QUANTUM
Information and Matter

MAX PLANCK INSTITUTE
OF QUANTUM OPTICS

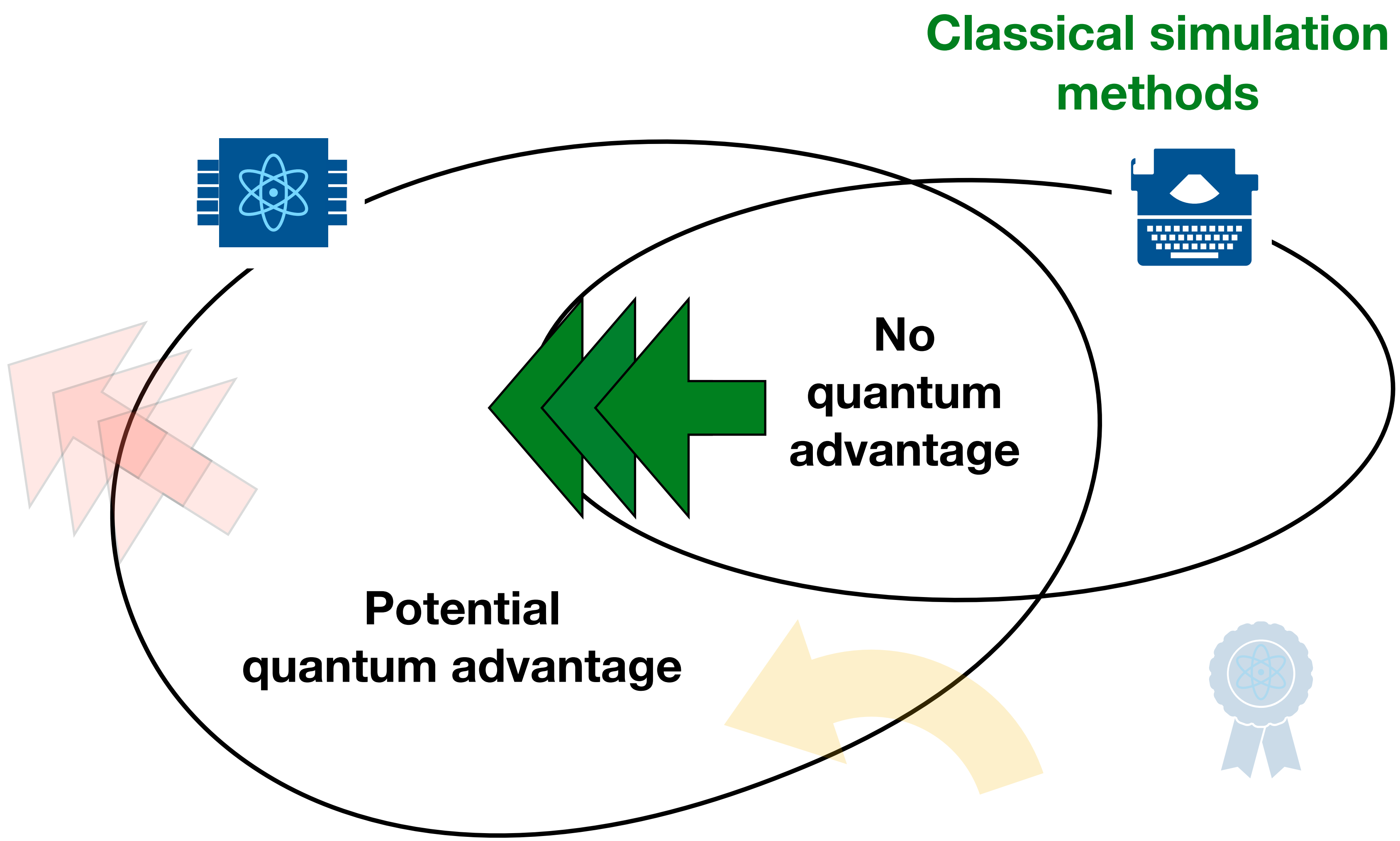
Average-computation benchmarking for local expectation values in digital quantum devices

F. Baccari, P. Kos, G. Styliaris

MARIE CURIE ACTIONS

arXiv:2507.18708

RESEARCH INTERESTS



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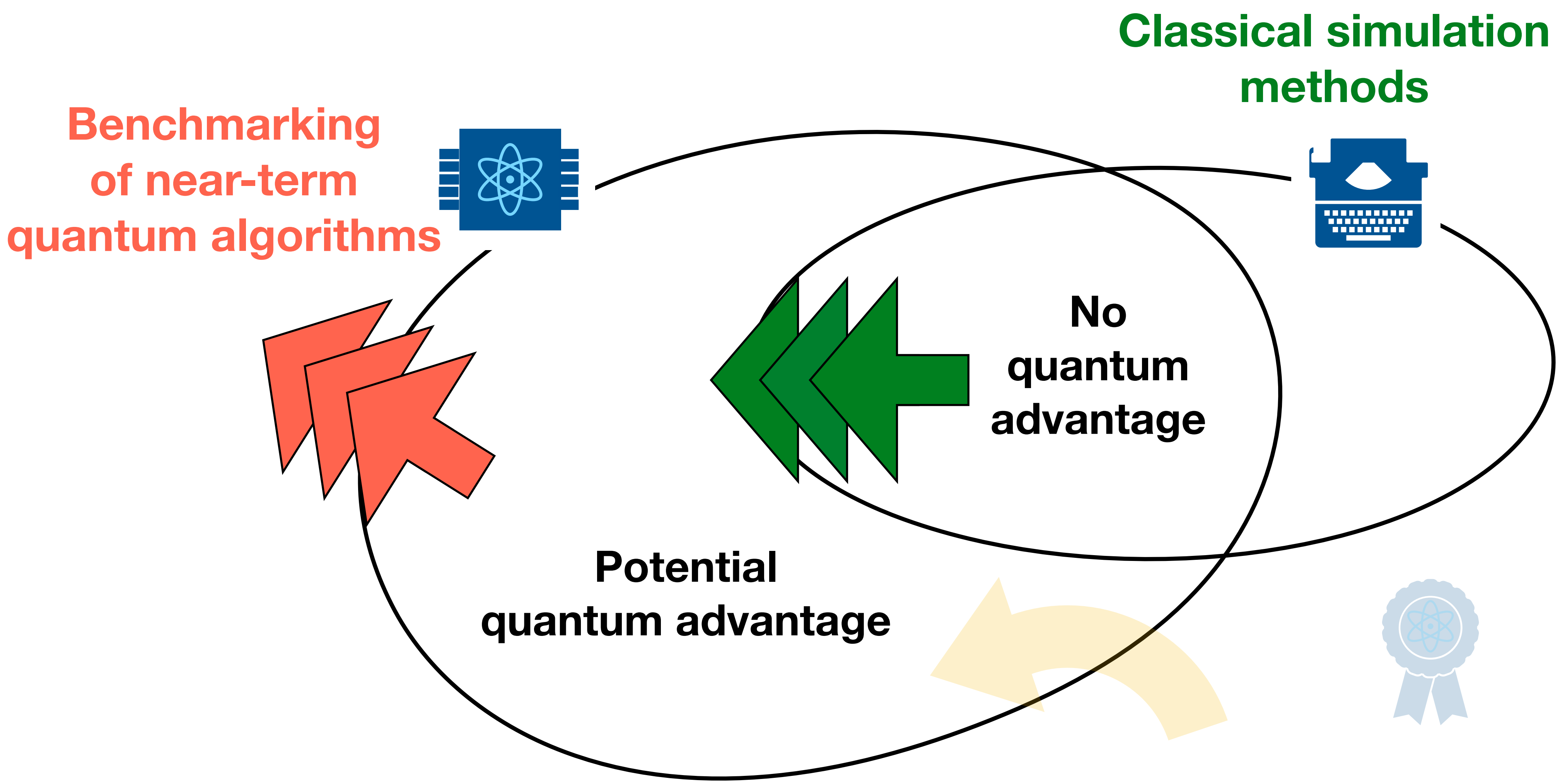

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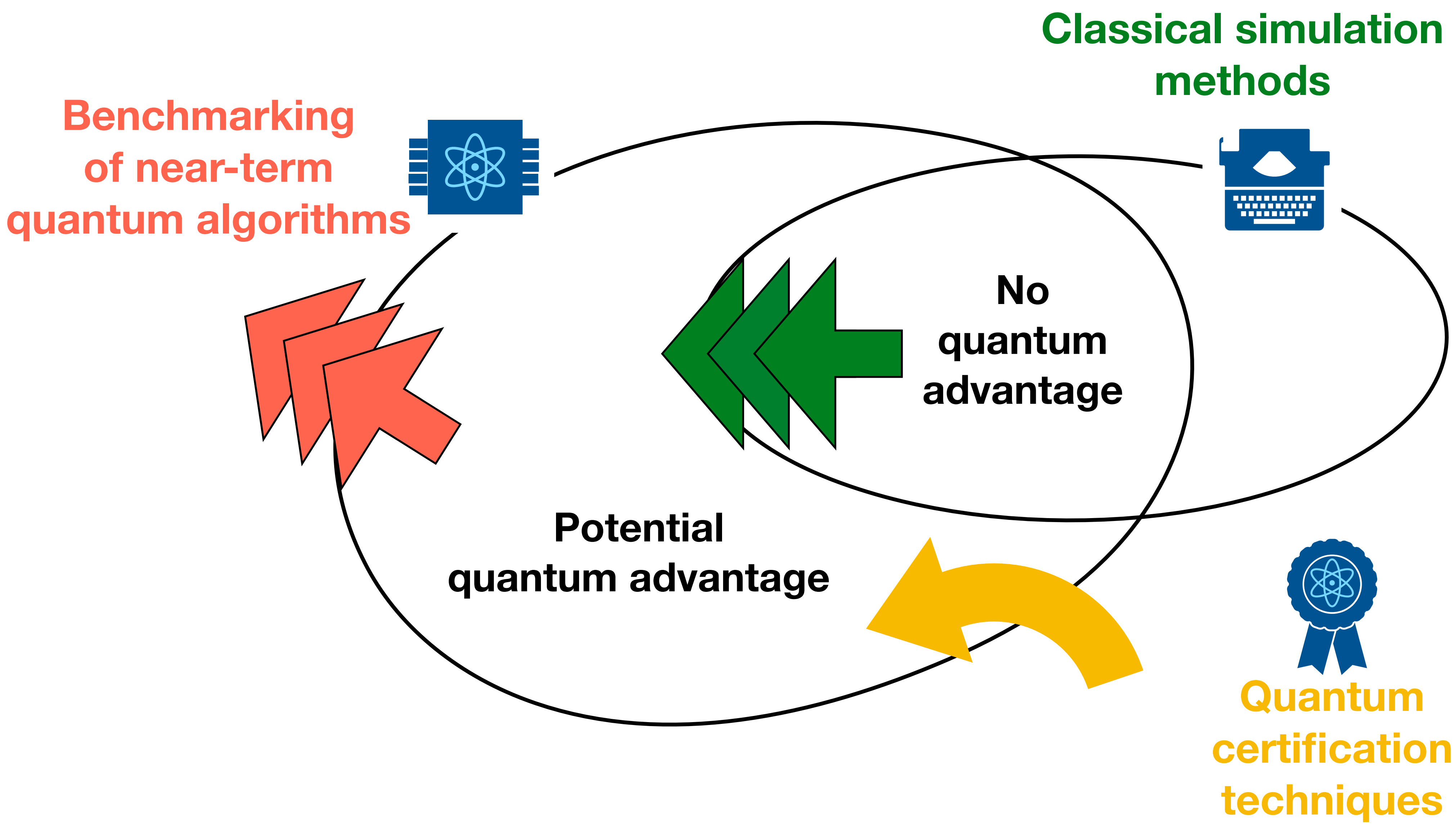

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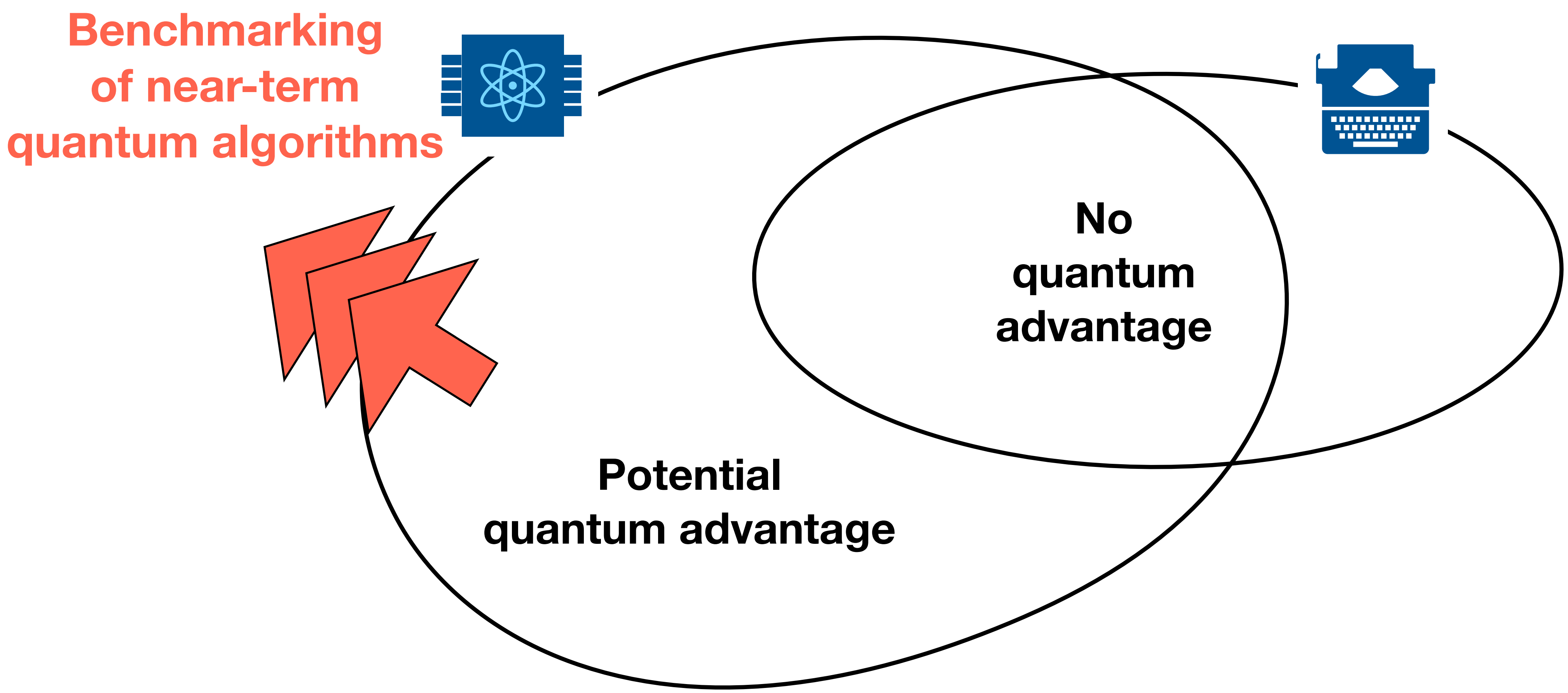

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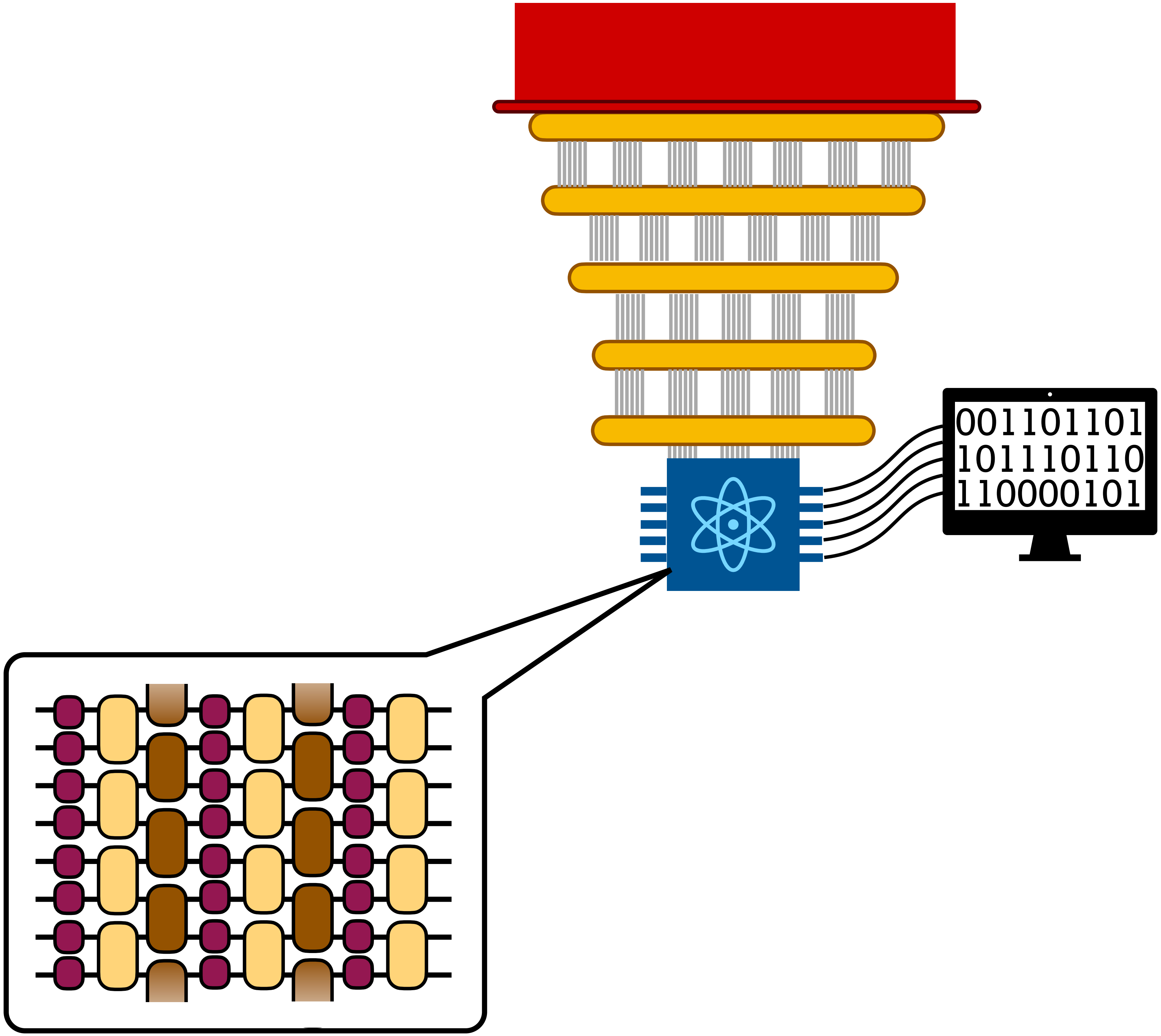
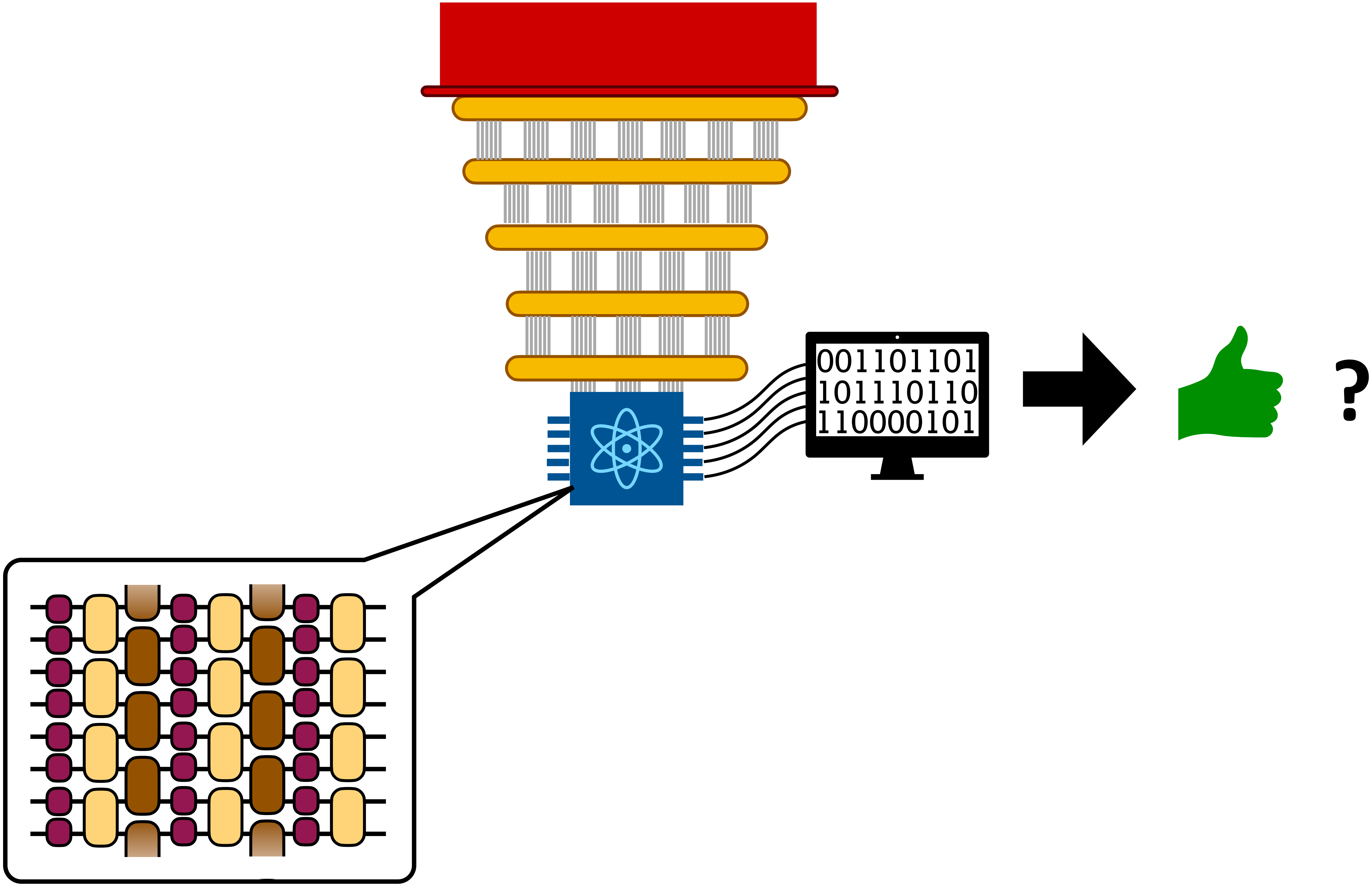
Motivation

WHAT IS BENCHMARKING?



WHAT IS BENCHMARKING?



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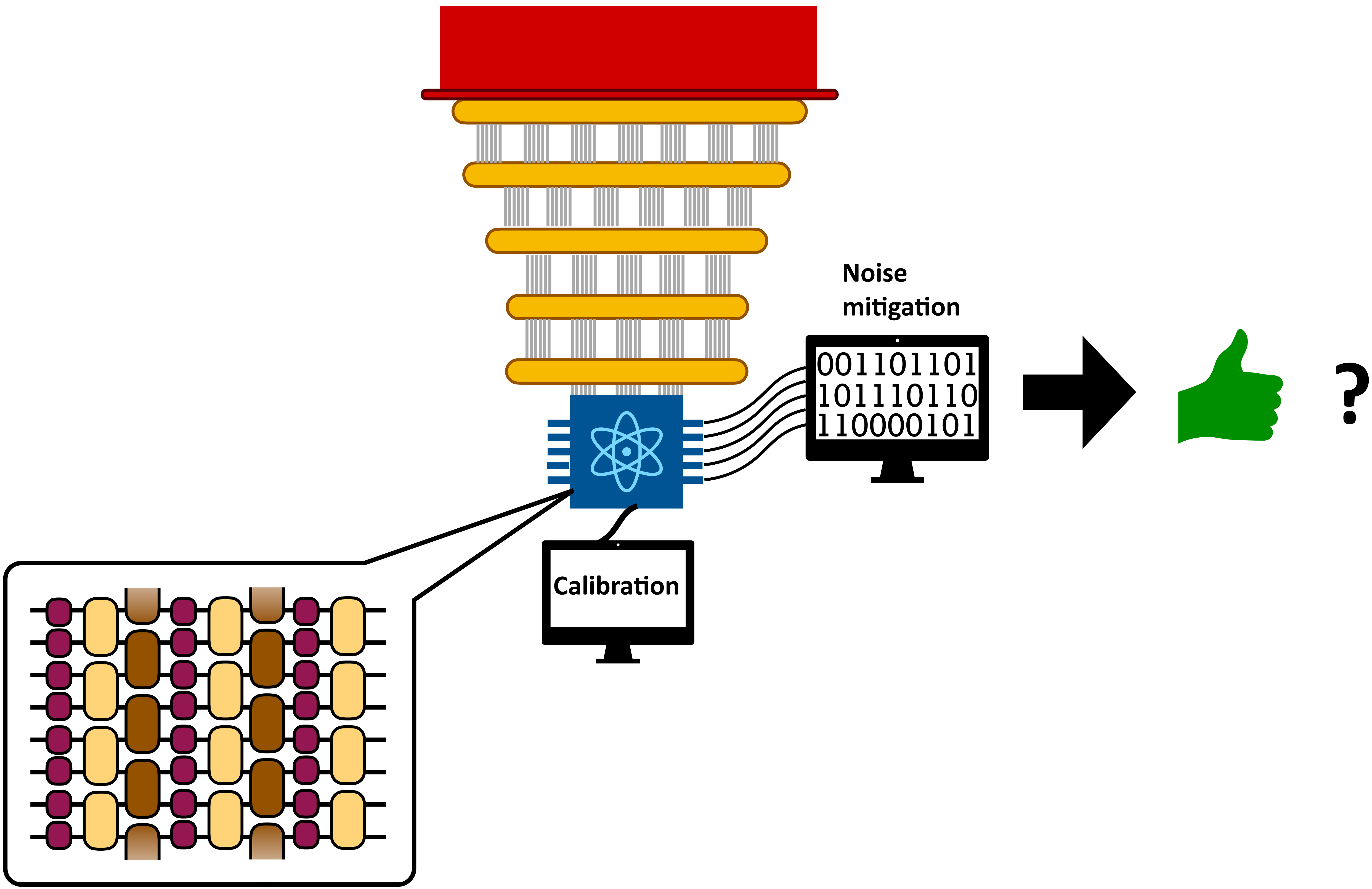

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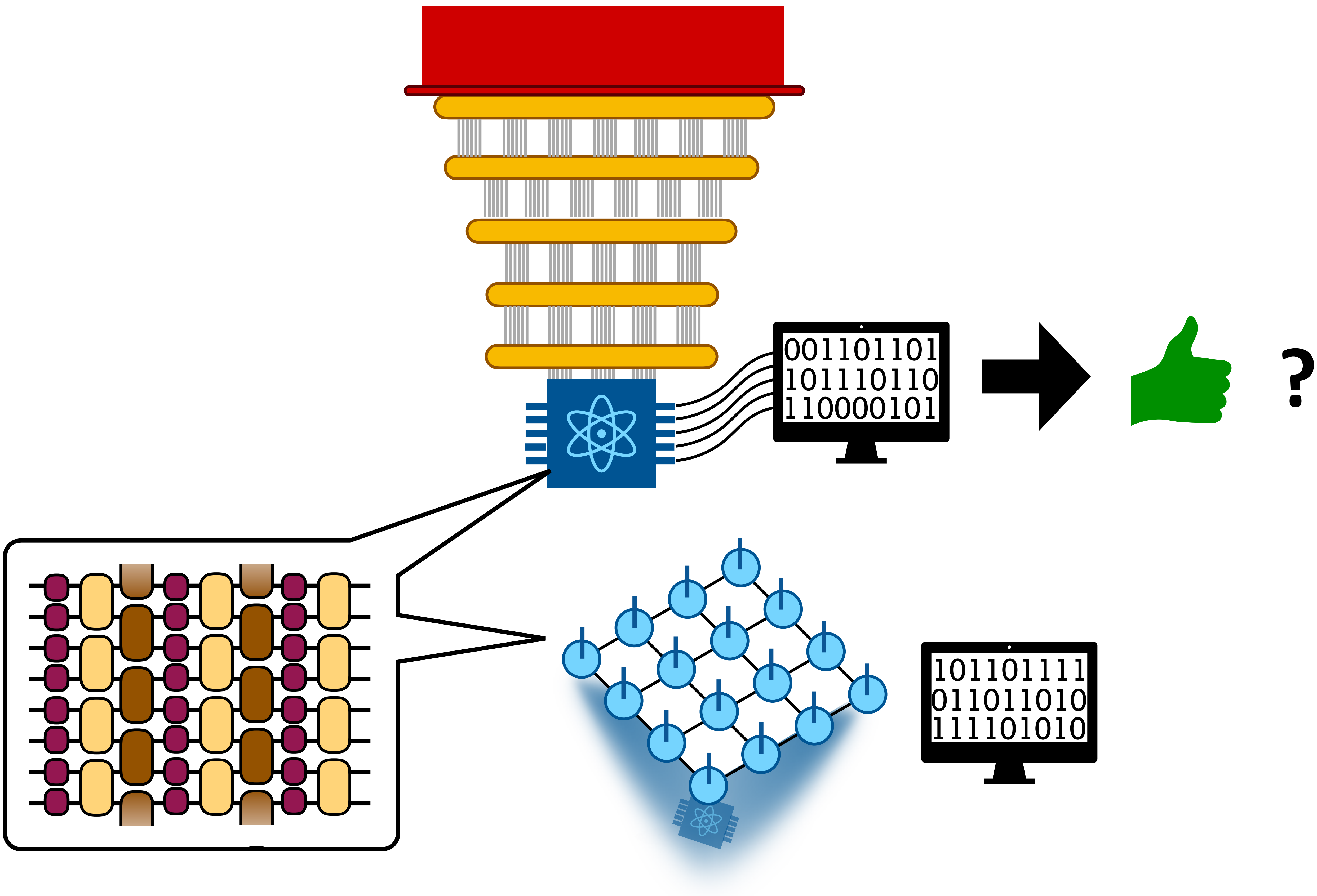

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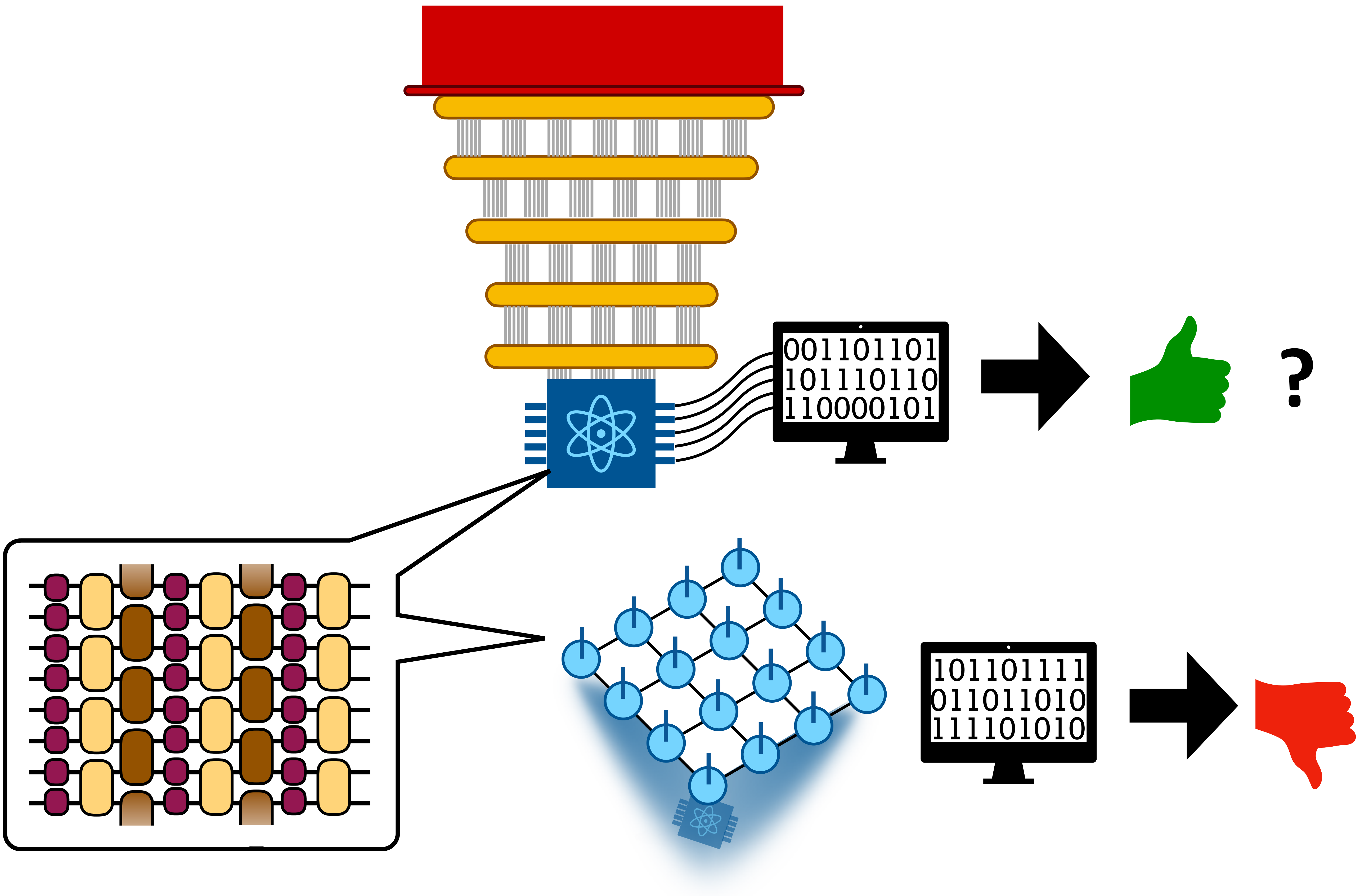
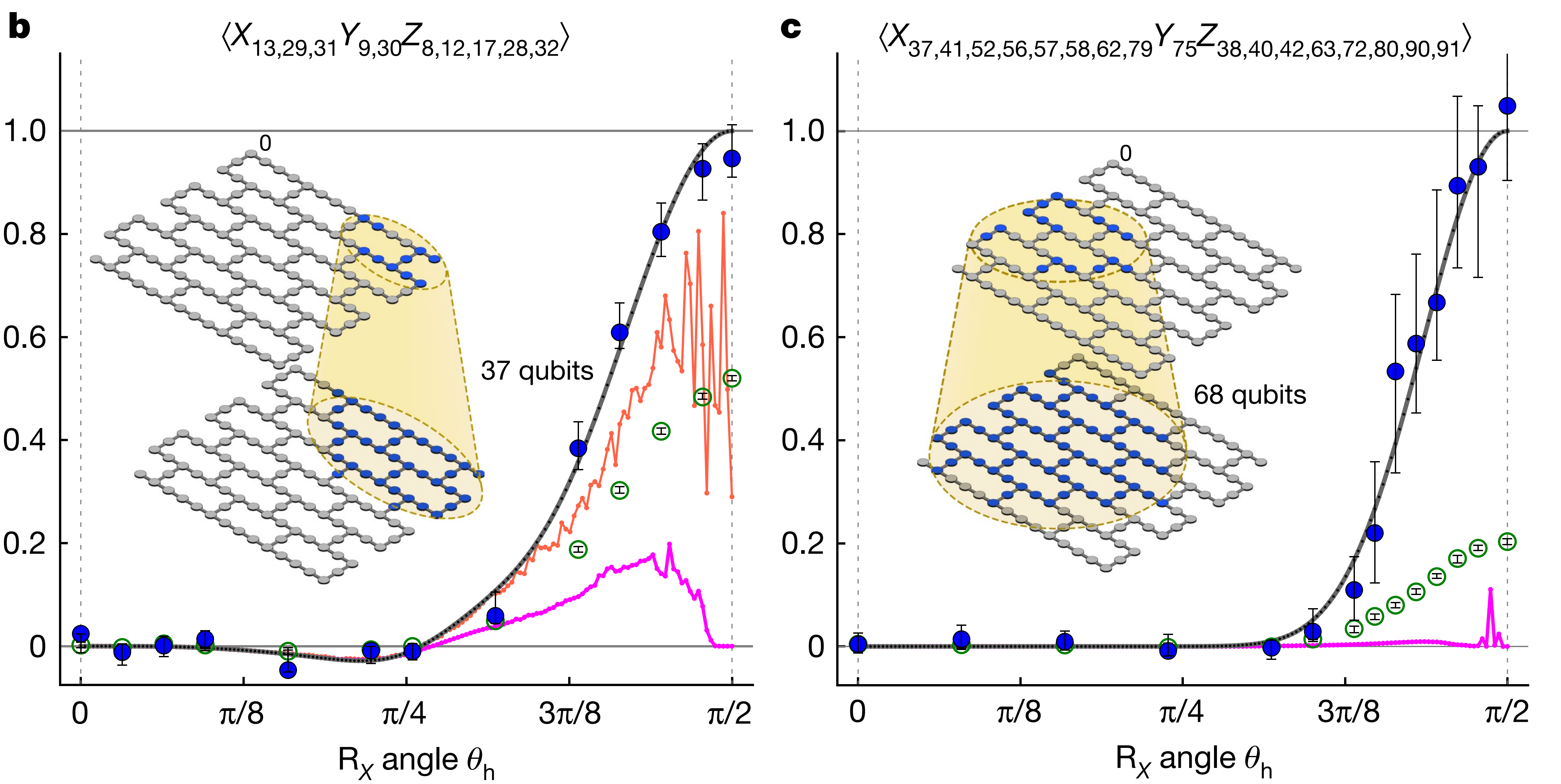


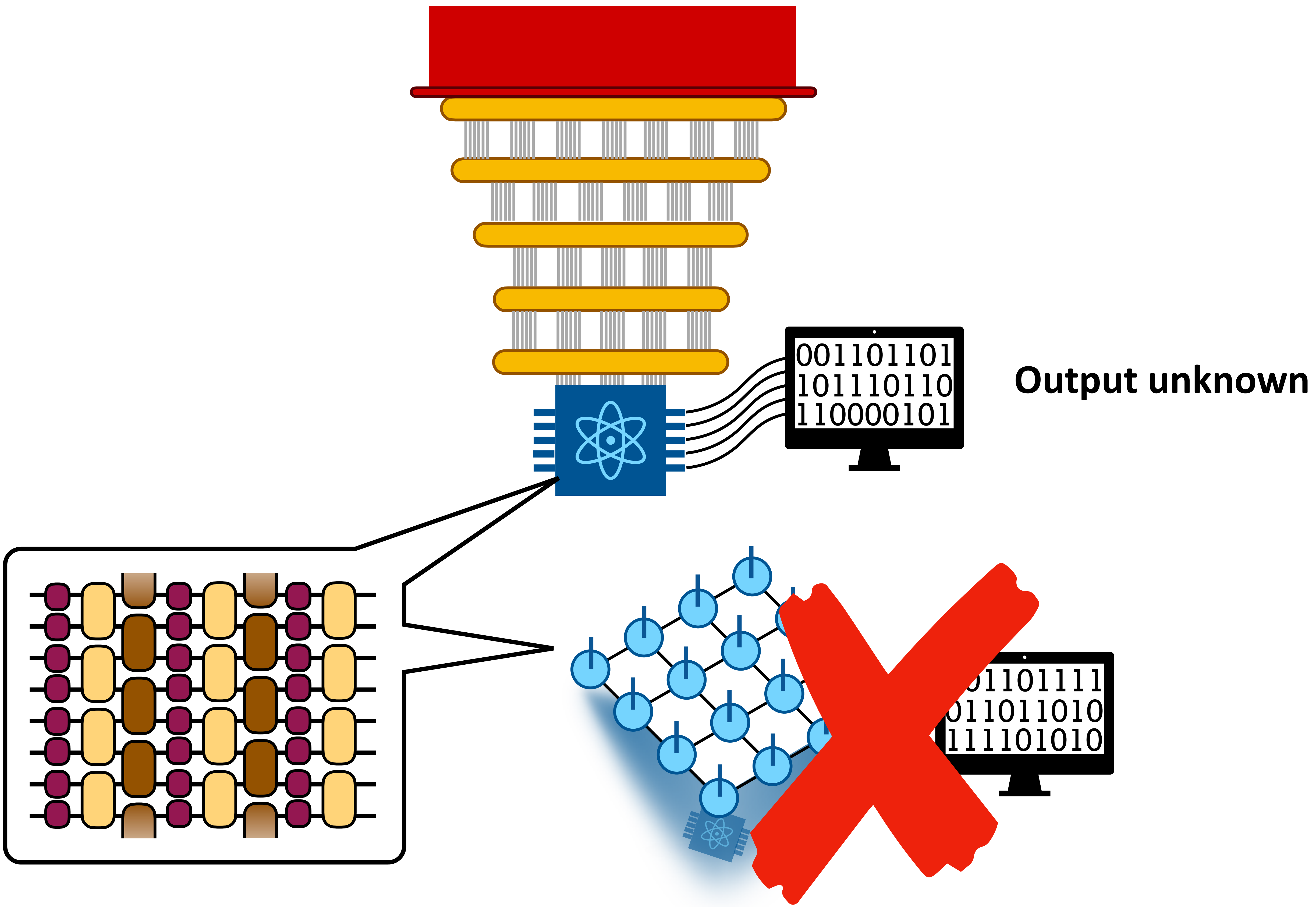
BENCHMARKING QUANTUM COMPUTATION IS USEFUL



Kim, Y., Eddins, A., Anand, S. *et al.* Evidence for the utility of quantum computing before fault tolerance, *Nature* **618**, 500–505 (2023)

What is the problem?

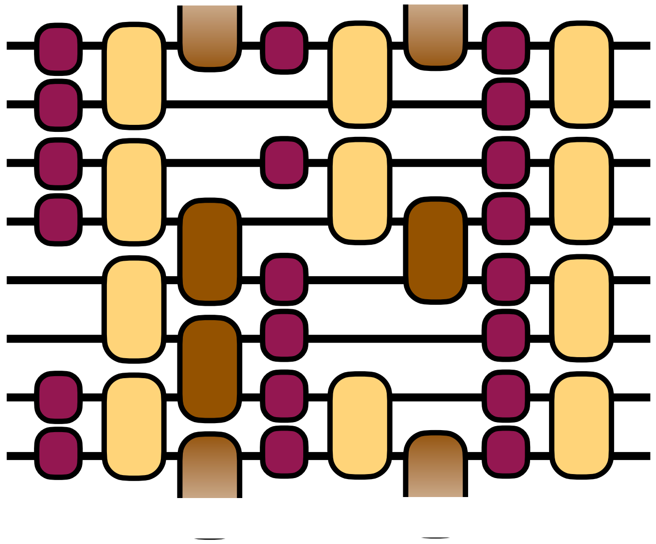
BENCHMARKING OF QUANTUM COMPUTATION IS LIMITED



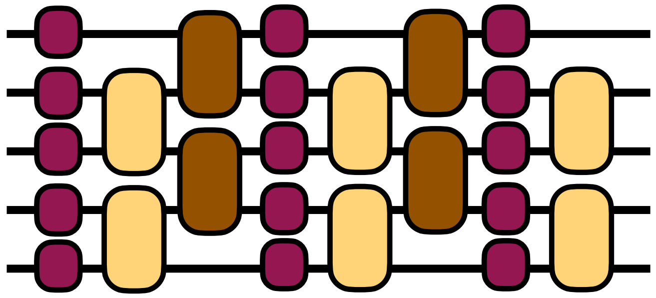
BENCHMARKING OF QUANTUM COMPUTATION IS LIMITED

Then I can only simplify the problem:

- **Use simulable gatesets**



- **Reduce the size/depth**



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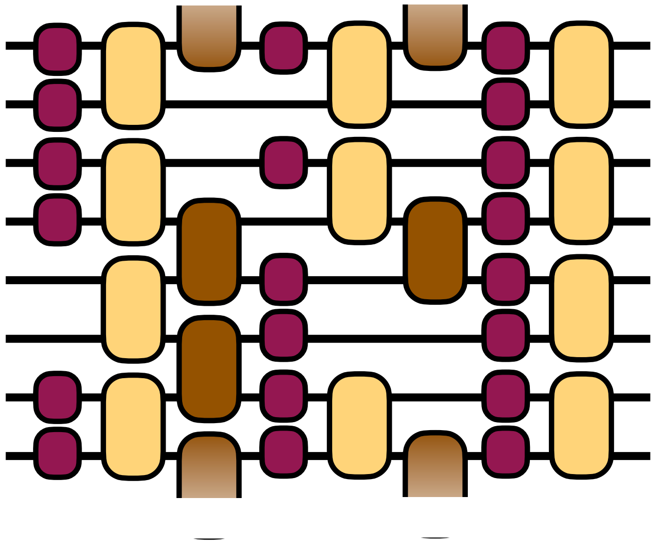
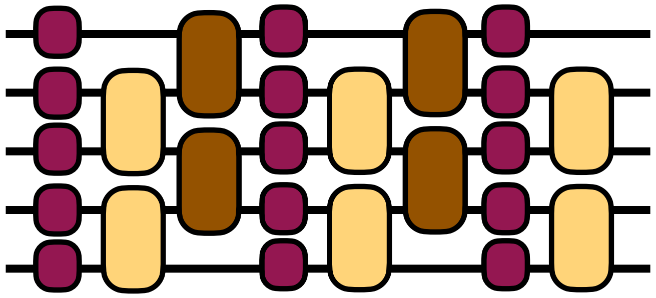


Problem: **one never runs on the actual computation**

- **Reduce the size/depth**



BENCHMARKING OF QUANTUM COMPUTATION IS LIMITED

Desiderata: get some way to run a benchmark on the computation of interest

- Same size
- Same layout
- Same classical simulation complexity (more later)
- …

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Establishing trust in quantum computations

Timothy Proctor,[1,*] Stefan Seritan,[1] Erik Nielsen,[1] Kenneth Rudinger,[1] Kevin Young,[1] Robin Blume-Kohout,[1] and Mohan Sarovar[2,†]
[1] *Quantum Performance Laboratory, Sandia National Laboratories, Albuquerque, NM 87185, USA and Livermore, CA 94550, USA*
[2] *Sandia National Laboratories, Livermore, CA 94550*

nature physics
ARTICLES
https://doi.org/10.1038/s41567-021-01409-7
Check for updates

Measuring the capabilities of quantum computers

Timothy Proctor[1,2] ✉, Kenneth Rudinger[1,2], Kevin Young[1,2], Erik Nielsen[1,2] and Robin Blume-Kohout[1,2]

Quantum computers can now run interesting programs, but each processor's capability—the set of programs that it can run successfully—is limited by hardware errors. These errors can be complicated, making it difficult to accurately predict a processor's capability. Benchmarks can be used to measure capability directly, but current benchmarks have limited flexibility and scale poorly to many-qubit processors. We show how to construct scalable, efficiently verifiable benchmarks based on any program by using a technique that we call circuit mirroring. With it, we construct two flexible, scalable volumetric benchmarks based on randomized and periodically ordered programs. We use these benchmarks to map out the capabilities of twelve publicly available processors, and to measure the impact of program structure on each one. We find that standard error metrics are poor predictors of whether a program will run successfully on today's hardware, and that current processors vary widely in their sensitivity to program structure.

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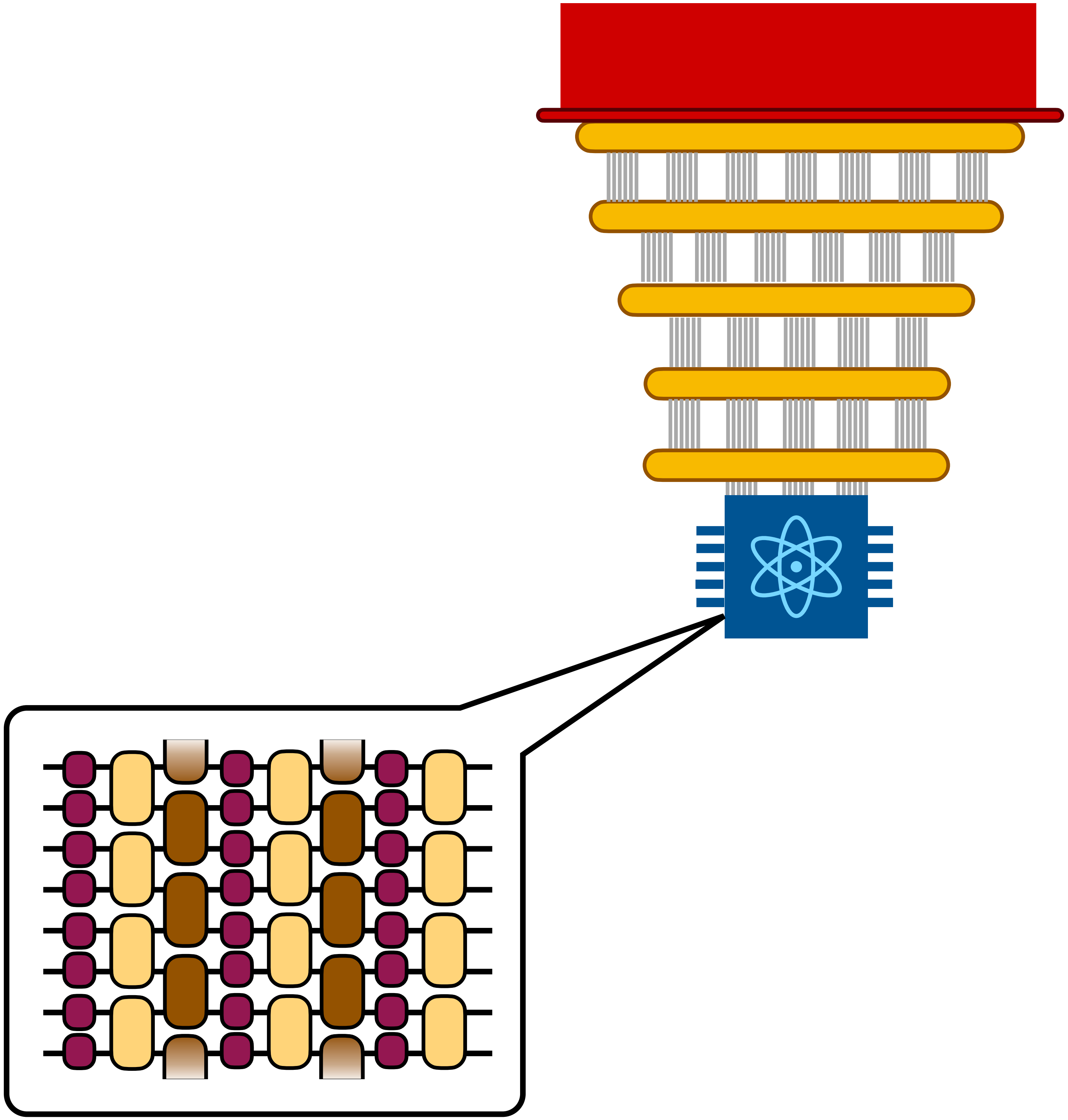
We test the performance on a specific task: estimating local observables

Average-computation benchmarking

TAKE DATA FROM A FAMILY OF CIRCUITS



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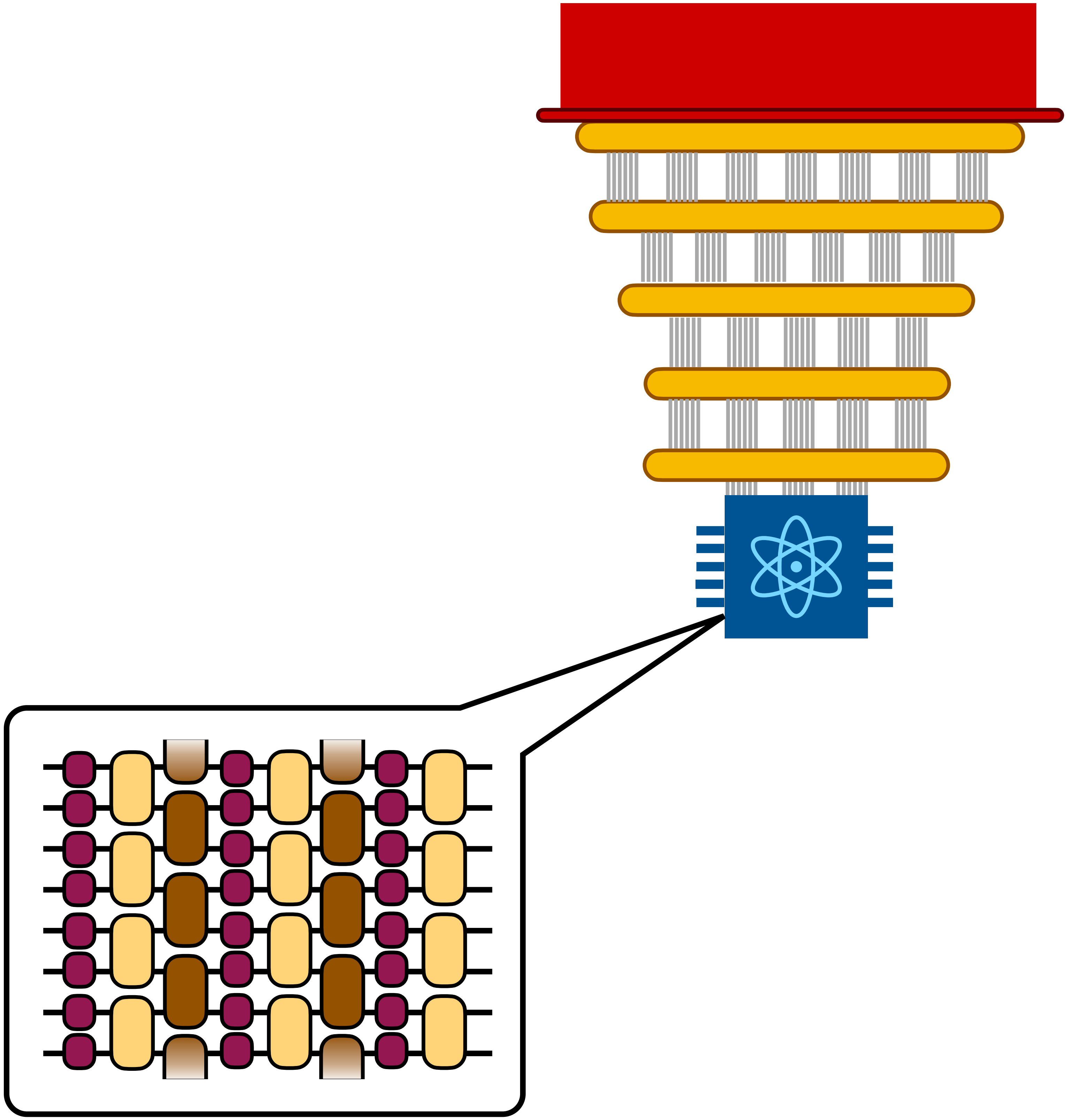
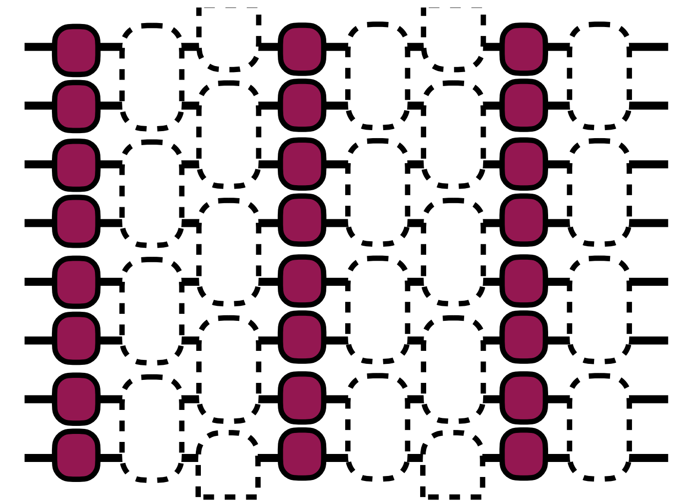
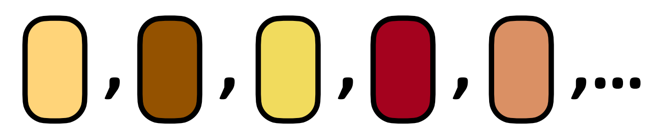




Sample each gate independently from



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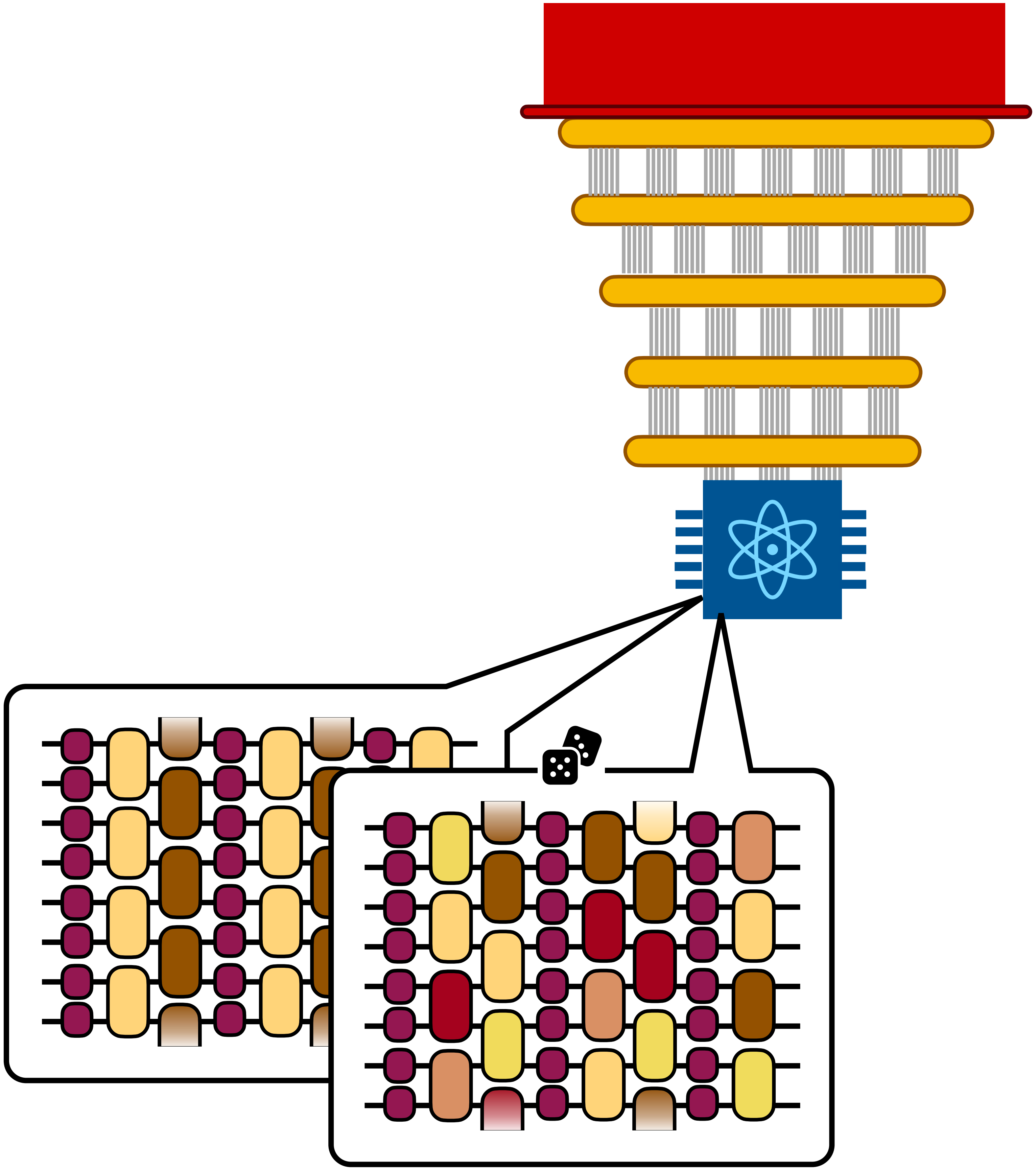

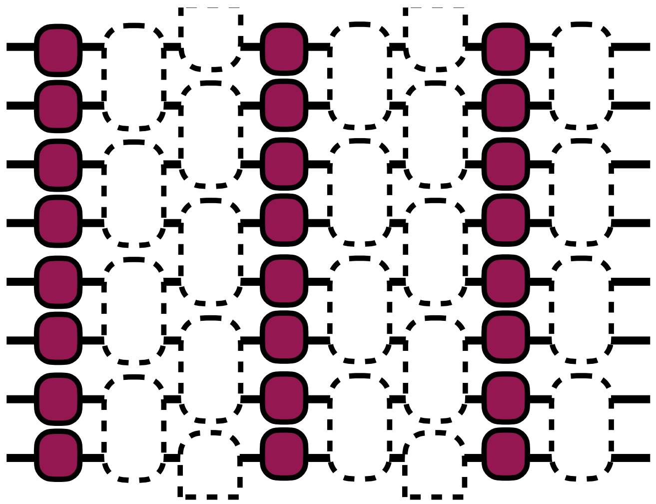

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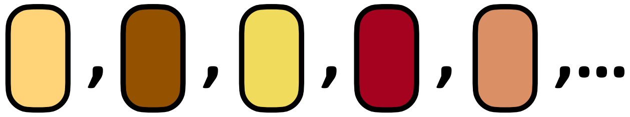

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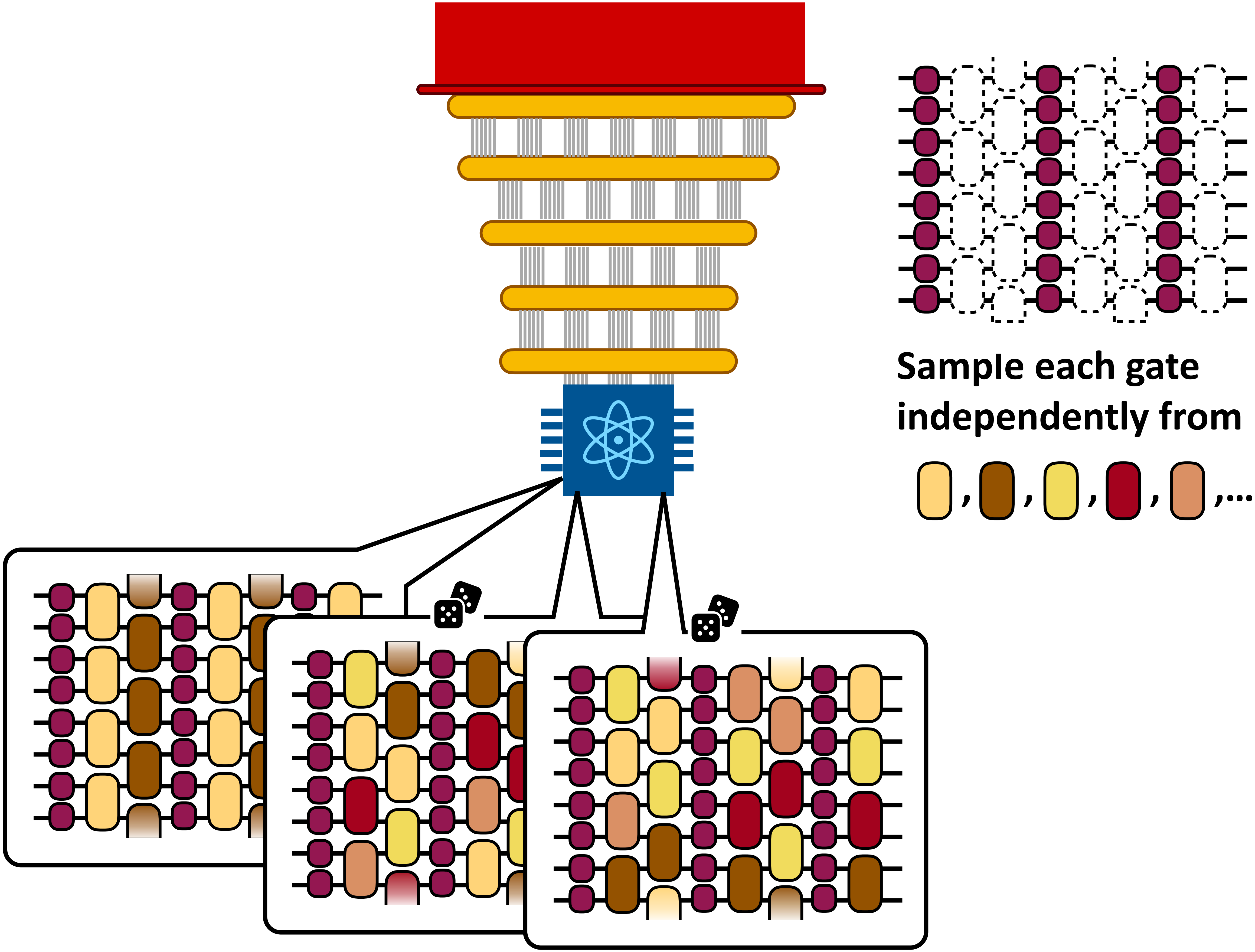

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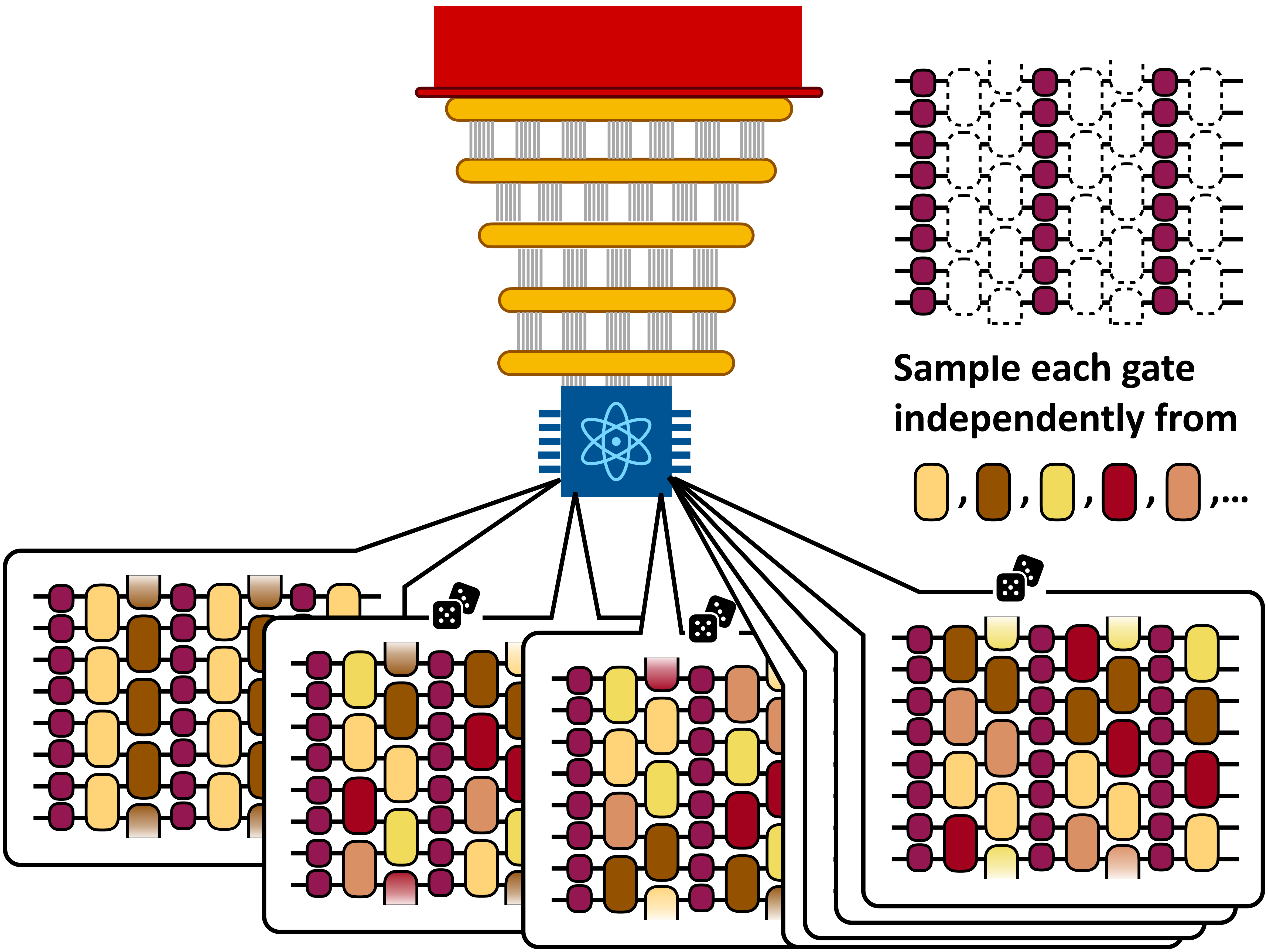
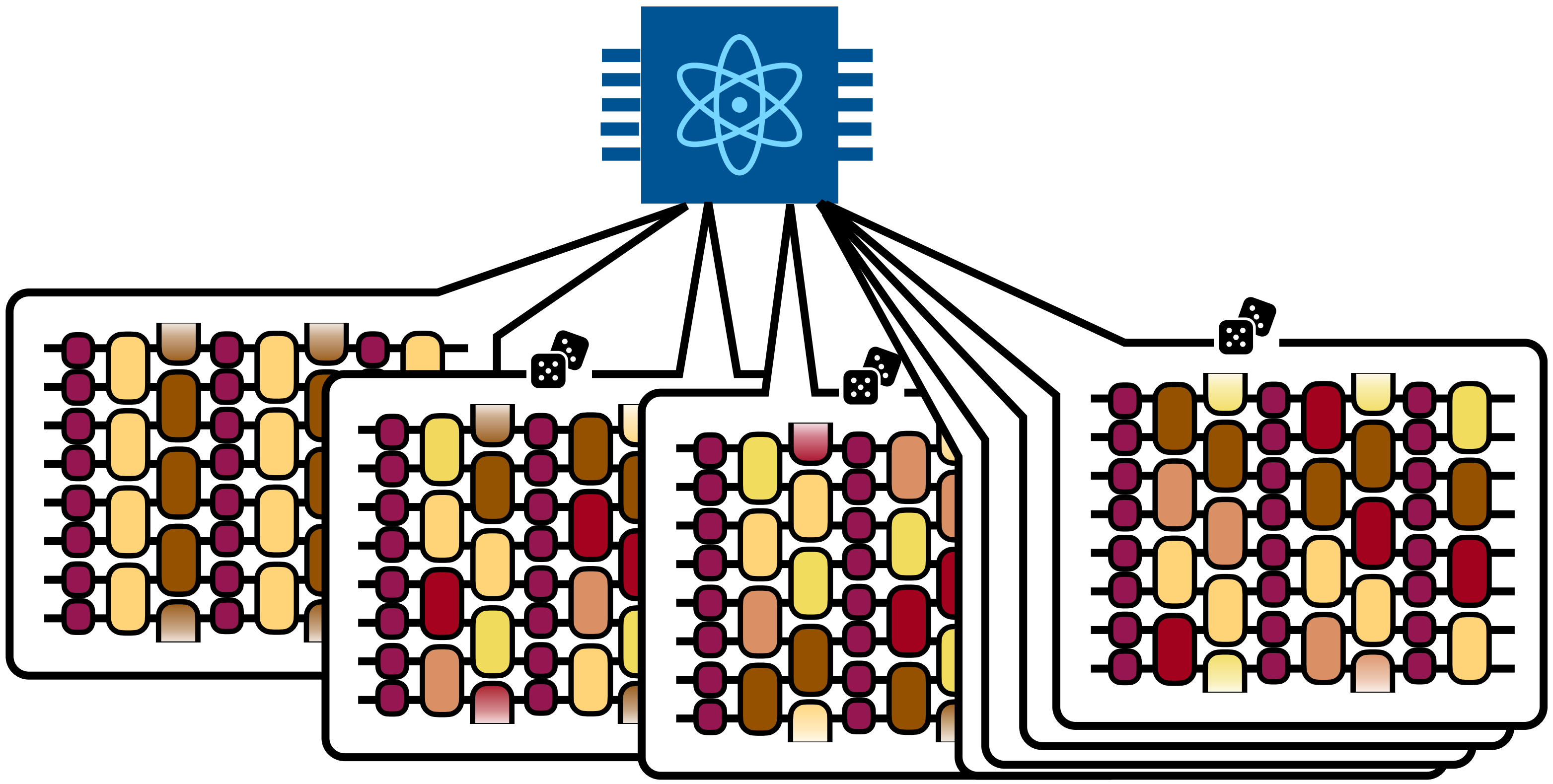
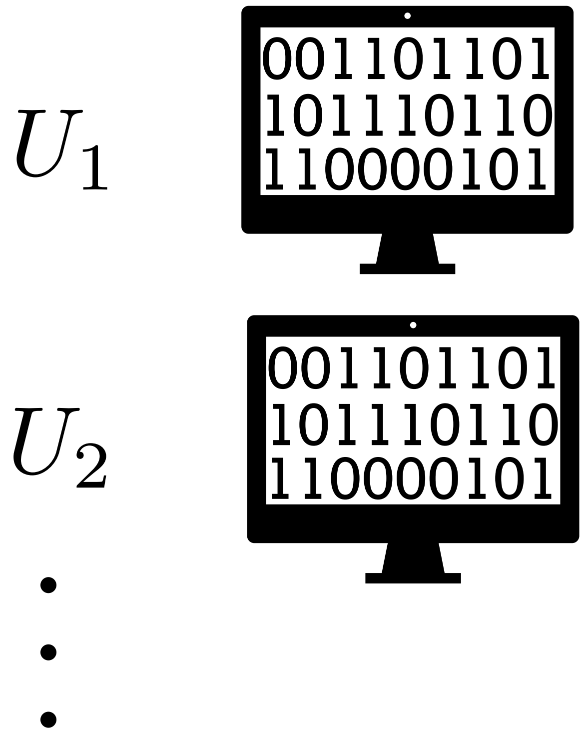


COMPUTE AVERAGE DATA IN TWO DIFFERENT WAYS





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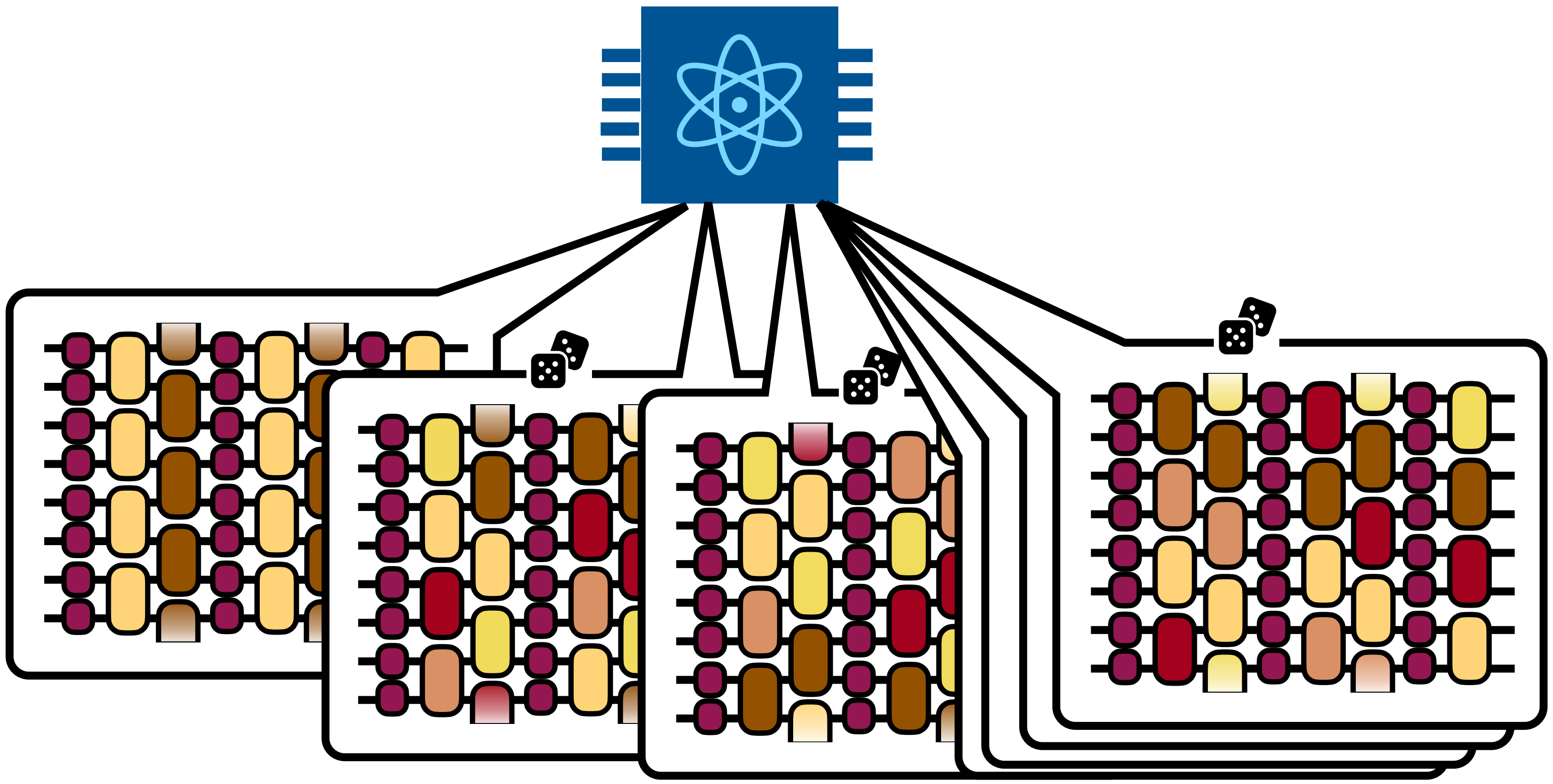
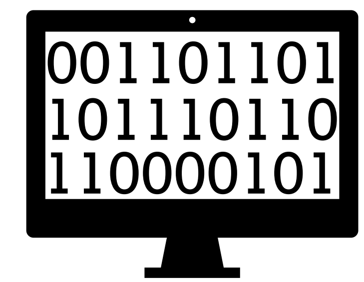


$$\mathrm{tr}[O_{\mathrm{test}}\ (U_1^\dagger|\psi_0\rangle\langle\psi_0|U_1)]$$

U_2

⋮



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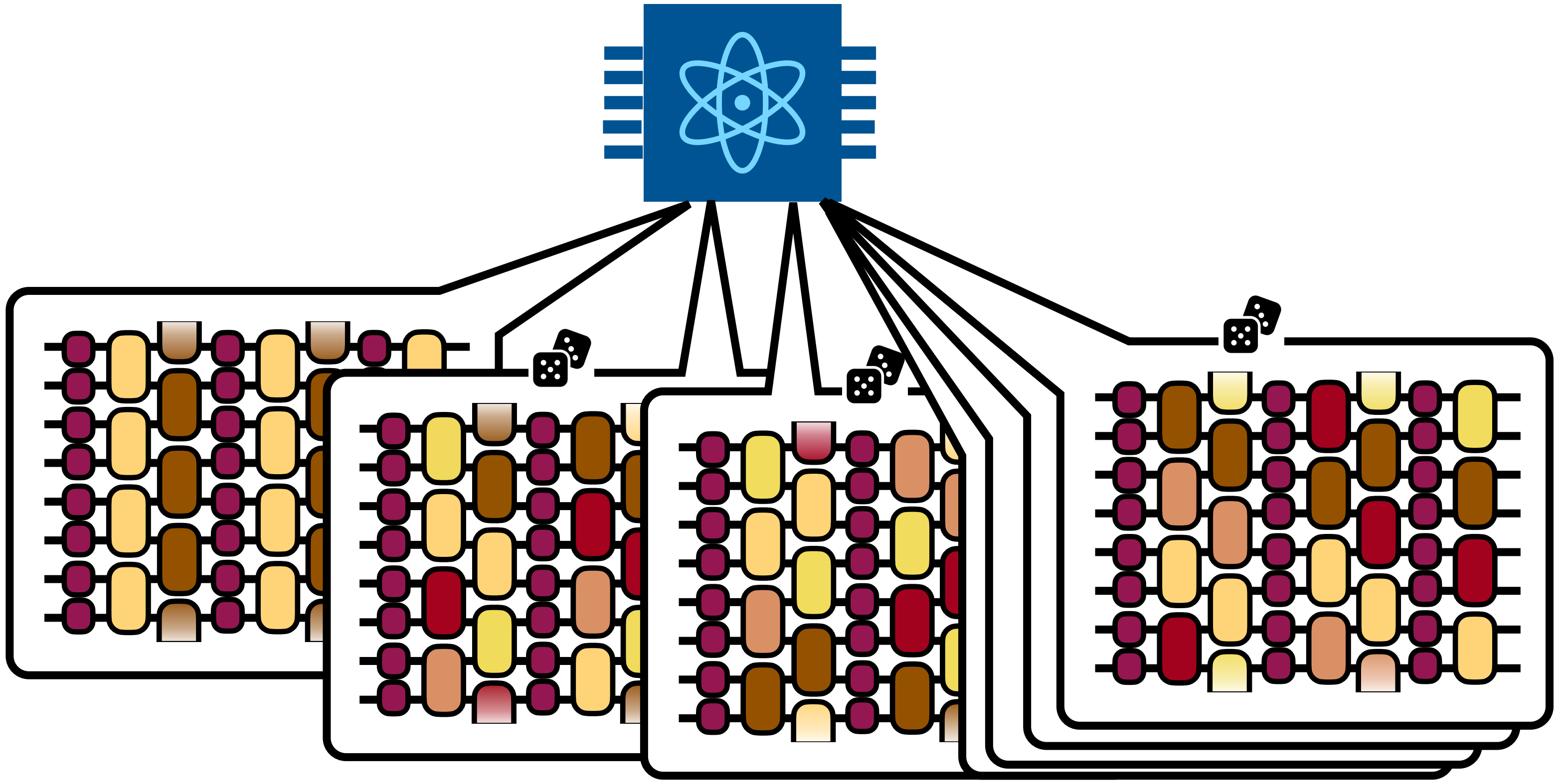


$$\mathrm{tr}[O_{\text{test}}\ (U_1^\dagger|\psi_0\rangle\langle\psi_0|U_1)]$$

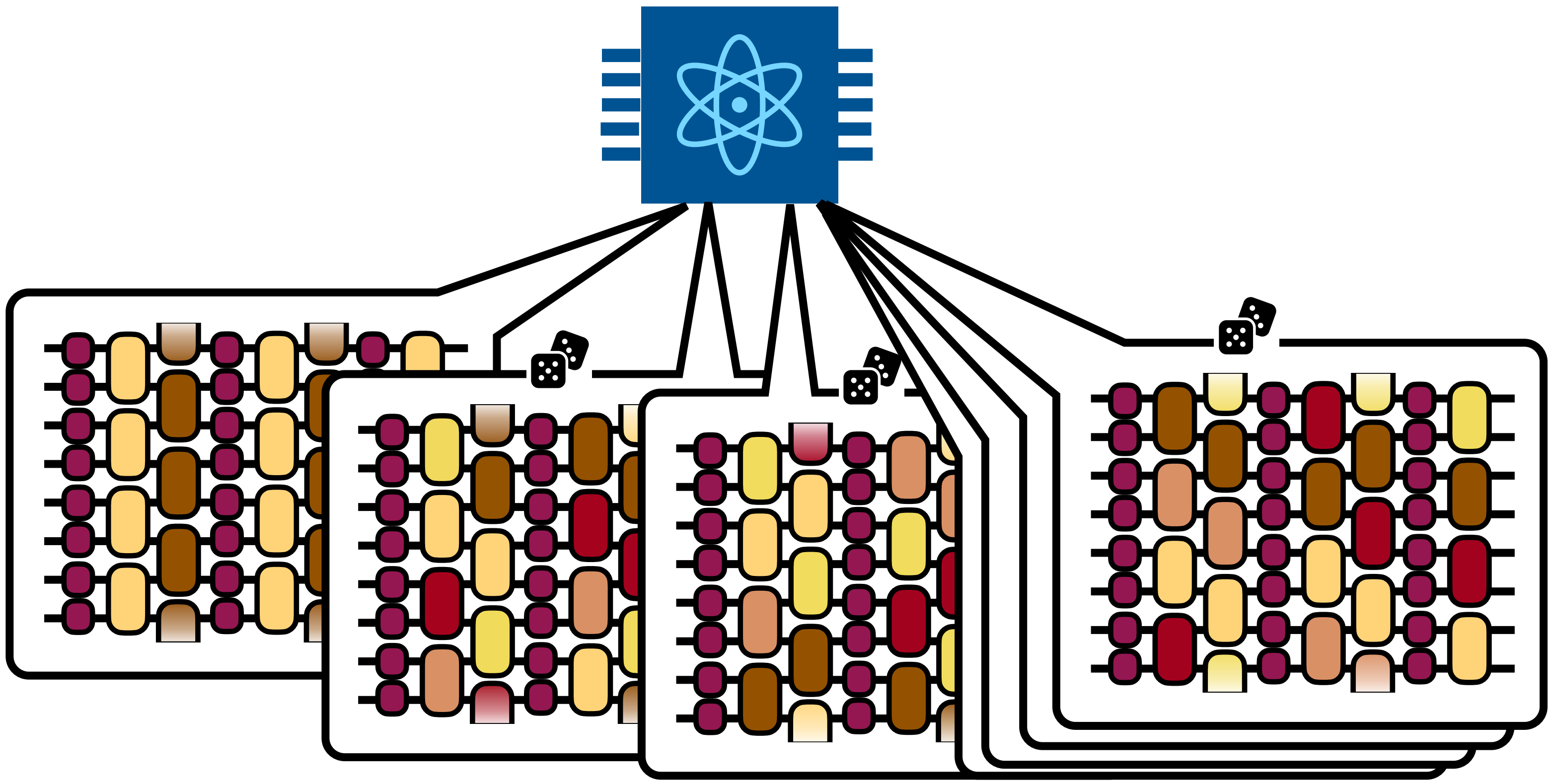
$$+$$

$$\mathrm{tr}[O_{\text{test}}\ (U_2^\dagger|\psi_0\rangle\langle\psi_0|U_2)]$$

$$+$$

$$\vdots$$

COMPUTE AVERAGE DATA IN TWO DIFFERENT WAYS



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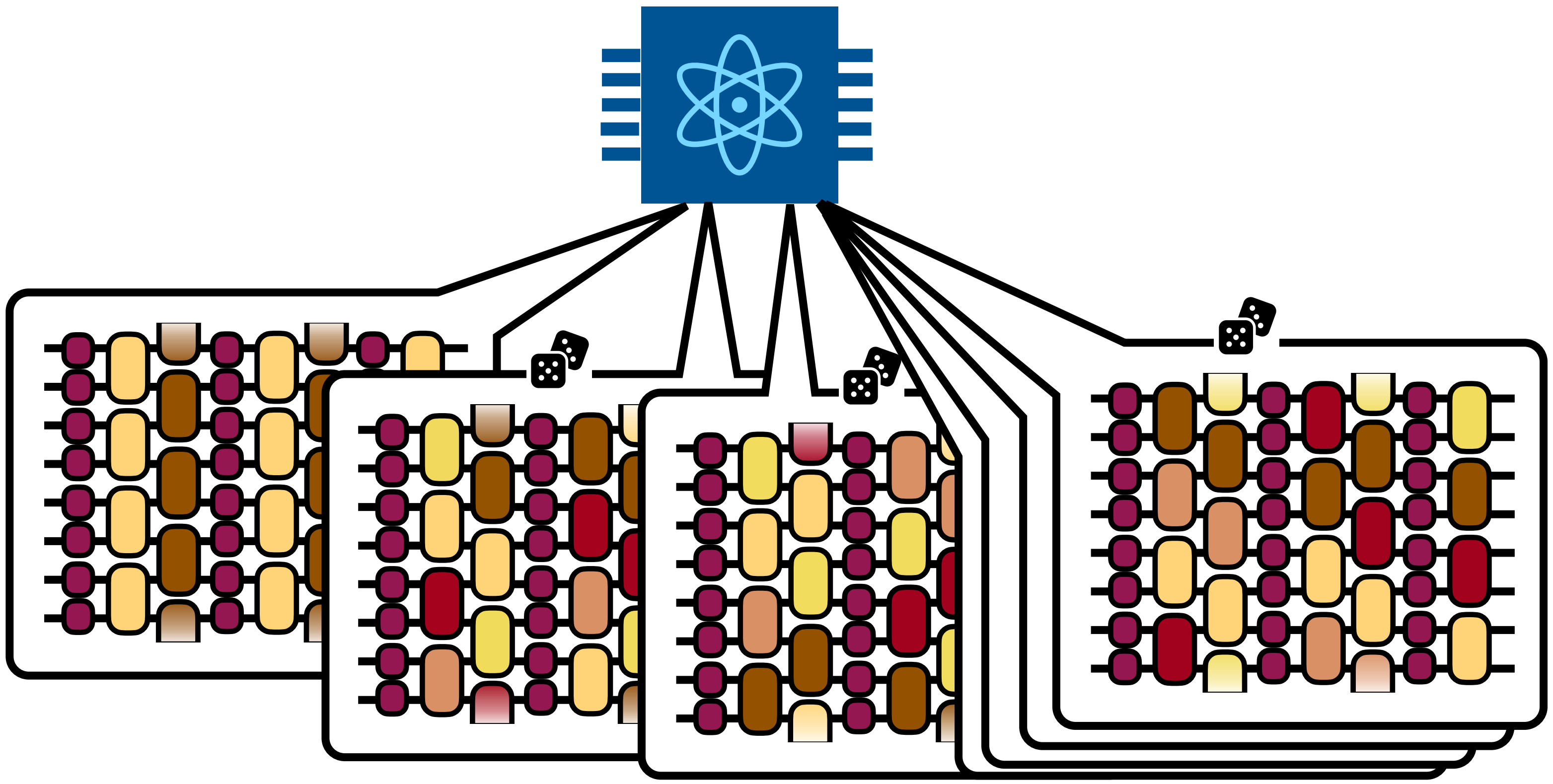
$$+$$

$$\vdots$$

Quantum data

$$\mathbb{E}_U\ [\mathrm{tr}[O_{\text{test}}\ (U^\dagger|\psi_0\rangle\langle\psi_0|U)]]$$

COMPUTE AVERAGE DATA IN TWO DIFFERENT WAYS



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$$+$$

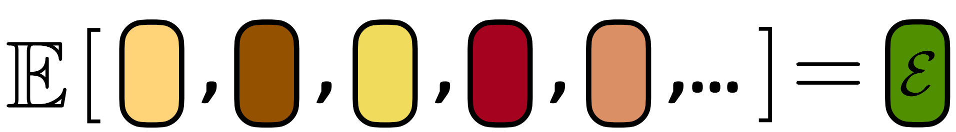
$$\vdots$$

Quantum data

$$\mathbb{E}_U\ [\mathrm{tr}[O_{\mathrm{test}}\ (U^\dagger|\psi_0\rangle\langle\psi_0|U)]]$$

$$=$$

$$\mathrm{tr}[O_{\mathrm{test}}\ \mathbb{E}_U[(U^\dagger|\psi_0\rangle\langle\psi_0|U)]]$$



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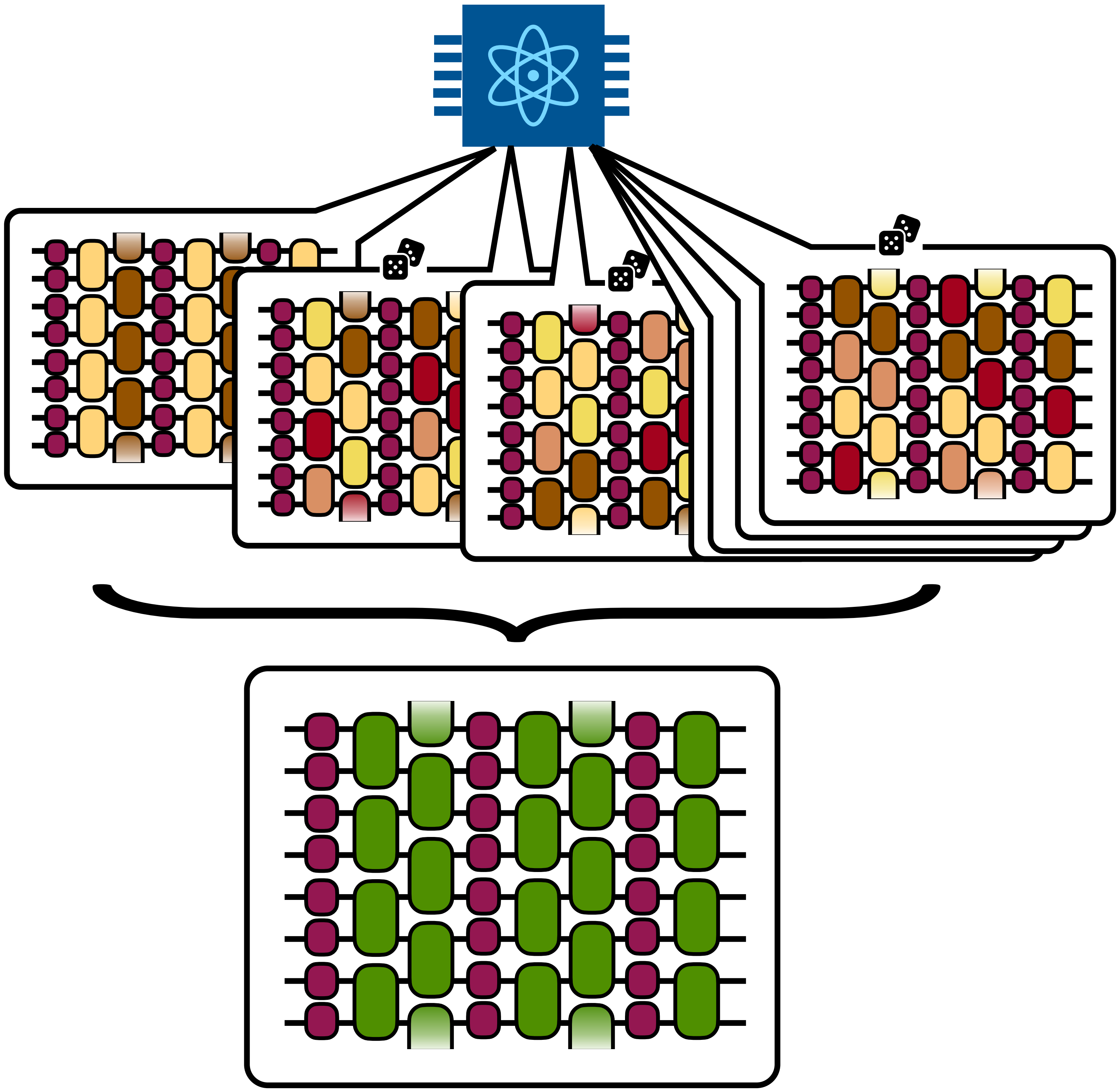

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$$\vdots$$

Quantum data

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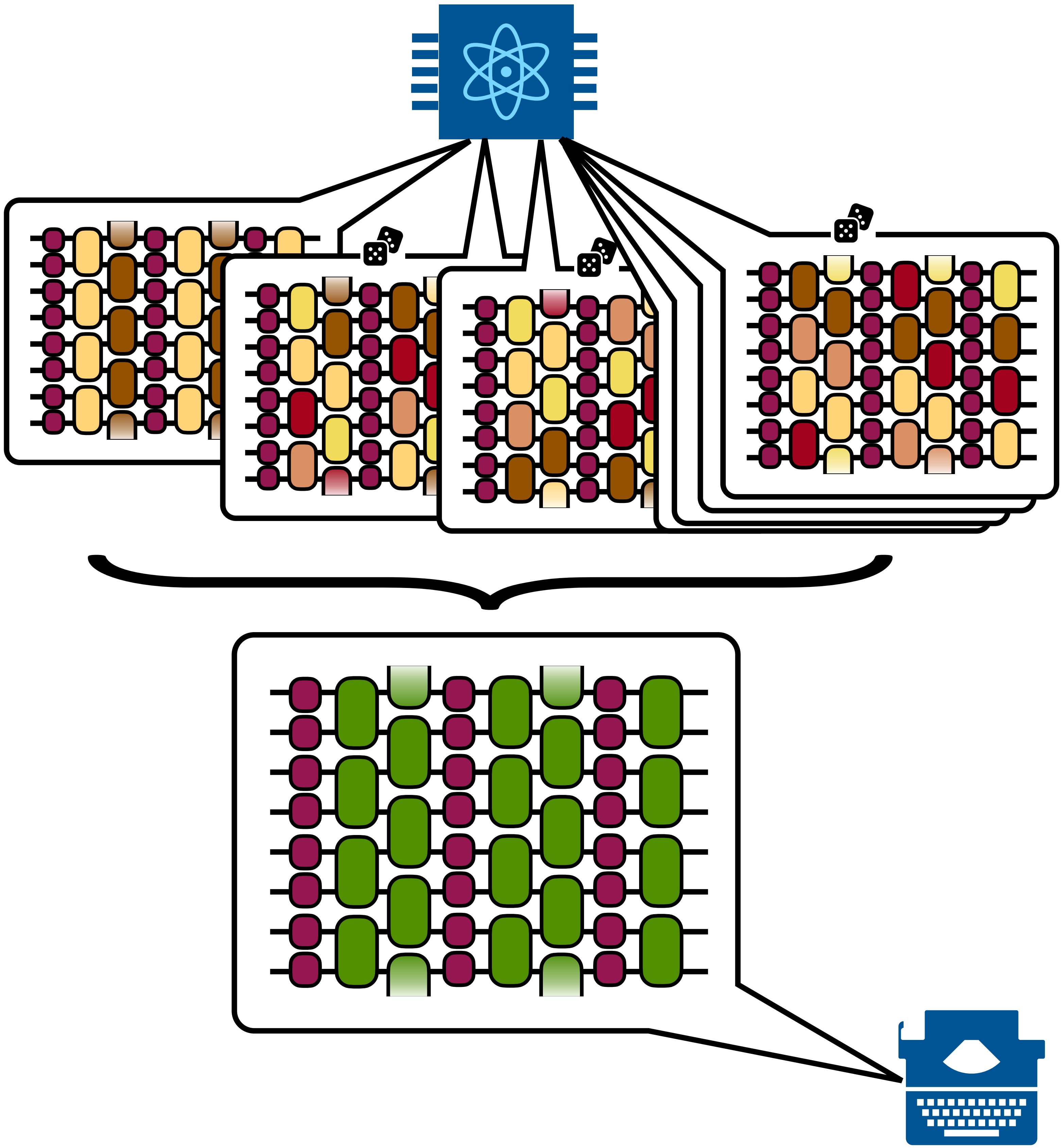

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$$+$$

$$\mathrm{tr}[O_{\mathrm{test}}\ (U_2^\dagger|\psi_0\rangle\langle\psi_0|U_2)]$$

$$+$$

$$\vdots$$

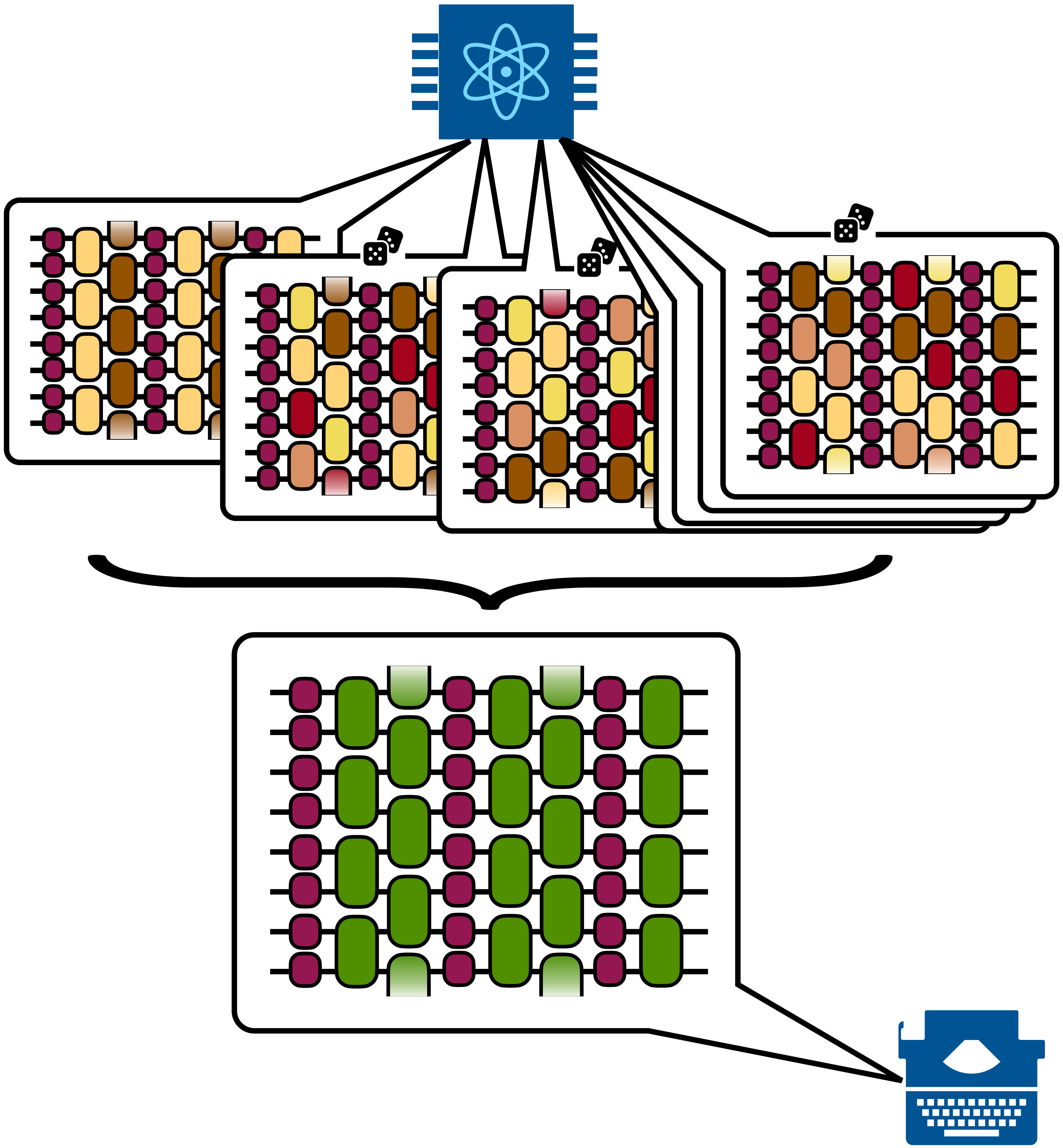
Quantum data

$$\mathbb{E}_U\left[\mathrm{tr}[O_{\mathrm{test}}\ (U^\dagger|\psi_0\rangle\langle\psi_0|U)]\right]$$

$$\mathrm{tr}[O_{\mathrm{test}}\ \mathcal{E}(|\psi_0\rangle\langle\psi_0|)]$$

Classical simulation

COMPUTE AVERAGE DATA IN TWO DIFFERENT WAYS



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$$+$$

$$\vdots$$

Quantum data

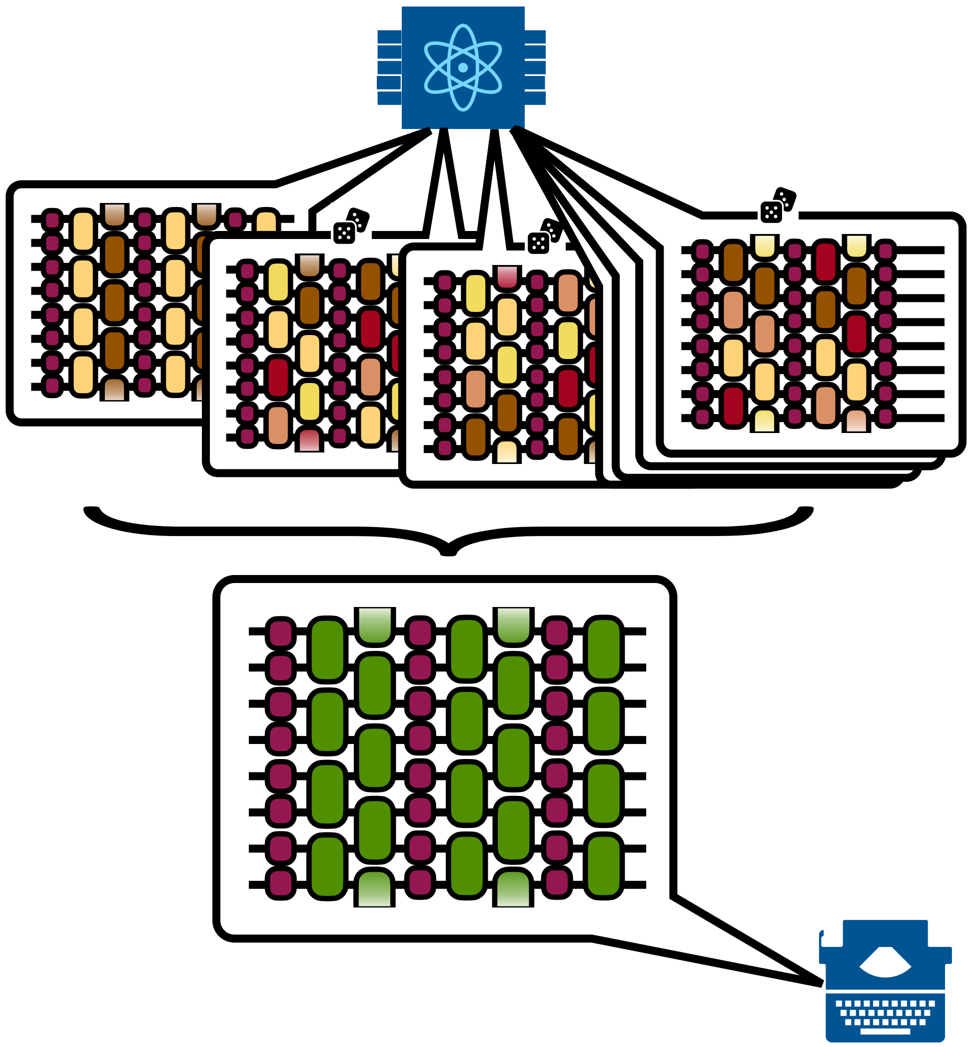
$$\mathbb{E}_U\left[\mathrm{tr}[O_{\mathrm{test}}\ (U^\dagger|\psi_0\rangle\langle\psi_0|U)]\right]$$

VS

$$\mathrm{tr}[O_{\mathrm{test}}\ \mathcal{E}(|\psi_0\rangle\langle\psi_0|)]$$

Classical simulation

MAKE IT INFORMATIVE



Quantum data

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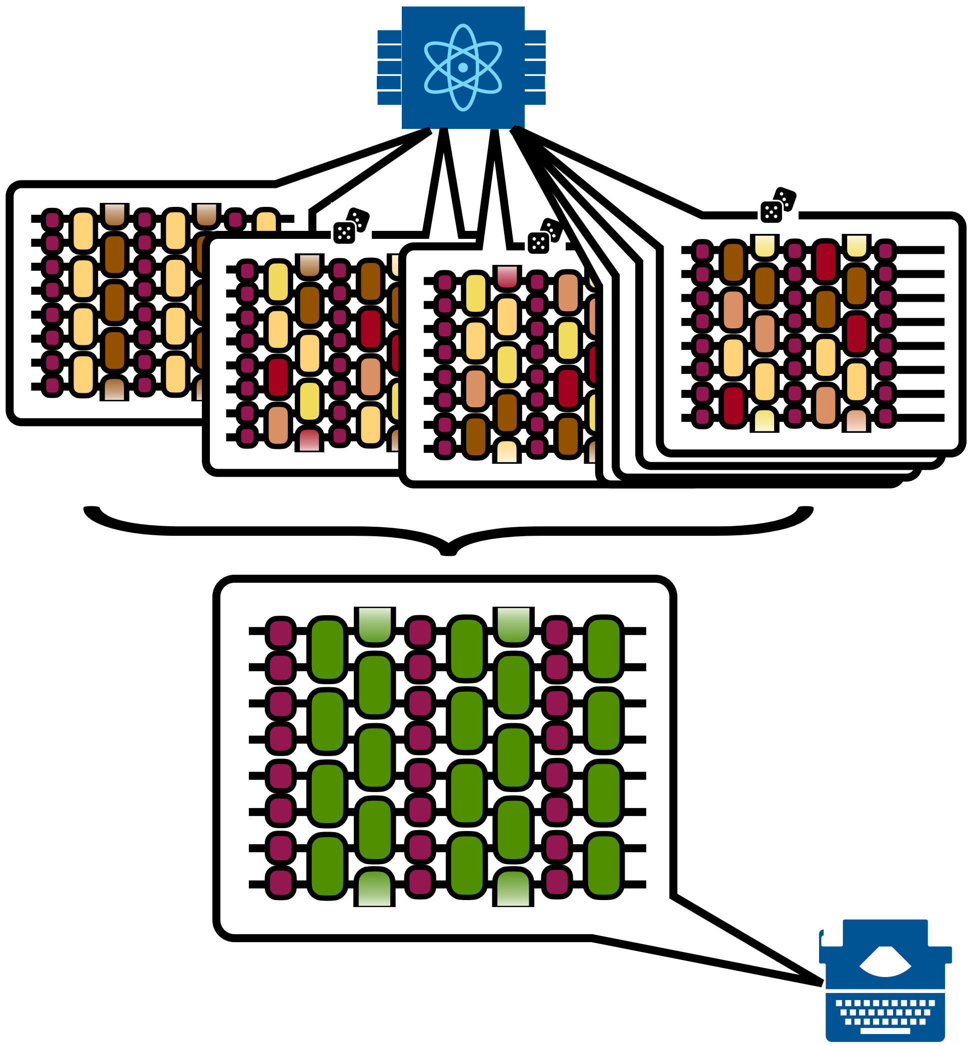

Quantum data

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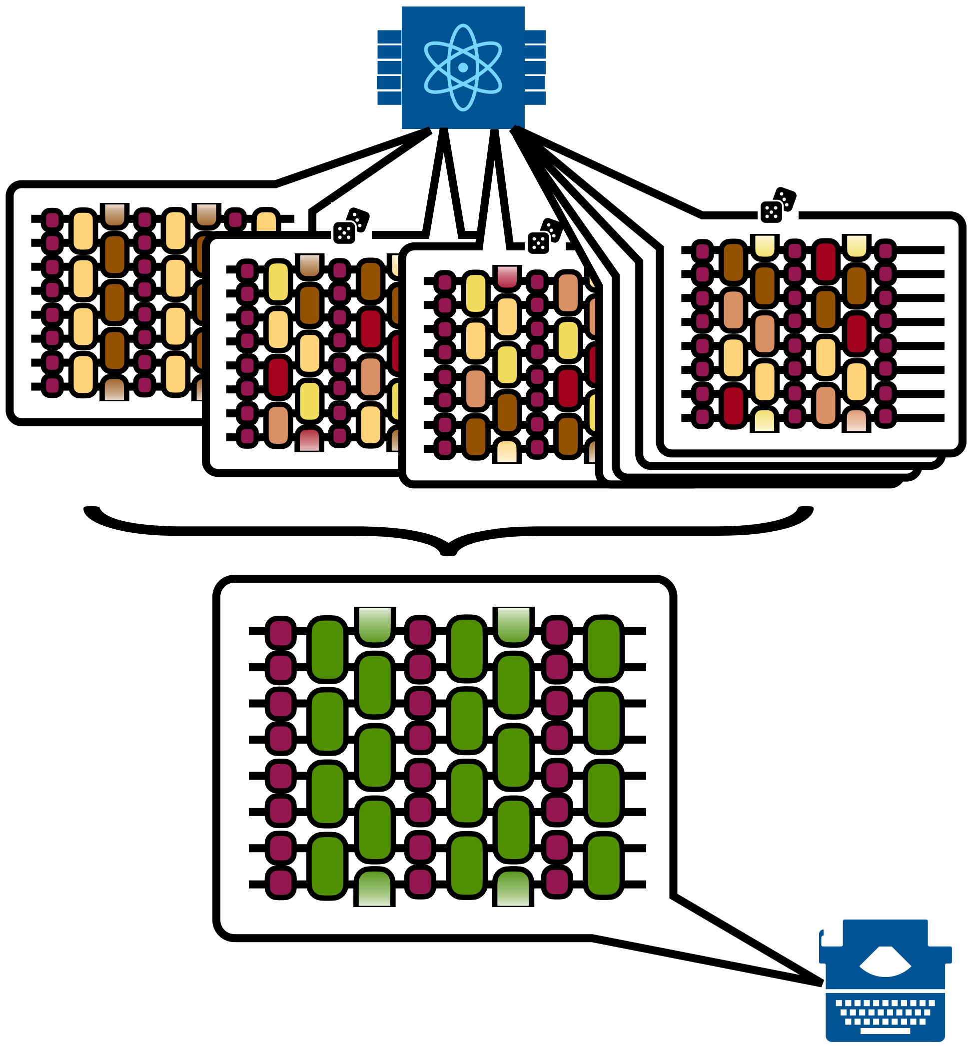
Classical simulation

O_{test} **Few-body expectation value**

MAKE IT INFORMATIVE



Quantum data

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VS

$$\mathrm{tr}[O_{\mathrm{test}}\ \mathcal{E}(|\psi_0\rangle\langle\psi_0|)]$$

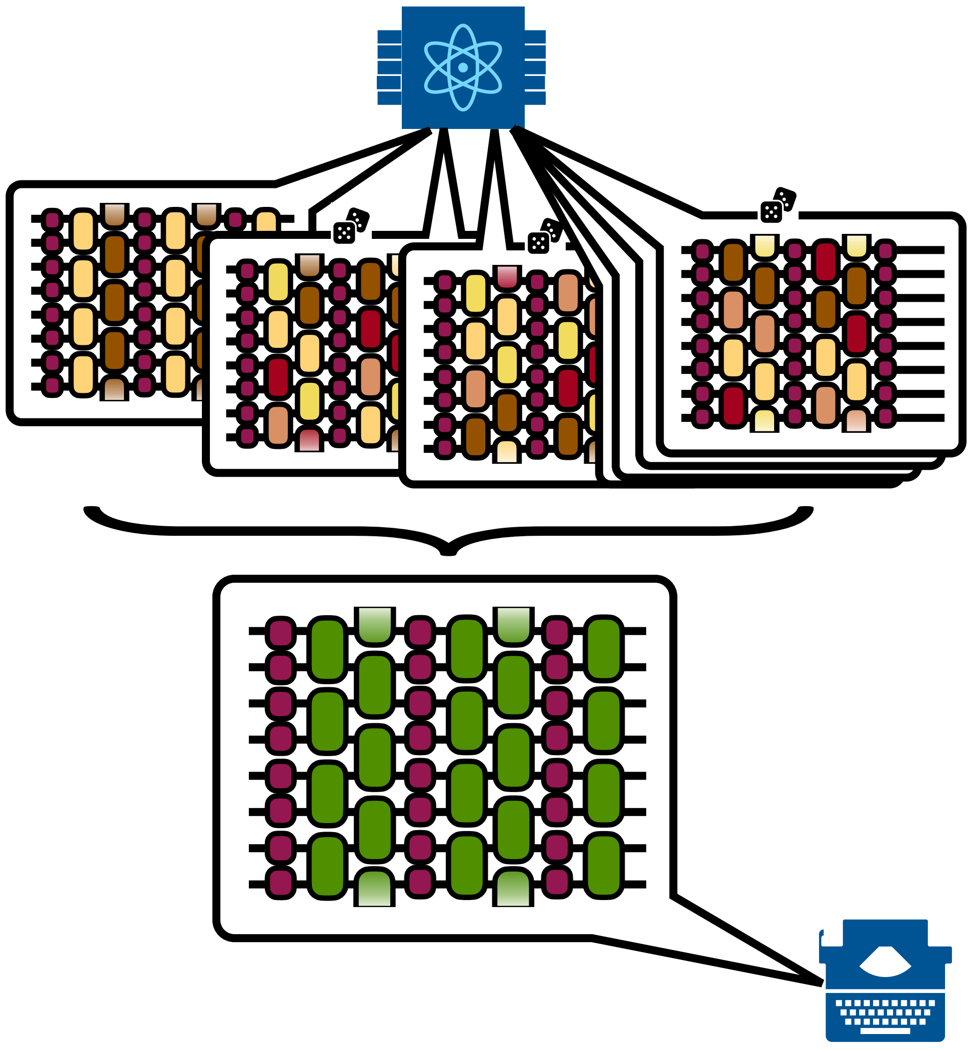
Classical simulation

O_{test} **Few-body expectation value**

Do it in a way that the average computation retains information about the original computation

$$\mathcal{E} \to \mathcal{E}_U$$

MAKE IT INFORMATIVE



Quantum data

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VS

$$\mathrm{tr}[O_{\mathrm{test}} \; \mathcal{E}(|\psi_0\rangle\langle\psi_0|)]$$

Classical simulation

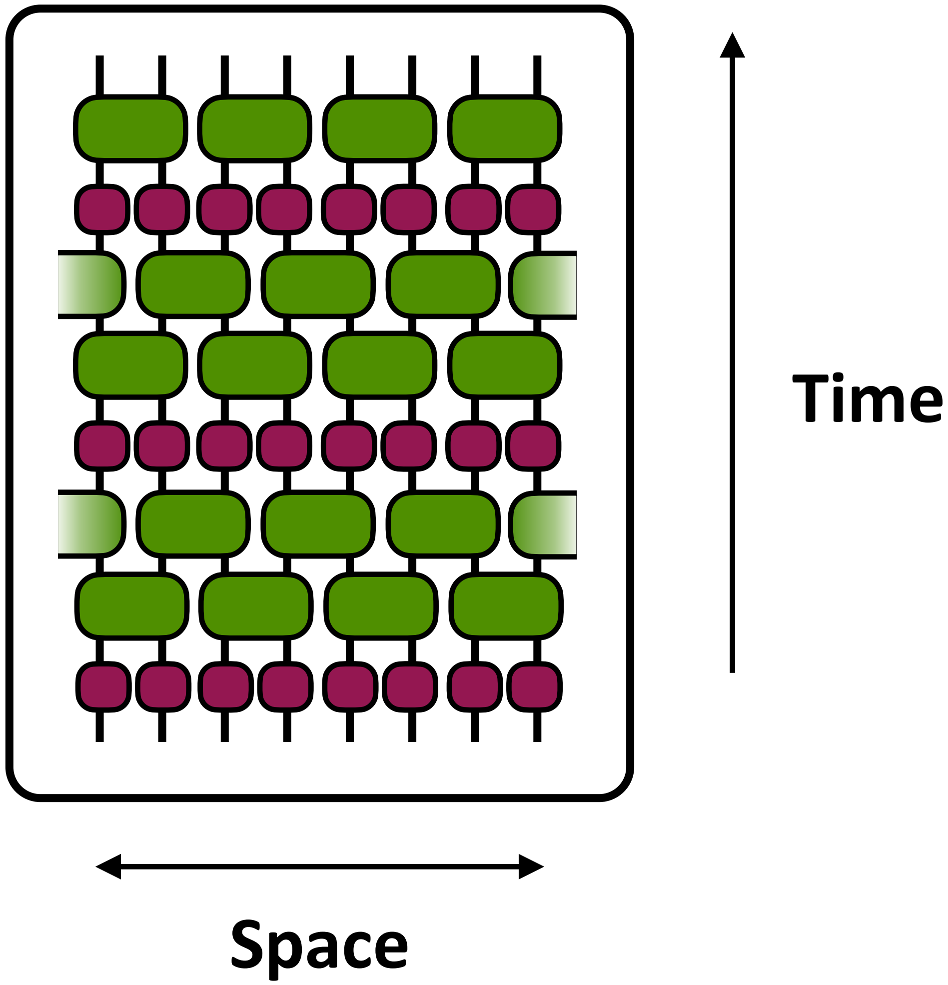
O_{test} **Few-body expectation value**

Do it in a way that the average computation retains information about the original computation

Bad example: Haar random unitaries $\mathcal{E} \to \mathcal{E}_U$

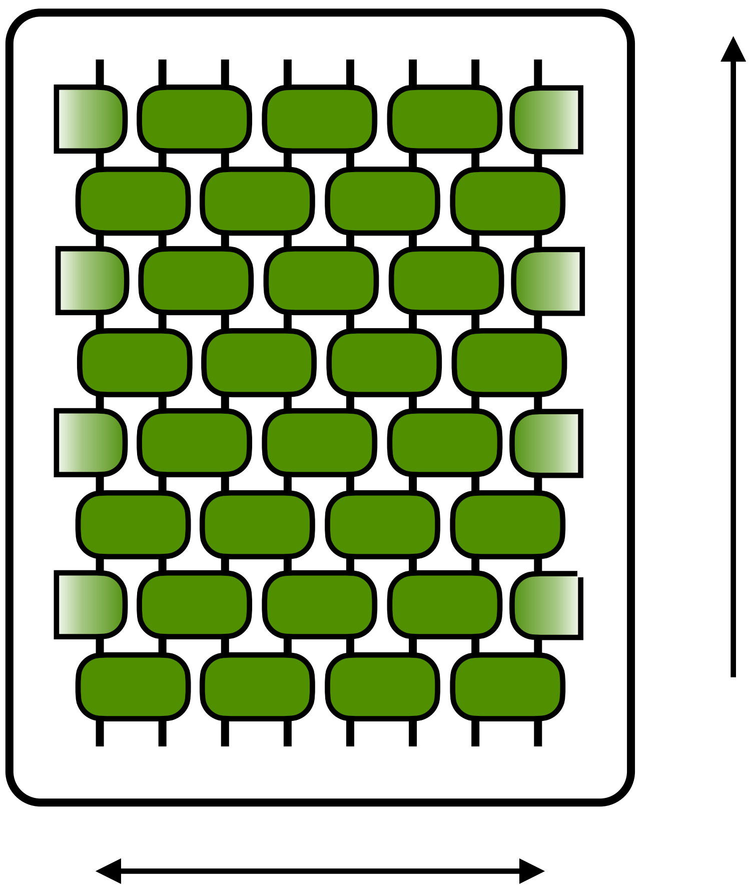
The method(s)

SPACE-TIME CHANNELS



P. Kos, G. Styliaris, Circuits of space and time quantum channels, *Quantum* 7 (2023)

SPACE-TIME CHANNELS



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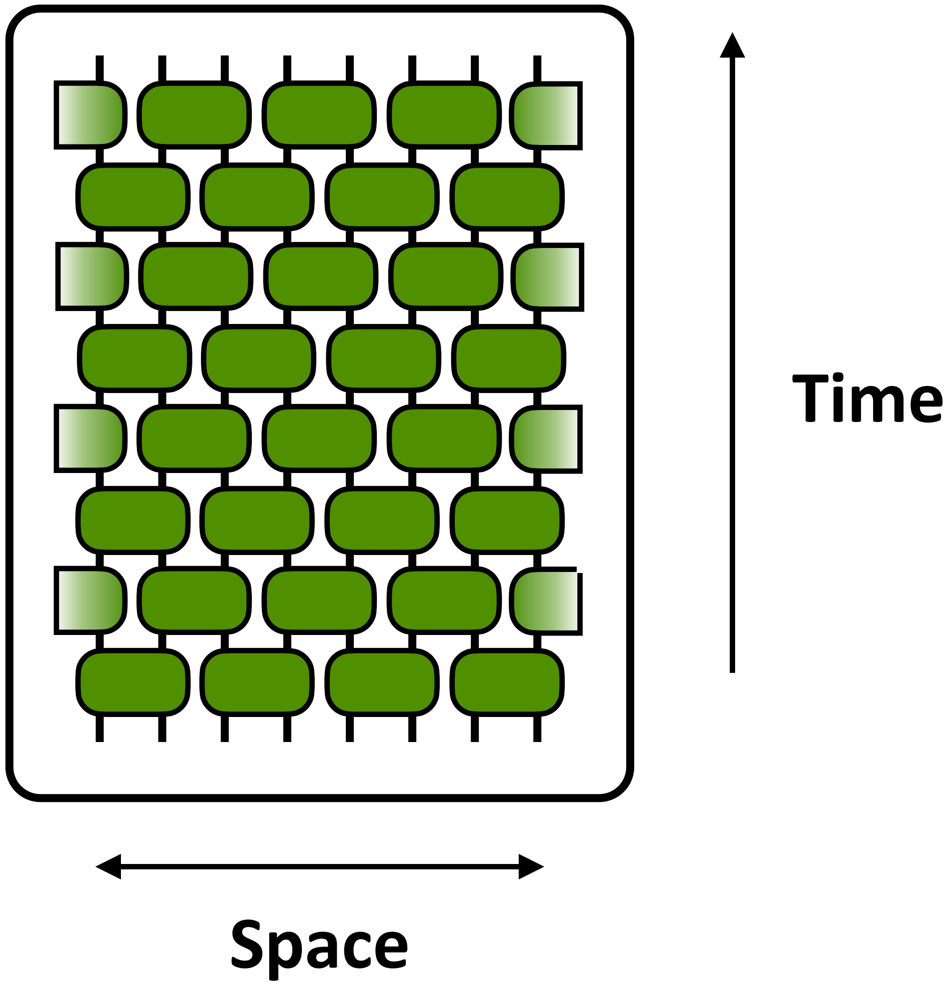

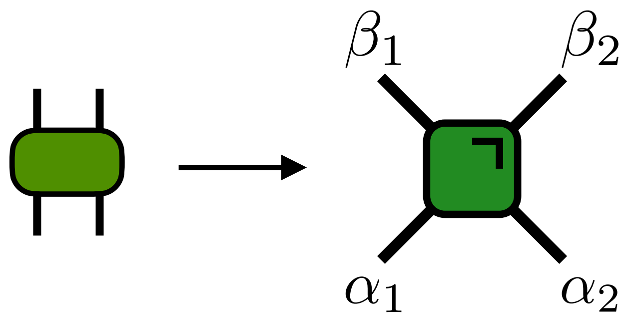

$$\alpha_i, \beta_i = \mathbb{1}, x, y, z$$

$$\mathrm{tr}(\sigma_{\beta_1} \otimes \sigma_{\beta_2} \mathcal{E}(\sigma_{\alpha_1} \otimes \sigma_{\alpha_2}))$$

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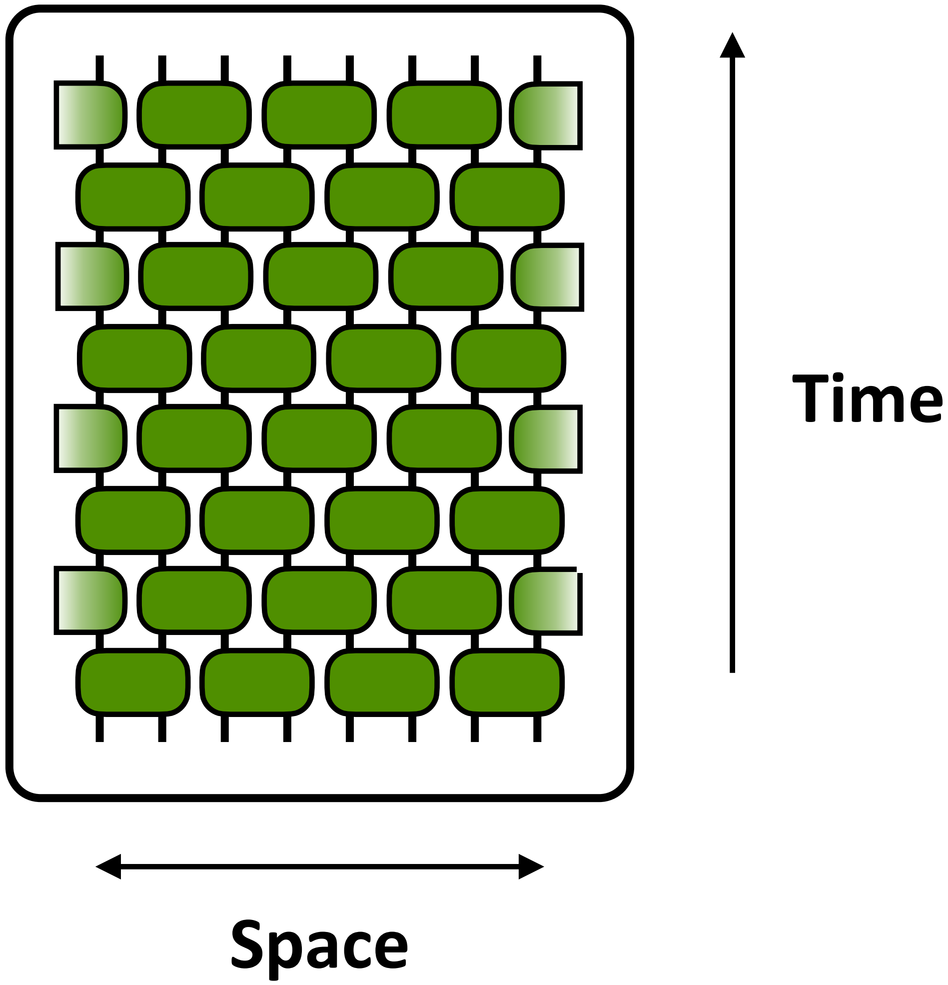
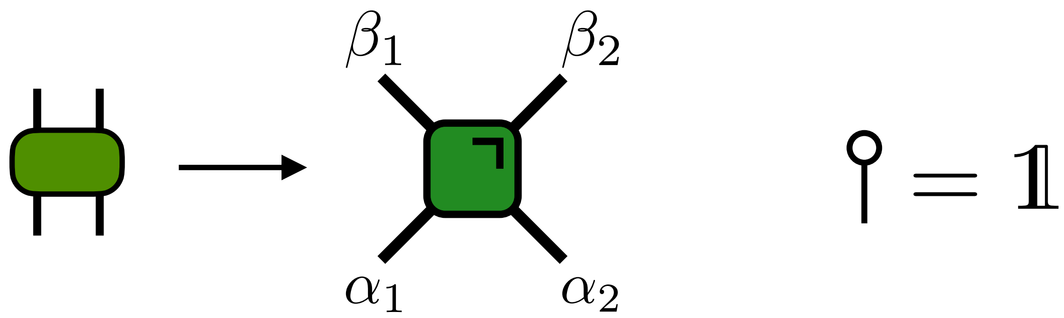
SPACE-TIME CHANNELS





$$\mathrm{tr}(\sigma_{\beta_1} \otimes \sigma_{\beta_2} \mathcal{E}(\sigma_{\alpha_1} \otimes \sigma_{\alpha_2}))$$

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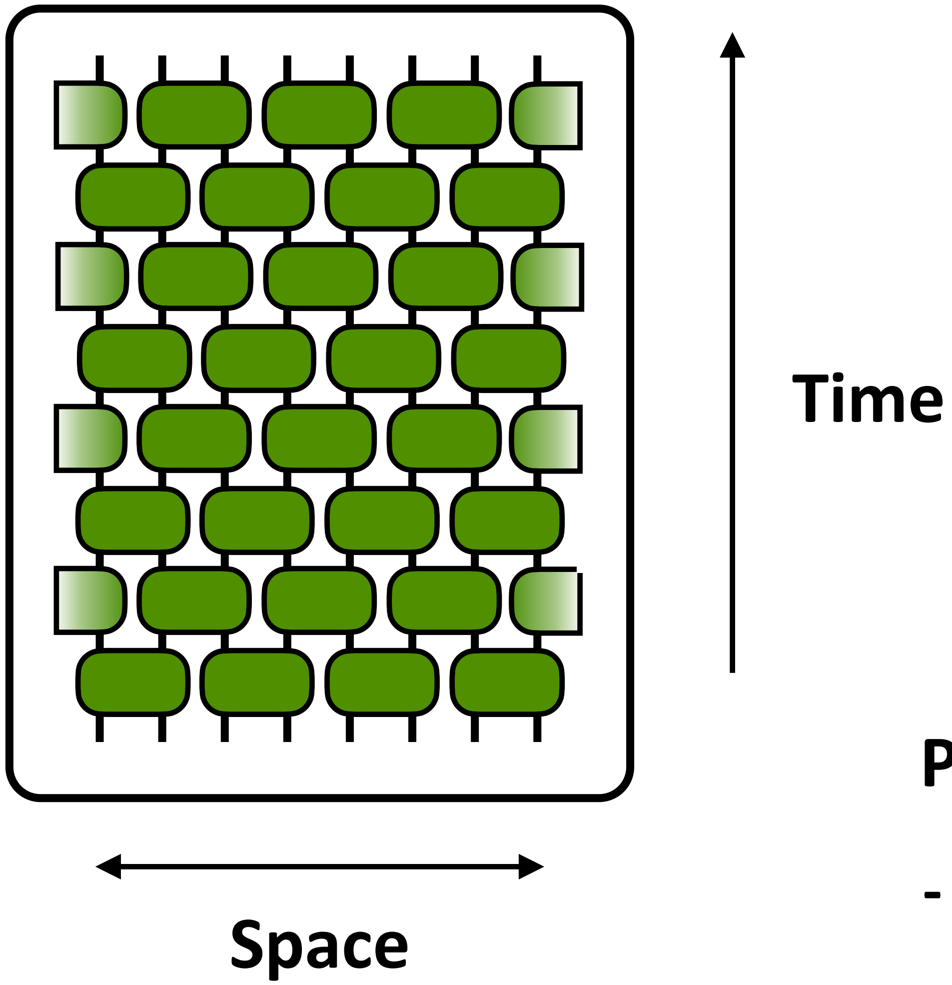
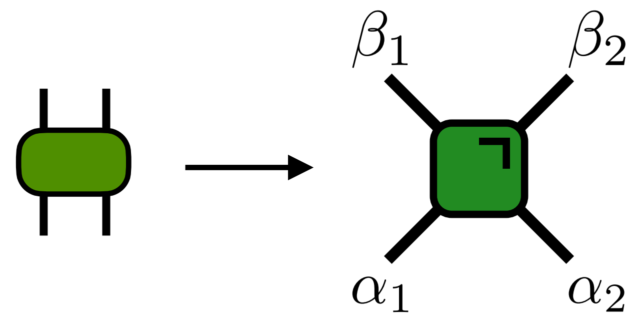
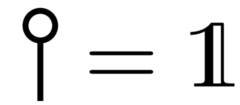
SPACE-TIME CHANNELS



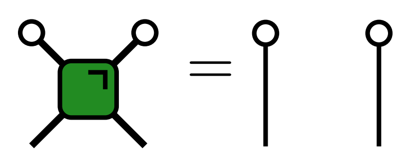




$$\mathrm{tr}(\sigma_{\beta_1} \otimes \sigma_{\beta_2} \mathcal{E}(\sigma_{\alpha_1} \otimes \sigma_{\alpha_2}))$$

Properties:

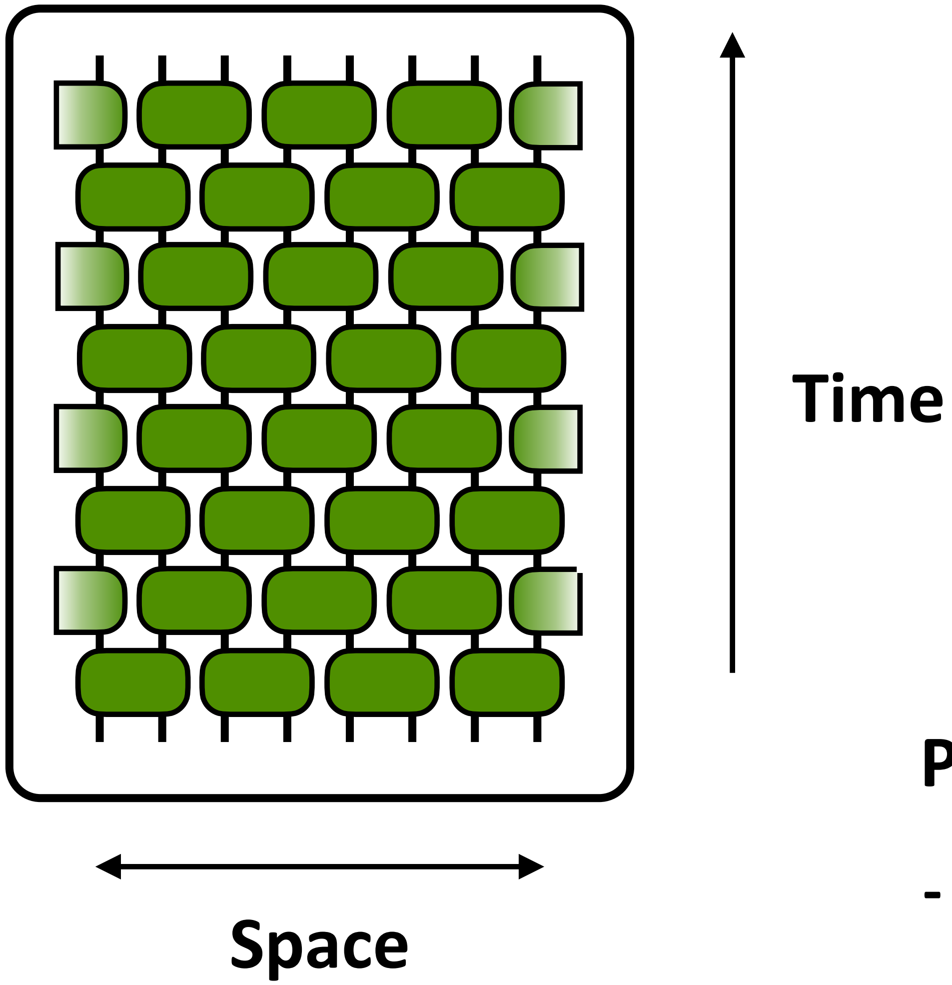
- Trace preservation

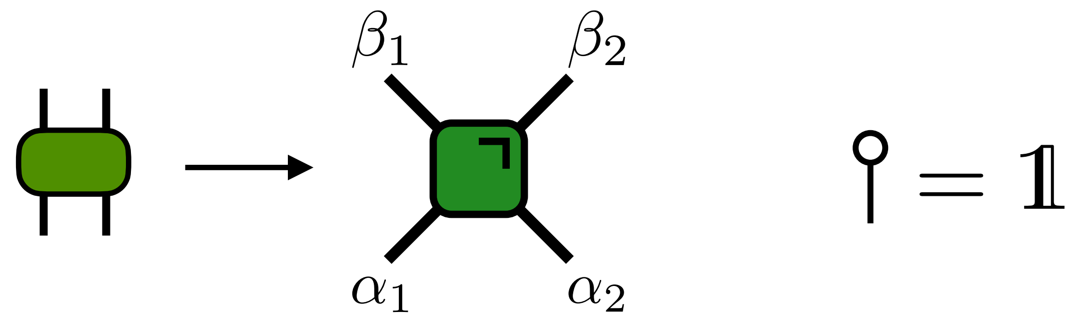


$$\mathrm{tr}(\mathcal{E}(\sigma_{\alpha_1} \otimes \sigma_{\alpha_2})) = \delta_{\alpha_1 \mathbb{1}} \delta_{\alpha_2 \mathbb{1}}$$

P. Kos, G. Styliaris, Circuits of space and time quantum channels, *Quantum* 7 (2023)

SPACE-TIME CHANNELS





$$\mathrm{tr}(\sigma_{\beta_1} \otimes \sigma_{\beta_2} \mathcal{E}(\sigma_{\alpha_1} \otimes \sigma_{\alpha_2}))$$

Properties:

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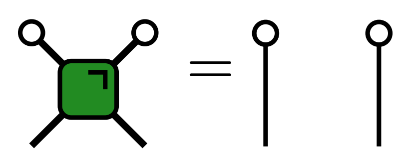
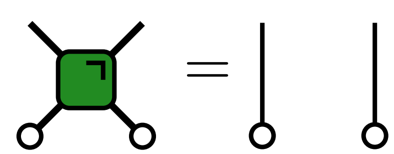


- Unitality



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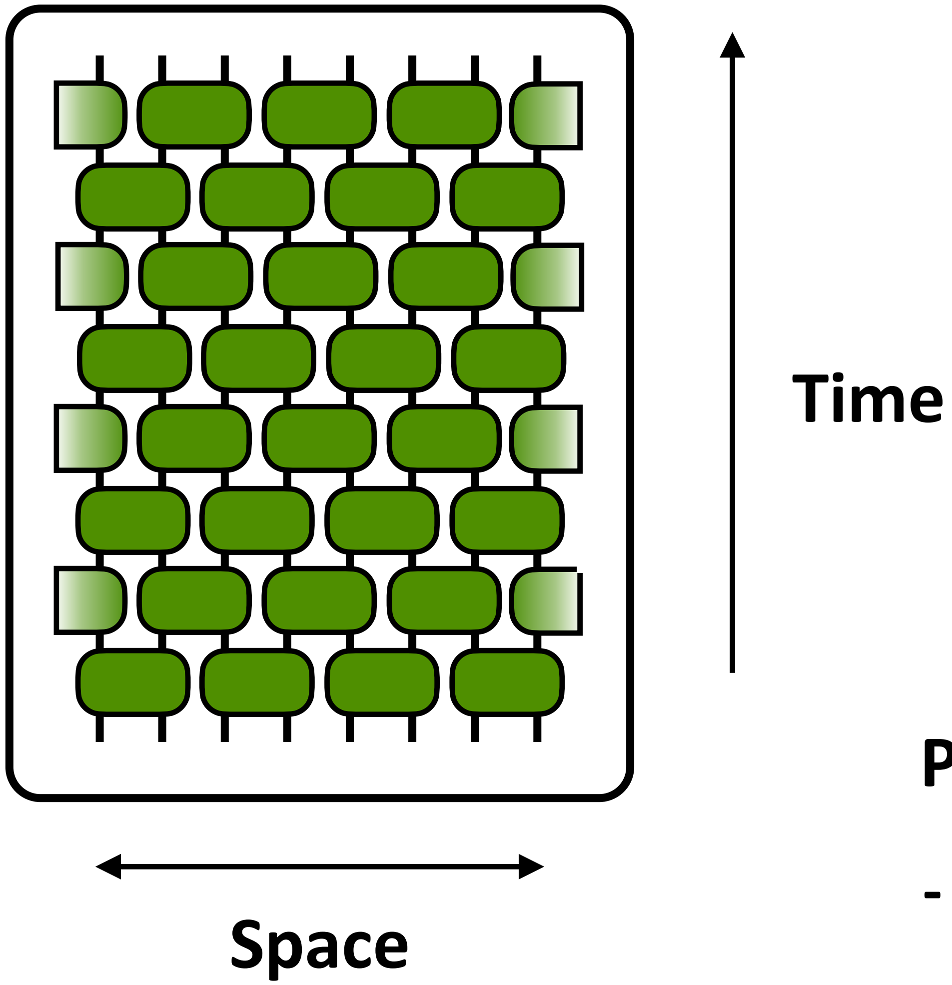
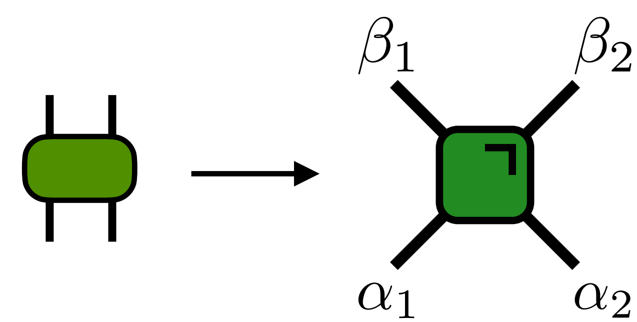
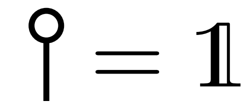
SPACE-TIME CHANNELS







$$\mathrm{tr}(\sigma_{\beta_1} \otimes \sigma_{\beta_2} \mathcal{E}(\sigma_{\alpha_1} \otimes \sigma_{\alpha_2}))$$

Properties:

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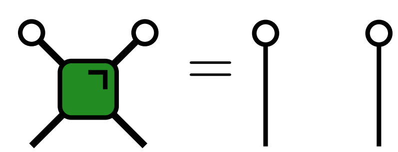
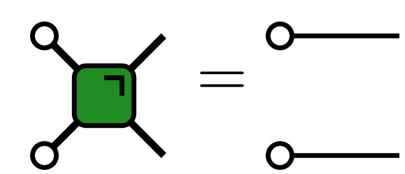
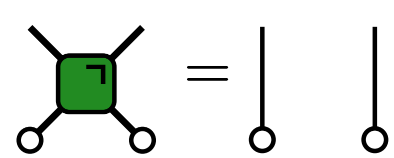


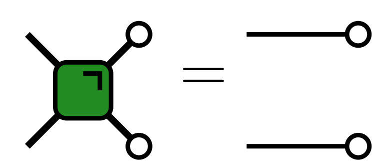
- Left unitality



- Unitality



- Right unitality



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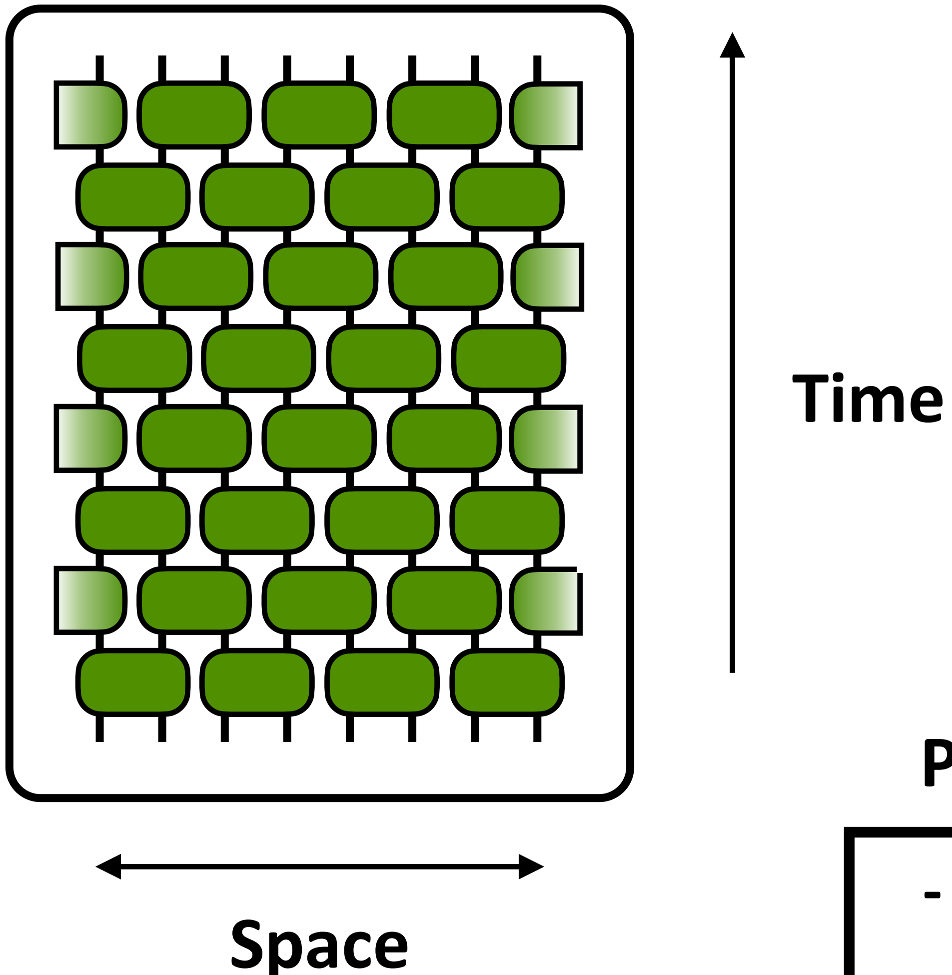
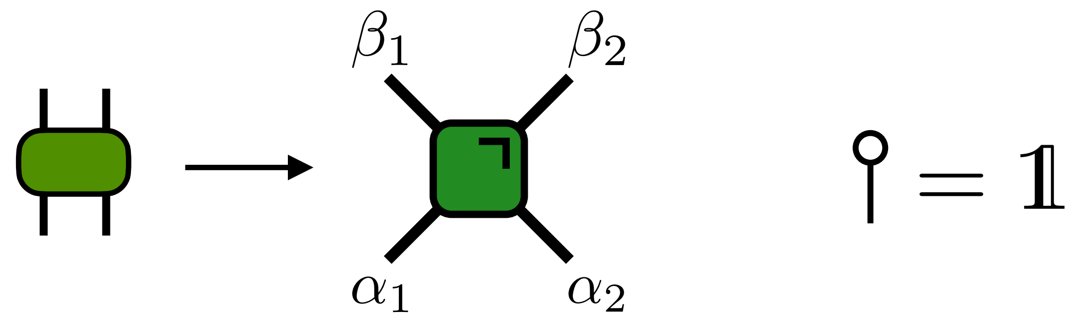
SPACE-TIME CHANNELS

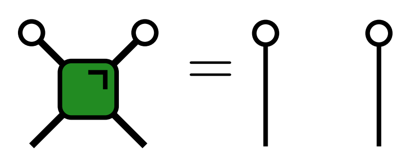




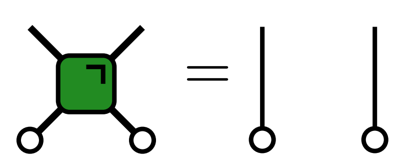
$$\mathrm{tr}(\sigma_{\beta_1} \otimes \sigma_{\beta_2} \mathcal{E}(\sigma_{\alpha_1} \otimes \sigma_{\alpha_2}))$$

Properties:

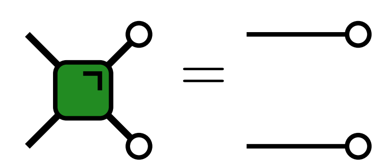
- **Trace preservation**



- **Unitality**

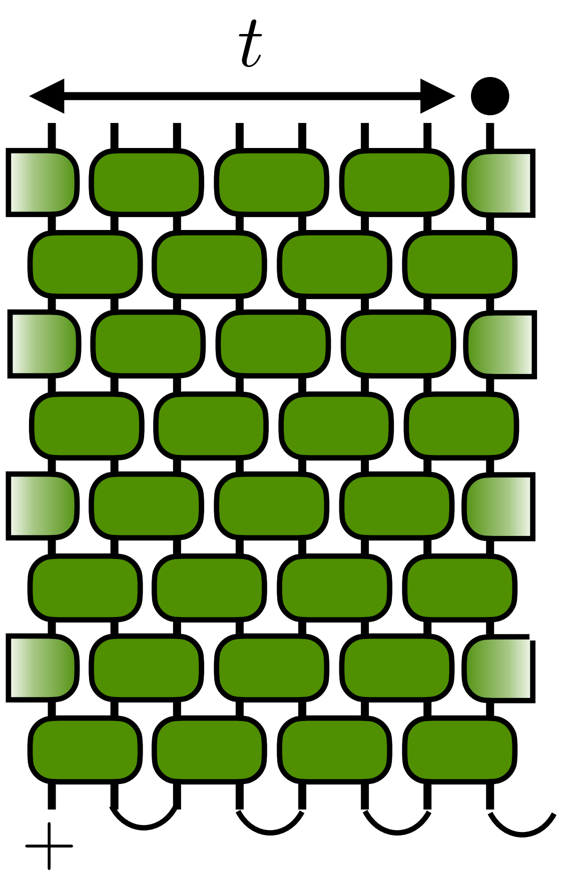


- **Right unitality**



3-way

COMPUTING CORRELATIONS

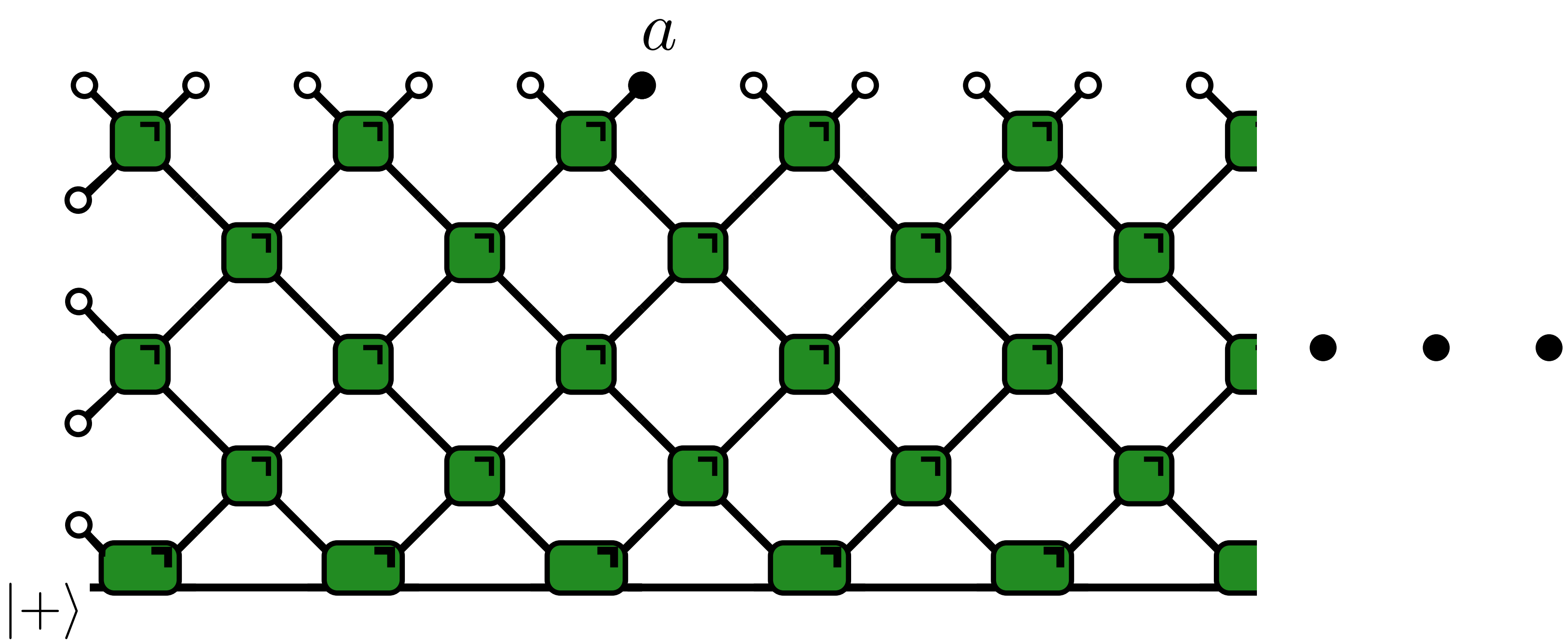


$$\mathrm{tr}[\sigma_a^t \, \mathbb{E}_U[(U^\dagger|\psi_0\rangle\langle\psi_0|U)]]$$

$$|\psi_{\mathrm{in}}\rangle = |+_0\rangle|\Psi_{12}^+\rangle|\Psi_{34}^+\rangle|\Psi_{56}^+\rangle\ldots$$

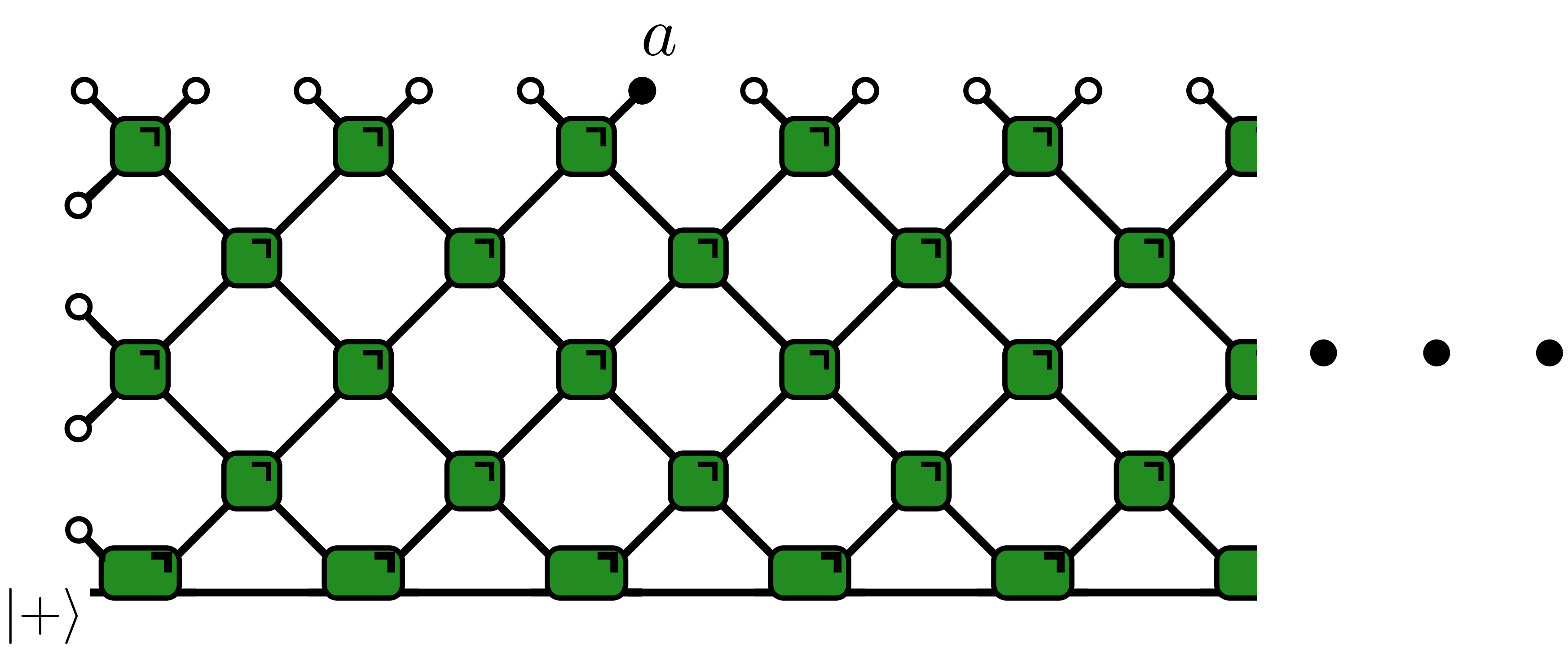
COMPUTING CORRELATIONS

$$\mathrm{tr}[\sigma_a^t \; \mathbb{E}_U[(U^\dagger|\psi_0\rangle\langle\psi_0|U)]]$$

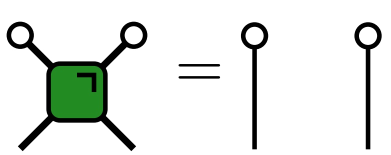


COMPUTING CORRELATIONS

$$\mathrm{tr}[\sigma_a^t \, \mathbb{E}_U[(U^\dagger|\psi_0\rangle\langle\psi_0|U)]]$$



- **Trace preservation**



COMPUTING CORRELATIONS

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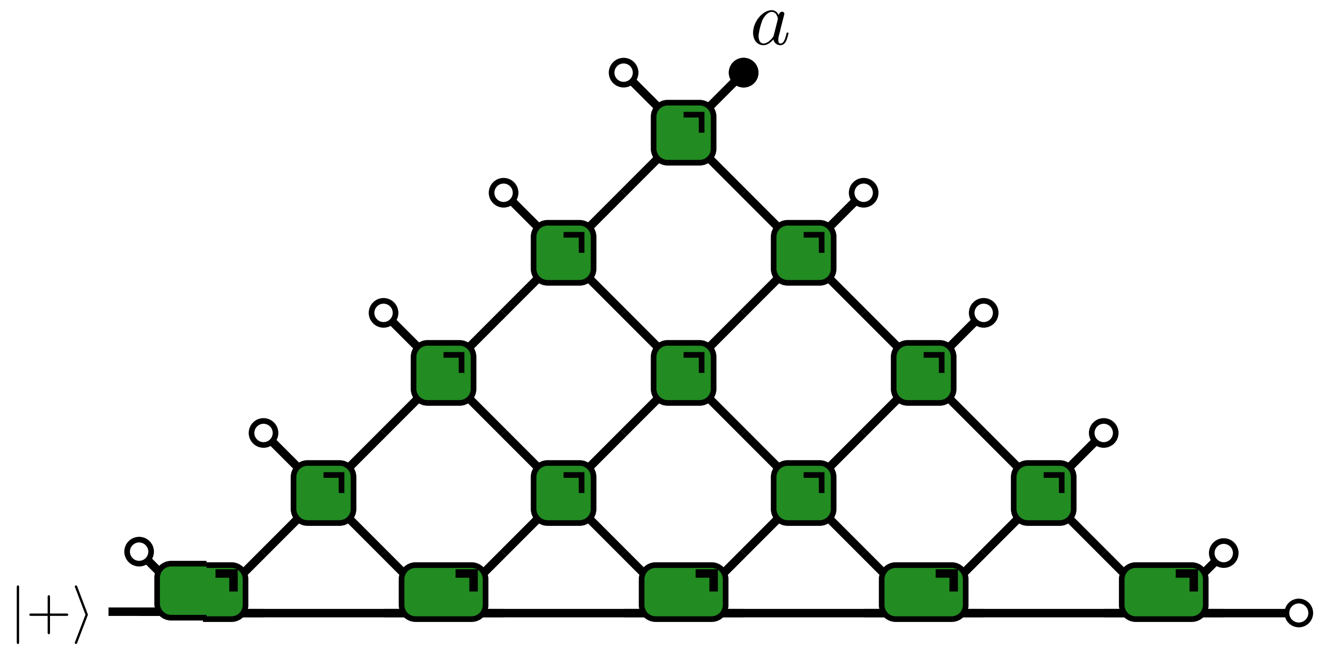

COMPUTING CORRELATIONS

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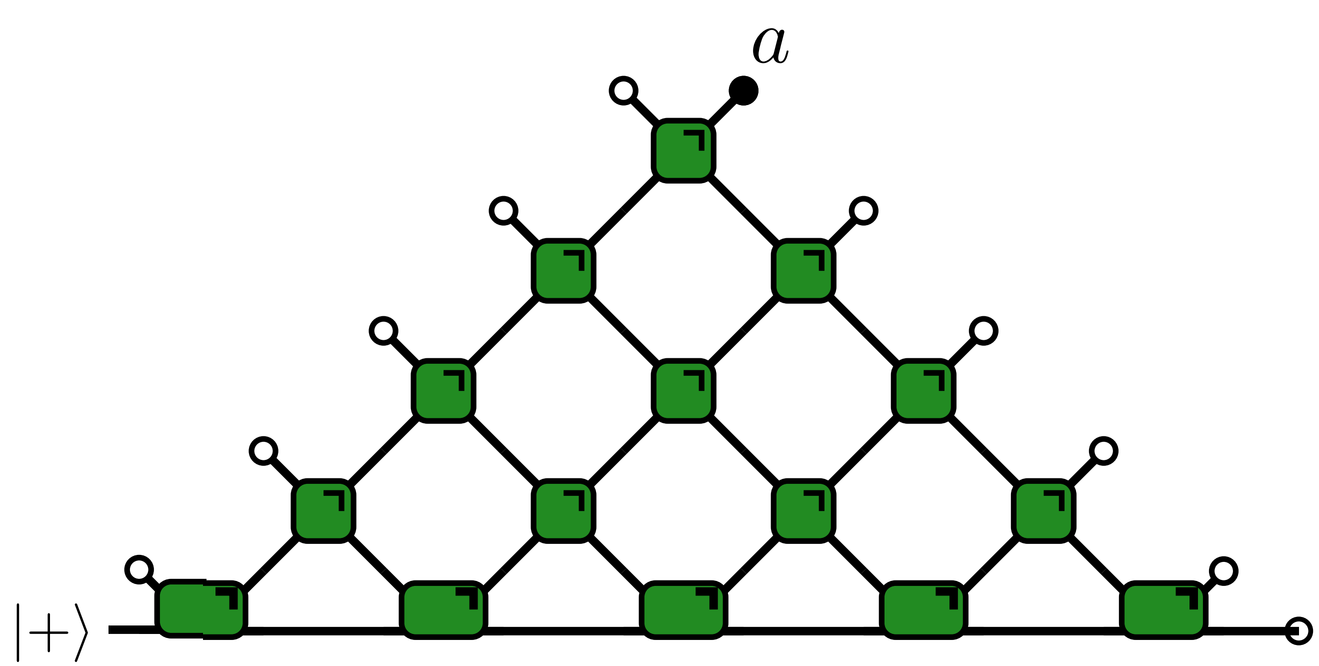
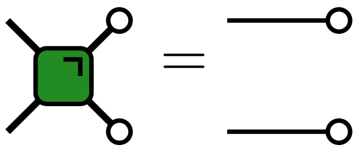
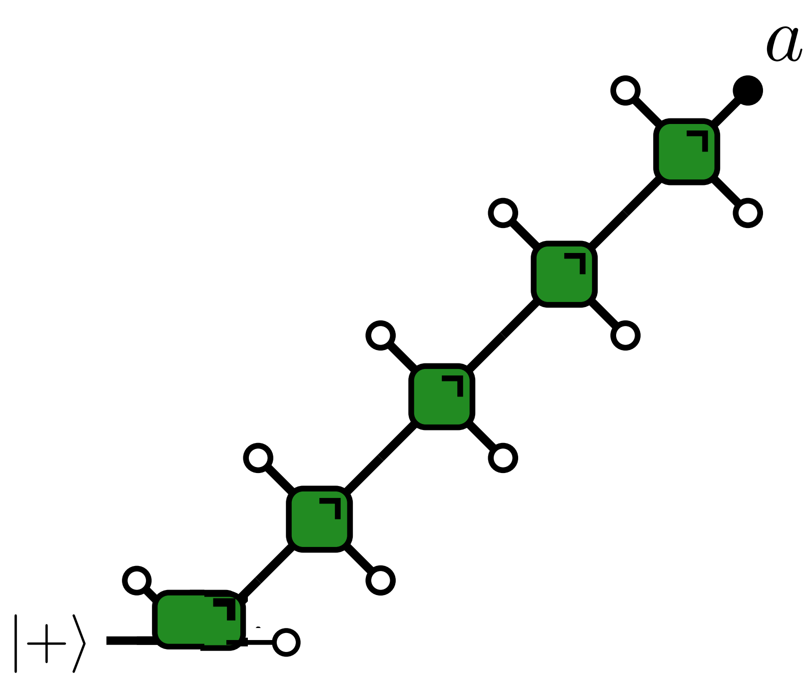


- Right unitality

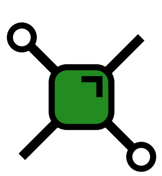


COMPUTING CORRELATIONS

$$\mathrm{tr}[\sigma_a^t\ \mathbb{E}_U[(U^\dagger|\psi_0\rangle\langle\psi_0|U)]]$$



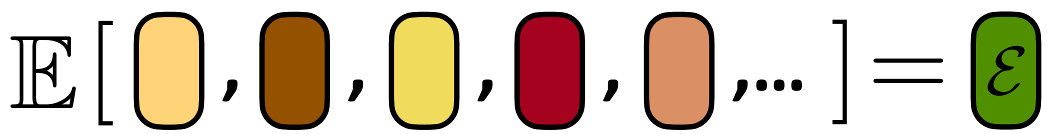
Matrix multiplication

$\mathcal{M}_+ =$ 

Transfer matrices

AVERAGING TO GET SPACE-TIME CHANNELS

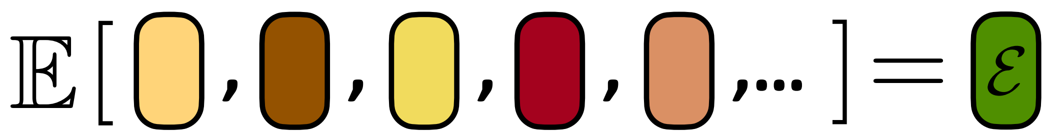
Define an averaging strategy such that the resulting channel is 3-way



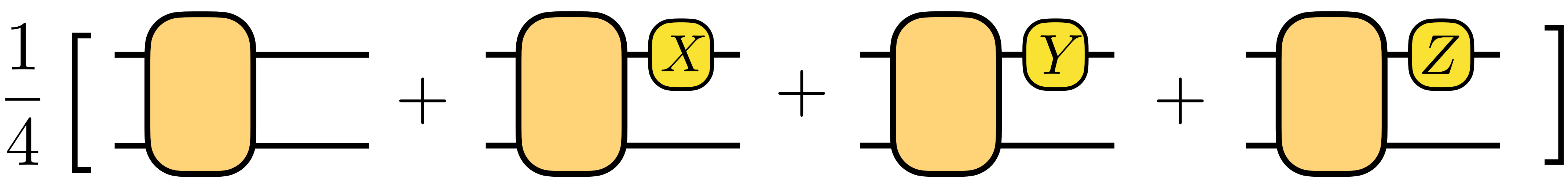
3-way unital

AVERAGING TO GET SPACE-TIME CHANNELS

Define an averaging strategy such that the resulting channel is 3-way



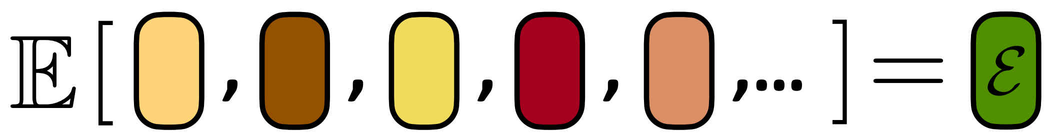
3-way unital



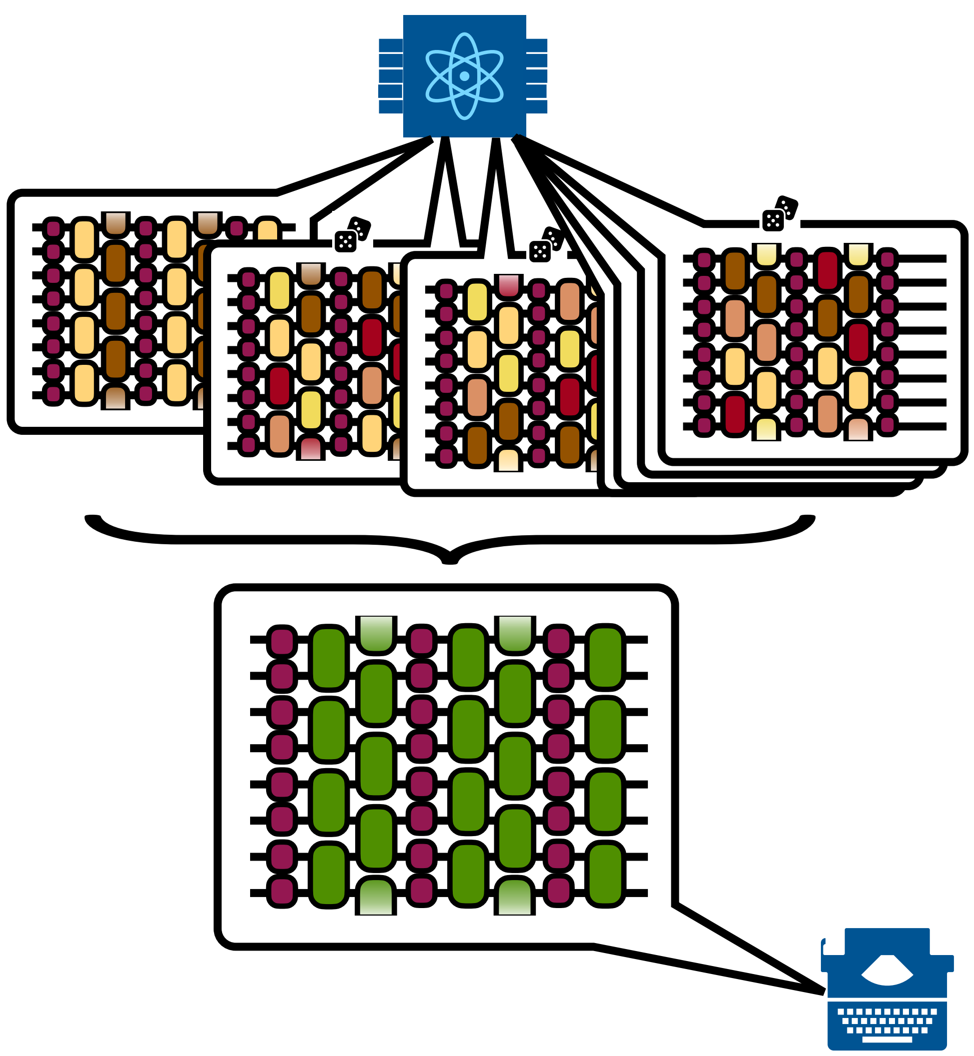
3-way for any unitary

AVERAGING TO GET SPACE-TIME CHANNELS

Define an averaging strategy such that the resulting channel is 4-way



3-way unital

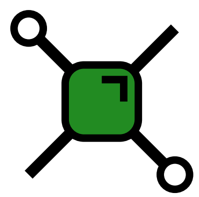


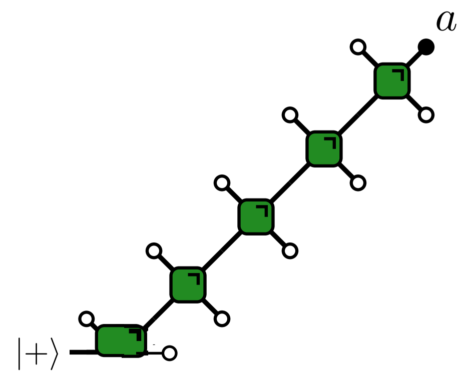
$$O_{\text{test}} = \sigma_a^t$$

$$O_{\text{test}} = \sigma_a^i \sigma_b^{i+1} \sigma_c^{i+2}$$

AVERAGING TO GET SPACE-TIME CHANNELS

1) The averaging procedure retains information about the original unitary

$\mathcal{M}_+ =$ 



AVERAGING TO GET SPACE-TIME CHANNELS

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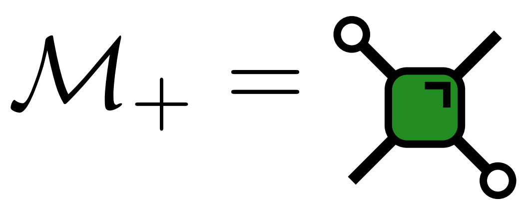
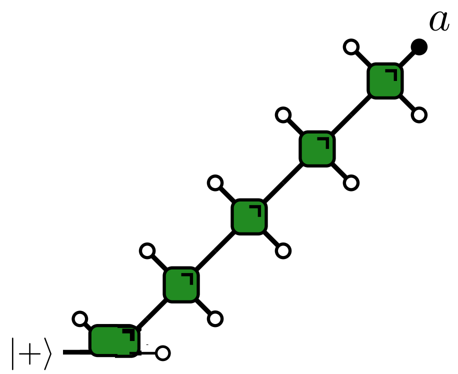
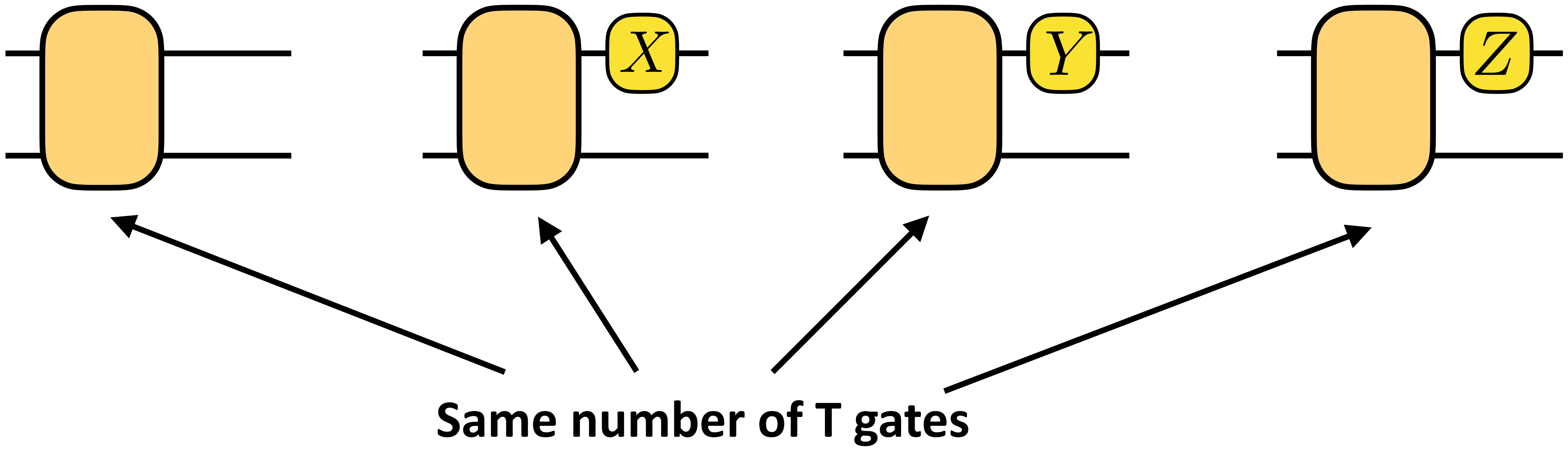




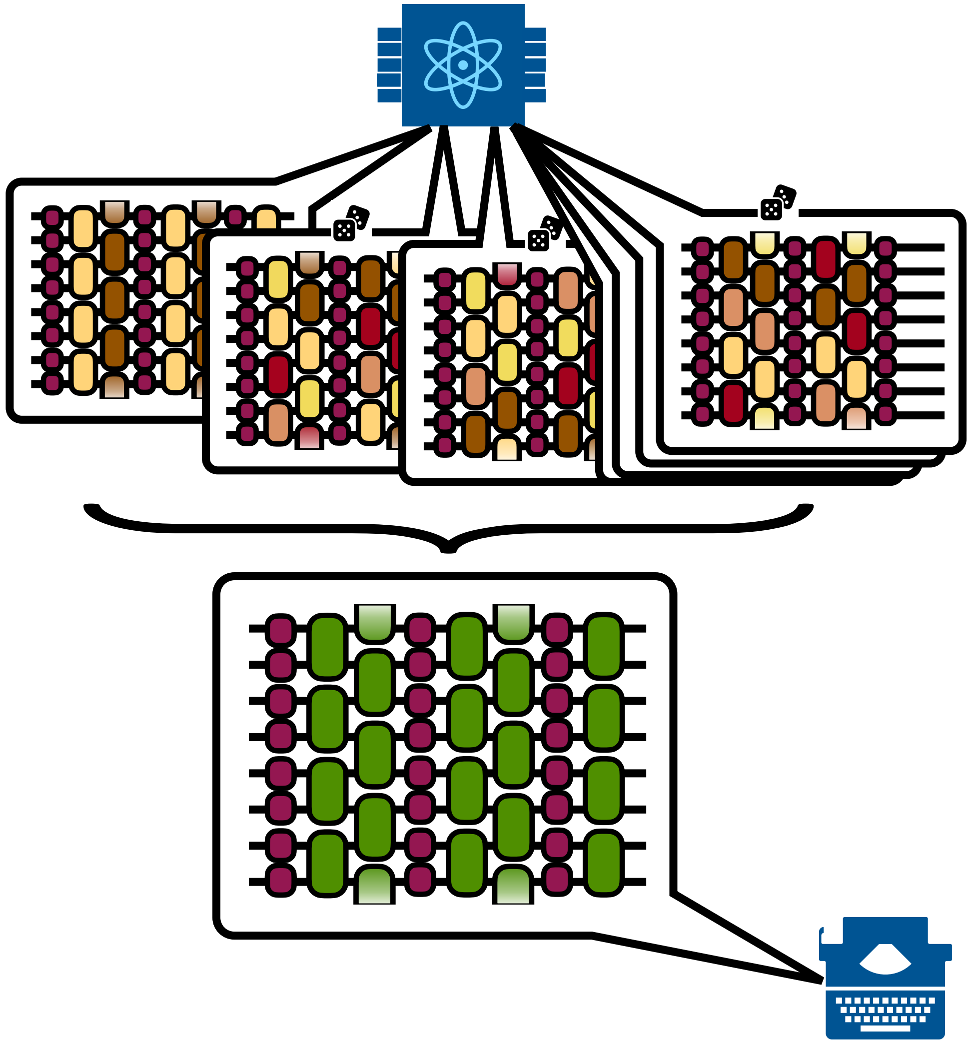
2) Number of non-Clifford operations in preserved



Outlook

OUTLOOK

Average-computation benchmarking strategy:
- involves running circuits of same layout/size/complexity



Quantum data

$$\mathbb{E}_U \left[\mathrm{tr}[O_{\mathrm{test}} \; (U^\dagger|\psi_0\rangle\langle\psi_0|U)]\right]$$

VS

$$\mathrm{tr}[O_{\mathrm{test}} \; \mathcal{E}(|\psi_0\rangle\langle\psi_0|)]$$

Classical simulation

OUTLOOK

Average-computation benchmarking strategy:
- involves running circuits of same layout/size/complexity

OUTLOOK

Average-computation benchmarking strategy:
- involves running circuits of same layout/size/complexity

Connection between benchmarking and classical simulation of open system dynamics.

OUTLOOK

Average-computation benchmarking strategy:
- involves running circuits of same layout/size/complexity

Connection between benchmarking and classical simulation of open system dynamics.
Can we export it to other simulation methods?

- **Simulation of noisy circuits**
- **Pauli path**
- **…**

THANKS

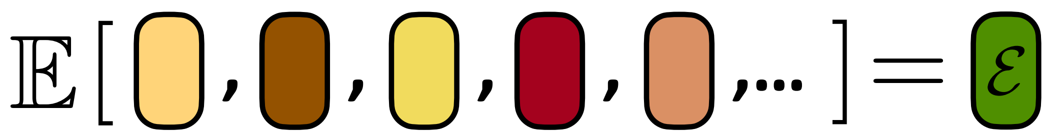
Pavel Kos

Georgios Styliaris

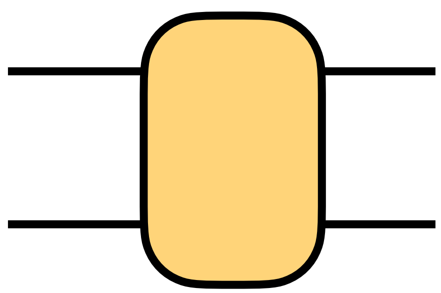
Additional infos

AVERAGING TO GET SPACE-TIME CHANNELS

Define an averaging strategy such that the resulting channel is 4-way



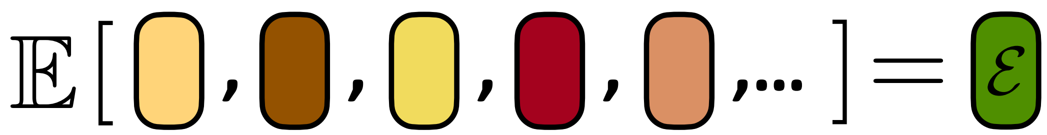
4-way unital



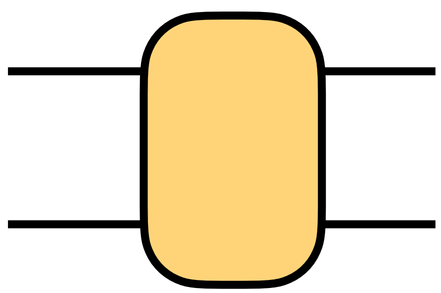
$$U_1 \otimes U_2 \, e^{i\theta_x \sigma_x \sigma_x} e^{i\theta_y \sigma_y \sigma_y} e^{i\theta_z \sigma_z \sigma_z} V_1 \otimes V_2$$

AVERAGING TO GET SPACE-TIME CHANNELS

Define an averaging strategy such that the resulting channel is 4-way



4-way unital



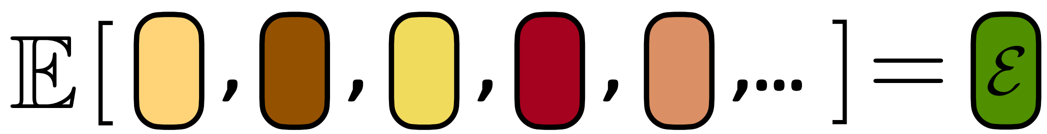
$$U_1 \otimes U_2 \, e^{i\theta_x \sigma_x \sigma_x} e^{i\theta_y \sigma_y \sigma_y} e^{i\theta_z \sigma_z \sigma_z} V_1 \otimes V_2$$

$$\theta_x^{(+)} = \frac{\pi}{4} + \delta_x$$

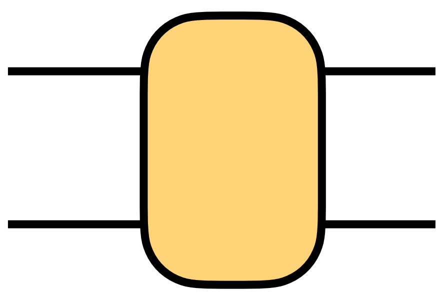
$$\theta_y^{(+)} = \frac{\pi}{4} + \delta_y$$

AVERAGING TO GET SPACE-TIME CHANNELS

Define an averaging strategy such that the resulting channel is 4-way



4-way unital



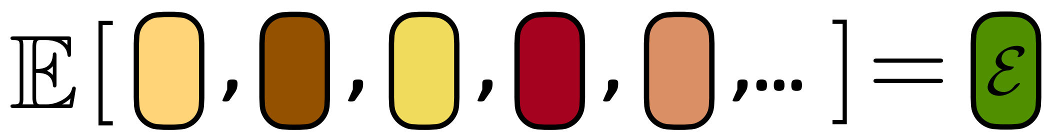
$$U_1 \otimes U_2 \, e^{i\theta_x \sigma_x \sigma_x} e^{i\theta_y \sigma_y \sigma_y} e^{i\theta_z \sigma_z \sigma_z} V_1 \otimes V_2$$

$$\theta_x^{(+)} = \frac{\pi}{4} + \delta_x \qquad \theta_x^{(-)} = \frac{\pi}{4} - \delta_x$$

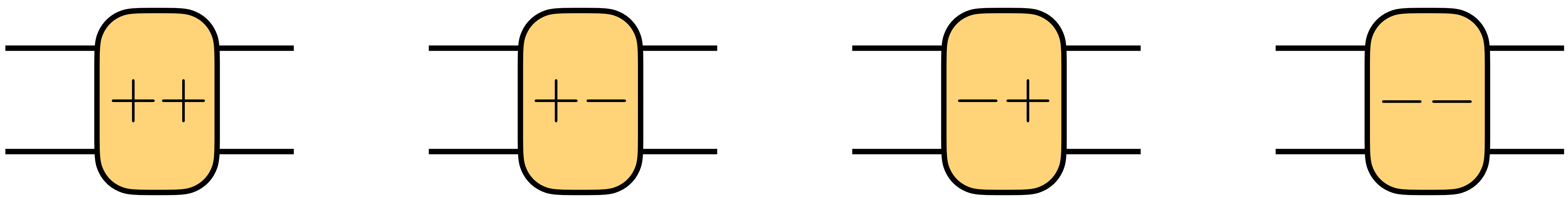
$$\theta_y^{(+)} = \frac{\pi}{4} + \delta_y \qquad \theta_y^{(-)} = \frac{\pi}{4} - \delta_y$$

AVERAGING TO GET SPACE-TIME CHANNELS

Define an averaging strategy such that the resulting channel is 4-way



4-way unital

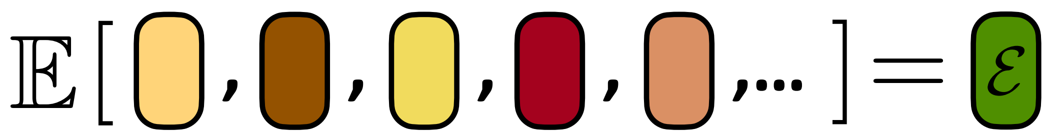


$$\theta_x^{(+)} = \frac{\pi}{4} + \delta_x \qquad \theta_x^{(-)} = \frac{\pi}{4} - \delta_x$$

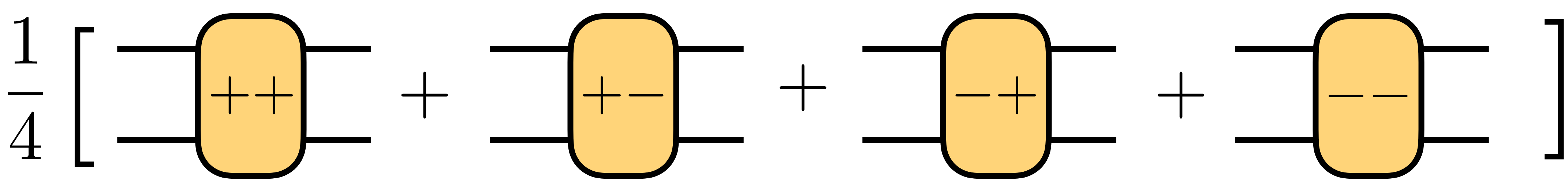
$$\theta_y^{(+)} = \frac{\pi}{4} + \delta_y \qquad \theta_y^{(-)} = \frac{\pi}{4} - \delta_y$$

AVERAGING TO GET SPACE-TIME CHANNELS

Define an averaging strategy such that the resulting channel is 4-way

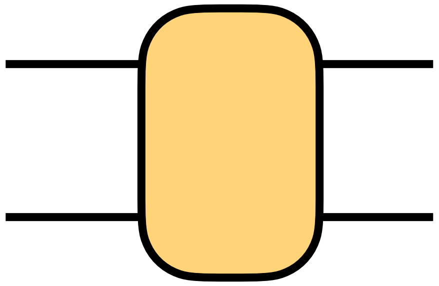


4-way unital



4-way for any unitary

SAMPLE COMPLEXITY



$$= \mathrm{CNOT}_{12}(u_n \otimes u_n)\mathrm{CNOT}_{21}(u_n \otimes u_n)\mathrm{CNOT}_{12}(u_n \otimes u_n)$$