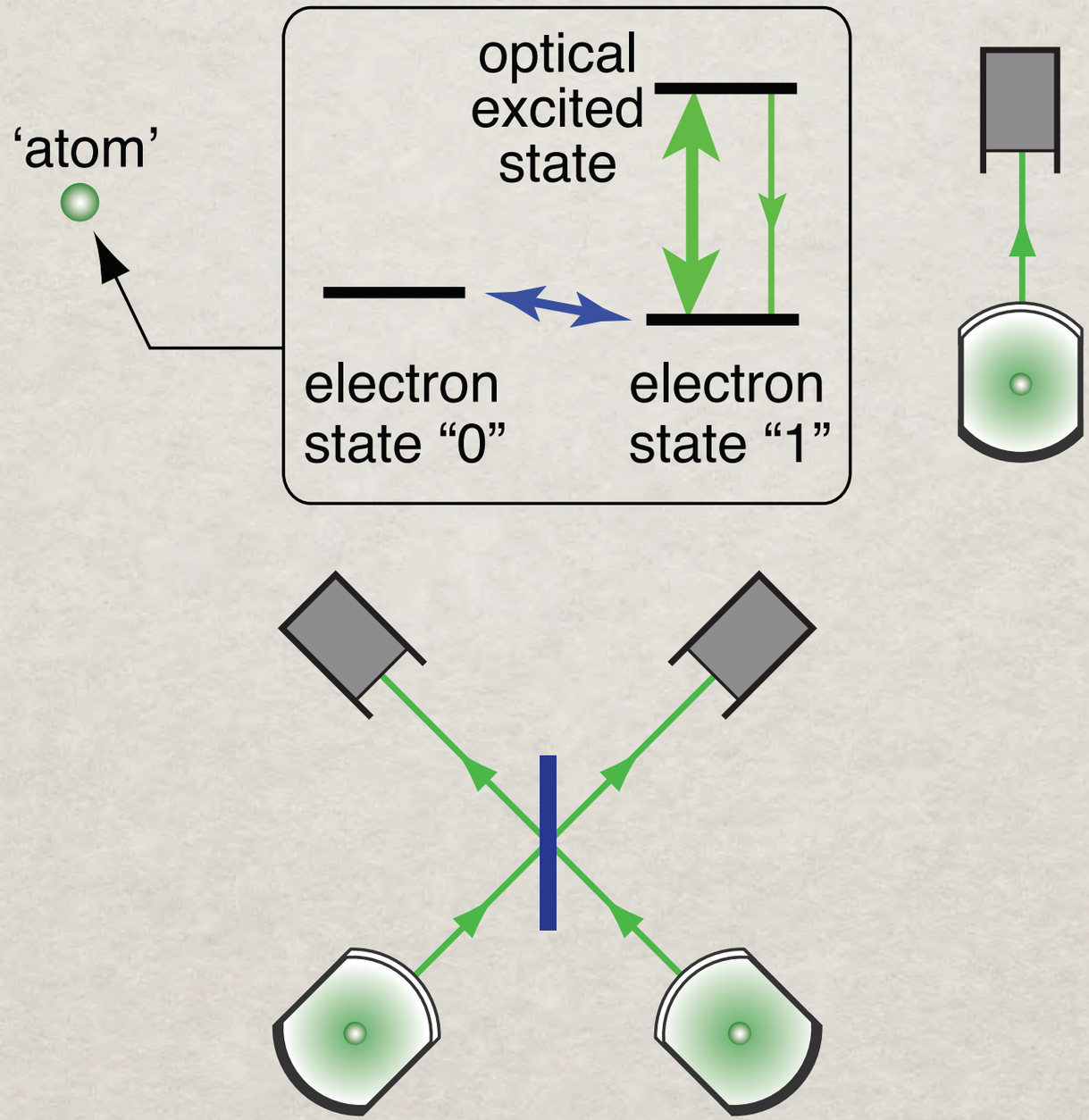
Fault Tolerant QIP Using Probabilistic Entanglement

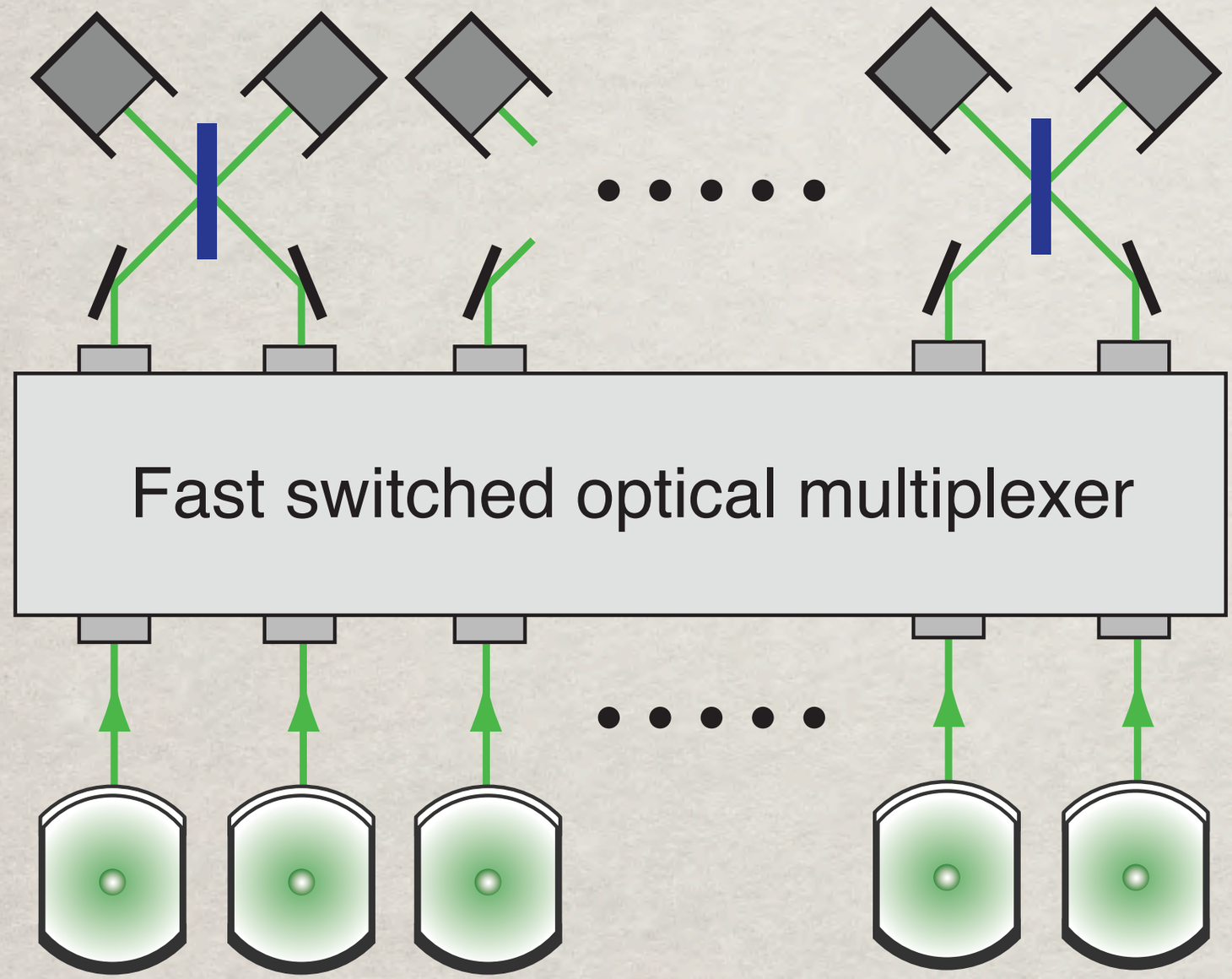
The basic question:
How should we perform quantum computation (and communication) when the entanglement operations are very prone to *heralded* failure?

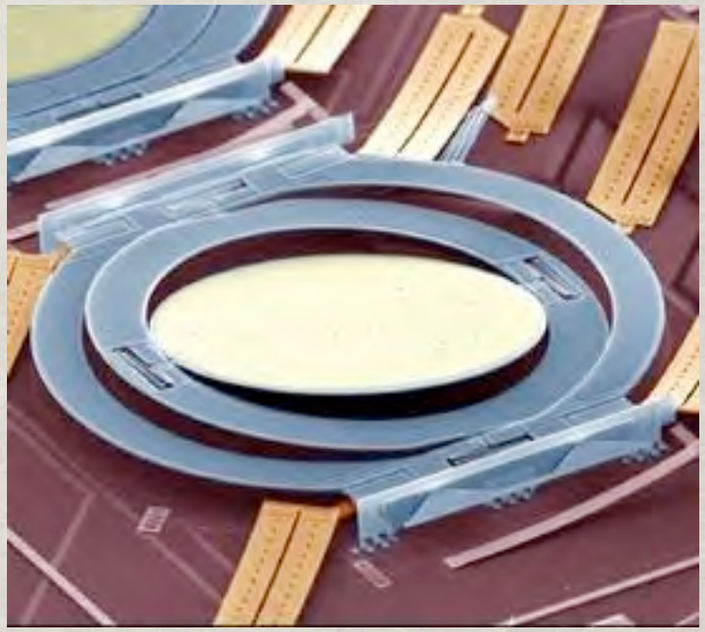
- How will the failure rate affect error accumulation and resource overhead?
- Can we find thresholds for fault tolerant QIP as a function of both failure rate and error rate?

One example to have in mind:



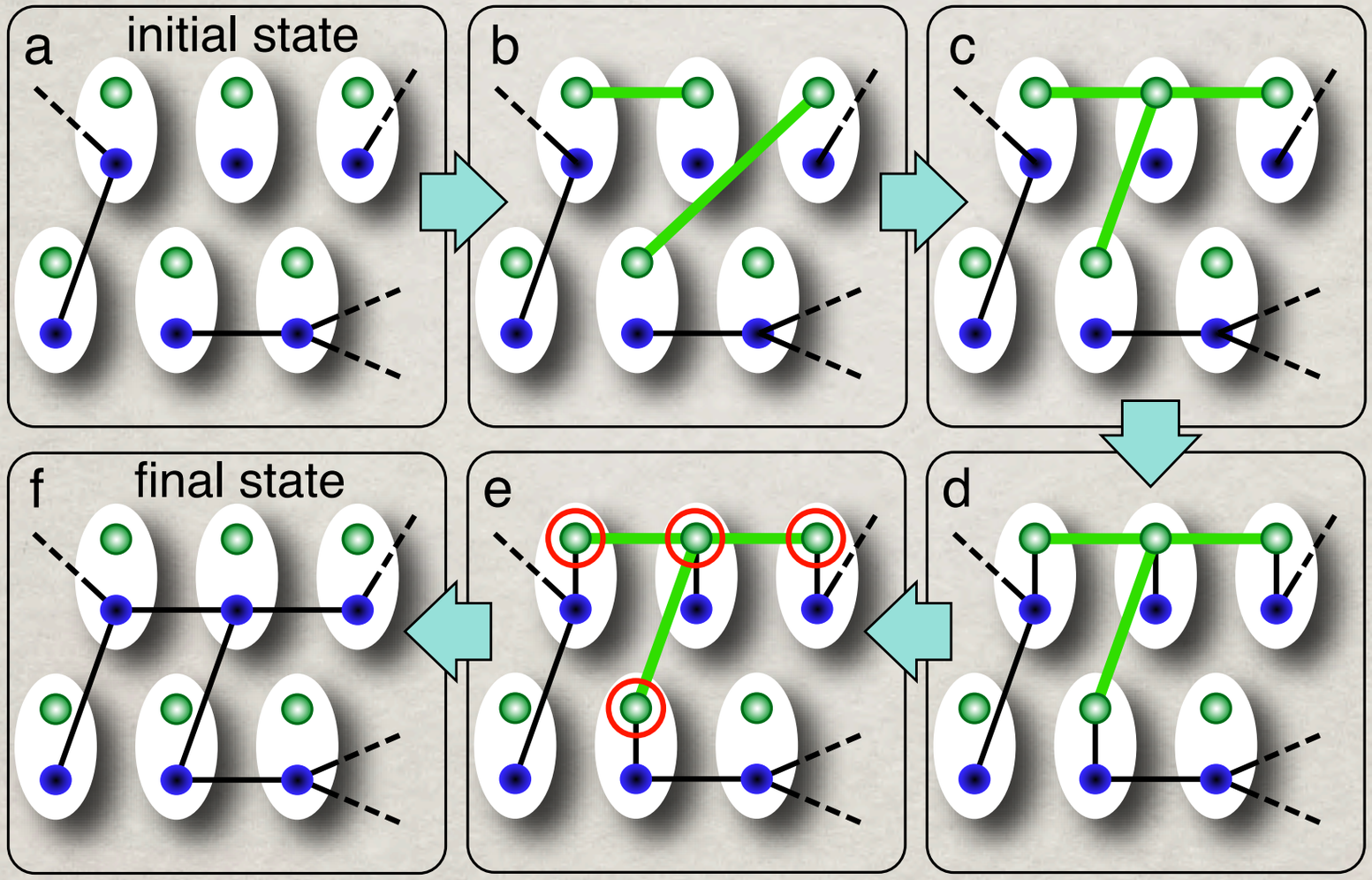
Matter qubits entangled via optical emission





Potentially nice scalability

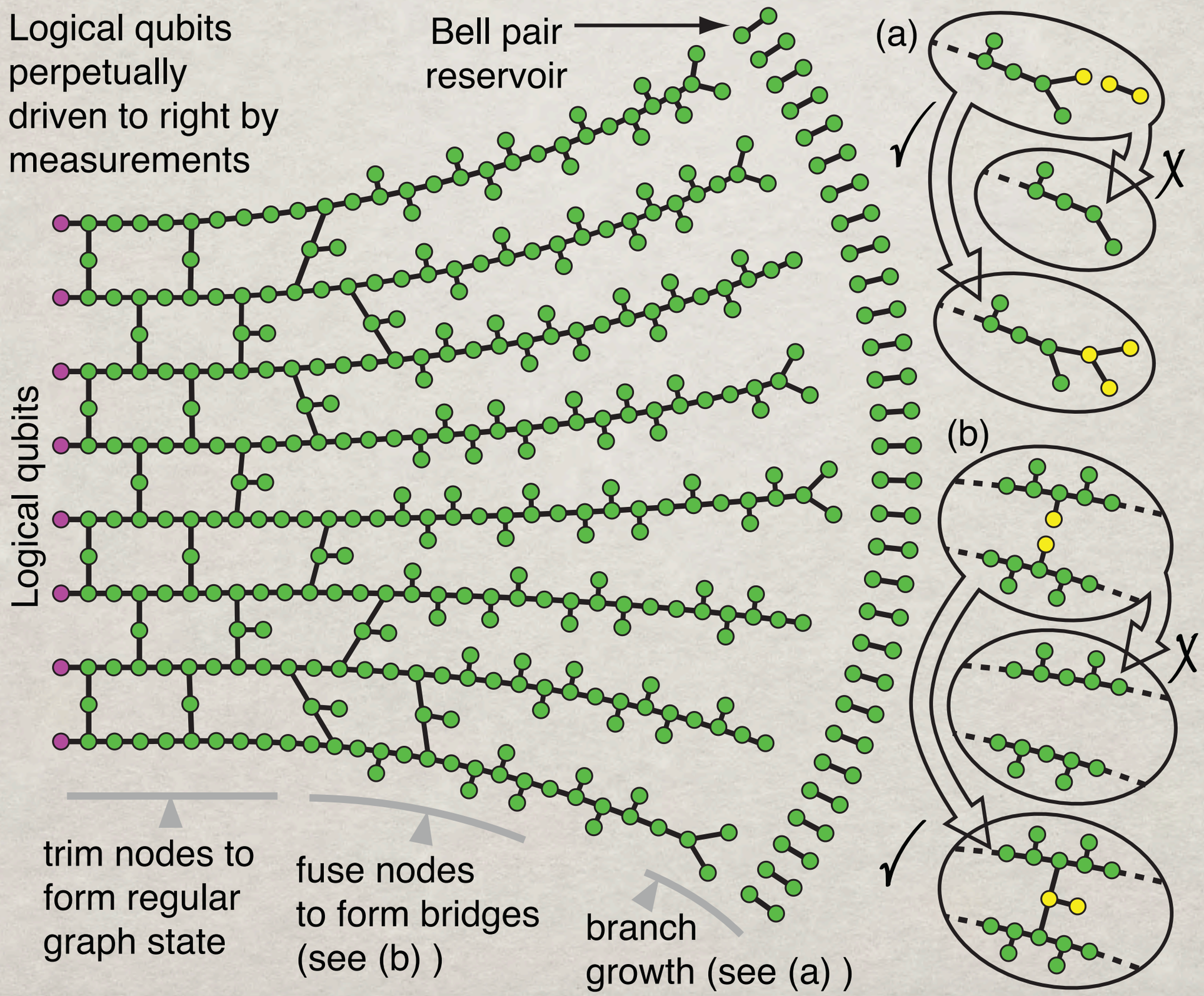
With 2+ qubits per module, it's easy to see options



Brokered graph-state quantum computation, NJP **8**, 141 (2006).

- How about with only one qubit per module?

Easy to tolerate modest heralded failure rates, e.g. 60%

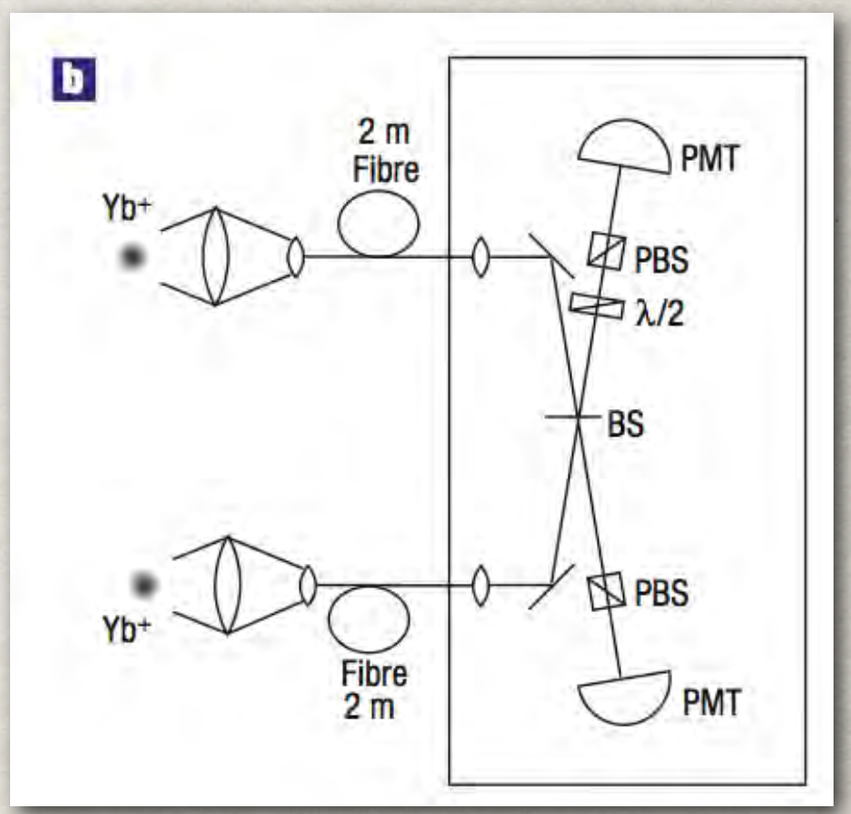


Laser and Photon. Rev., **3**, 556 (2009)

So, efficient universal QIP with one 3-level system per node!

But what if photon loss is *really bad!?*

Moehring et al, Nature 449, 68 (2007).



output ports, there is an additional factor of 1/4 in our success probability: $P = (1/4)[(1/2)\eta\zeta T\rho P_{\mathrm{exc}}(\Delta\Omega/4\pi)]^2 \approx (0.25)[(0.5)(0.15)(0.2)(0.8)(0.995)(0.5)(0.02)]^2 \approx 3.6 \times 10^{-9}$. With an experiment repetition rate of $R \approx 5.5 \times 10^5\ \mathrm{s}^{-1}$, this results in a heralded entanglement event approximately every 8.5 min.

Improvement x13: PRL **100**, 150404 (2008).

NV centres - still a lot of losses

news & views

QUANTUM COMPUTING

Snapshots of diamond spins

Defects in diamond crystals possess rare physical properties that can enable new forms of technology. Unlocking this potential requires rapid quantum-state measurement, a 'quantum snapshot', which has now been achieved.

John J. L. Morton and Simon C. Benjamin

When Nicéphore Niépce created the first photographic images in the 1820s, each frame required eight hours of exposure. Fifty years later, technology had advanced enough for Eadweard Muybridge's famous demonstration that horses become 'airborne' in mid-stride (see Fig. 1). Photography had become a tool to investigate timescales beyond human perception. Numerous devices now depend on swift measurement, but none more so than the emerging family of quantum technologies. These use measurement not only to read out, but also to prepare and entangle quantum states to create exotic new sensors, simulators and computers. A certain kind of defect that occurs in diamond are particularly exciting because it is possible to measure the electron spin of

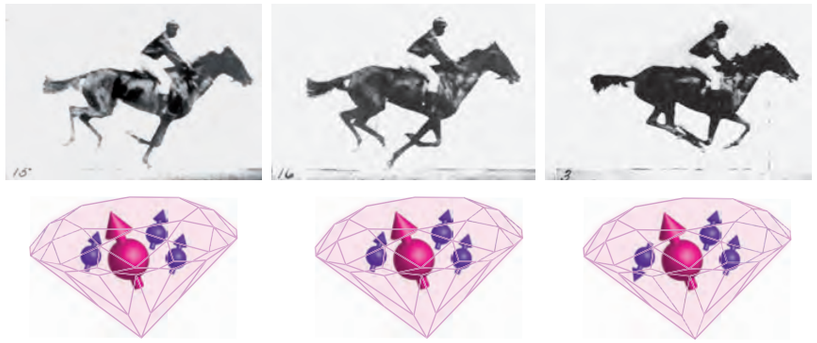


Figure 1 | Today, as in 1877 when Eadweard Muybridge photographed a horse in motion, it is crucial to be able to perform measurements that are fast on the timescale of the natural dynamics of an object. This is especially important in emerging quantum technologies given the unique power of quantum e nitrogen–vacancy defect in diamond consists of a collection of electron and nuclear e can now be probed by fast, high-fidelity optical measurement in a single experimental ge © Eadweard Muybridge Collection/Kingston Museum/Science Photo Library.)

ough optical methods[3]. This s crudely exciting the NV iminate optical pulse, and at the emitted fluorescence me dependence on the ate. Although this highly nique has underpinned an search into NV centres, it ntial averaging of many ns (or 'shots') to determine n state. Achieving fast, easurements requires new ingle-spin measurement es.

years have seen significant derstanding the nature of of the NV centre[4], laying for more sophisticated By picking particular NV w strain and working at emperatures, it is possible nt optical techniques to e the centre only when the in a particular state[5]. This ement can be made much faster and more efficient than the previous technique. This has now allowed Lucio Robledo *et al.*[1] to measure the NV electron spin in a single shot for the first time. With their approach they could, also in a single shot, read out the state of up to three nuclear spins in the immediate vicinity of the NV centre. Emre Togan *et al.*[2] borrowed a further technique from the toolbox of trapped atoms, exploiting a phenomenon known as coherent population trapping[6]. In this method, if the magnetic field at the NV centre is precisely zero, the energy levels of the electron spin possess a symmetry that causes them to fall into a 'dark state', which scatters no photons. This measurement is also fast, providing a glimpse of the environment of the NV centre in real time, by monitoring the fluctuating magnetic field created by a bath of more distant carbon-13 nuclear spins.

High-fidelity quantum measurements can do more than just probe the state of a system; they can also be used to initialize it into a given state. Although the result of the measurement may be intrinsically random, the system could then, in principle, be manipulated conditionally on the result of this measurement. This would ensure

Two-photon quantum interference from separate nitrogen vacancy centers in diamond

Hannes Bernien,[1,*] Lilian Childress,[2] Lucio Robledo,[1] Matthew Markham,[3] Daniel Twitchen,[3] and Ronald Hanson[1]

[1] *Kavli Institute of Nanoscience Delft, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands*

[2] *Department of Physics and Astronomy, Bates College, 44 Campus Avenue, Lewiston, Maine 04240, USA*

[3] *Element Six, Ltd., Kings Ride Park, Ascot, Berkshire SL5 8BP, United Kingdom*

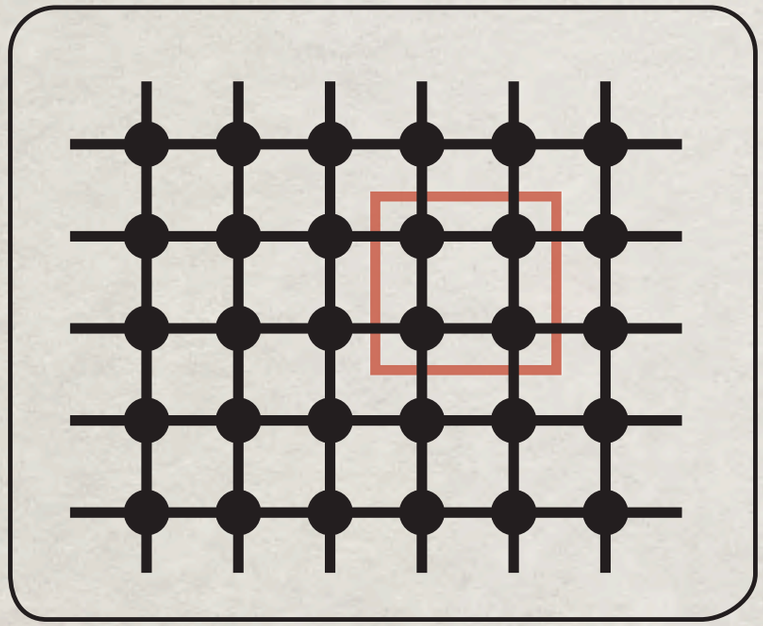
(Dated: October 18, 2011)

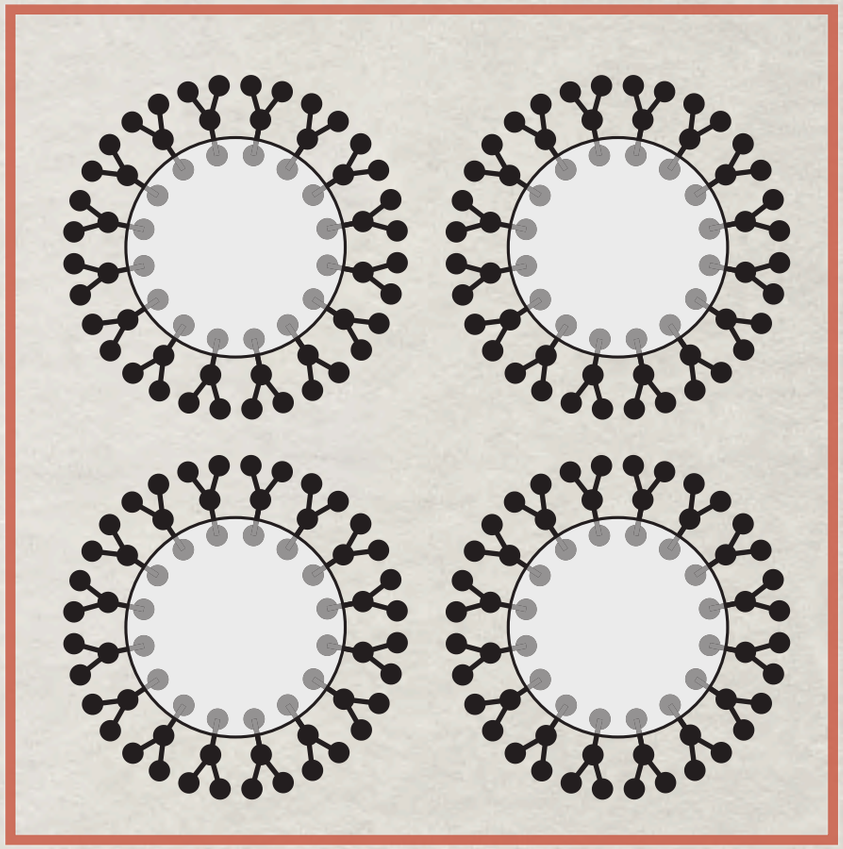
We report on the observation of quantum interference of the emission from two separate nitrogen vacancy (NV) centers in diamond. Taking advantage of optically induced spin polarization in combination with polarization filtering, we isolate a single transition within the zero-phonon line of the non-resonantly excited NV centers. The time-resolved two-photon interference contrast of this filtered emission reaches 66%. Furthermore, we observe quantum interference from dissimilar NV centers tuned into resonance through the dc Stark effect. These results pave the way towards measurement-based entanglement between remote NV centers and the realization of quantum networks with solid-state spins.

arXiv:1110.3329

So let's think about how to do QIP when there are *bad* (e.g. >90%) heralded failures

Target: A large cluster state type thing

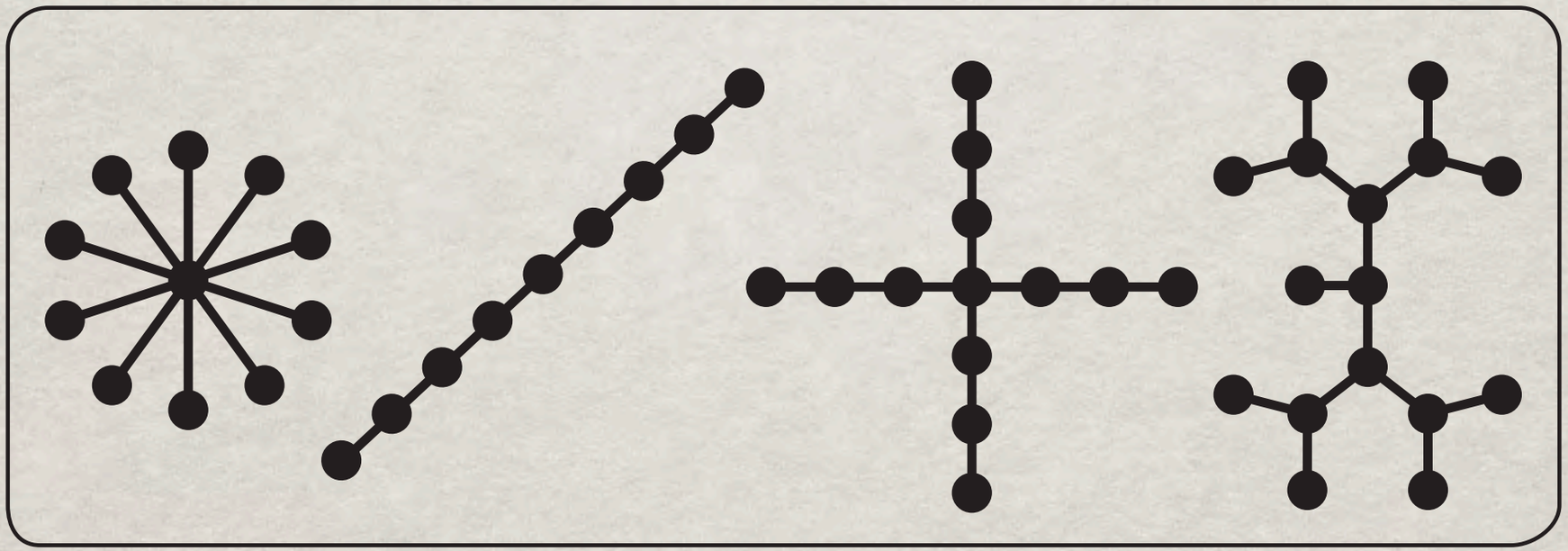




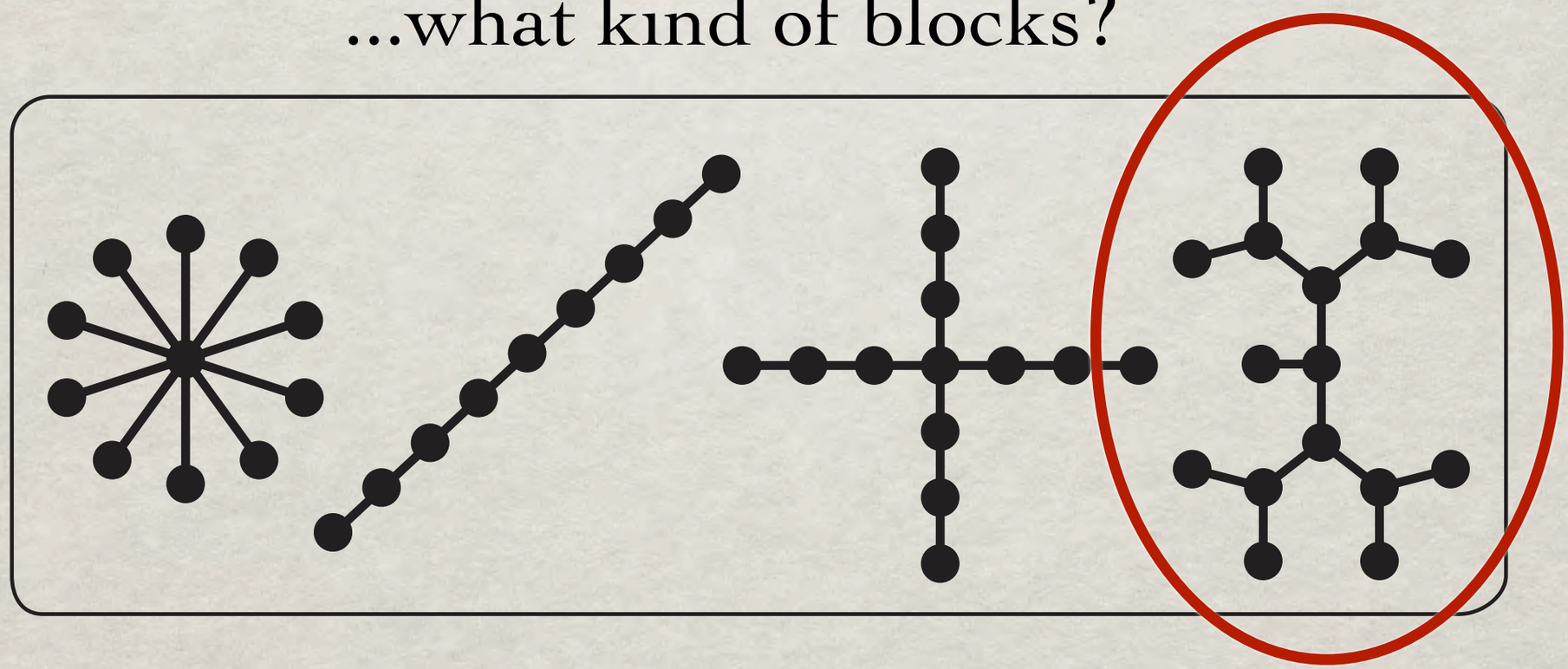
The plan (& do this with only logarithmic errors):

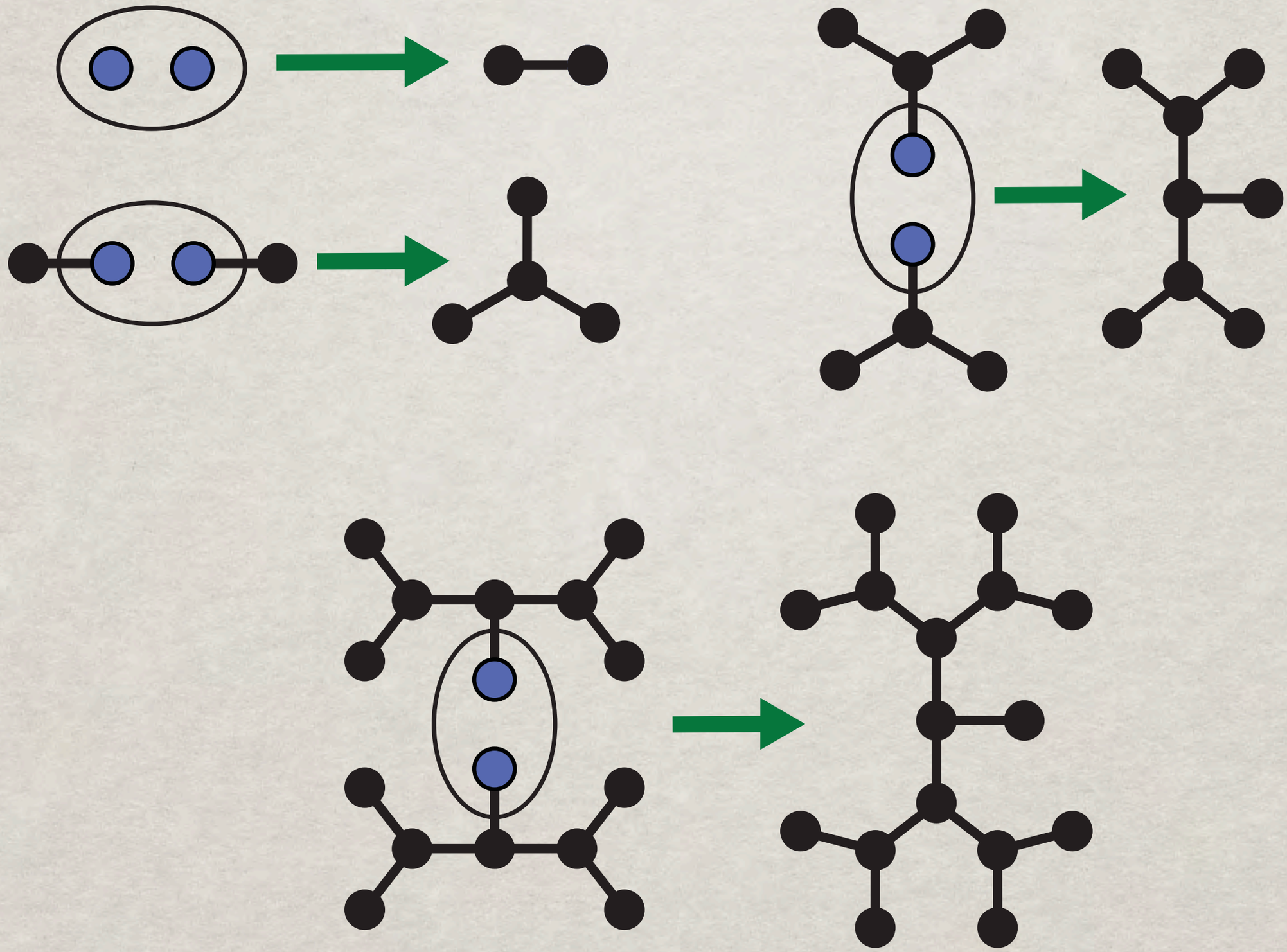
- Make a bunch of "building block" resources: blobs each with enough qubits that they can *probably* connect to four other blobs
- Join them all up (~ one step)
- Prune the resulting structure down.

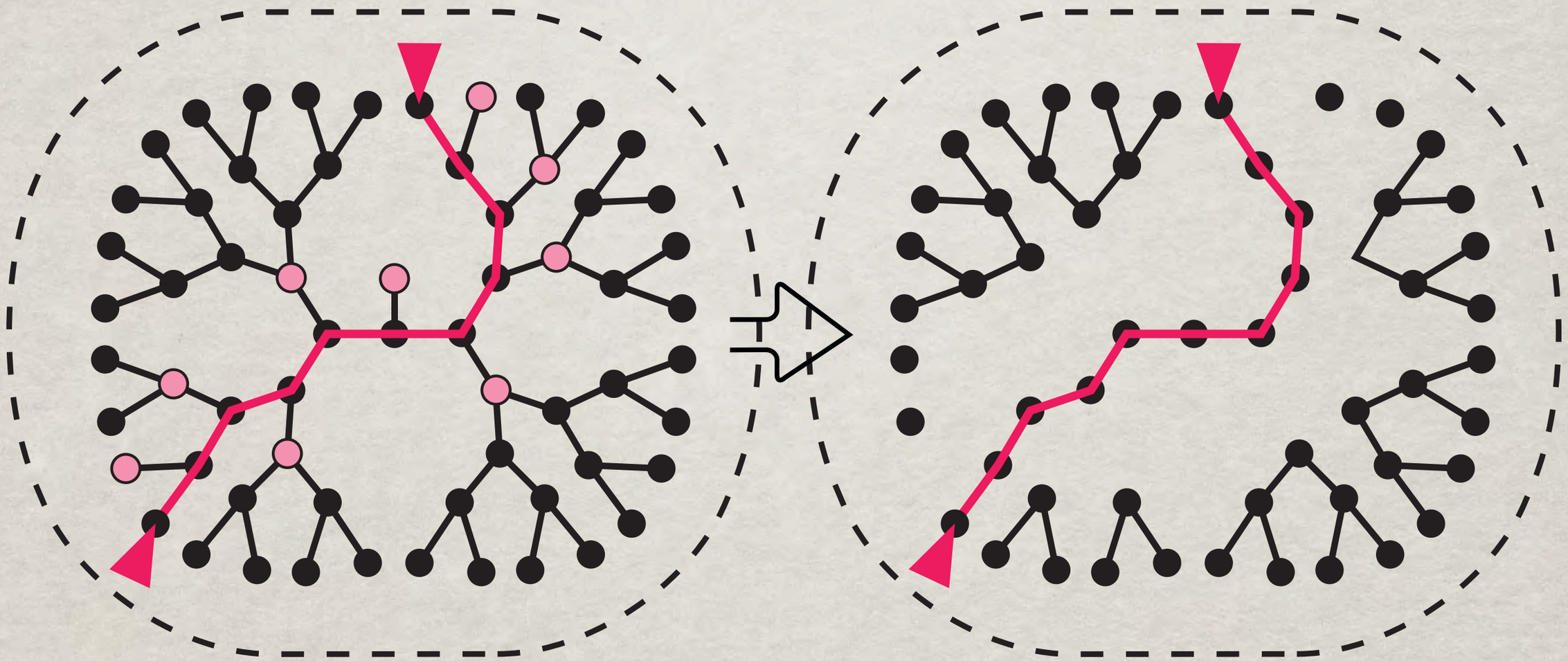
OK so building blocks...
...what kind of blocks?



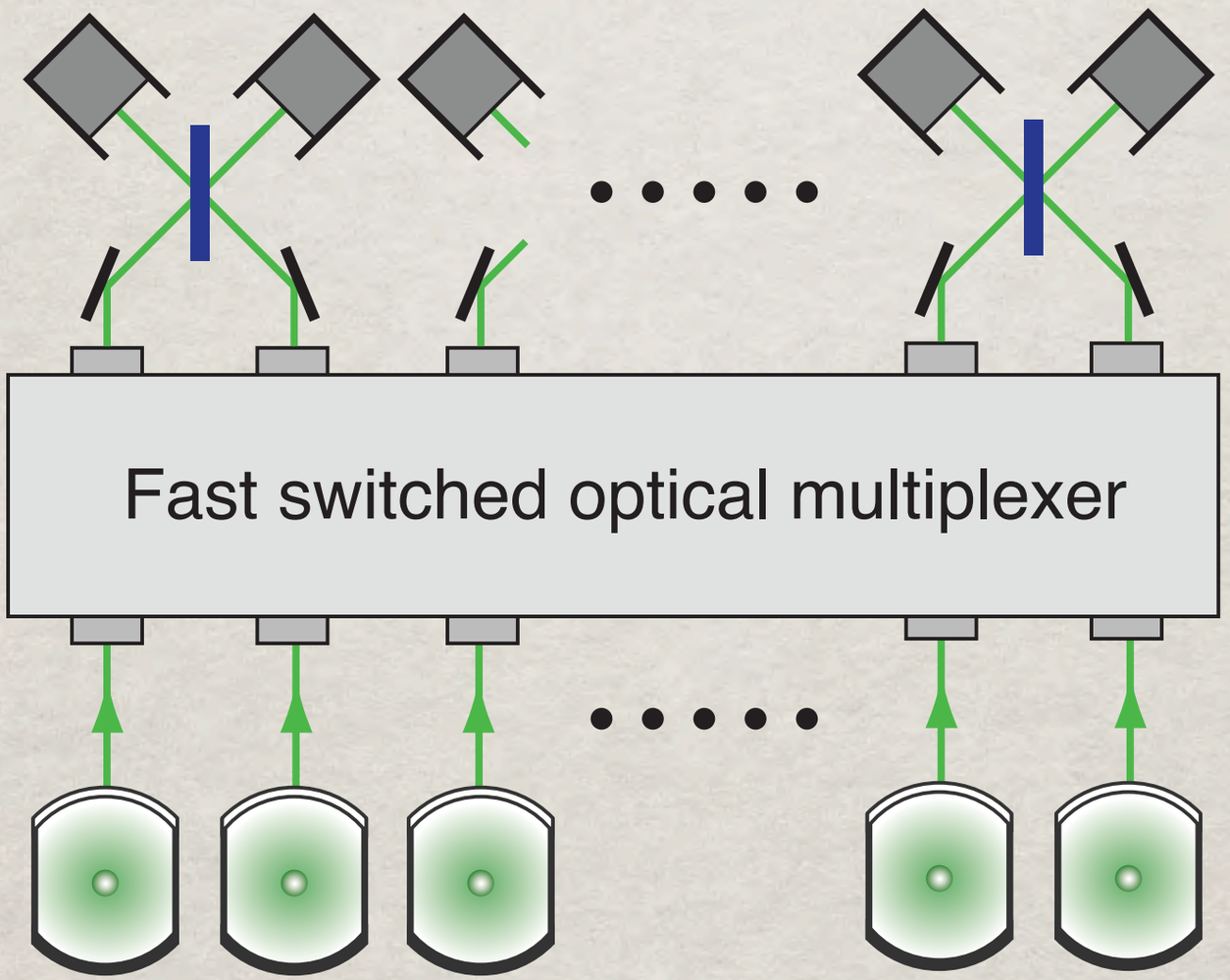
OK so building blocks...
...what kind of blocks?





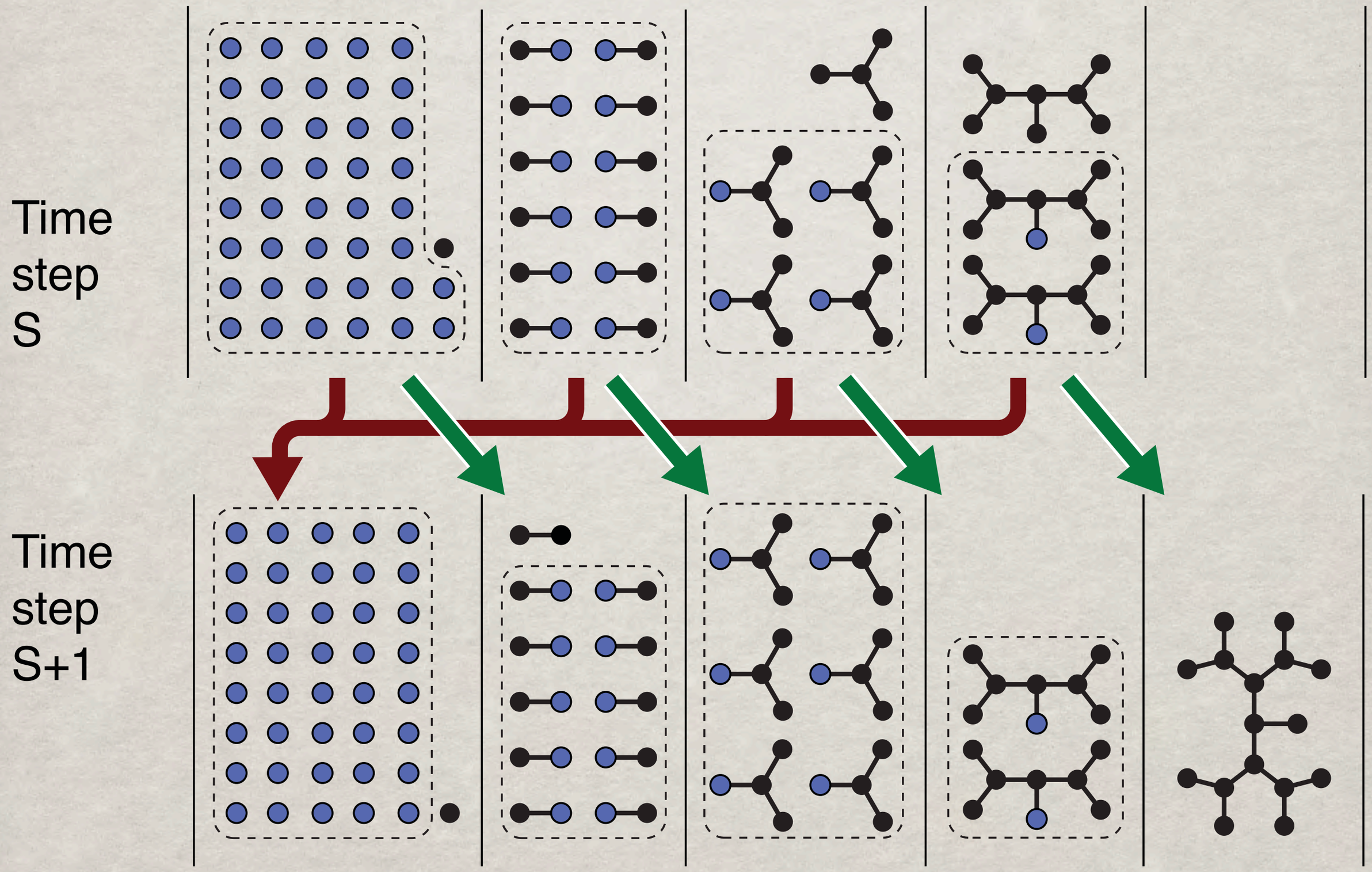


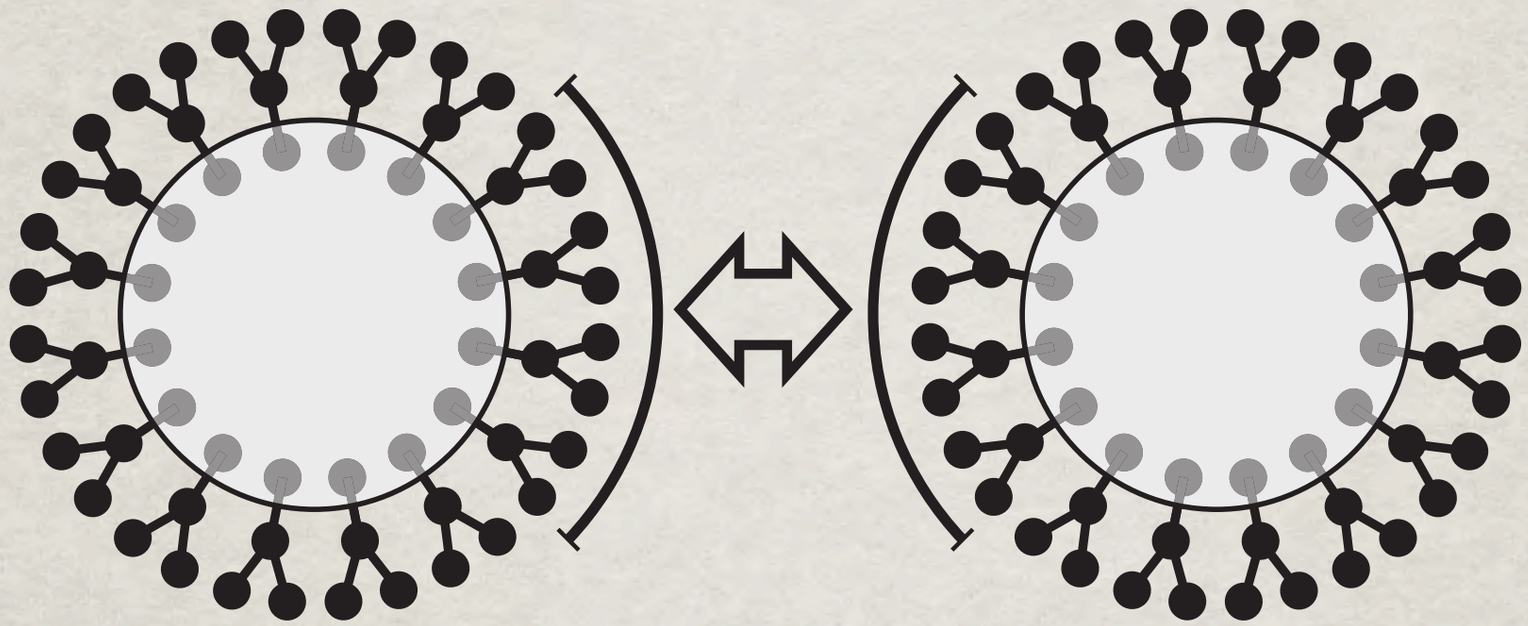
Remember our machine is something like this:

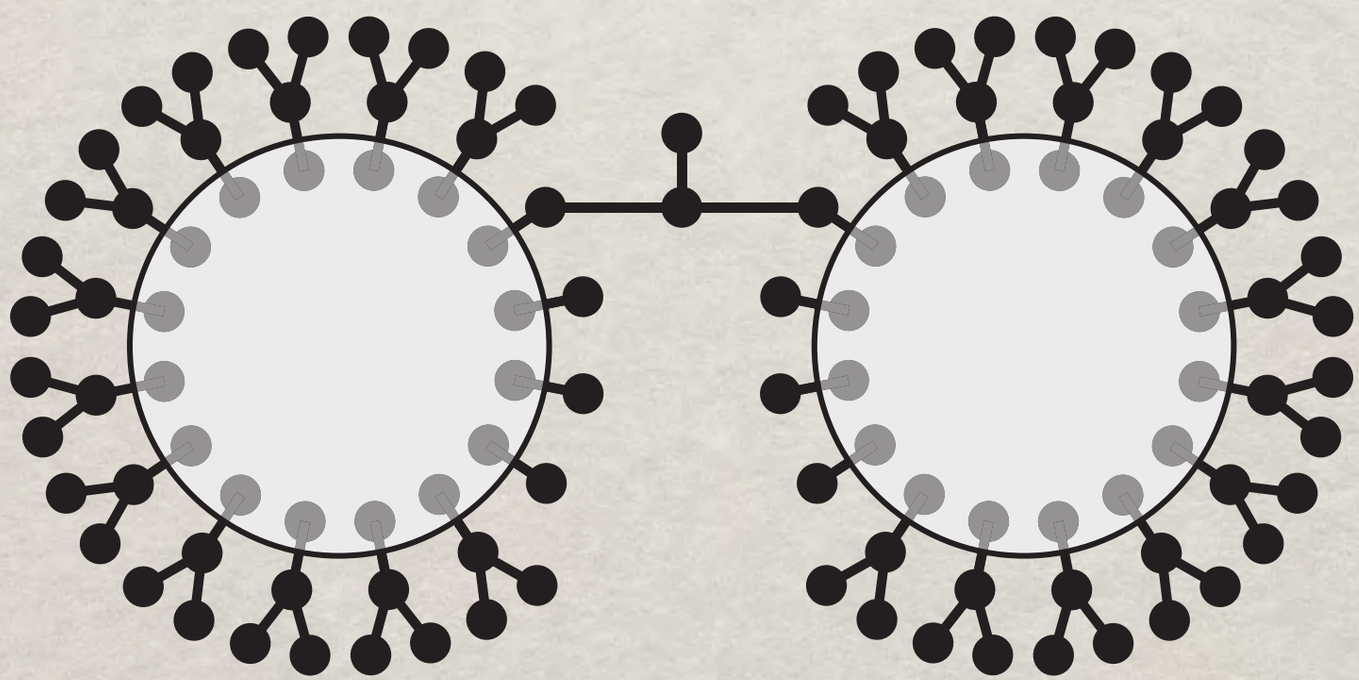


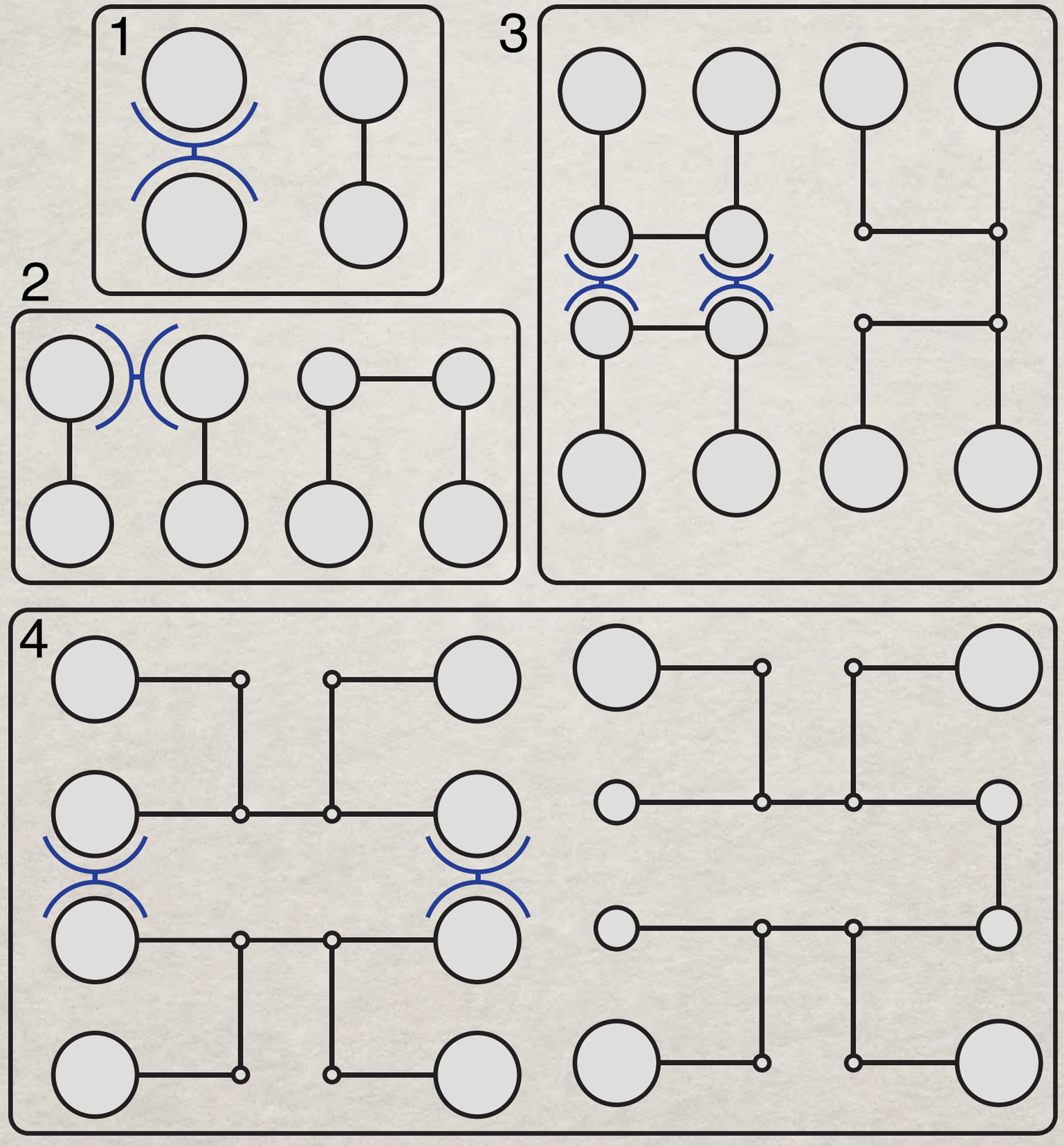
- Parallel operations
- Total connectivity (well...)

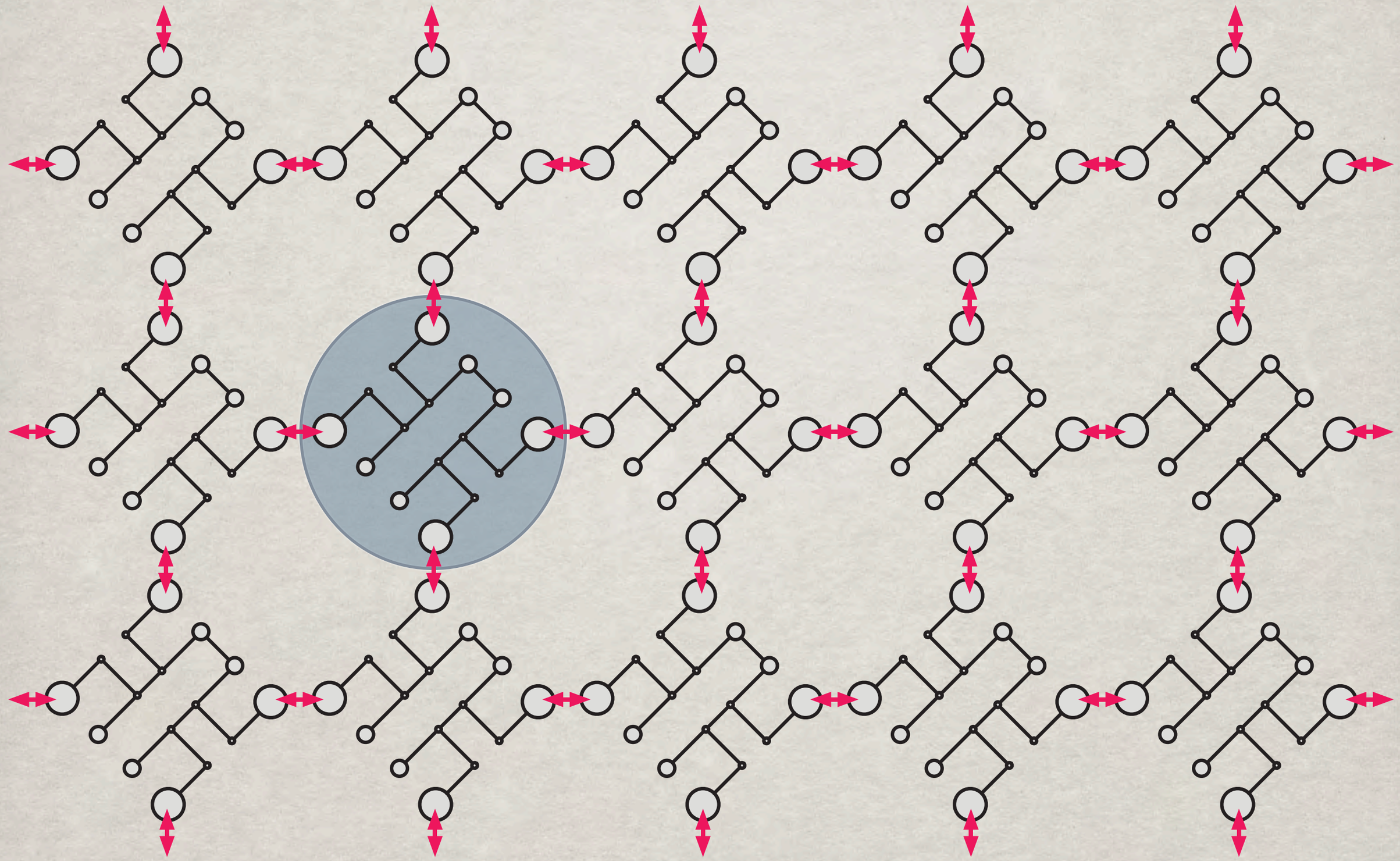
Inside, this is going on:



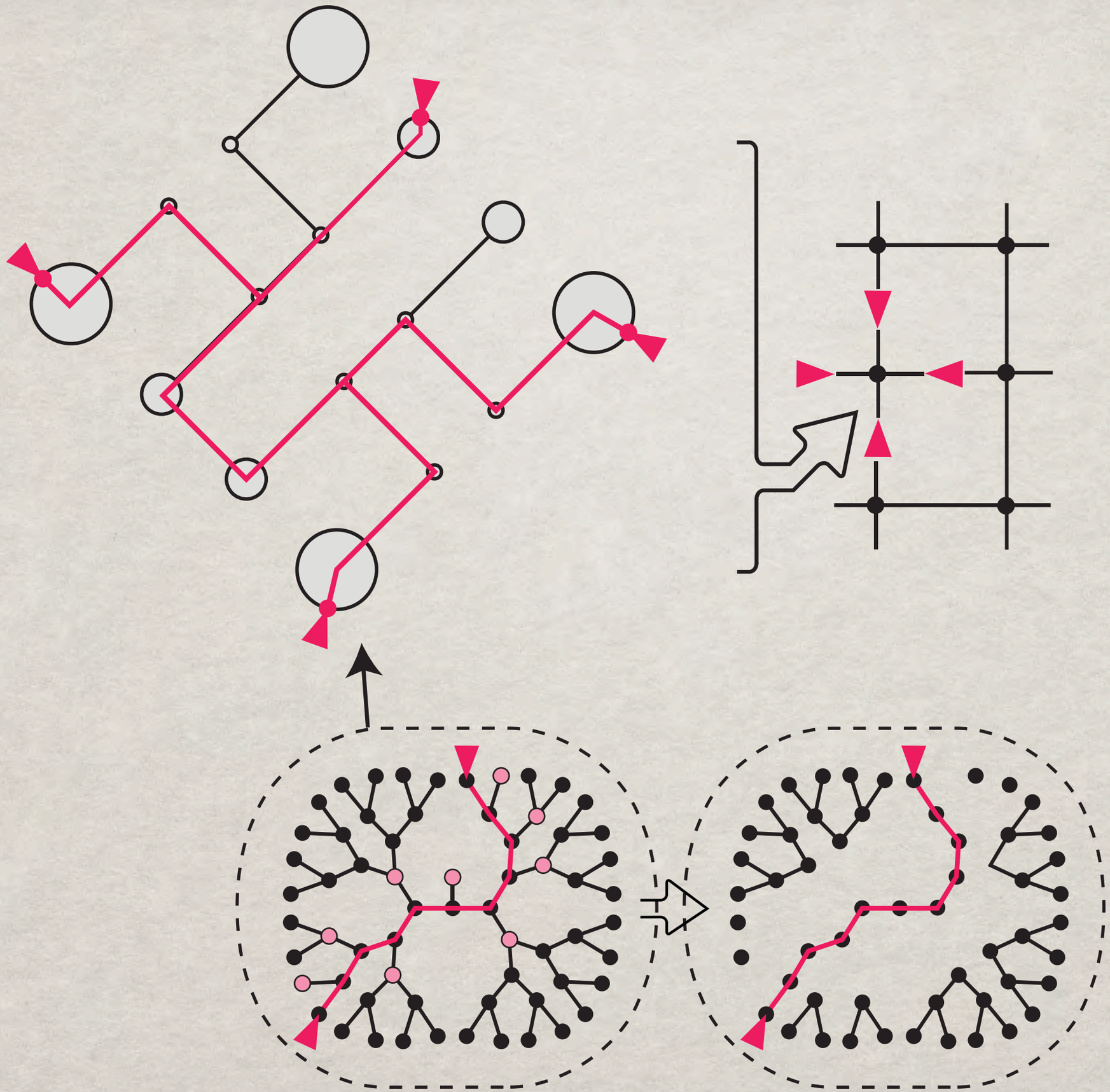


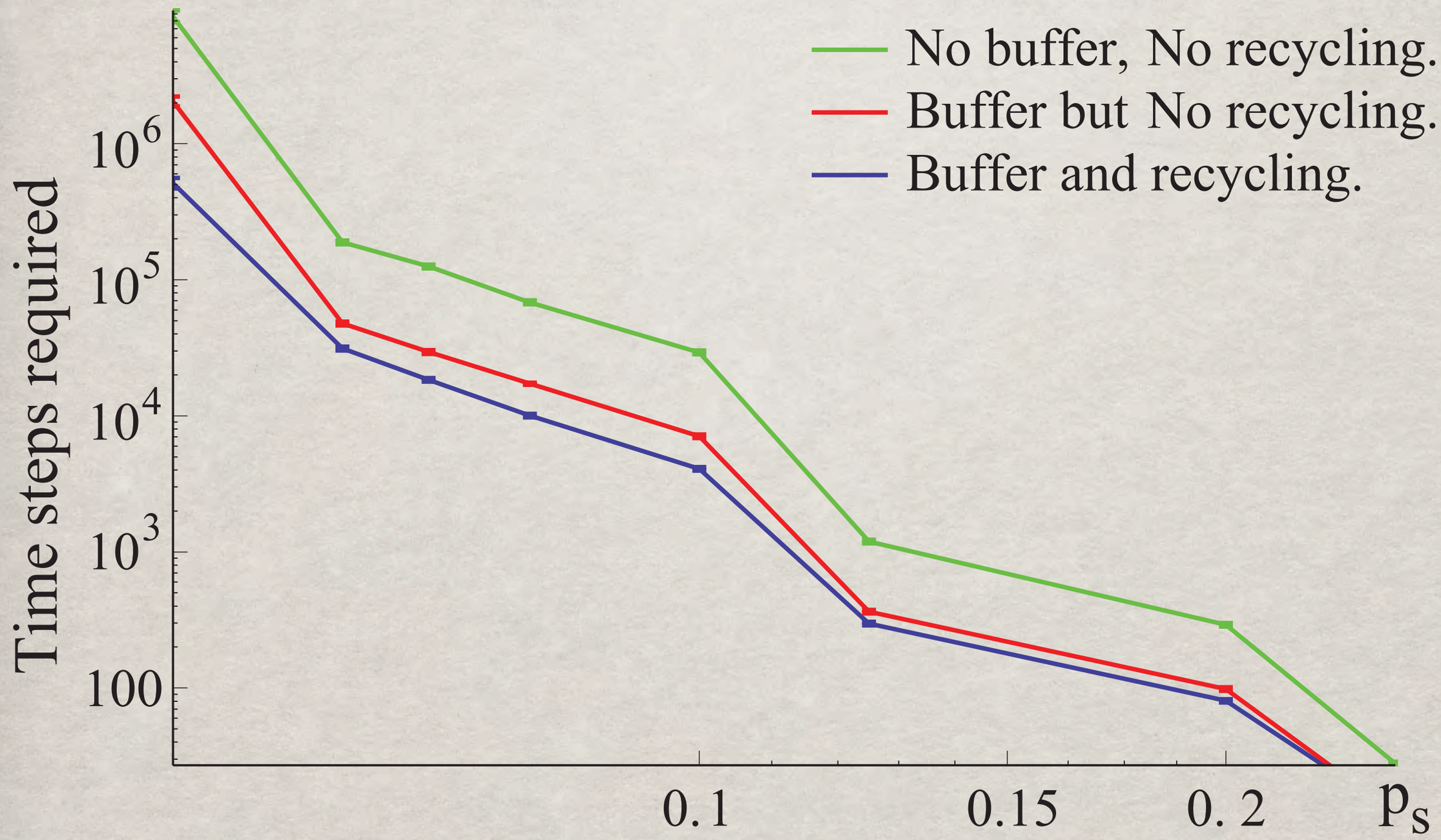


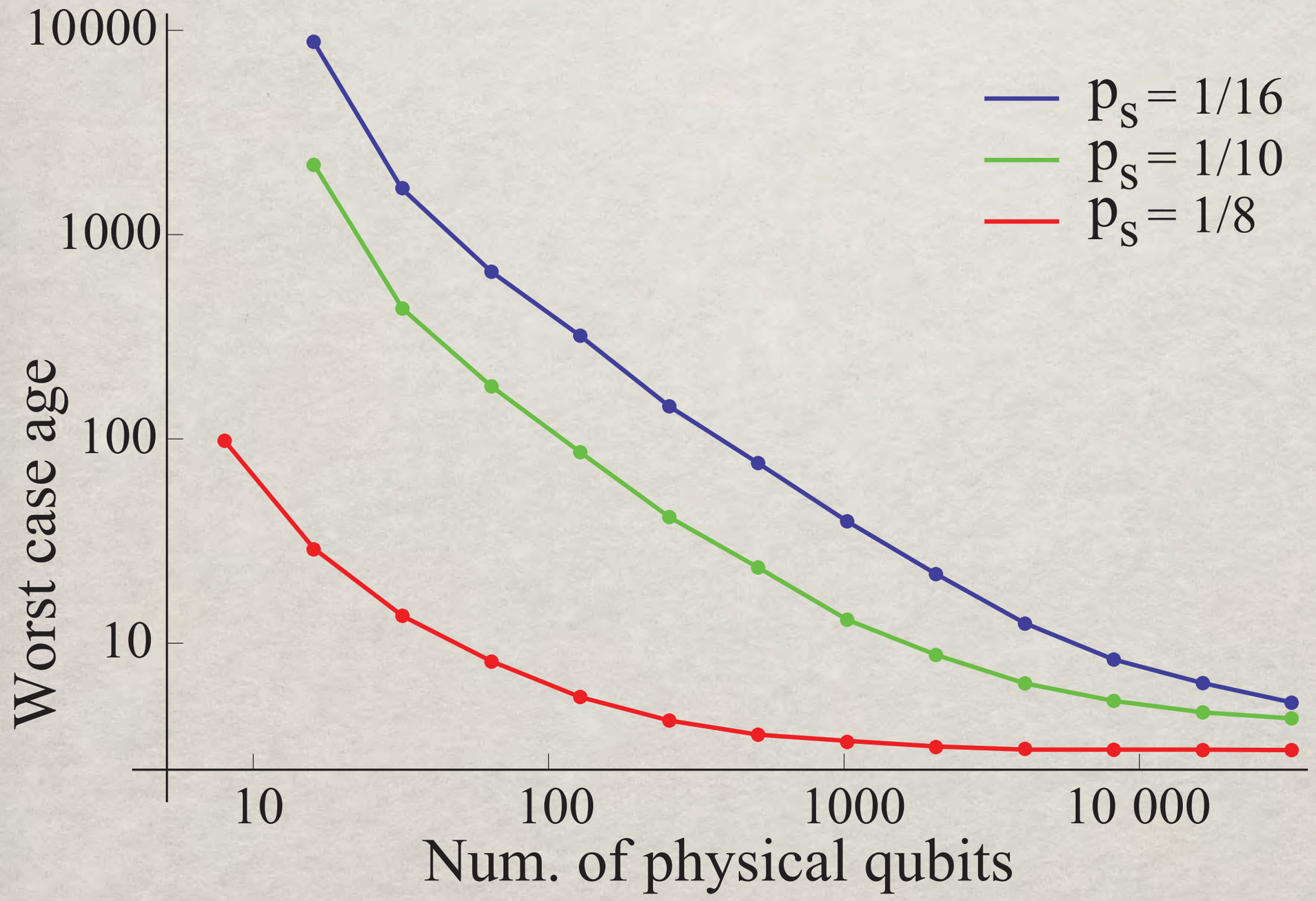

1
2
3
4

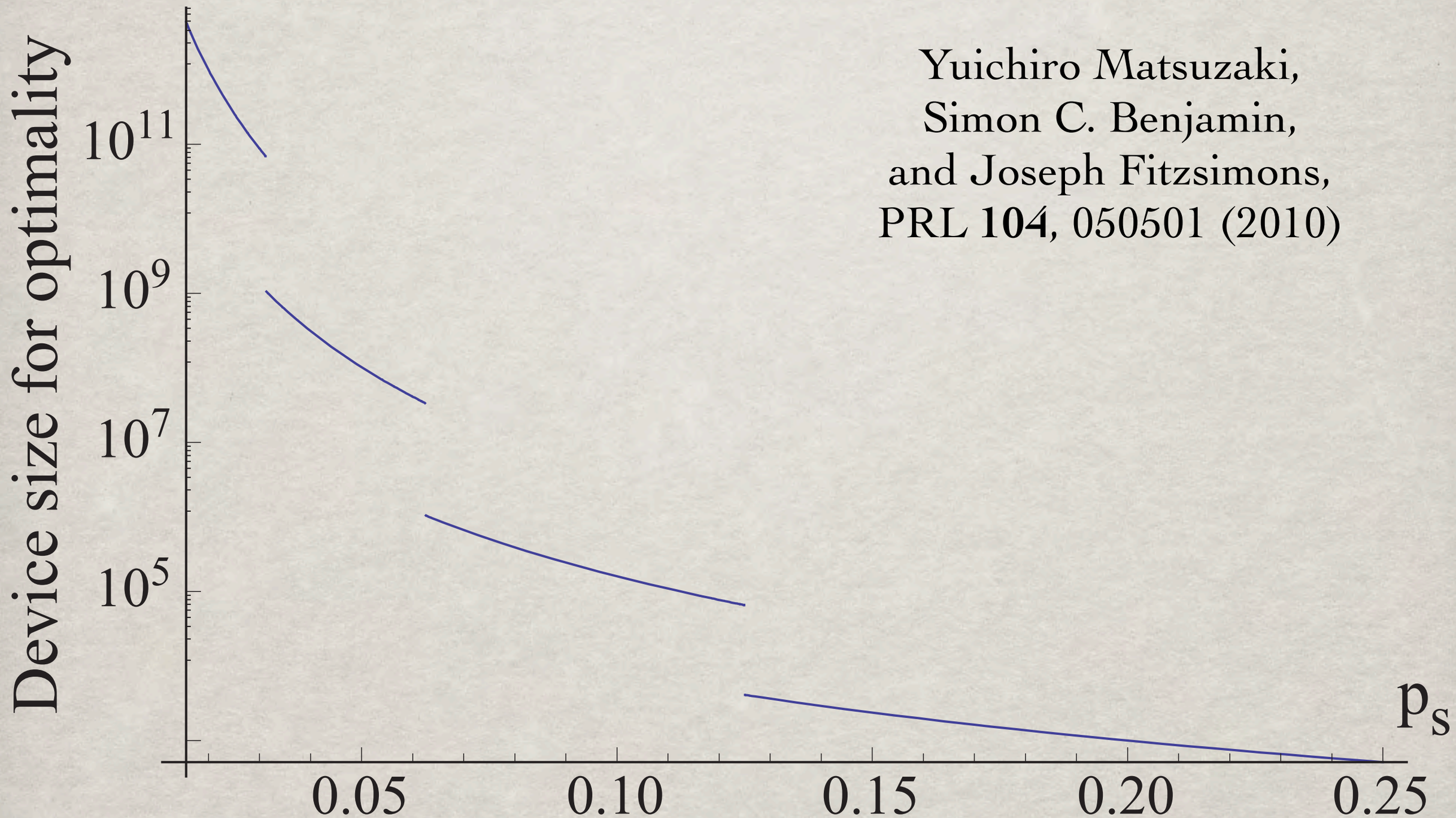


OK for some connections to fail (percolation).




No buffer, No recycling.
Buffer but No recycling.
Buffer and recycling.
Time steps required
10^6
10^5
10^4
10^3
100
0.1
0.15
0. 2
p_s


10000
1000
100
10
Worst case age
10
100
1000
10 000
Num. of physical qubits
$p_s = 1/16$
$p_s = 1/10$
$p_s = 1/8$

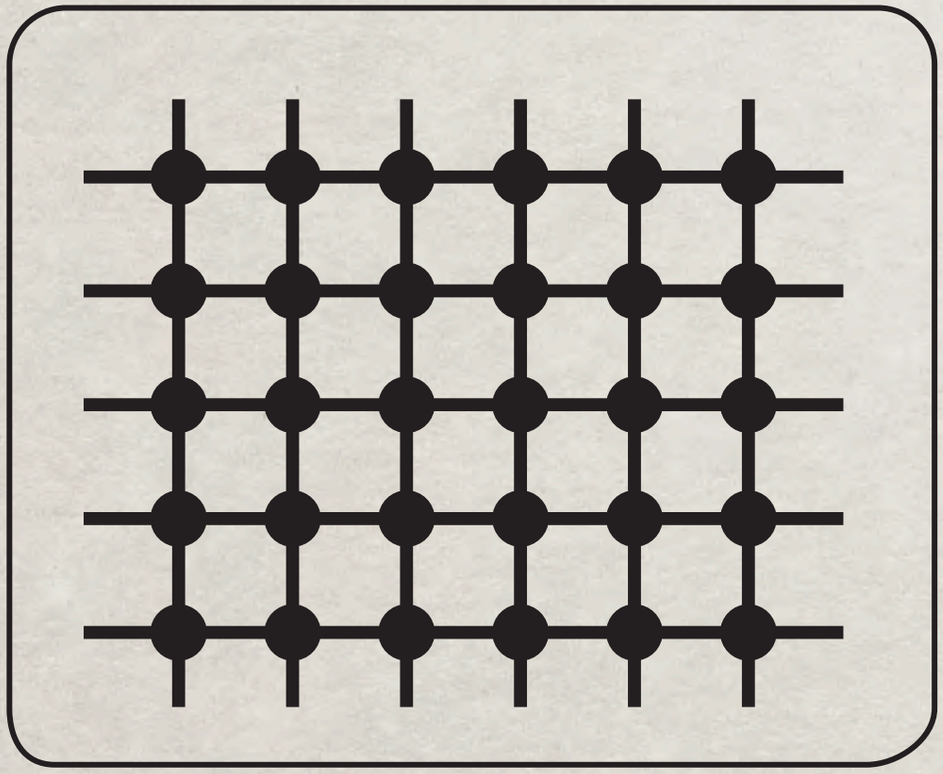


Yuichiro Matsuzaki,
Simon C. Benjamin,
and Joseph Fitzsimons,
PRL **104**, 050501 (2010)

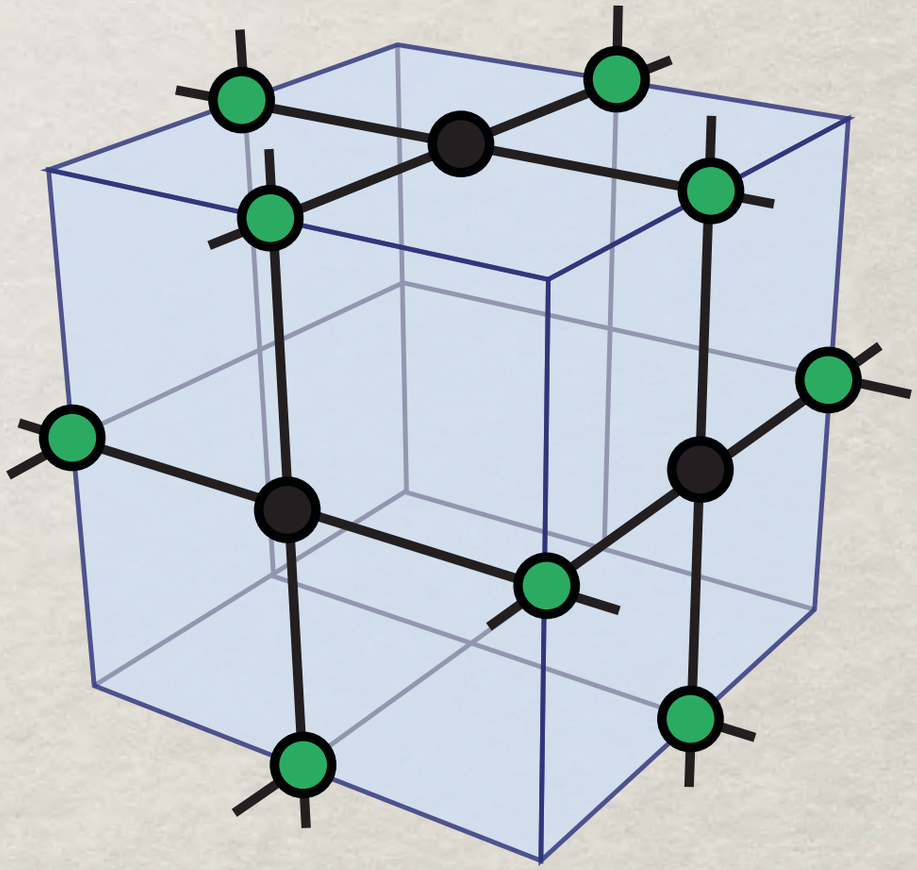
That's merely showing that errors can be kept to (poly) log rates.

How about actually getting a threshold!

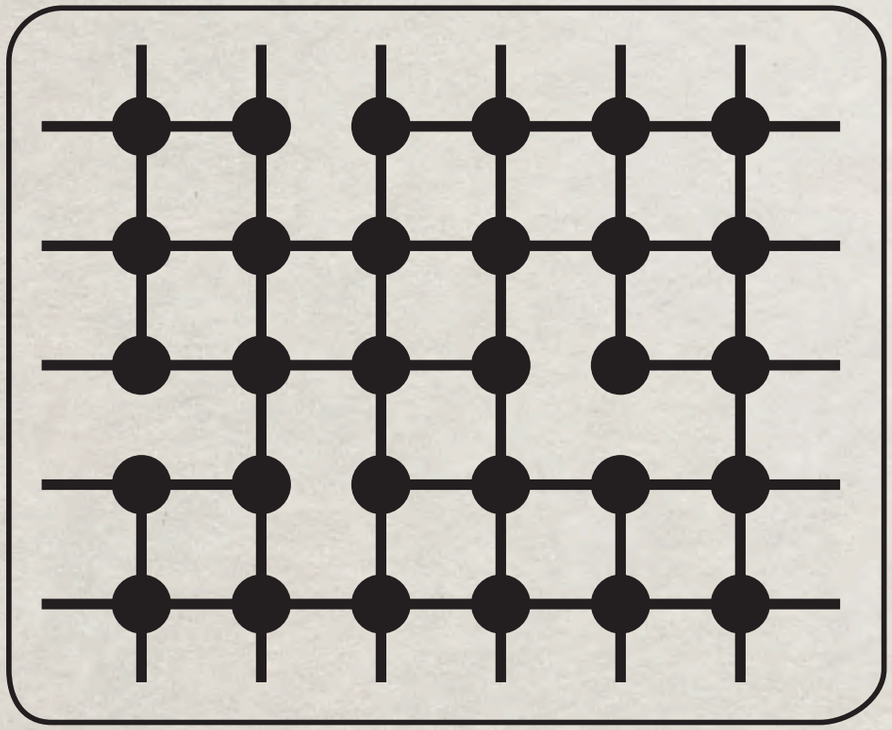
Then instead of
this target...



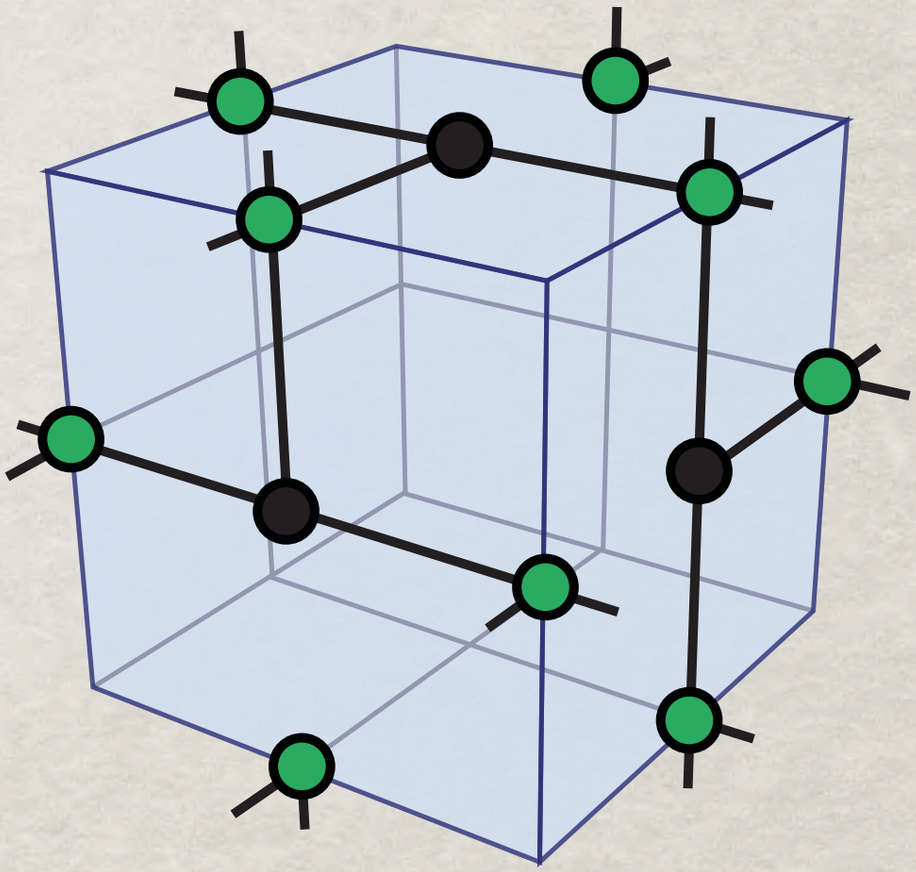
...make this thing.



Will that work?
We need some kind of threshold for tolerance of missing edges

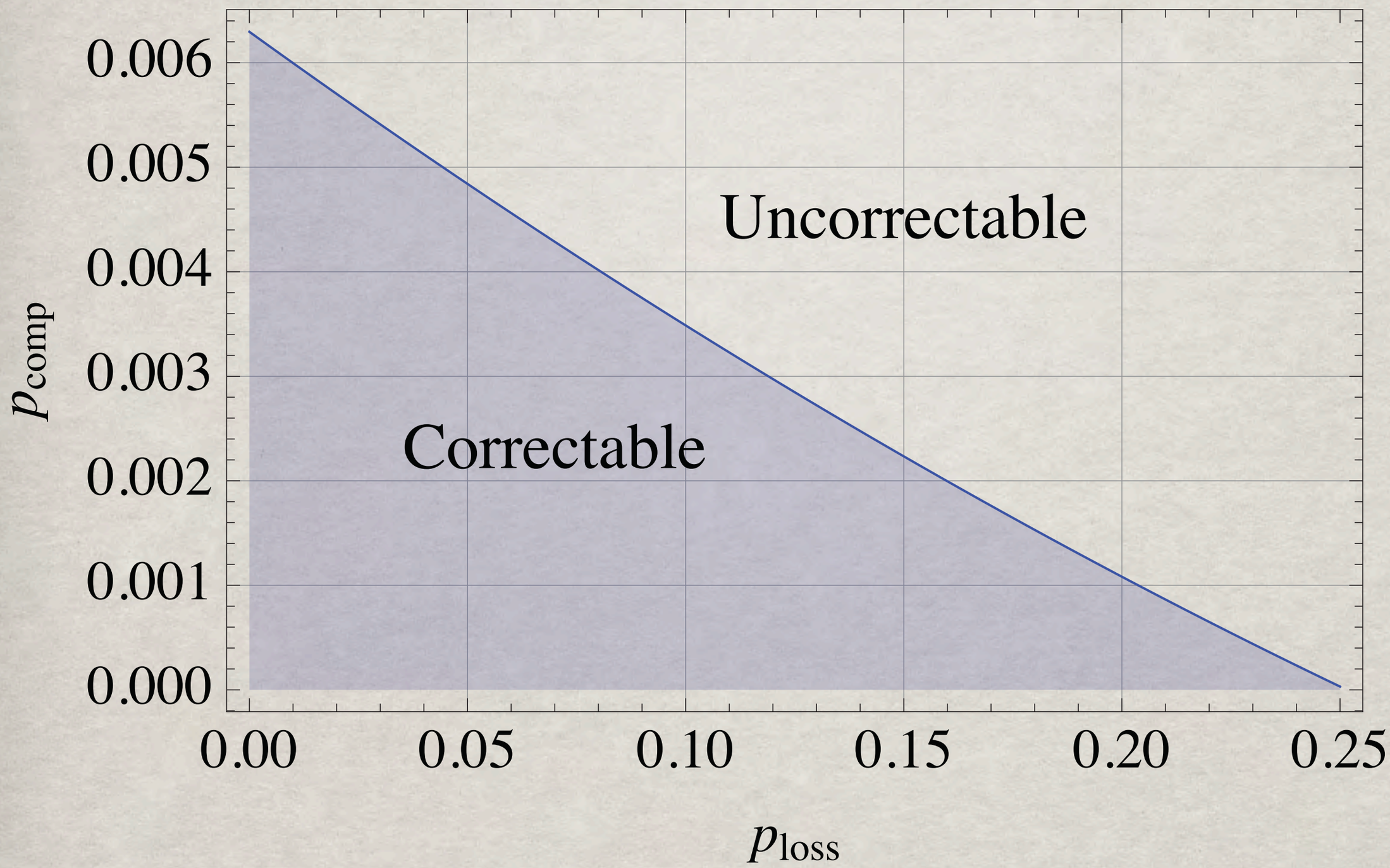


...for the simple cluster state we had percolation.

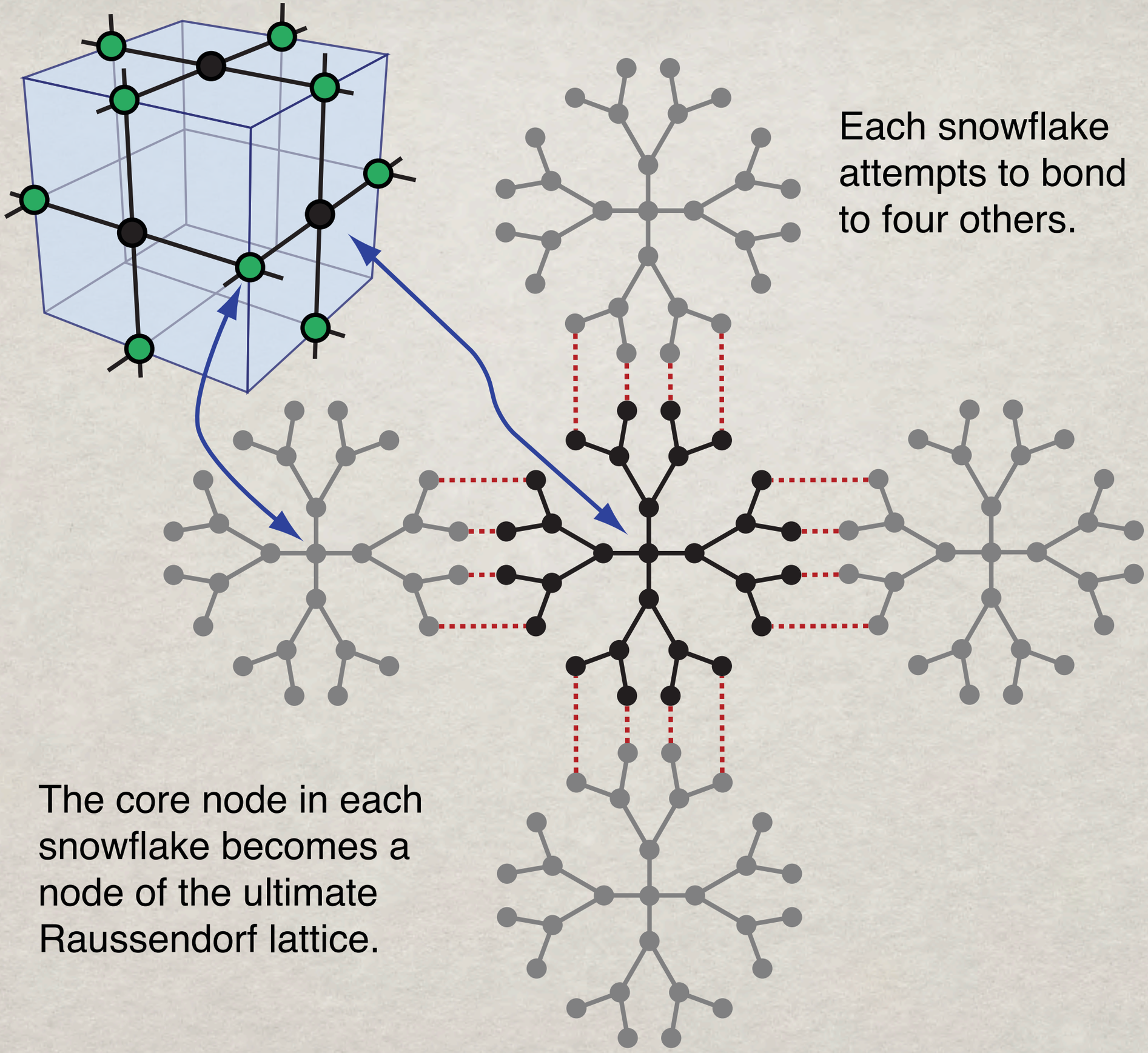


What in this case?

...Now we have Barrett/Stace result for missing qubits



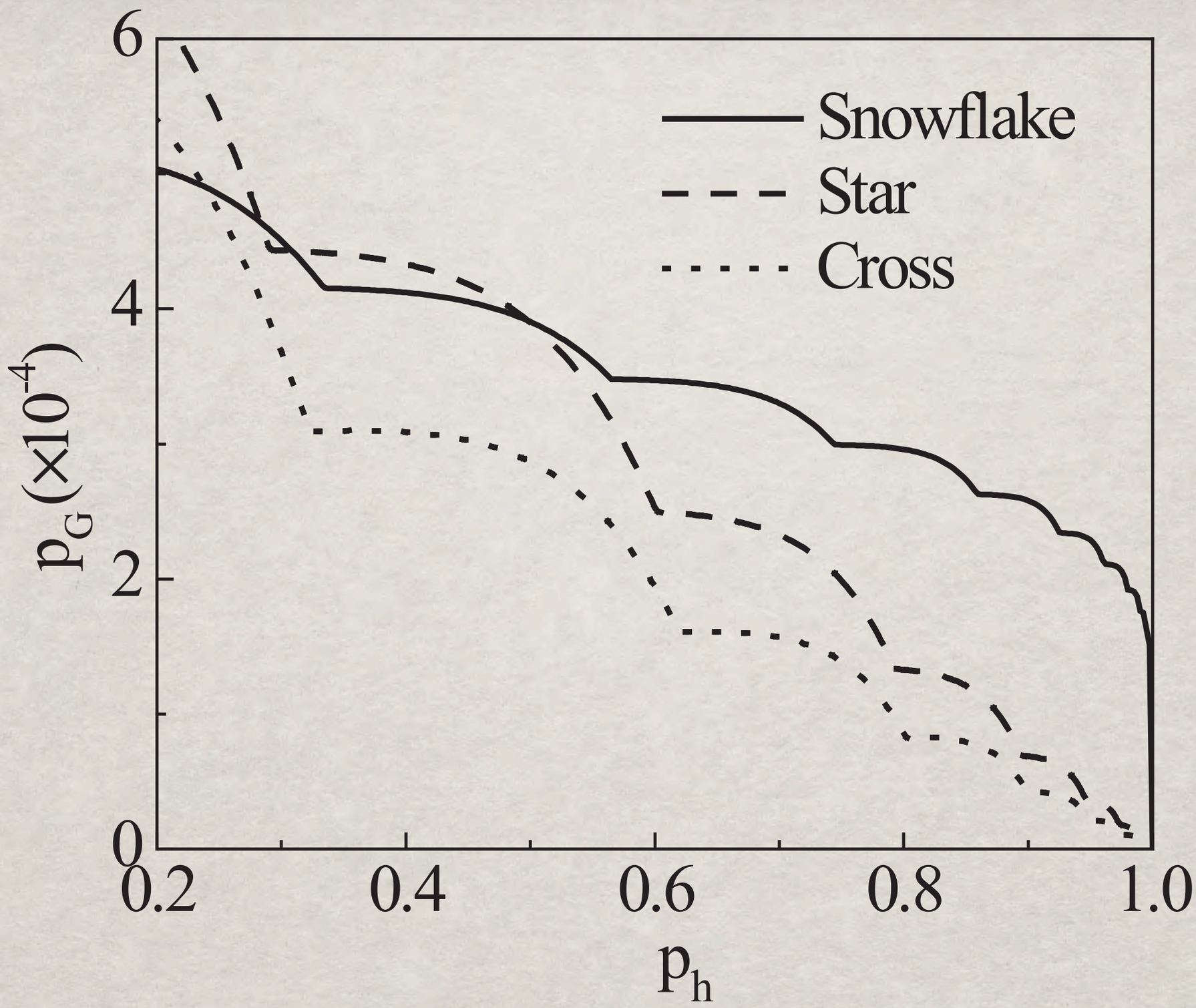
Sean and Tom, Phys. Rev. Lett. **105**, 200502 (2010).



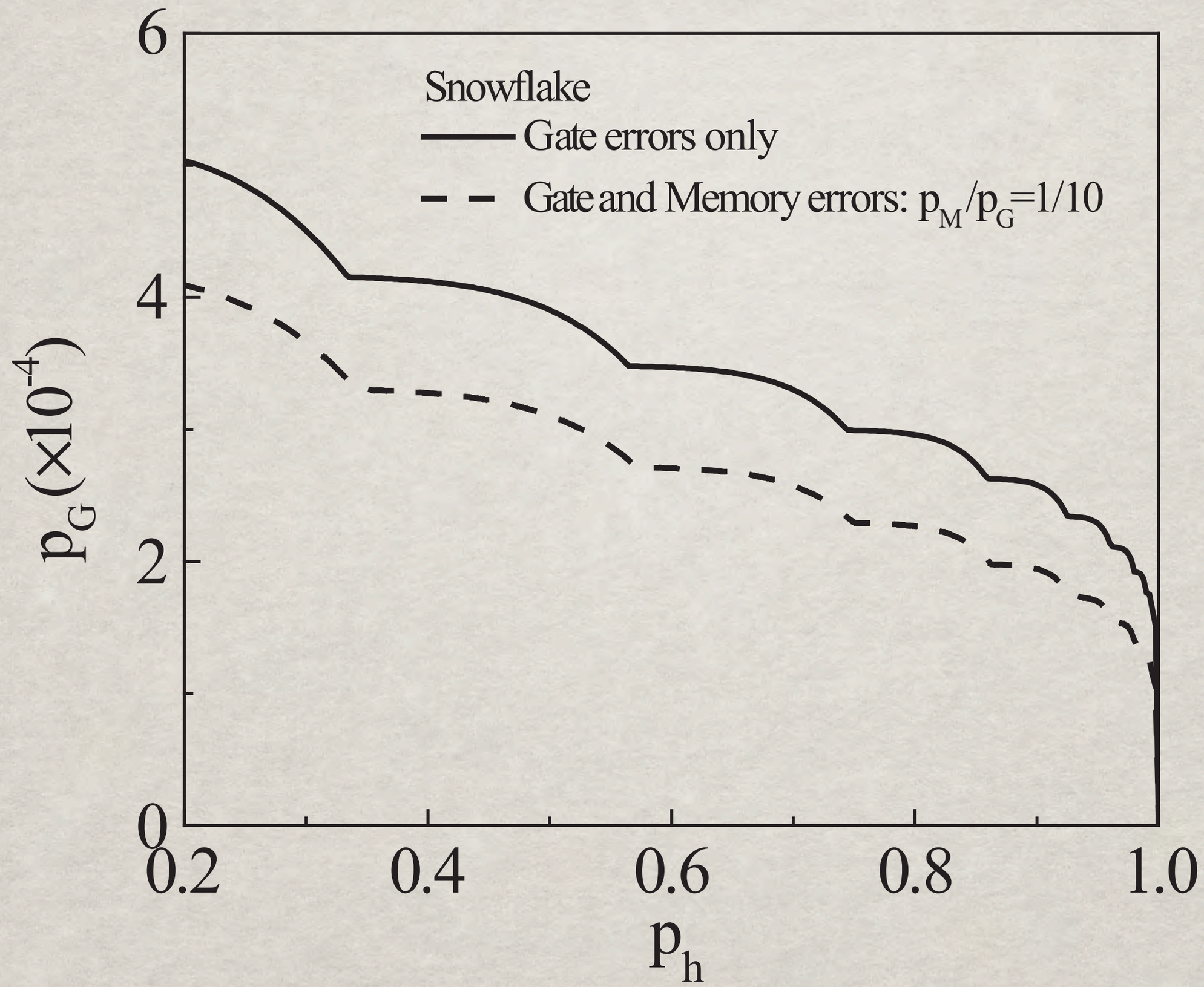
Each snowflake attempts to bond to four others.

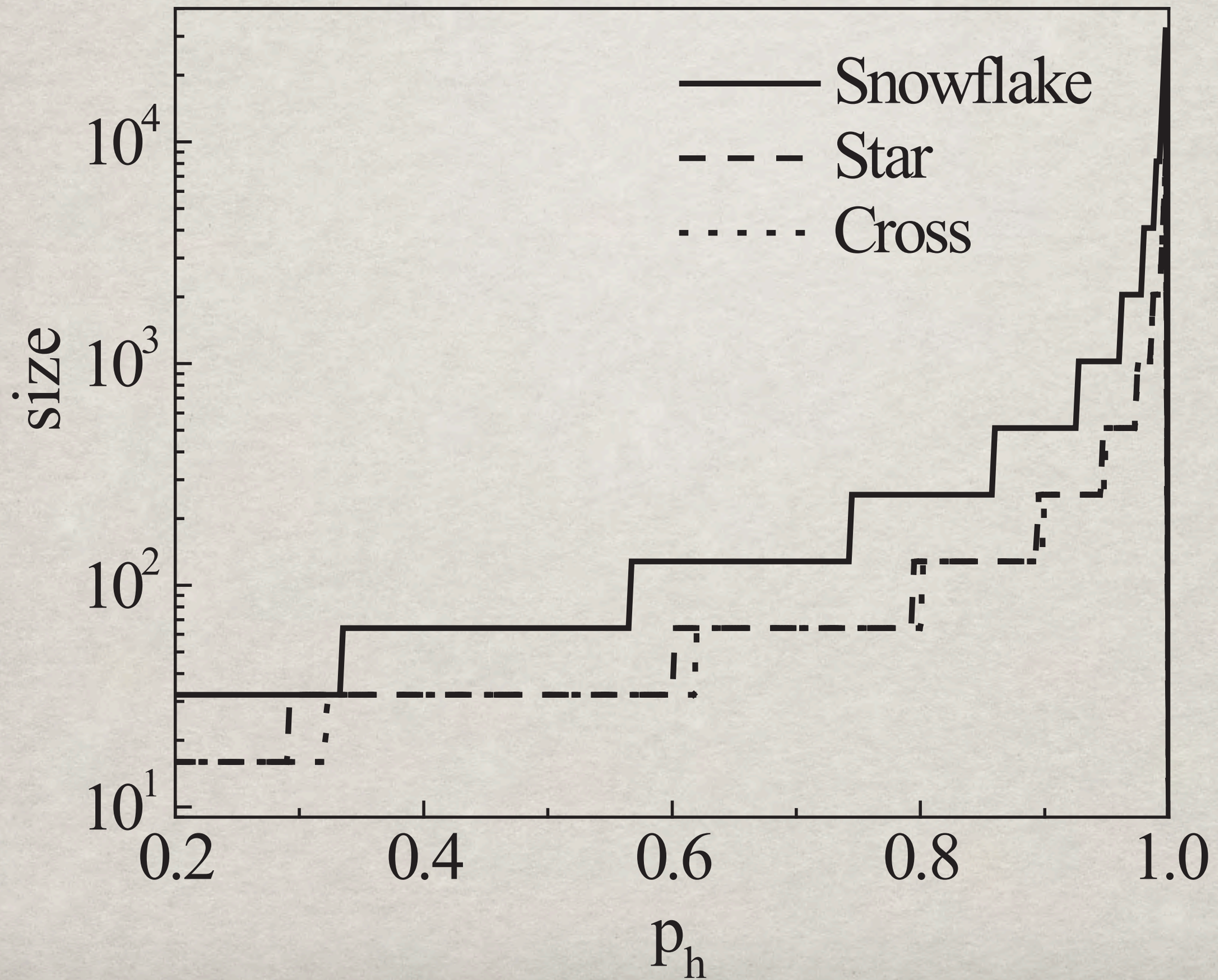
The core node in each snowflake becomes a node of the ultimate Raussendorf lattice.

Error tracking from sup material



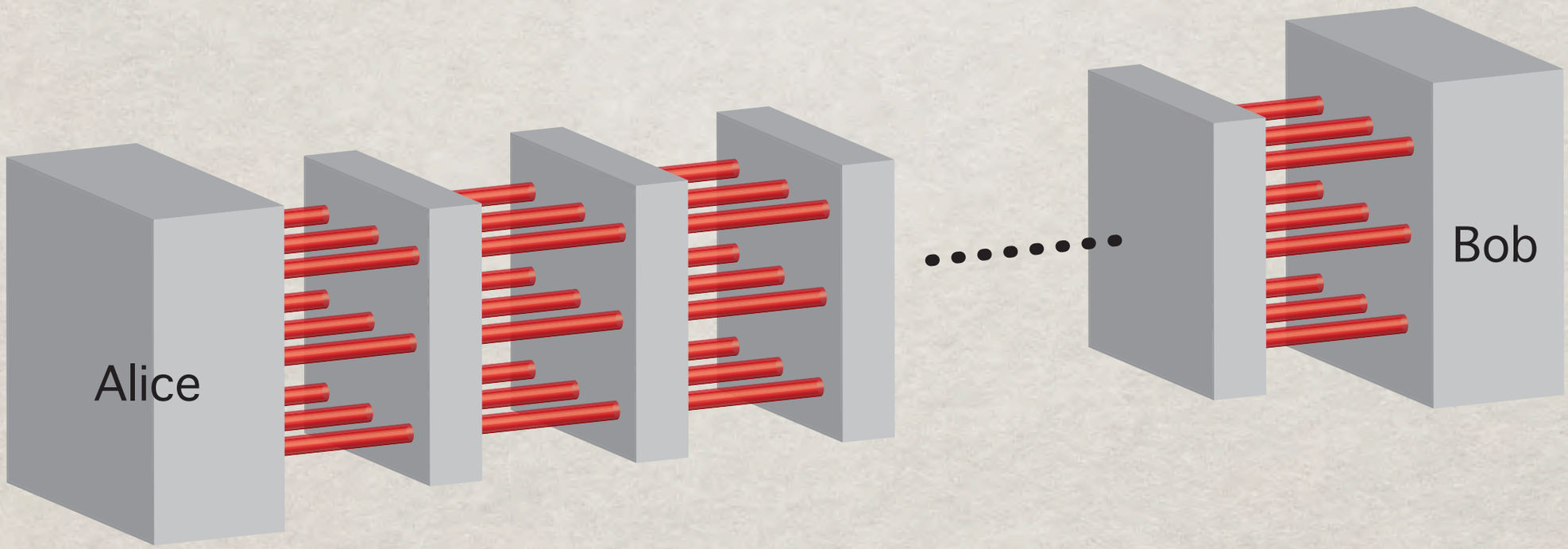
Ying Li, Sean Barrett, Tom Stace and Simon Benjamin,
PRL **105**, 250502 (2010).

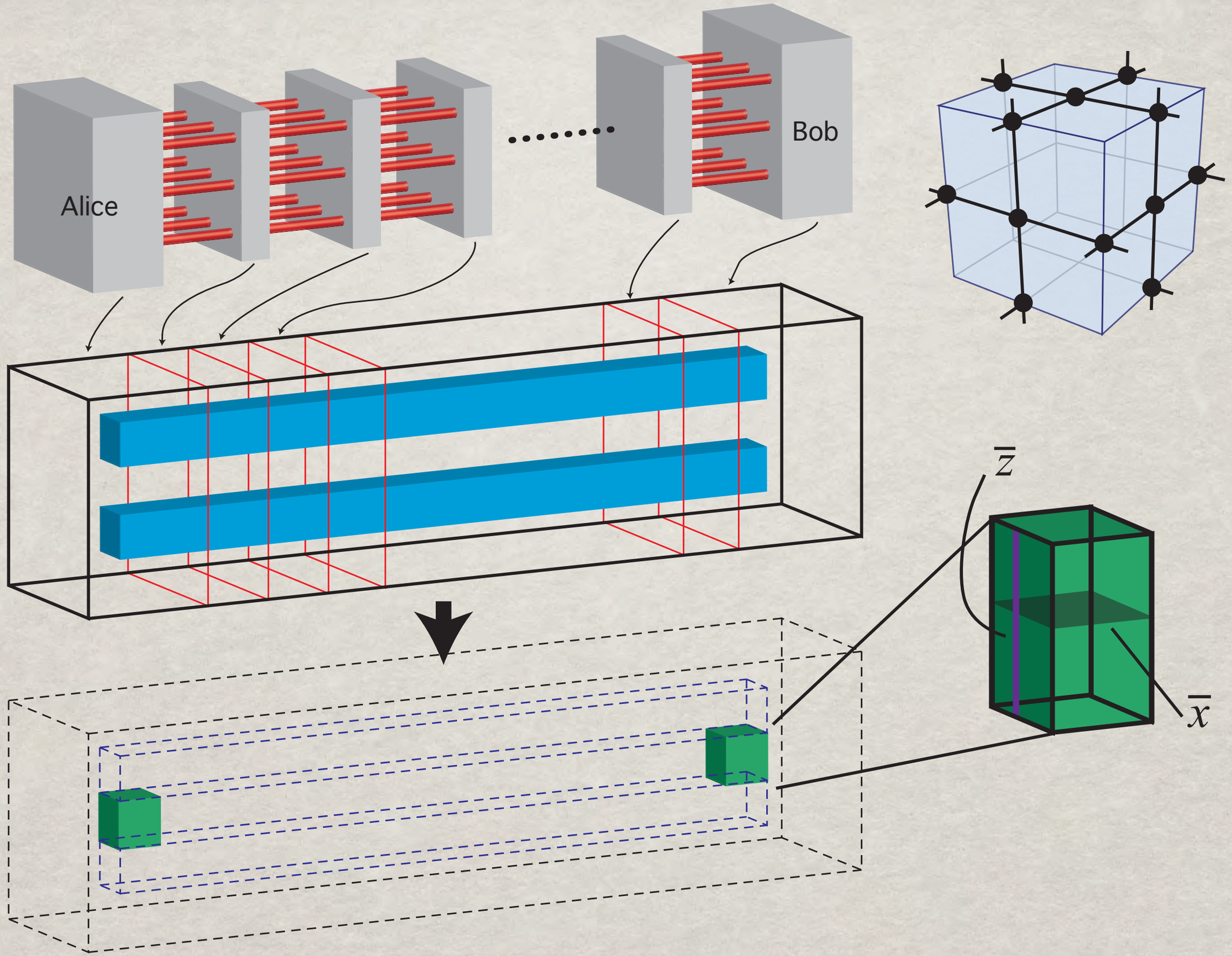

Snowflake
Gate errors only
Gate and Memory errors: p_M/p_G=1/10
p_G ($\times 10^{-4}$)
6
4
2
0
0.2
0.4
0.6
0.8
1.0
p_h

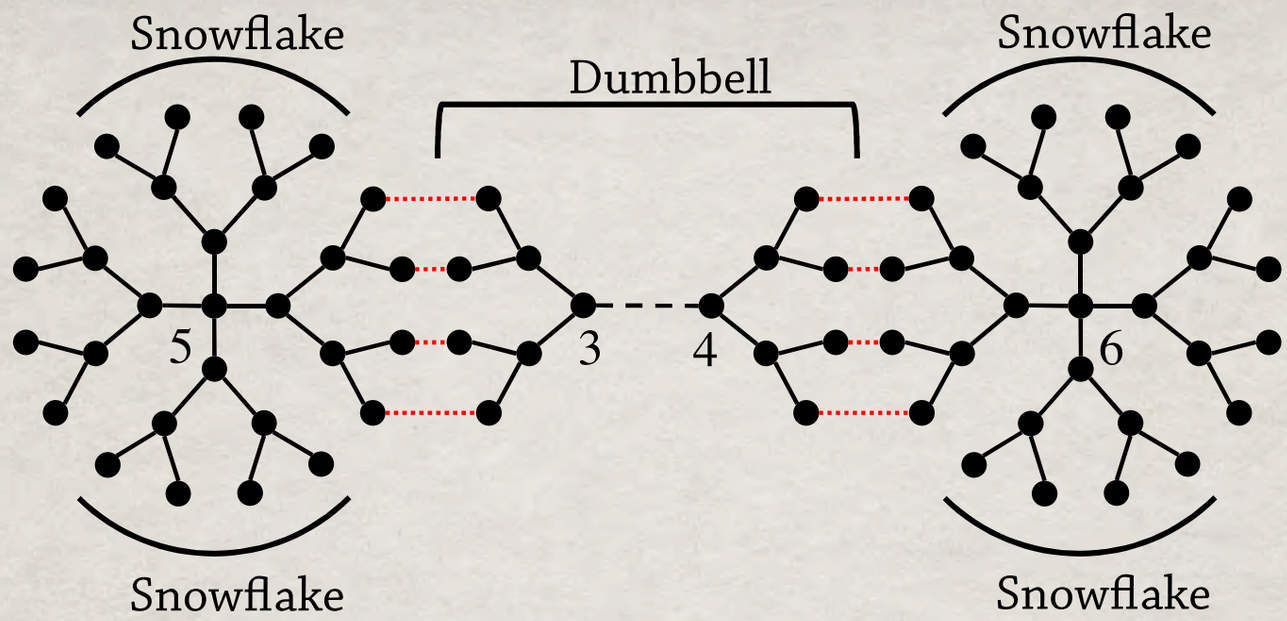

Snowflake
Star
Cross
size
10^4
10^3
10^2
10^1
0.2
0.4
0.6
0.8
1.0
p_h

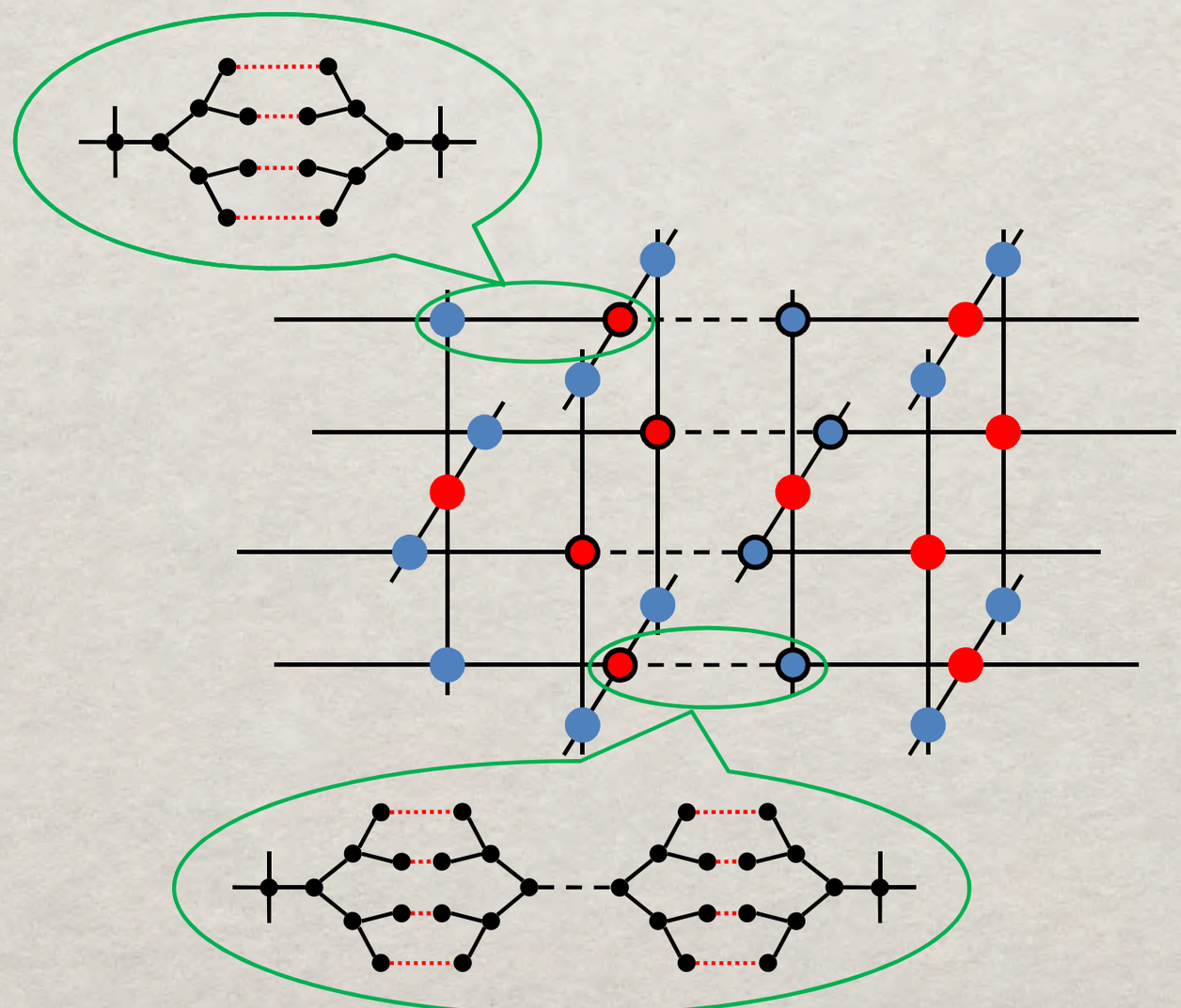
also
K. Fujii and Y. Tokunaga,
PRL **105**, 250503 (2010).

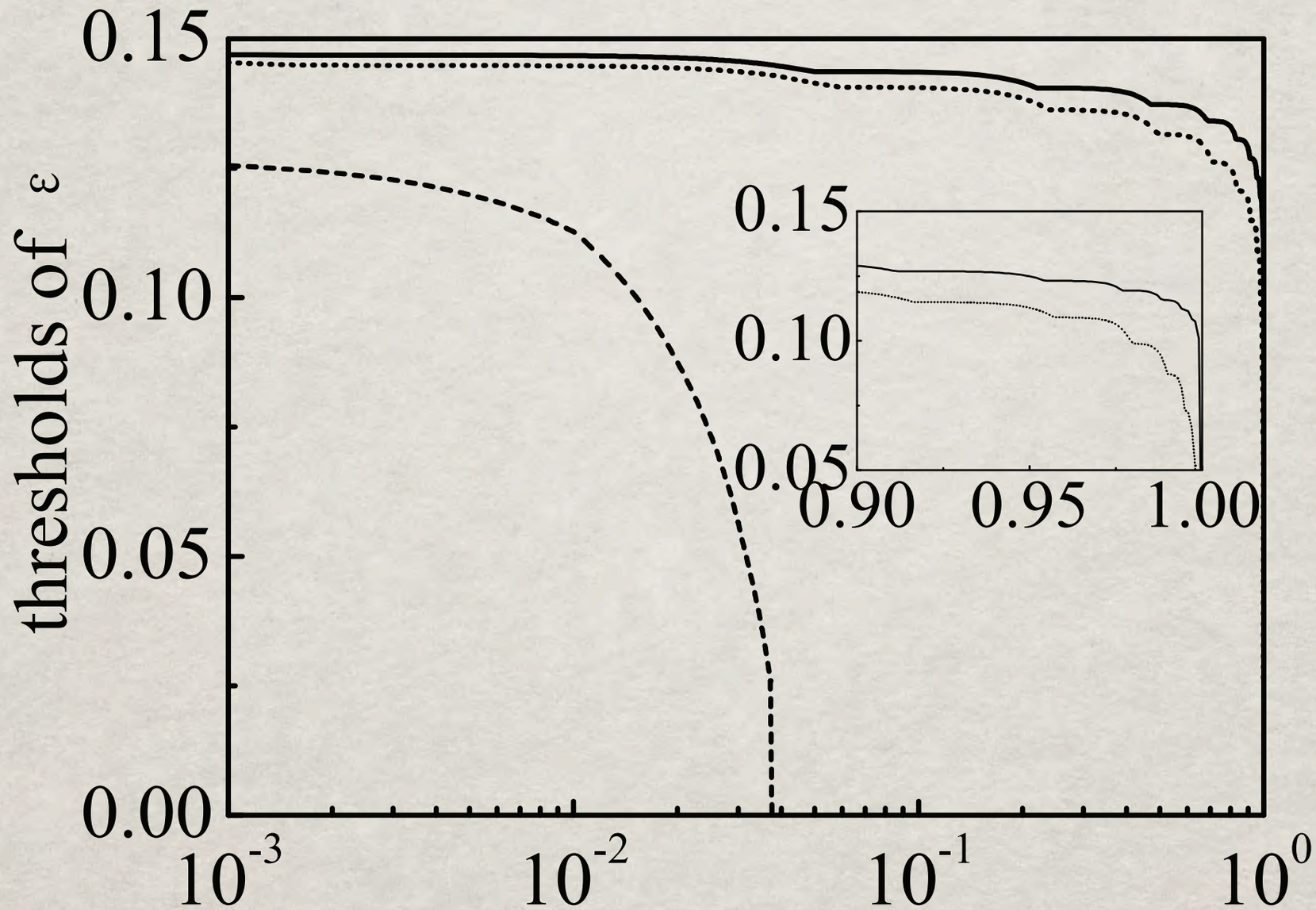
Encore: Let's get a threshold for communication.




Alice
Bob
$\bar{z}$
$\bar{x}$


Snowflake
Dumbbell
Snowflake
5
3
4
6
Snowflake
Snowflake





Ying Li, Sean Barrett, Tom Stace and Simon Benjamin,
in preparation.

Final thought:
Couldn't we do similar tricks
with multiple qubits?