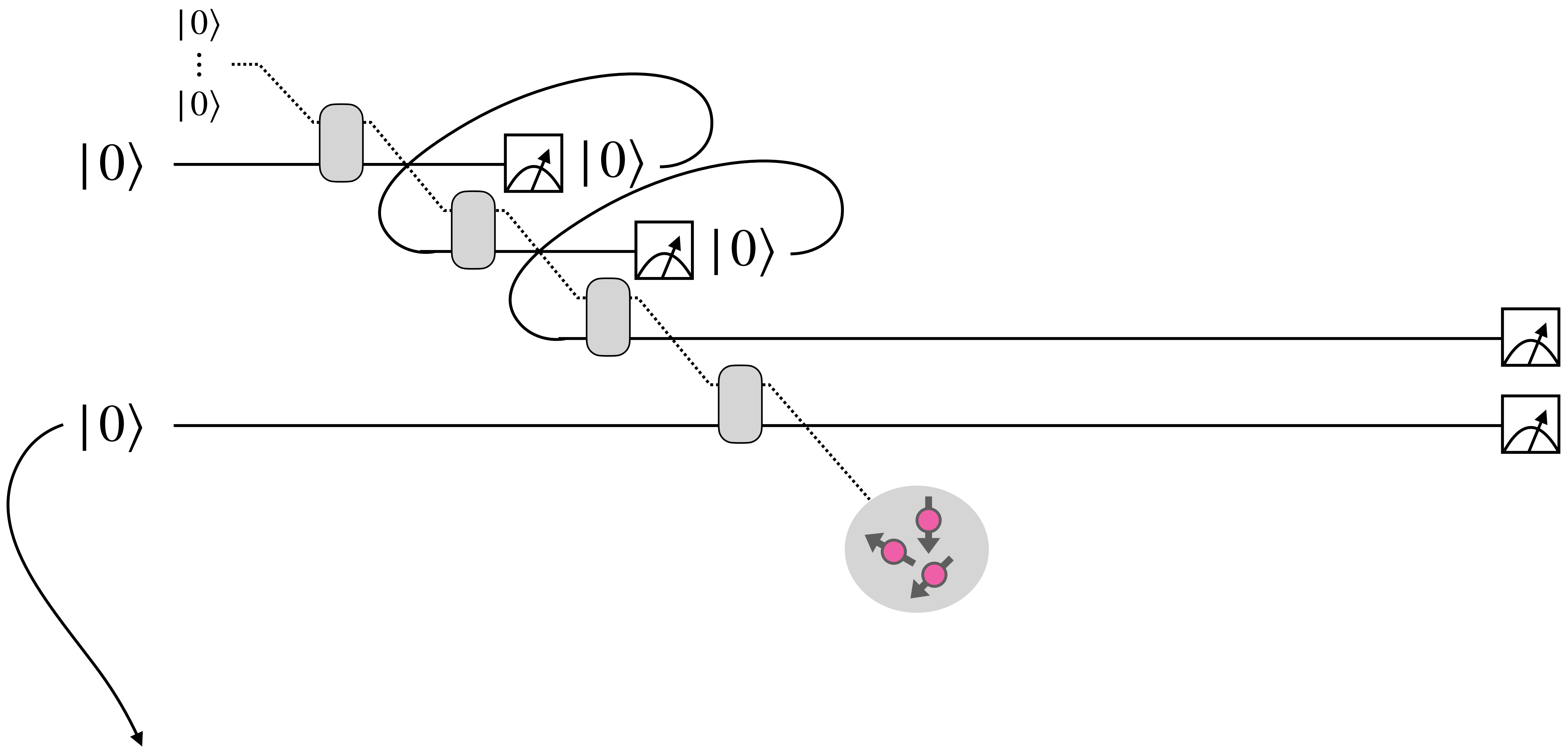

Now this qubit can be measured…

Before we need this one

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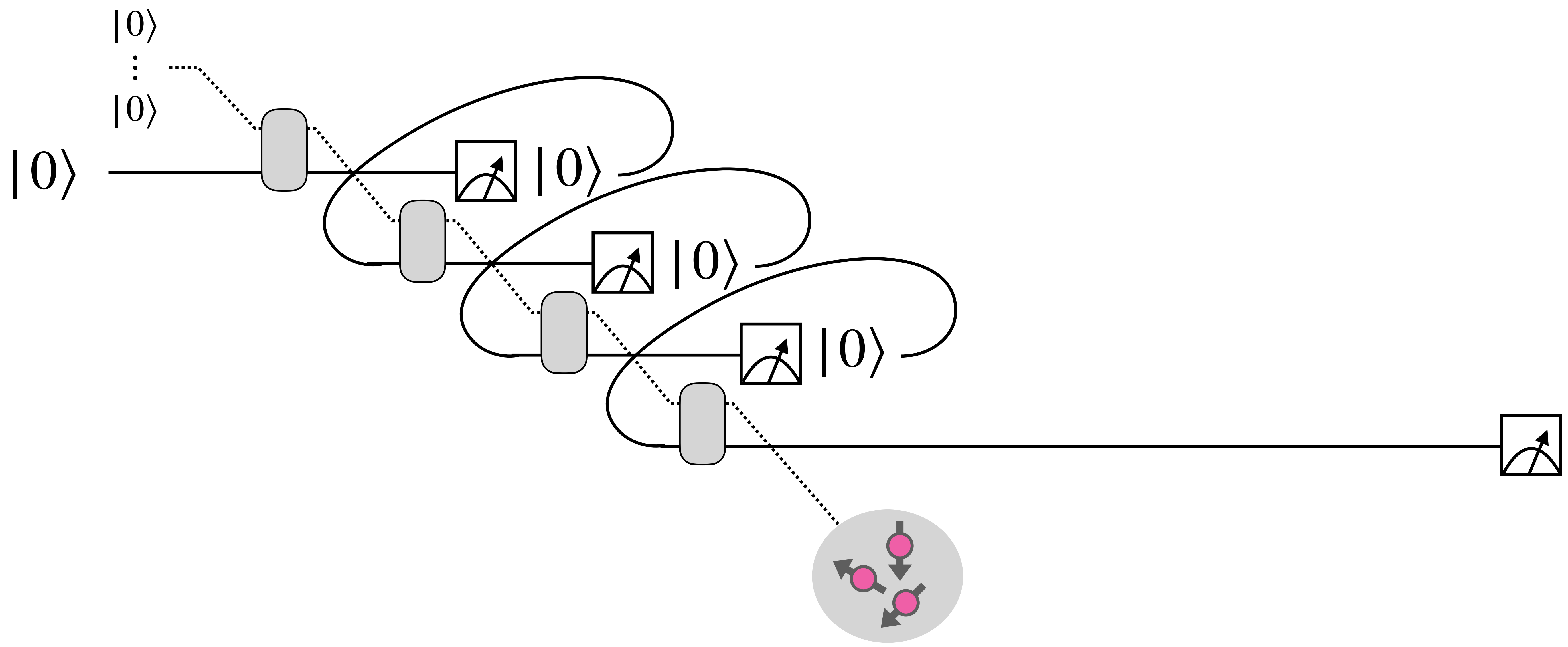
Quantum tensor networks with MCMR

Example: MPS as a quantum circuit



Quantum tensor networks with MCMR

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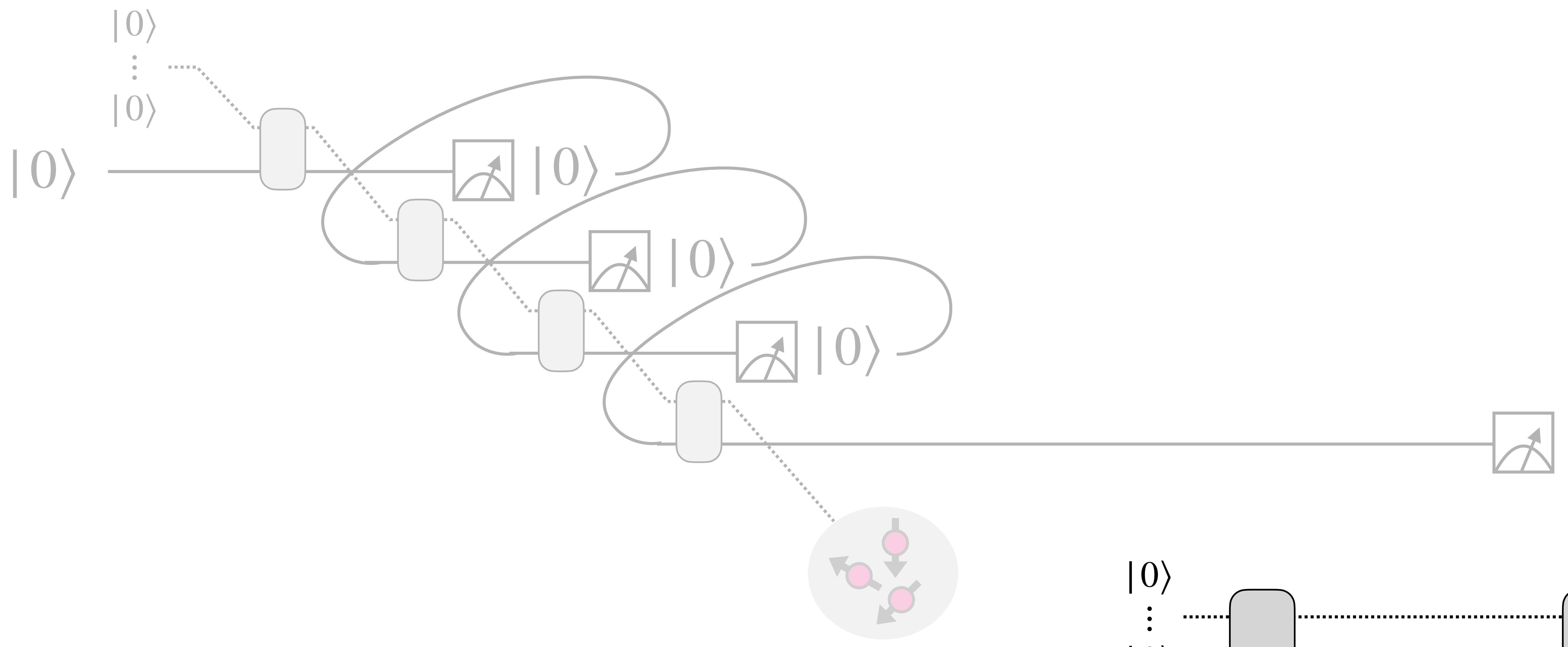

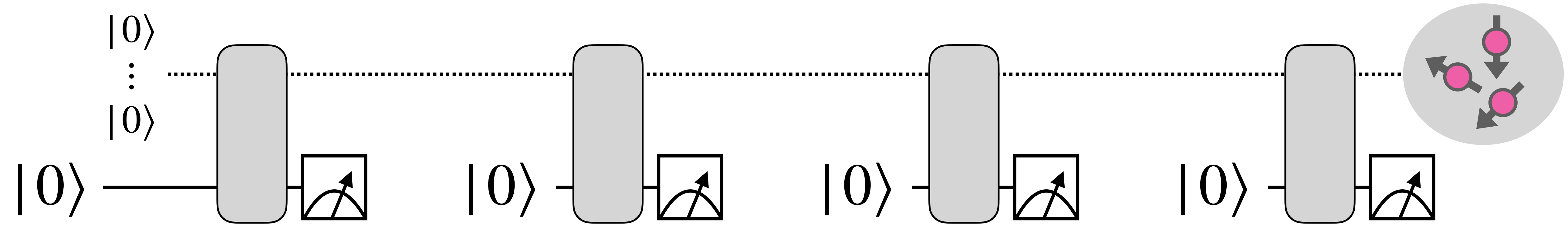

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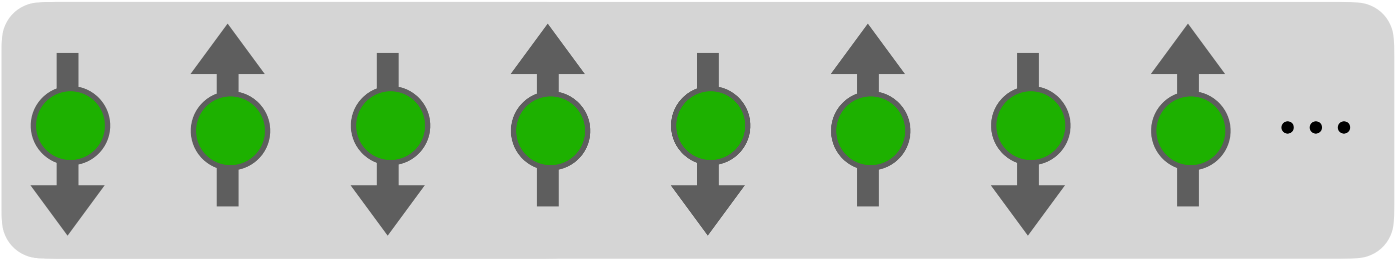
Quantum tensor networks with MCMR

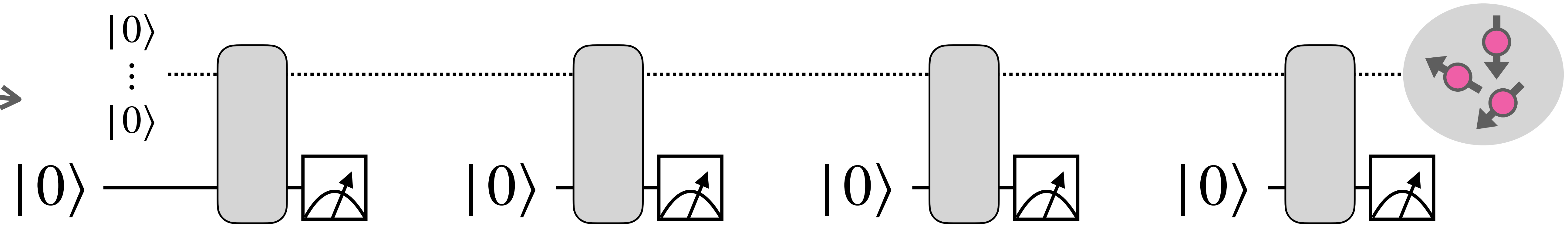
Example: MPS as a quantum circuit

Summary of all that:

$|\Psi\rangle$



We started with some complicated state involving lots of qubits, that for physical reasons had low entanglement entropy and therefore could be expressed as a (low-bond-dimension) MPS



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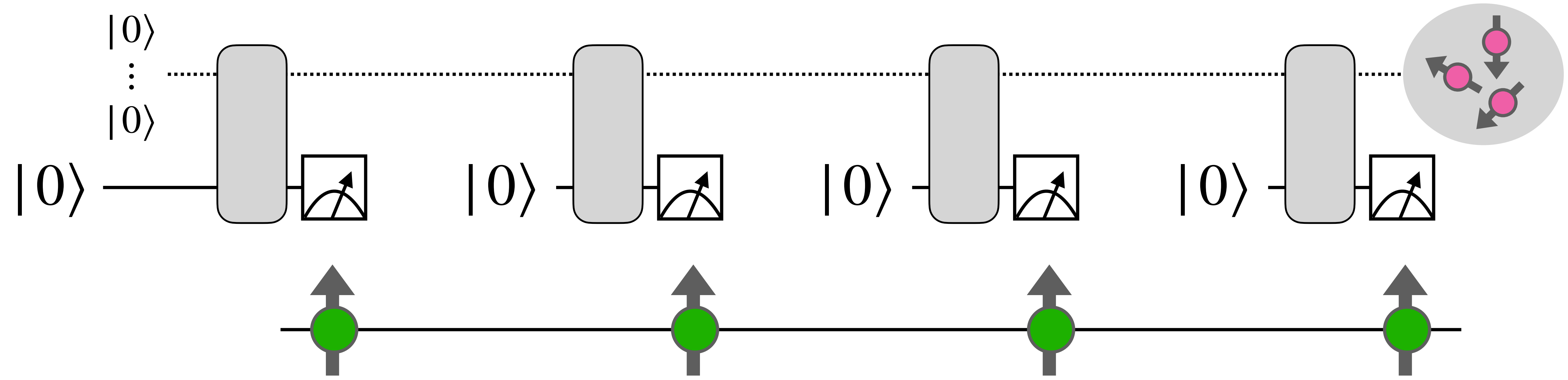
Quantum tensor networks with MCMR

Example: MPS as a quantum circuit

One qubit to represent the degrees of freedom of an infinite lattice: Measurements at a given time correspond to properties of the system at a given point in space.



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Quantum tensor networks with MCMR

Example: MPS as a quantum circuit

The qubit resources are pushed into a “bond” register (MPS language), with $n_b \sim \log \chi \sim S$ (qubit resources set by entanglement, not system size!)

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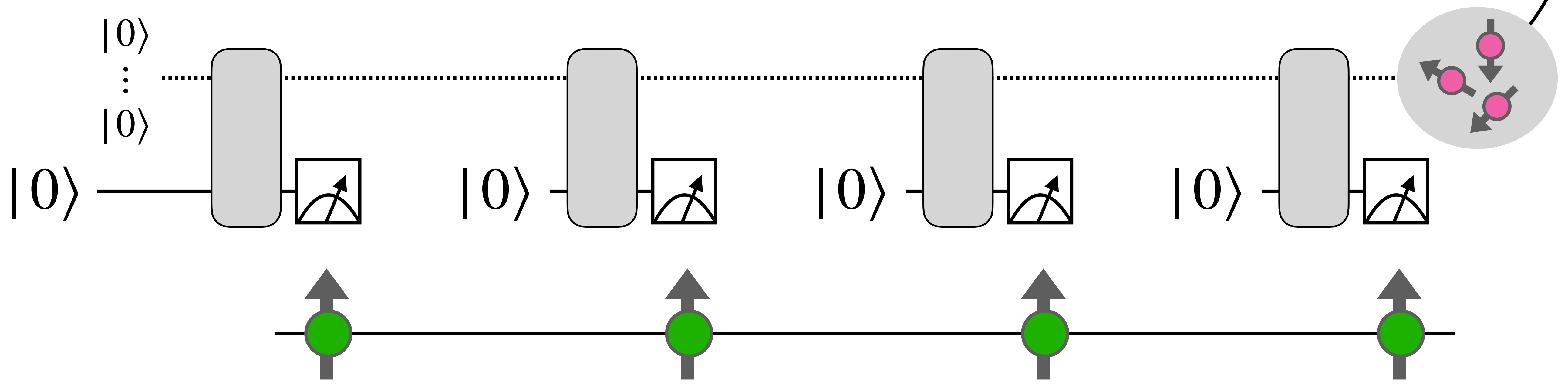

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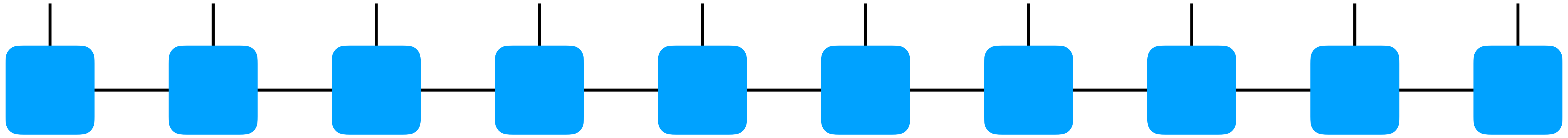
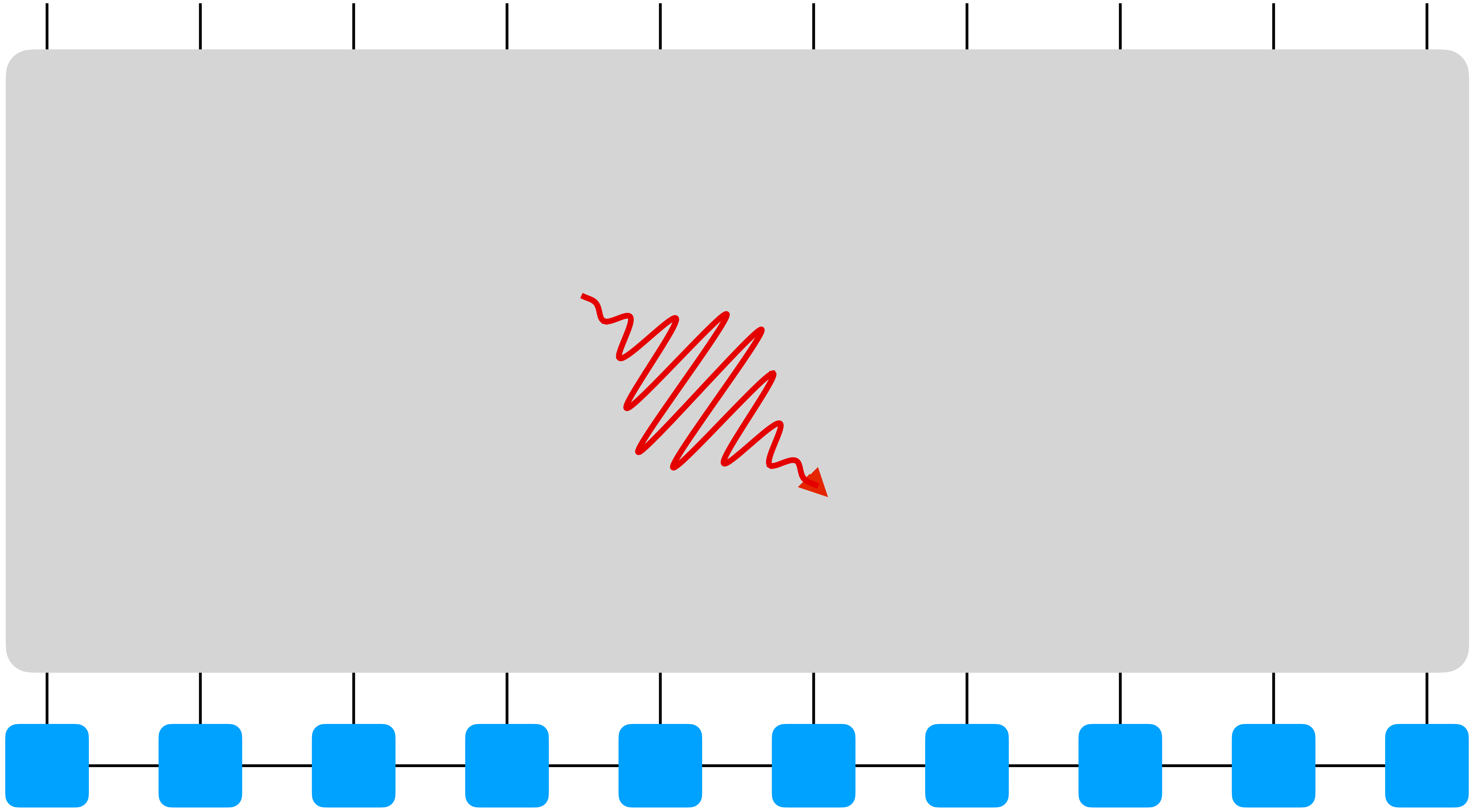
Algorithm for simulating quantum quenches

Initially correlated state:



Algorithm for simulating quantum quenches

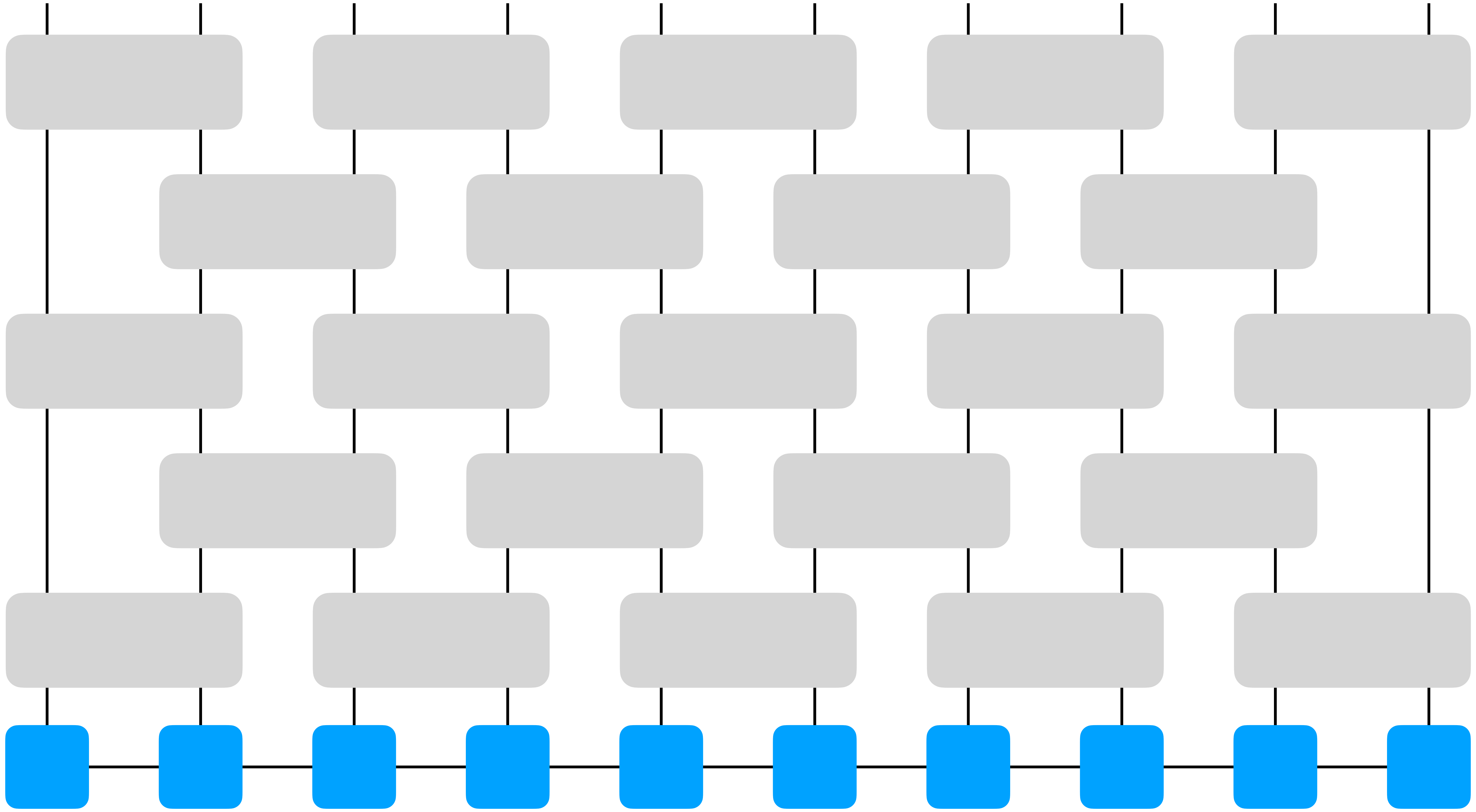
$$e^{-i\int_0^t d\tau H(\tau)} =$$



Algorithm for simulating quantum quenches

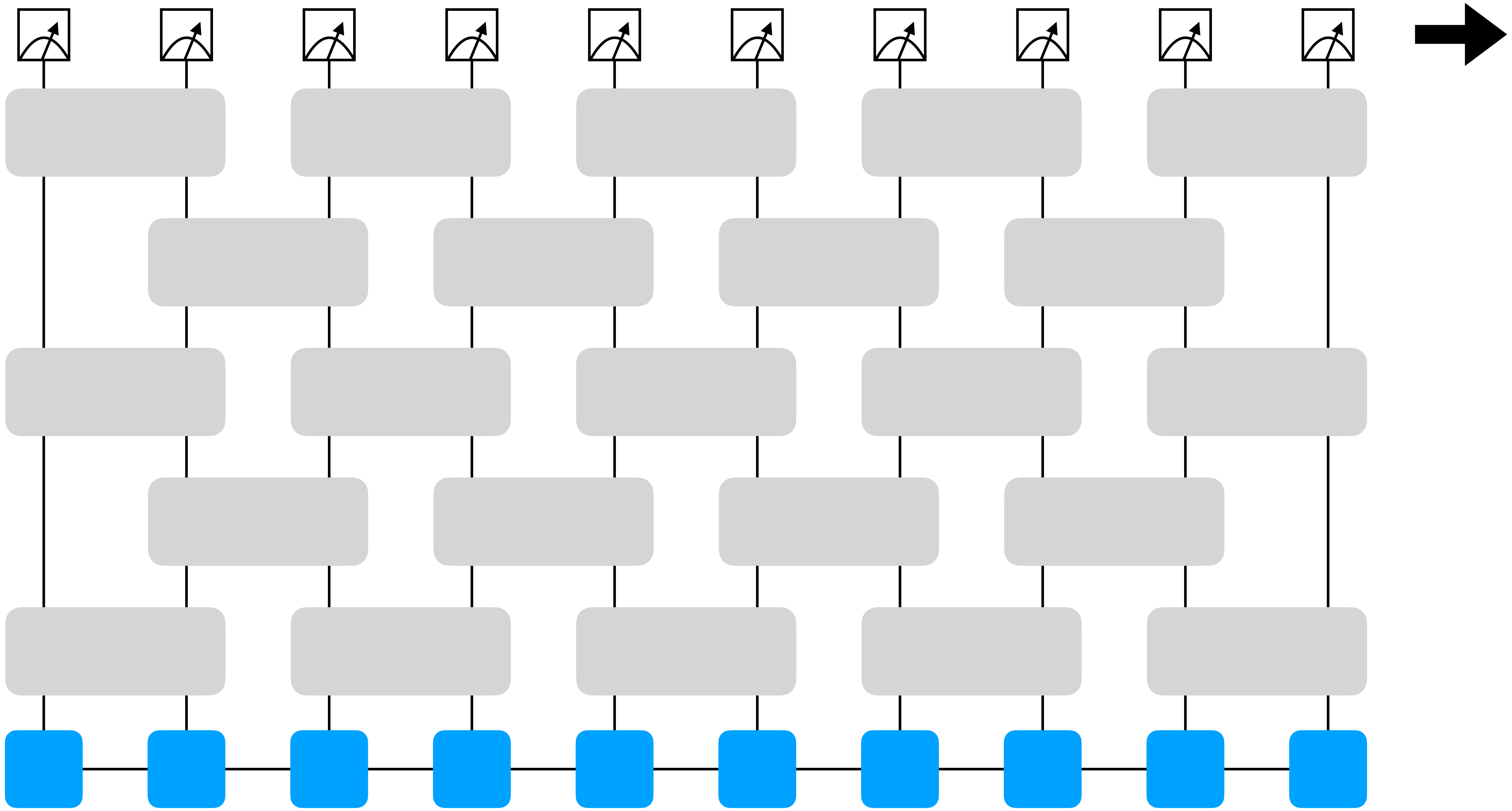
If we actually want to have the output state "in hand" (for example if we want to do generic quantum post-processing on it), then we just have to build the whole thing.

$$e^{-i\int_0^t d\tau H(\tau)} \approx$$



Algorithm for simulating quantum quenches

But in general we actually are satisfied with much less, for example, making arbitrary local measurements:



Equal time correlation functions:

$\langle S_i(t) S_j(t) \rangle$

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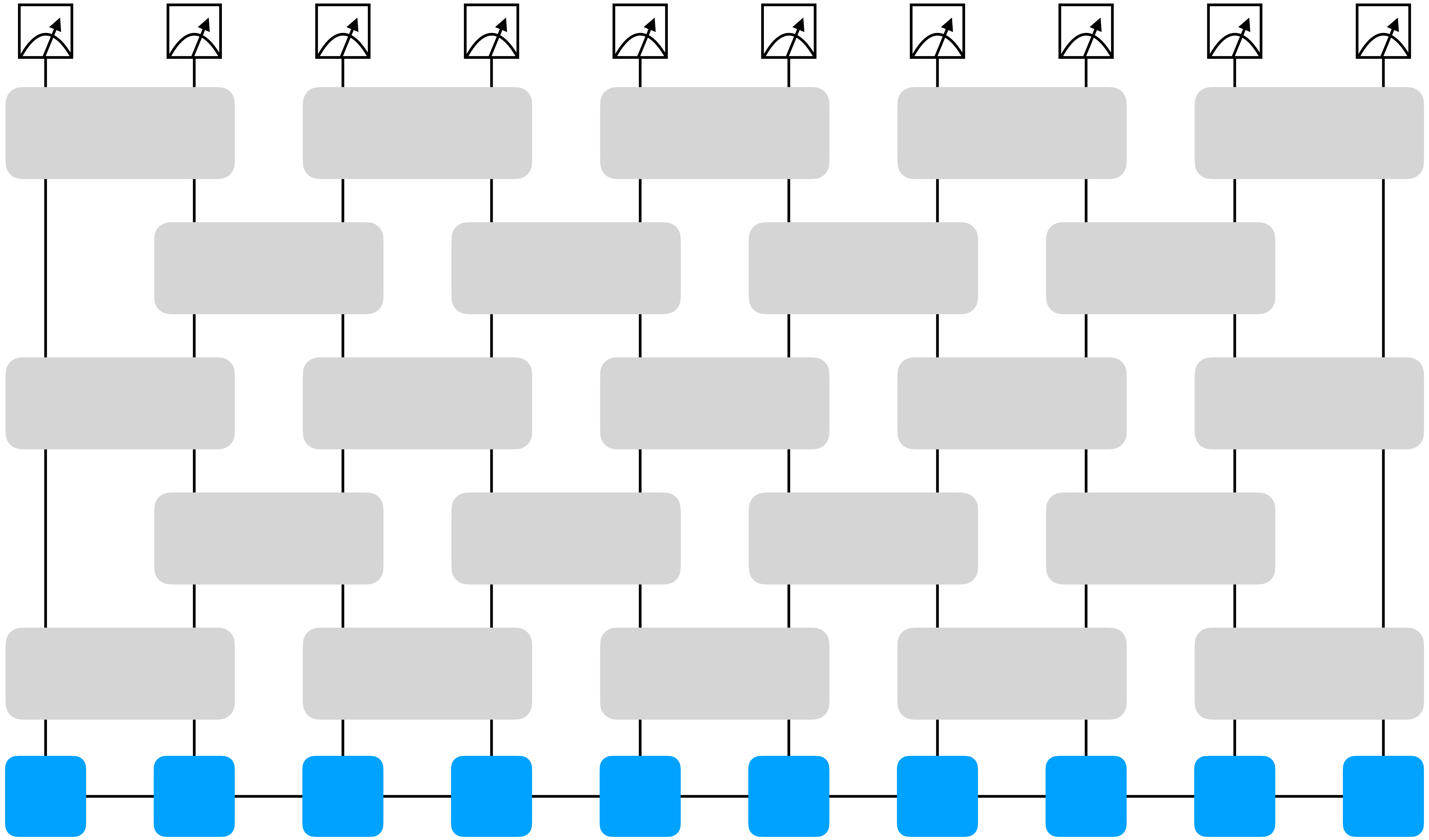
Algorithm for simulating quantum quenches

How many qubits do we actually need in order to make these measurements?



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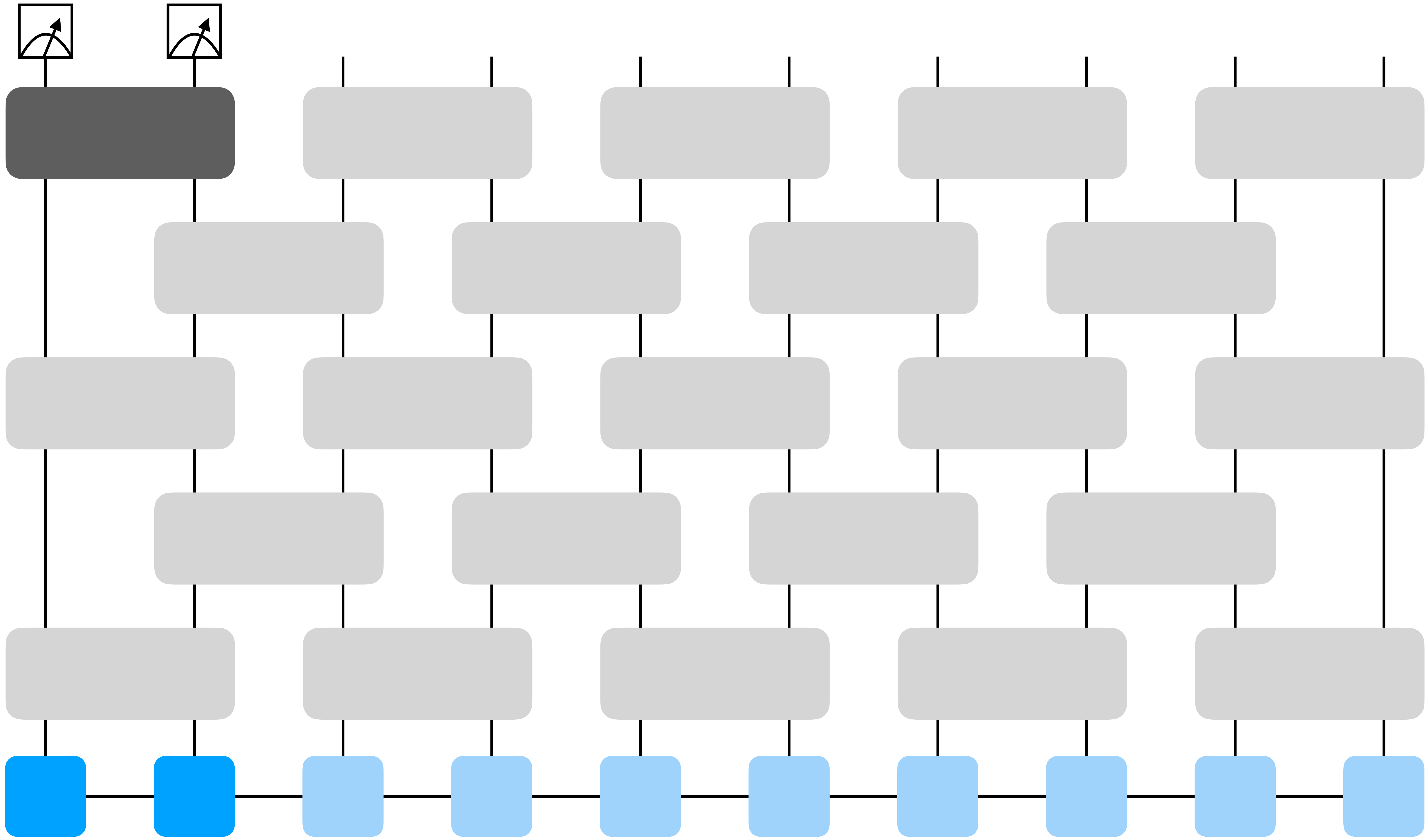

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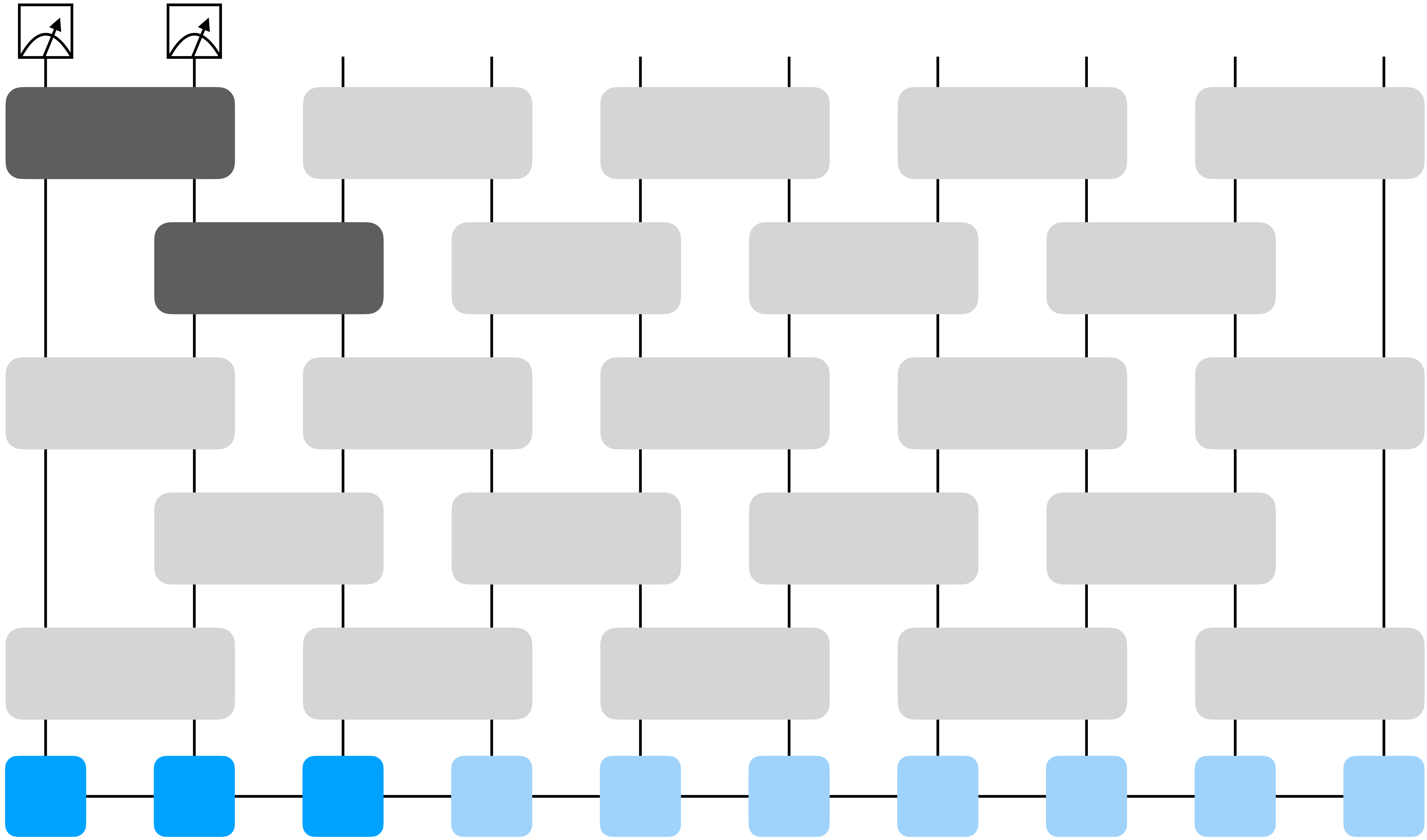

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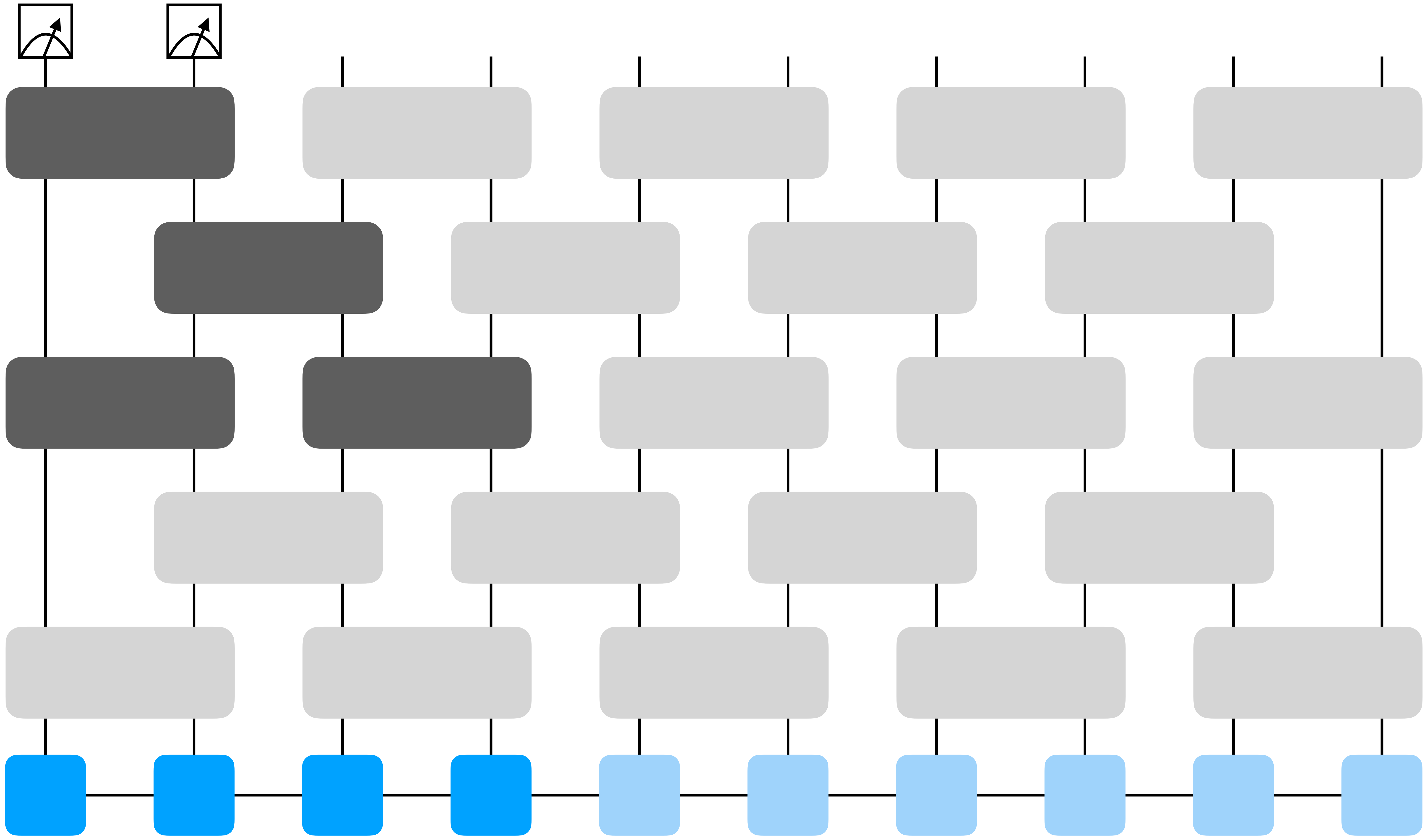

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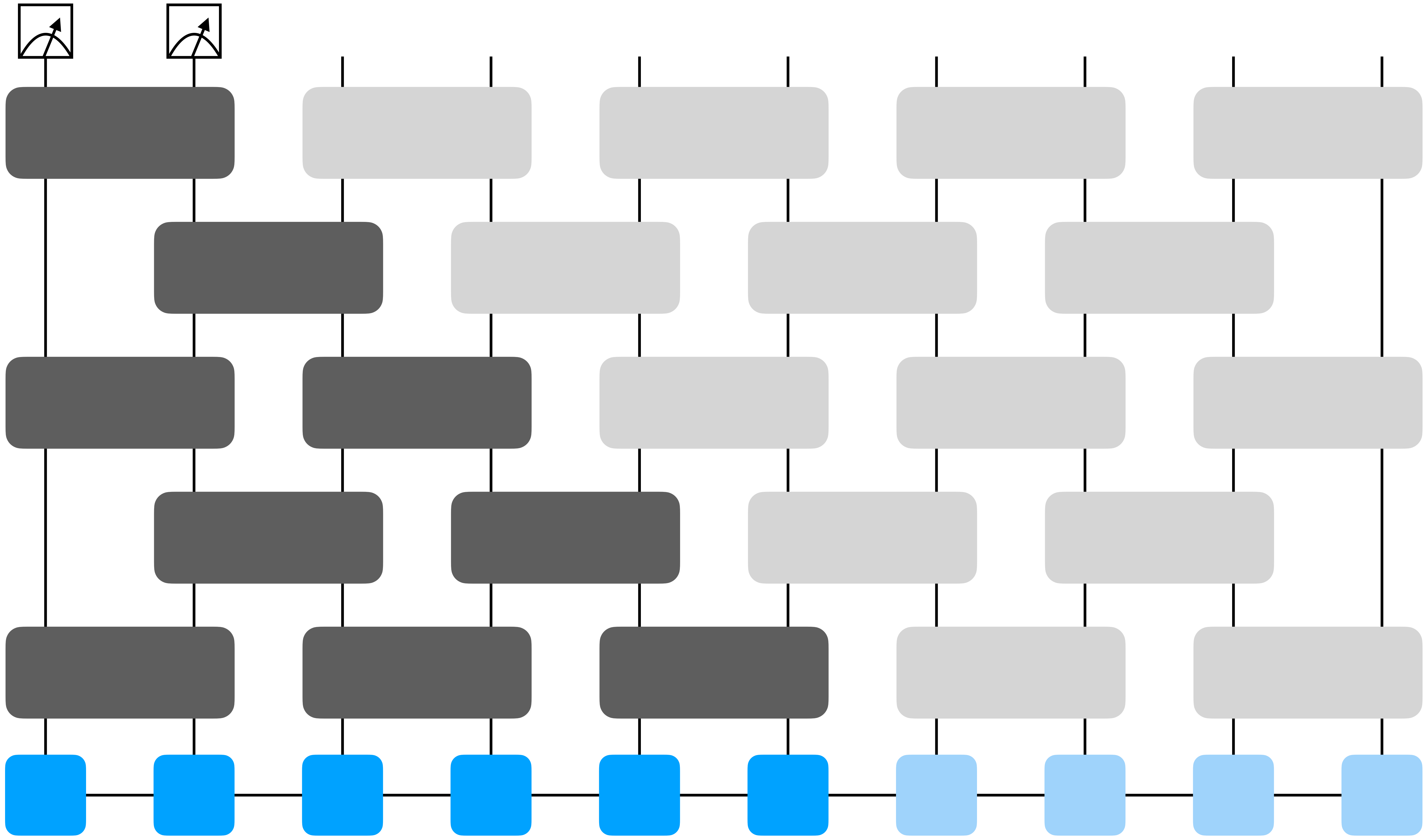

$N = 6?$

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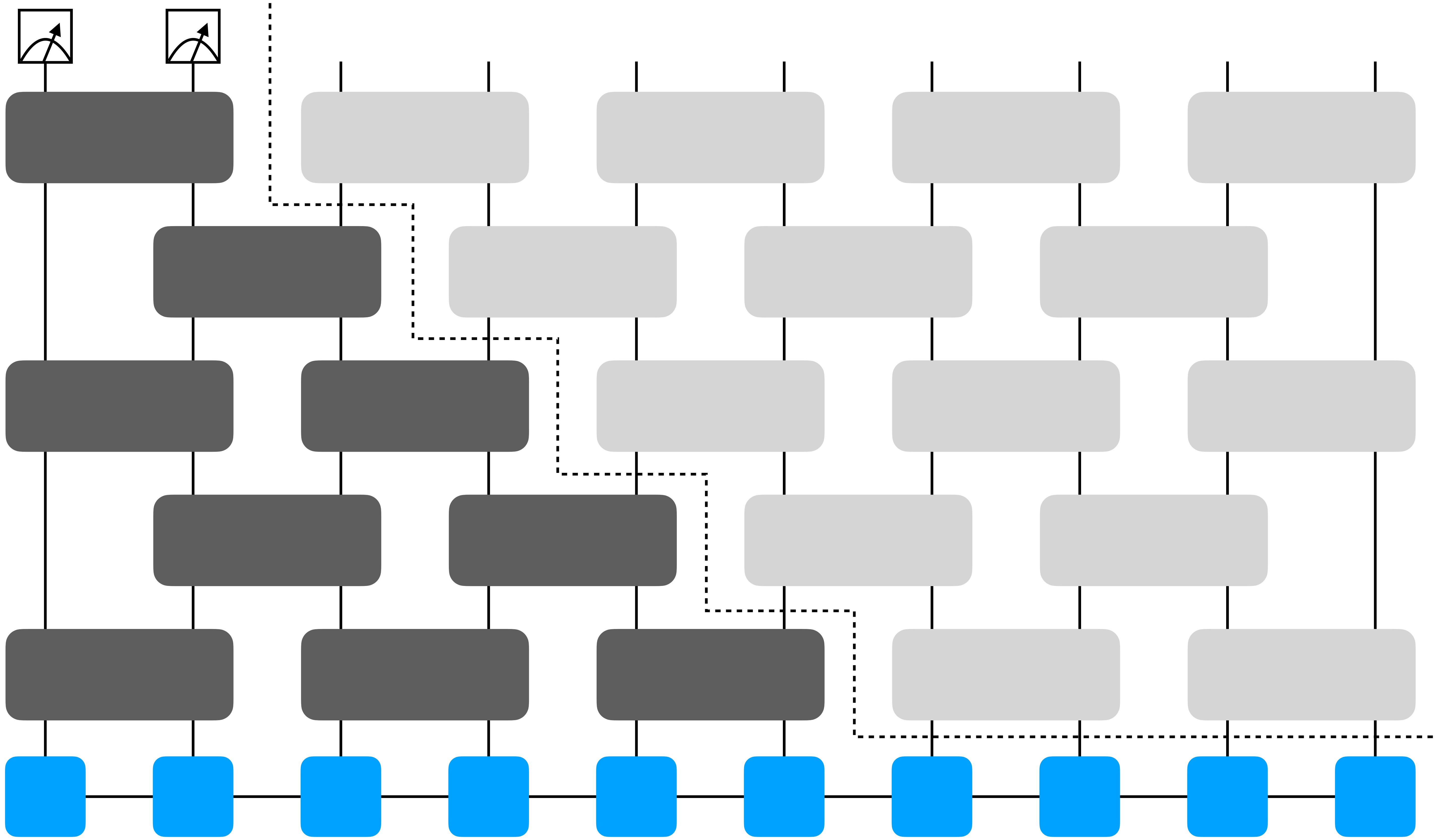
Algorithm for simulating quantum quenches

Correlations in the initial state seem to spoil any economization



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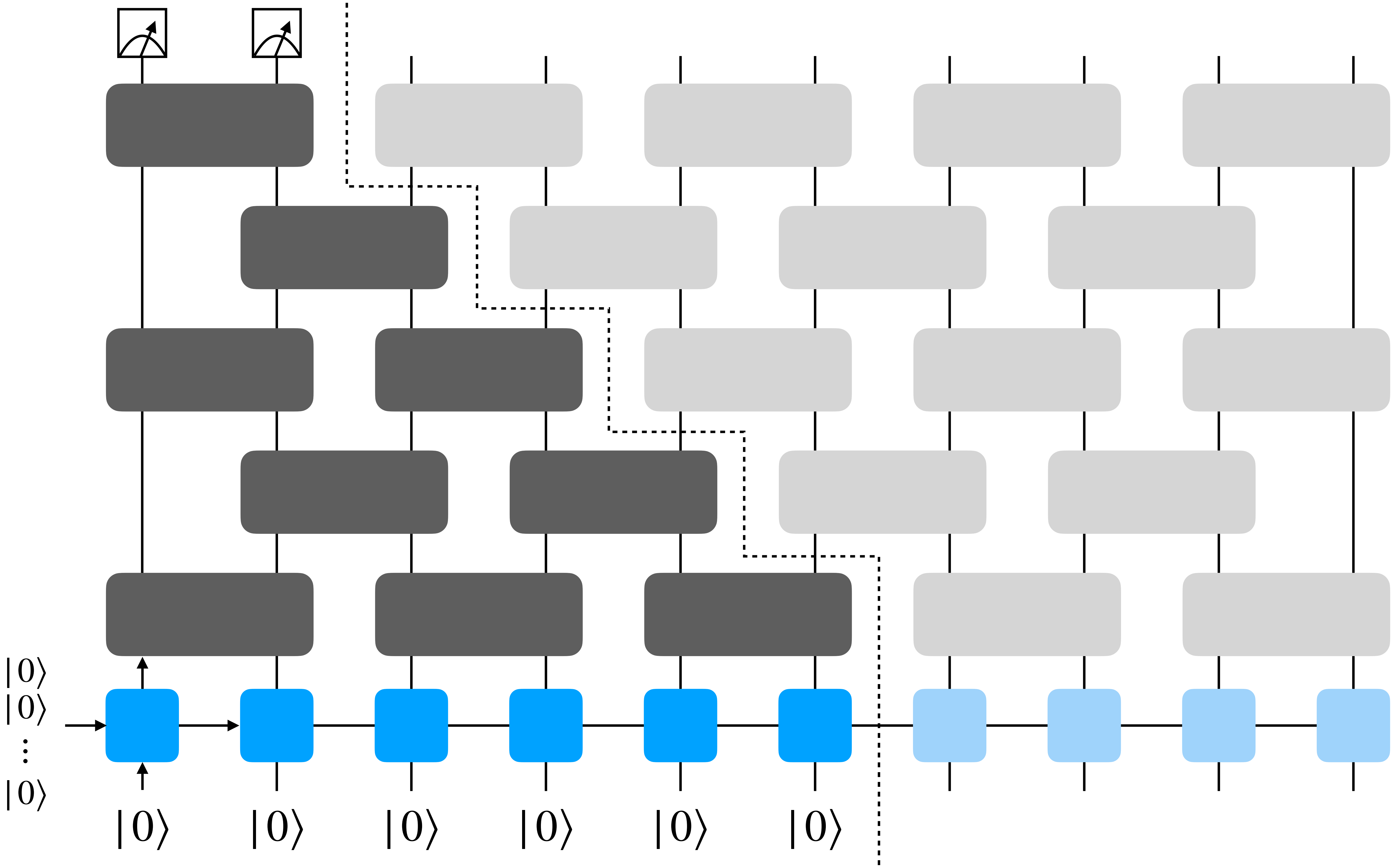
Algorithm for simulating quantum quenches

Measure, reset, and reuse



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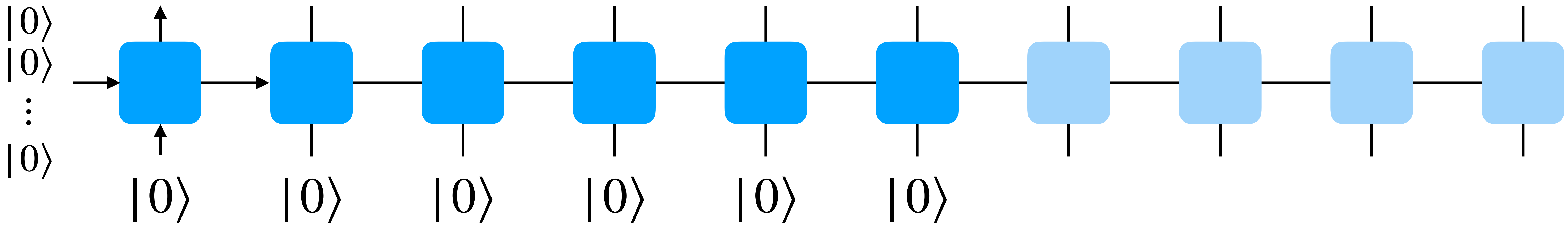
Algorithm for simulating quantum quenches

Looks a little different but this is exactly the “quantum MPS” circuit we looked at before:



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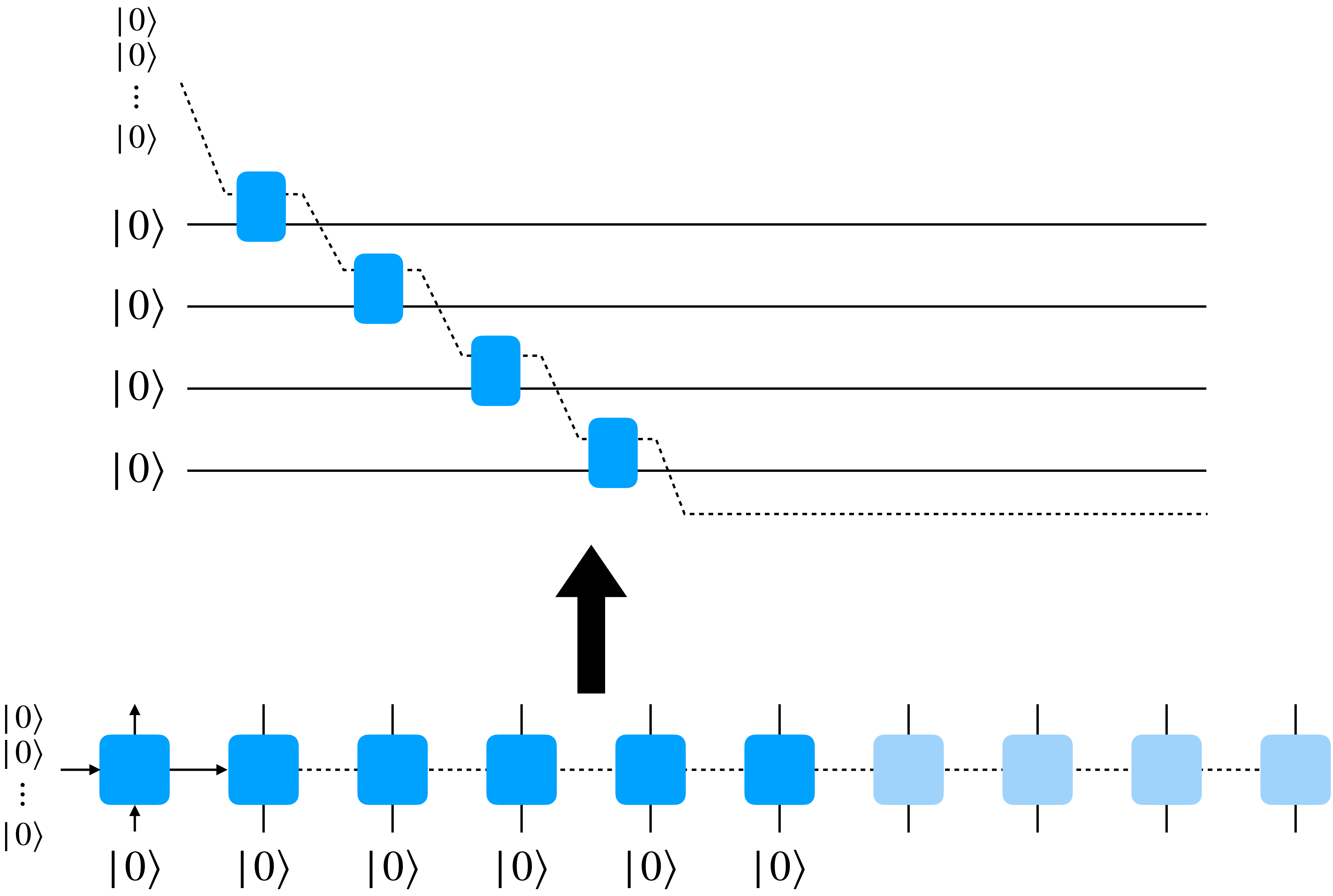

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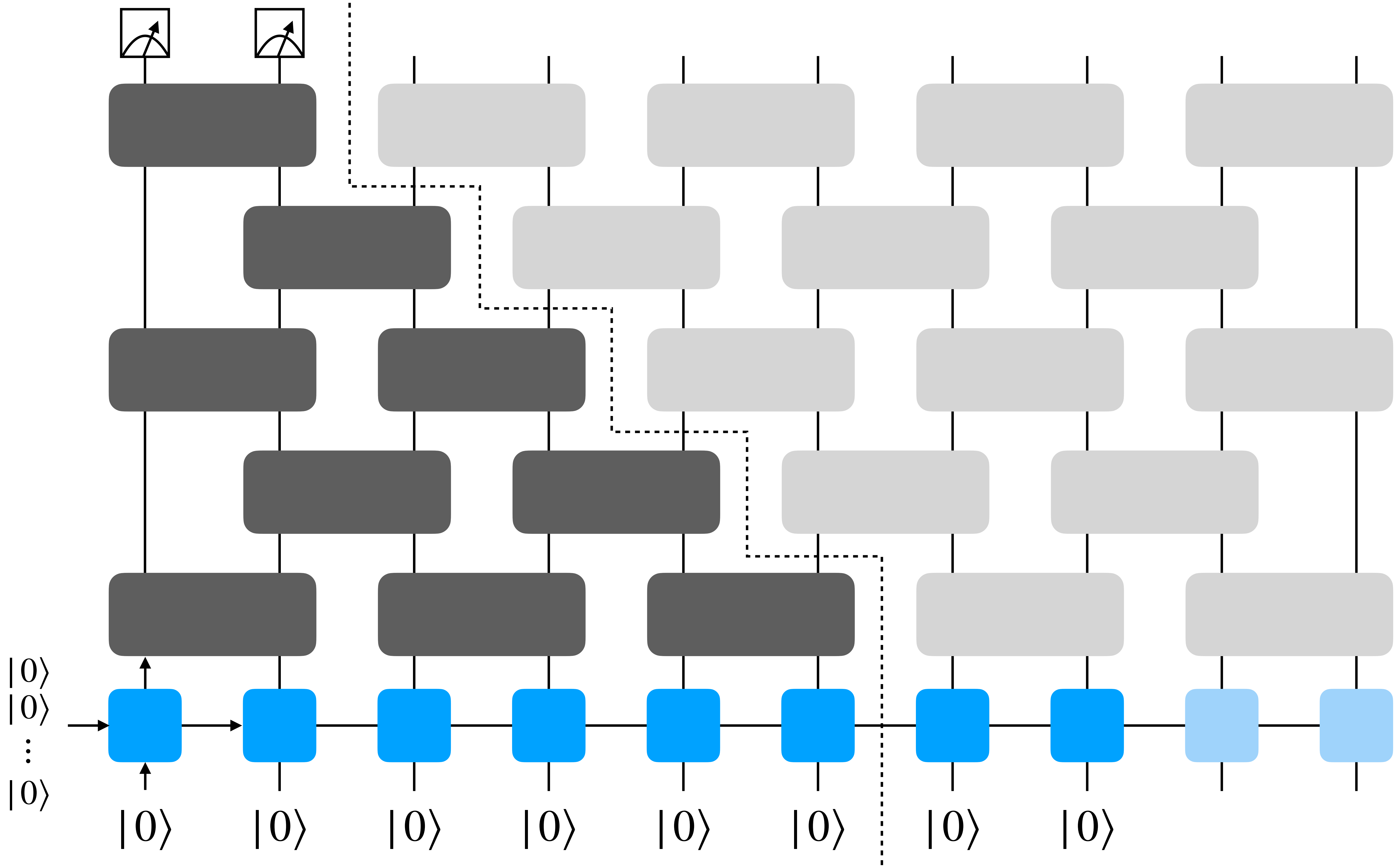

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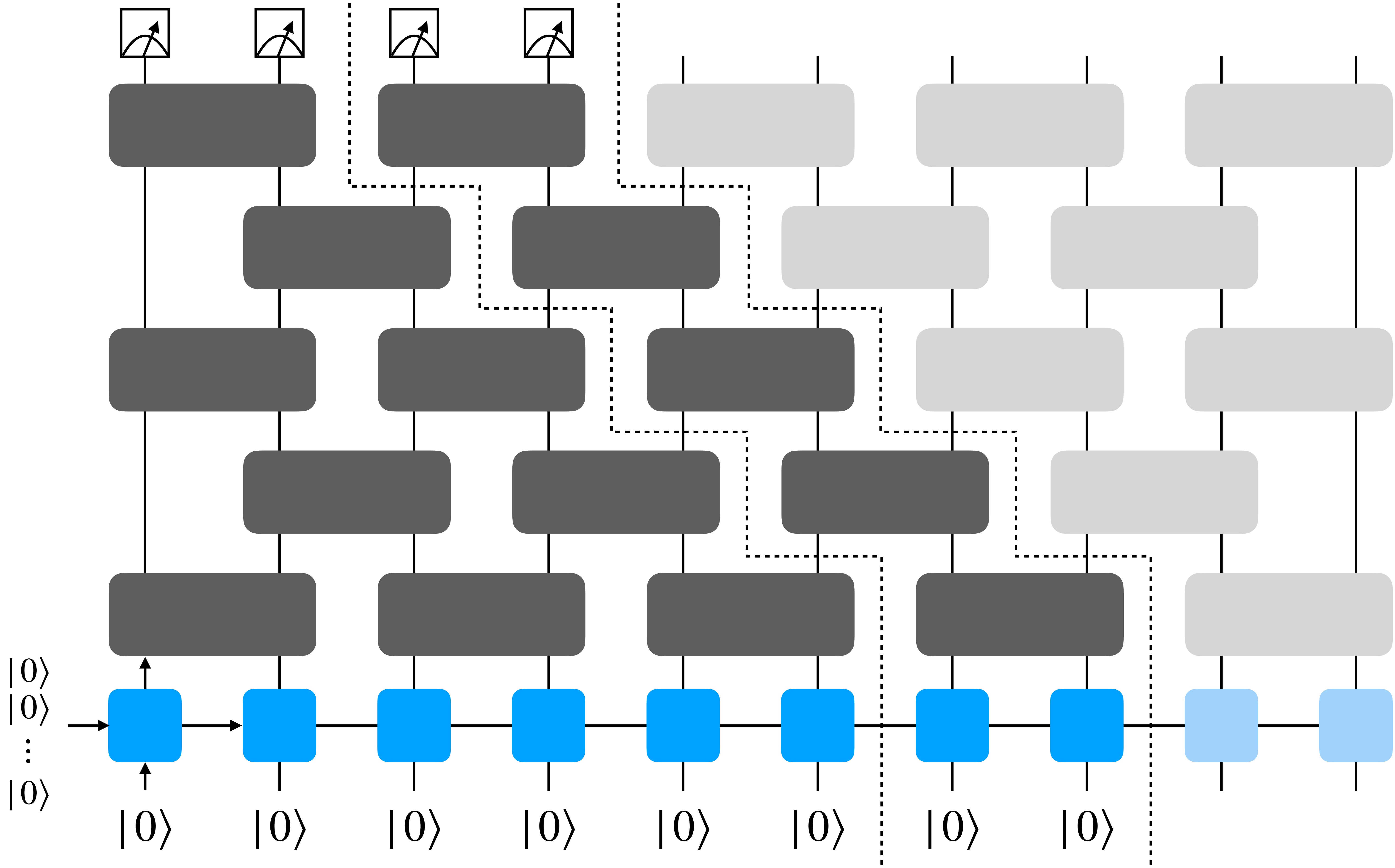

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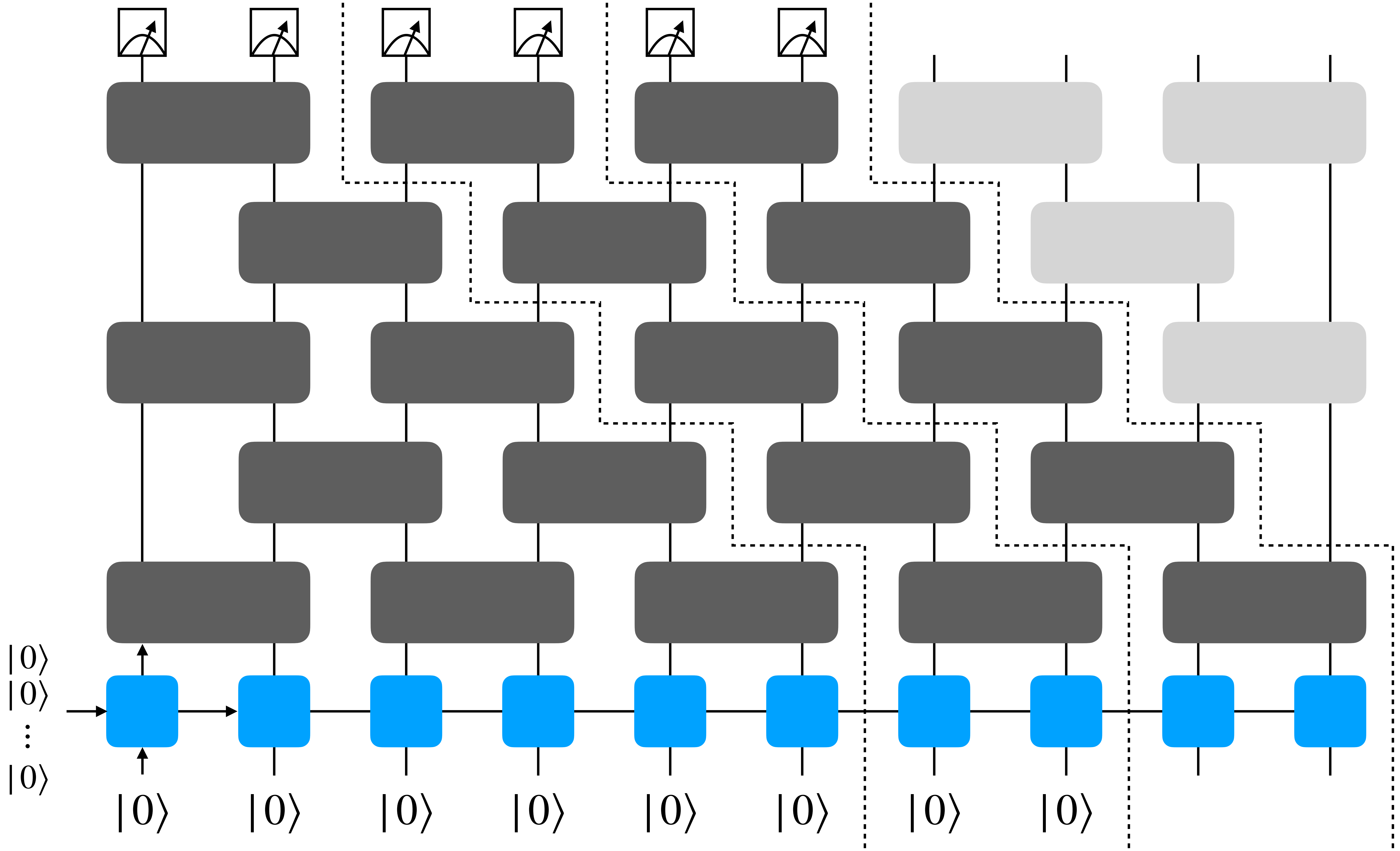
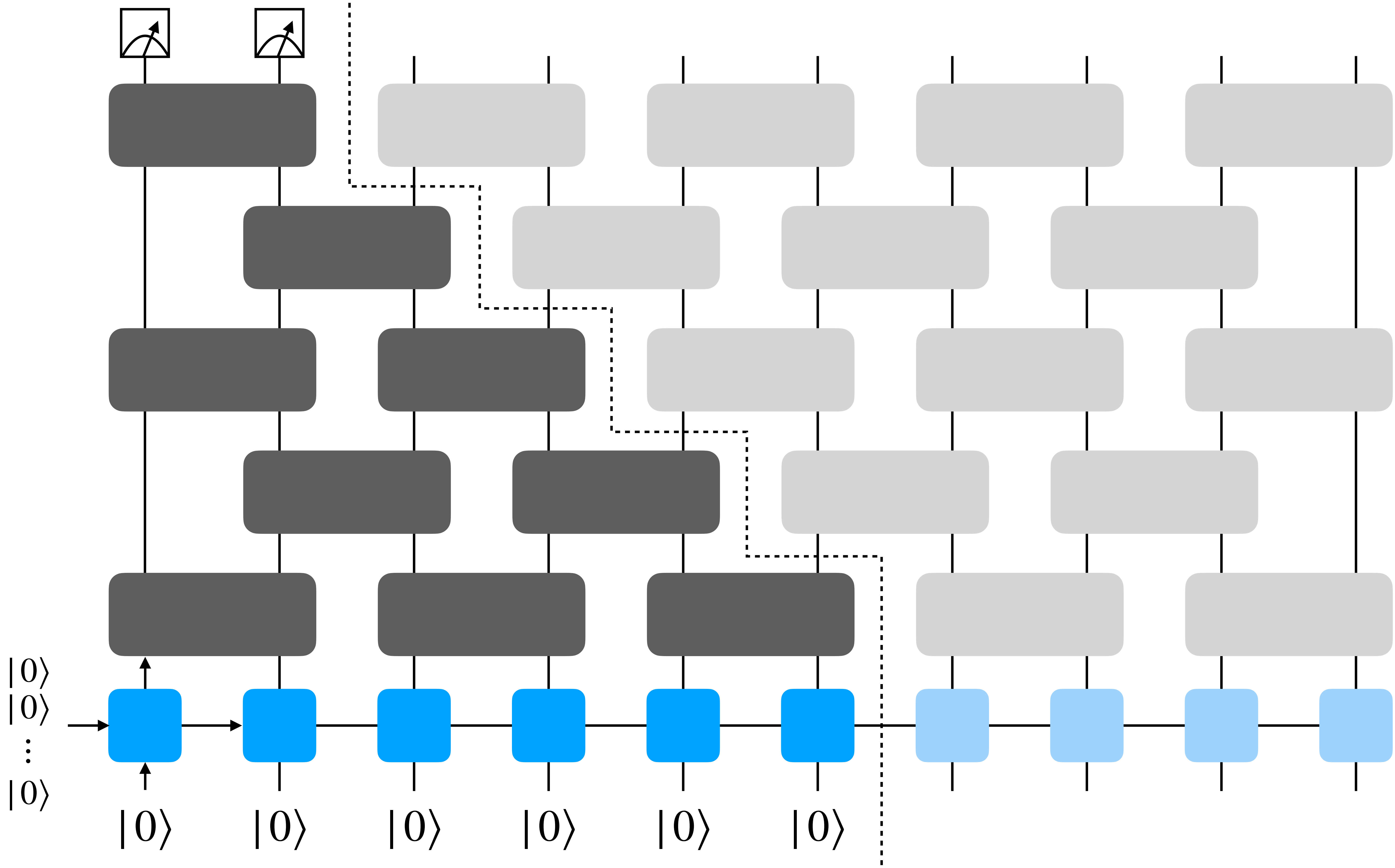


Algorithm for simulating quantum quenches

How many qubits do we actually need in order to make these measurements?



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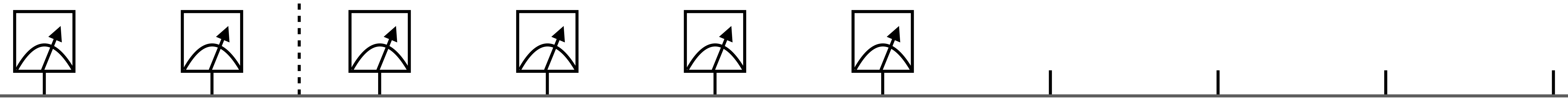


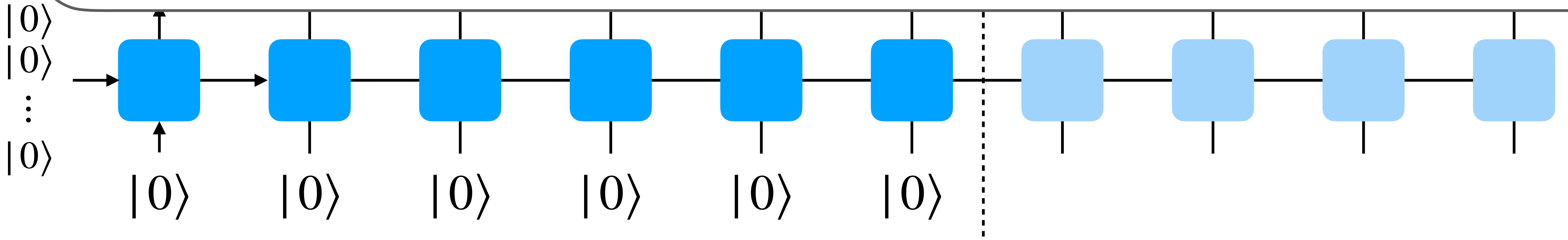
In general, can simulate time-evolution of an infinitely large state with only:

$$N \sim S_0 + t$$

qubits. Note that given (typical) ballistic growth of entanglement:

$$S(t) \sim S_0 + t,$$

every qubit is being put toward the classically hard part of simulation: Entanglement



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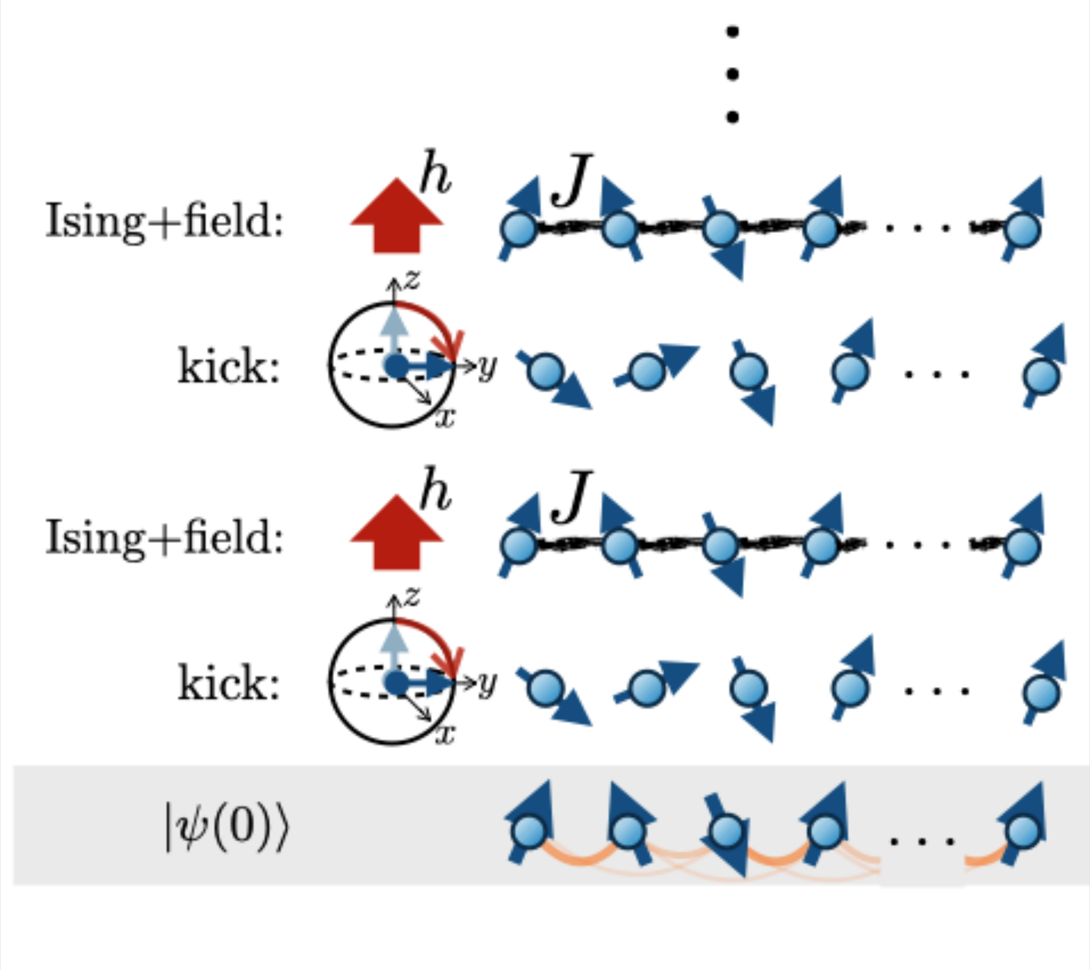
Kicked Ising model as a benchmark

Hamiltonian dynamics of “kicked” Ising spins

Initial correlated state

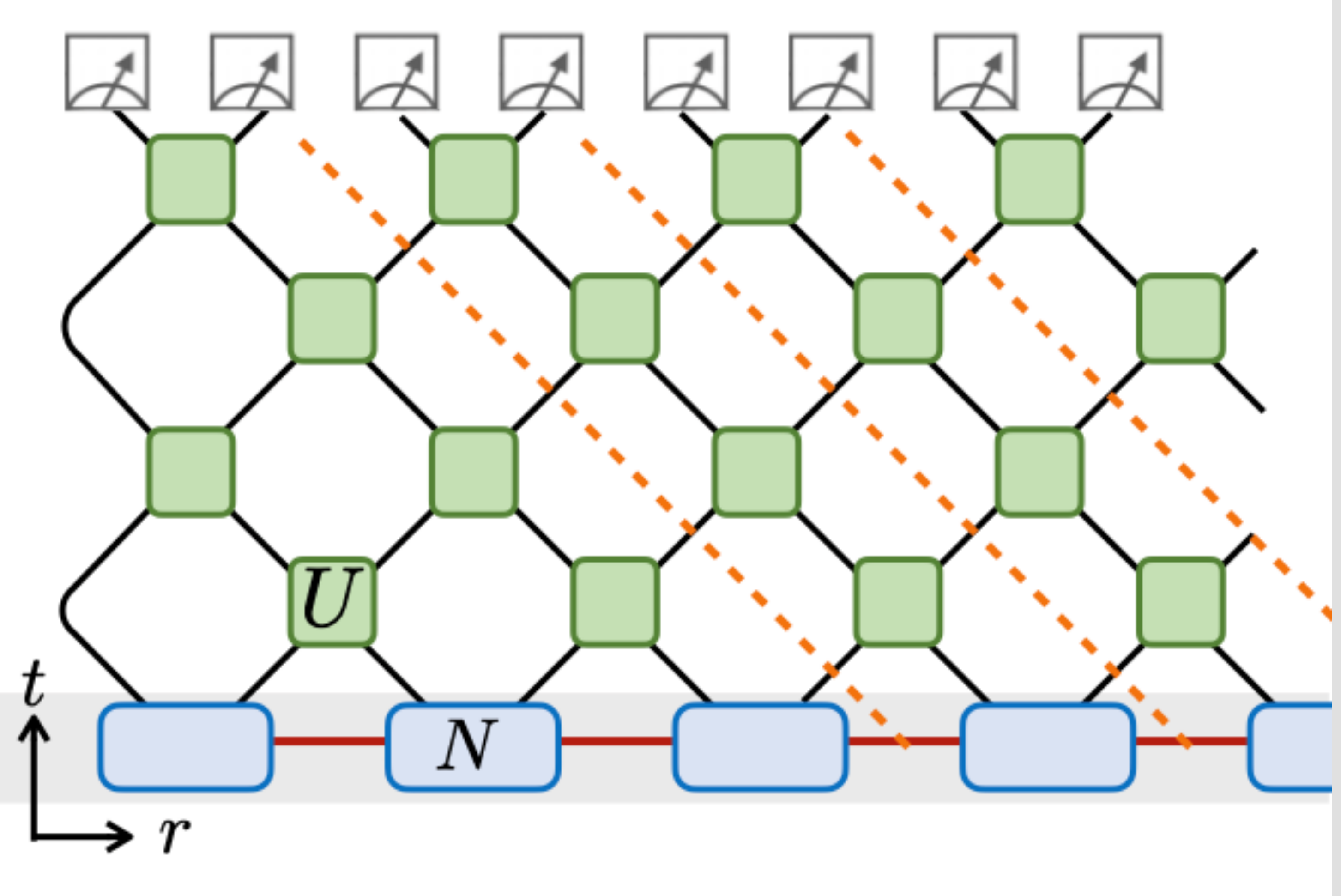


$$H(t) = \sum_i \left(\frac{\pi}{4}\sigma_i^z\sigma_{i+1}^z + h\sigma_i^z + \frac{\pi}{4}\sum_{n\in Z}\delta(t-n)\sigma_i^x\right)$$

$h \neq 0 \Rightarrow$ chaotic

converts to

Circuit dynamics of qubits



Exactly what we can simulate with quantum tensor networks

SDKI model is an example of a dual-unitary circuit

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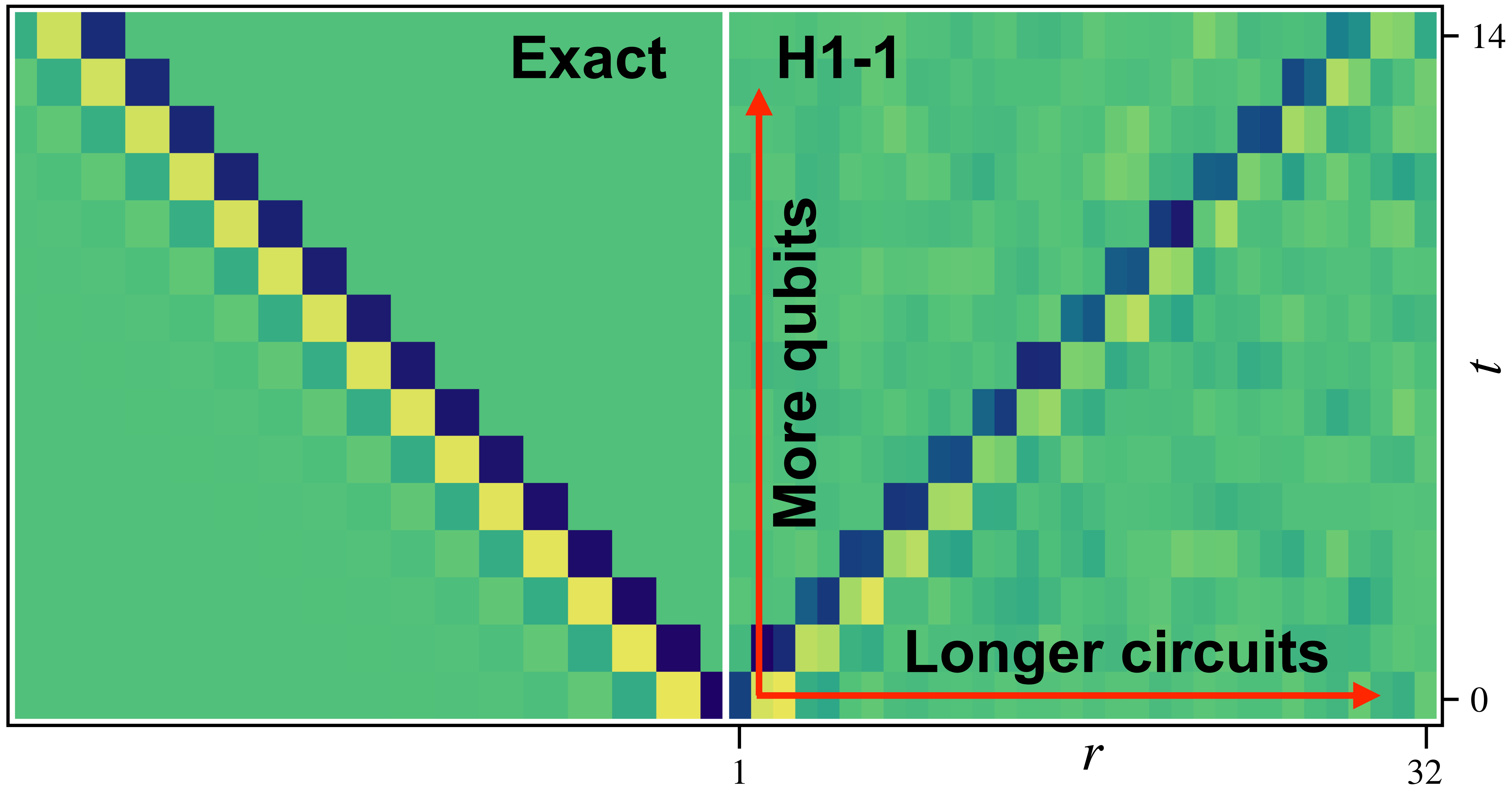
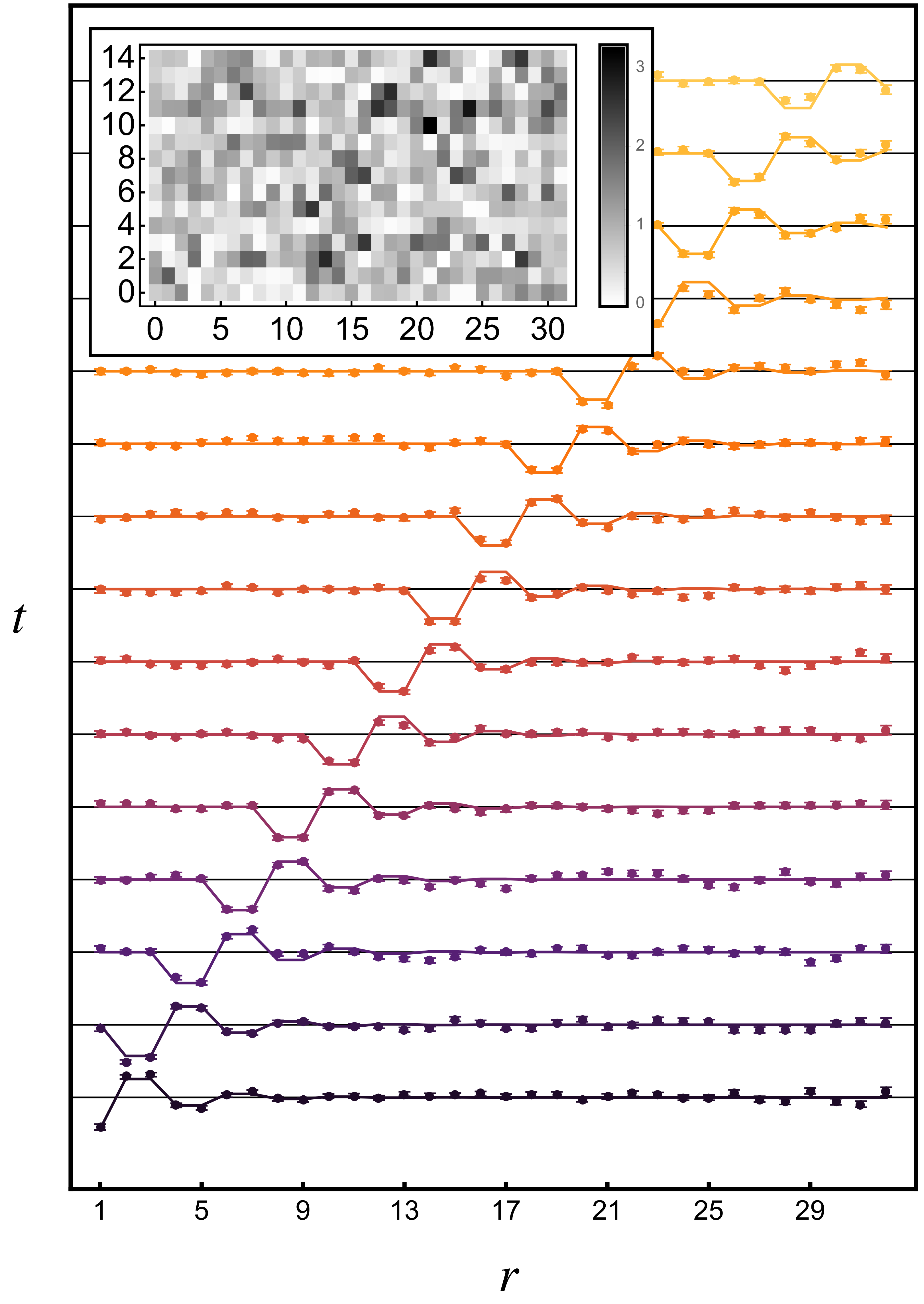
Data from H1-1 (uses up to 15 qubits)





- Dual unitary point → benchmark for the holoQUADS method.
- More qubits = longer times.
- Times accessible with 15 qubits agree well with theory.
- See E. Chertkov et al. for details arXiv:2105.09324, and simulations away from exactly-solvable DU point.

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Ongoing/Future work: Algorithms

Hierarchical tensor networks:

- TTN and MERA implementations are straightforward, though plenty of work to be done to understand best implementations given gate errors / runtime limitations.
- Potentially a good route to 2D simulations

What is the best hardware compatible ansatz in 2D?

- Sequential MPS?
- Isometric tensor networks?
- Plaquette-PEPS?

Continuous time evolution

- SVD/compression in TEBD is gives a constant-factor (but huge) reduction in classical complexity, is there any direct analogue to this on a quantum computer?
- Other variational approaches to reduce circuit depths for continuous-time evolution?

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ACCELERATING QUANTUM COMPUTING

PROVIDING H1 ACCESS FOR QC RESEARCH:

- **Quantum Computing User Program** from Oak Ridge National Laboratory

  https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/

- **Azure Quantum Credits Program** from Microsoft up to $10,000 credits

  https://aka.ms/aq/credits

  $500 Free Azure Quantum Credits when creating your workspace

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