Title: Phase transition of computational power of measurement-based quantum computer

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Abstract: One of the most significant questions in quantum information is about the origin of the computational power of the quantum computer; namely, from which feature of quantum mechanics and how does the quantum computer obtain its superior computational potential compared with the classical computer?

In my talk, I address this open question more concisely through the study of measurement-based quantum computer, in which all the quantum resource is attributed to entanglement since computation is carried through its consumption by local measurements. I also show a simple model of the phase transition of quantum computer occurring at some threshold, below which the quantum computer comes to allow an efficient classical simulation in accordance with an exponential drop in the amount of entanglement.

YRC@PI , December 4th (2007)

Phase transition of computational power of measurement-based quantum computer

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Motivation

fundamental question: origin of computational power of QC

rom which feature of quantum mechanics and how does the uantum computer obtain its superior computational power ompared with the classical computer?

easurement-based quantum computer

the role of entanglement is highlighted!

- the amount of entanglement reflects computational power
- phase transition (exponential change of entanglement)

Outline

. Motivation
origin of computational power of quantum computer

. Measurement-based quantum computer
role of entanglement for universal quantum computation

. Entanglement criterion for universality
the amount of entanglement must grow faster than polylogarithmic in the system size for universality

. Phase transition of computational power of a faulty cluster state.
exponential change of entanglement

. Summary

Measurement-based quantum computer

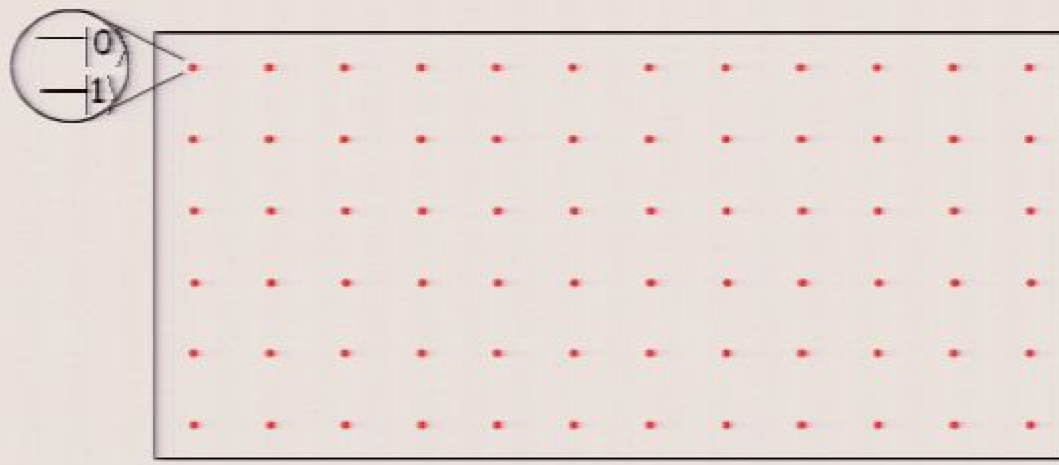
[Raussendorf & Briegel, PRL 86, 5188 (2001)]

. Resources

- preparation of a multipartite entangled state called 2D cluster state $|\phi\rangle_C$, which exhitbits the following quantum correlation:

$$K^{(a)}|\phi\rangle_C = |\phi\rangle_C \quad ,$$

eigenvalue equations



$$K^{(a)} \equiv \sigma_x^{(a)} \prod_{<a',a>} \sigma_z^{(a')}$$

set of correlation operators

- single-qubit projective measurements
- classical communication for feedforward of measurement outcomes

Graph states

[review: Hein et al., quant-ph/0602096]

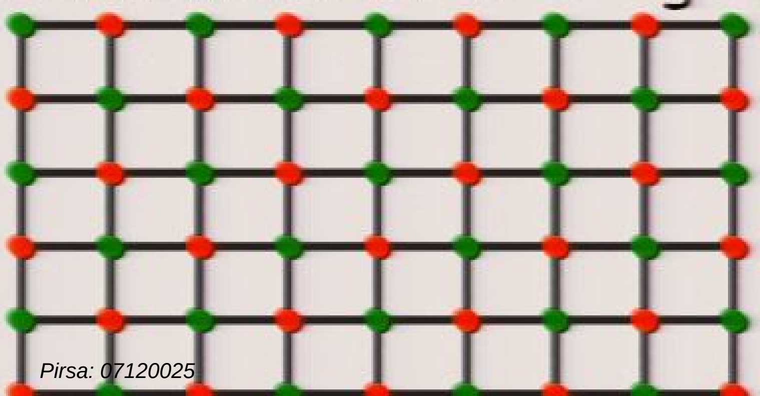
. For a graph G,
vertices = qubits, edges = Ising-type interaction pattern.
degree is the number of edges from a vertex.

$$|G\rangle = \prod_{(a,b)\in edges} CZ^{(a,b)} |+\rangle^{N}, \; CZ = \text{diag}(1,1,1,-1), |+\rangle = \tfrac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

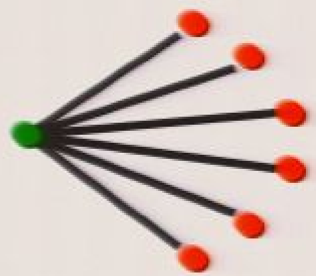
. joint eigenstate of N commuting correlation operators for N qubits.

$$K_a|G\rangle = |G\rangle, \quad K_a = \sigma_x^{(a)} \bigotimes_{b\in N_a} \sigma_z^{(b)}$$

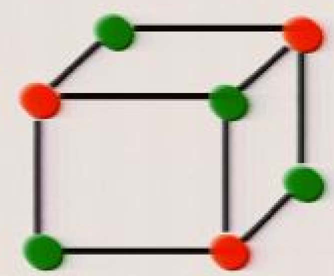
. stabilizer states = graph state, up to local unitaries.



2D cluster state



GHZ state



7-qubit error correction codeword

Measurement-based quantum computer

[Raussendorf & Briegel, PRL 86, 5188 (2001)]

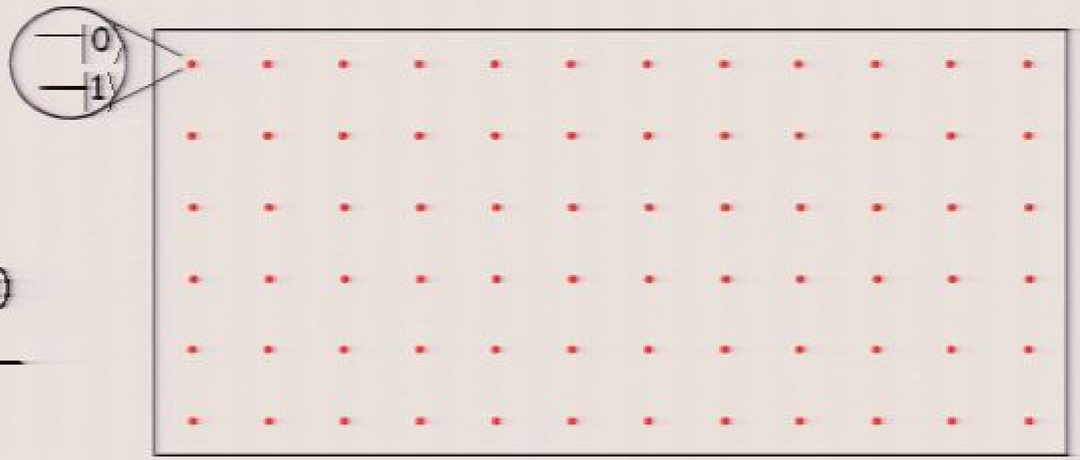
I. Computational process

According to quantum algorithms, the directions of single-qubit projective measurements are determined.

$$P_{0,\vec{n}} = |0\rangle_{\vec{n}}\langle 0|$$

$$P_{1,\vec{n}} = |1\rangle_{\vec{n}}\langle 1|$$

$$P_{j,\vec{n}}^{(a)} = \frac{1+(-1)^j \vec{n}^{(a)} \cdot \vec{\sigma}^{(a)}}{2}$$



$\{\vec{n}^{(a)} \mid a \in C\}$ → fixed / adaptive

The set of rules for adapting measurement directions and processing their outcomes by classical communication carries computation

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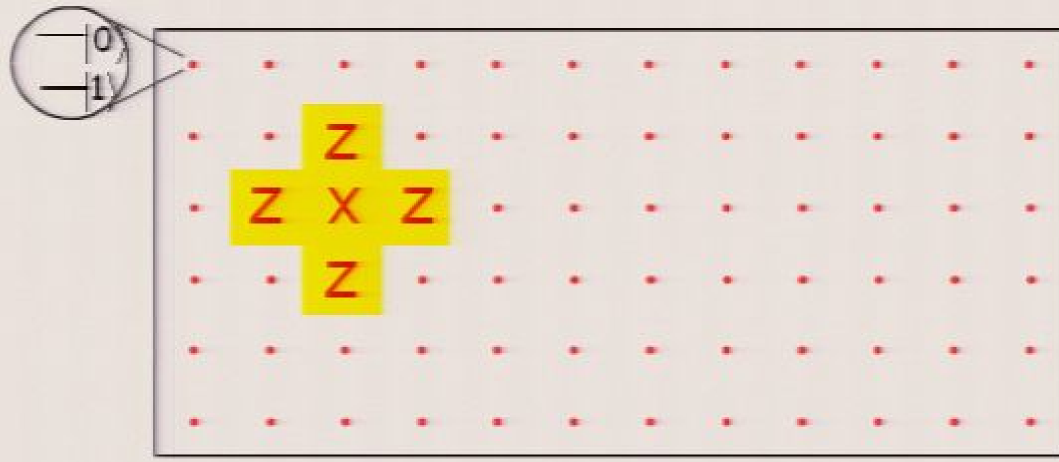

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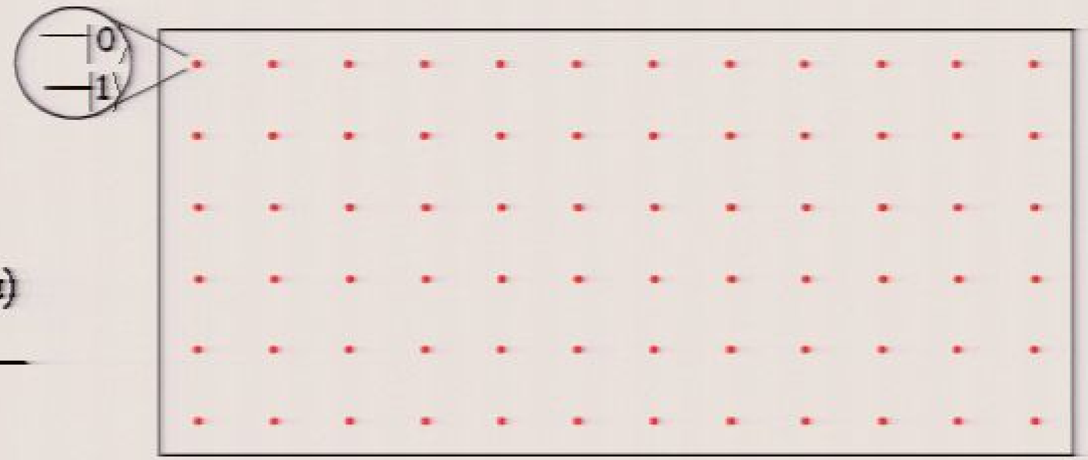

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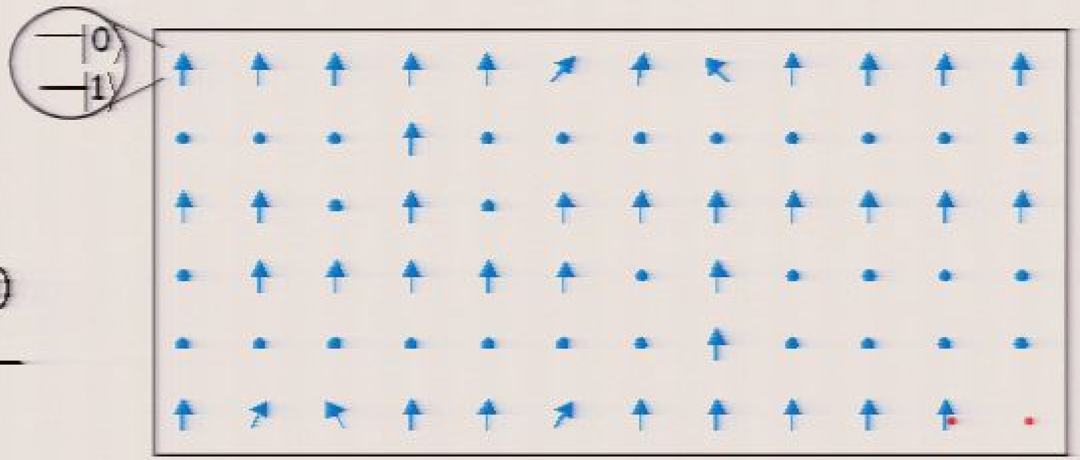

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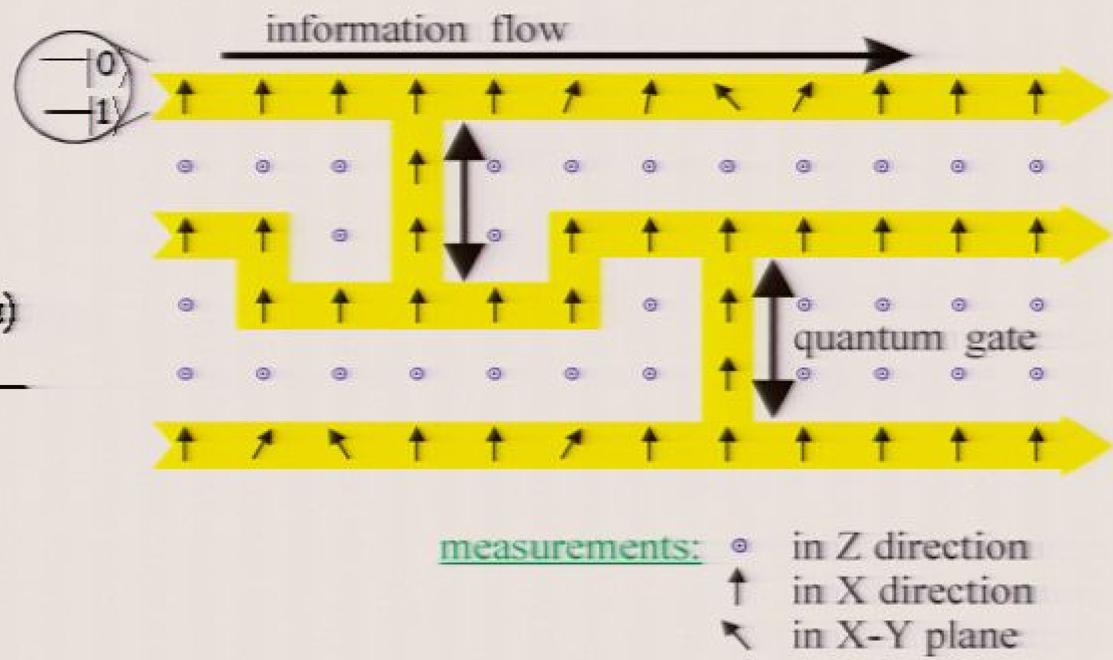

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The set of rules for adapting measurement directions and processing their outcomes by classical communication carries computation

Role of entanglement

The role of entanglement in the initial resource state is highlighted in measurement-based quantum computer, since computation is carried through its consumption by local measurements and classical communication.

role of entanglement for <u>universality</u> ("most powerful potential") of measurement-based quantum computation

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role of entanglement for universality ("most powerful potential") of measurement-based quantum computation

merits to consider universality as computational power:

- taking advantage of entanglement theory
- no direct consideration on speed-up (complexity) in comparison with classical computation
- but, some non-universal quantum computation may allow efficient classical simulation, ...indeed true in our case!

Universality of quantum computation

uantum computation is universal in the standard circuit model,
f any n-qubit unitary gate operation U can be realized (in
rbitrary accuracy) for the n logical quantum wires.

onventional (bottom-up) approach

o show a capability of a universal set of elementary gates
nd their composability

exact universality $\{\mathrm{CNOT}, \forall SU(2)\}$

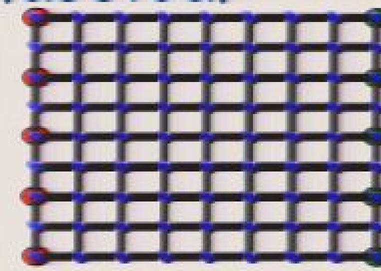
approximate universality $\left\{\underbrace{\mathrm{CNOT}, \mathrm{Hadmard}, \mathrm{Phase}}_{\mathrm{Clifford}}, \frac{\pi}{8}\right\}$

ntanglement (top-down) approach

o consider entanglement convertibility by local measurements
rom an initial entangled resource state in measurement-based
QC

Universality in one-way QC

Using single-qubit projective measurements and classical feedforward of measurement outcomes,



$$\underbrace{|\psi\rangle}_{N} \xrightarrow{\text{LOCC}} \underbrace{|\phi\rangle}_{n}\underbrace{|\text{measured}\rangle}_{N-n}$$

- it's capable to simulate <u>any</u> unitary gate operation on (known) input states deterministically
- it's capable to produce <u>any</u> corresponding output state $|\phi\rangle$

2D cluster states $\{|C_k\rangle, k=1,2,\ldots\}$ have been shown to be universal in the sense of the above (CQ-) definition.

efinition of Universal resource:

set of states $\Psi = \{|\psi_1\rangle, |\psi_2\rangle, \ldots,\}$ is universal for
easurement-based QC, if

$$\exists \underbrace{|\psi_k\rangle}_{N} \xrightarrow{\text{LOCC}} \forall \underbrace{|\phi\rangle}_{}\underbrace{|\text{measured}\rangle}_{}$$

symbolically,
$|\psi\rangle \geq_{\text{LOCC}} |\phi\rangle$

General framework for universal resources

niversal resource (exact deterministic):

$$\exists \underbrace{|\psi_k\rangle}_{N} \xrightarrow{LOCC} \forall \underbrace{|\phi\rangle}_{n} \underbrace{|\text{measured}\rangle}_{N-n}$$

ith fidelity F one, with success probability p one.

fidelity
- exact
- approximate (1-ϵ)

probability
- deterministic
- quasi-deterministic (1-δ)
- stochastic (nonzero, finite)

encoding
- logical subspac

fficiency
- universal resource is called efficient if it is capable of preparing efficiently as well any state preparable efficiently (poly time and size) in a standard universal (circuit/2D cluster) model

ame entanglement scaling, up to a polynomial overhead, must old true among the families of efficiently universal resources

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Entanglement criterion for universality

dea: if any significant entanglement feature exhibited by set of universal resource states (ex. the 2D cluster states) s not available from another set Ψ, then it cannot be universal

Condition for proper measures

$$E(|\phi\rangle) \geq E(|\phi'\rangle) \text{ whenever } |\phi\rangle \geq_{LOCC} |\phi'\rangle$$

e.x. by entanglement monotones such that $E(|\phi\rangle \otimes |0\rangle) = E(|\phi\rangle)$

- entanglement width: distinguish 1D and 2D cluster states
- geometric measure
- Schmidt measure
- ...

Criterion for universality

A set of states Ψ cannot be universal for one-way QC if

$$\sup_{\forall|\phi\rangle} E(|\phi\rangle) > \sup_{|\psi\rangle\in\Psi} E(|\psi\rangle)$$

$$\sup_{\forall|\phi\rangle} E(|\phi\rangle) = \sup_k E(|C_k\rangle)$$

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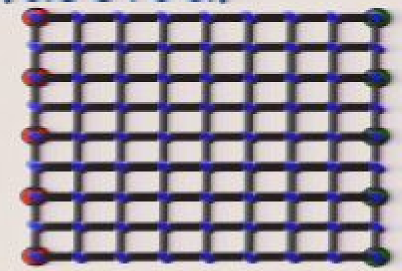

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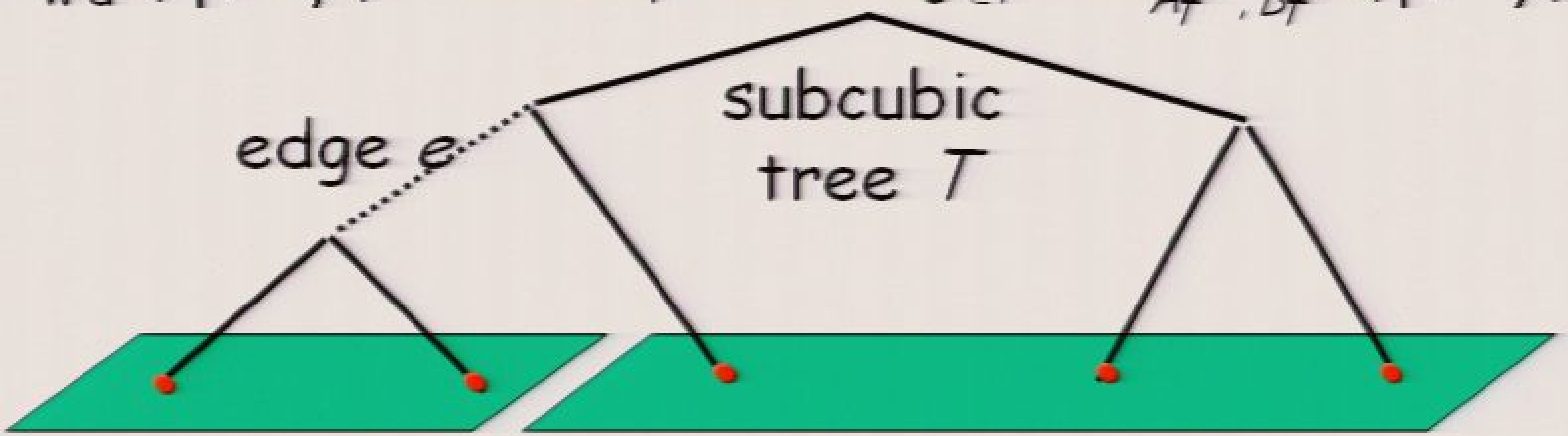
Entanglement width

Entanglement-width

maximal entropy of entanglement associated with certain bipartitions (cf. area law of entanglement)

$$E_{wd}(|\psi\rangle)=\min_T \max_{e\in T} E_{A_T^e, B_T^e}(|\psi\rangle)$$



- non-increasing under deterministic LOCC
- equivalent to the rank-width in graph theory

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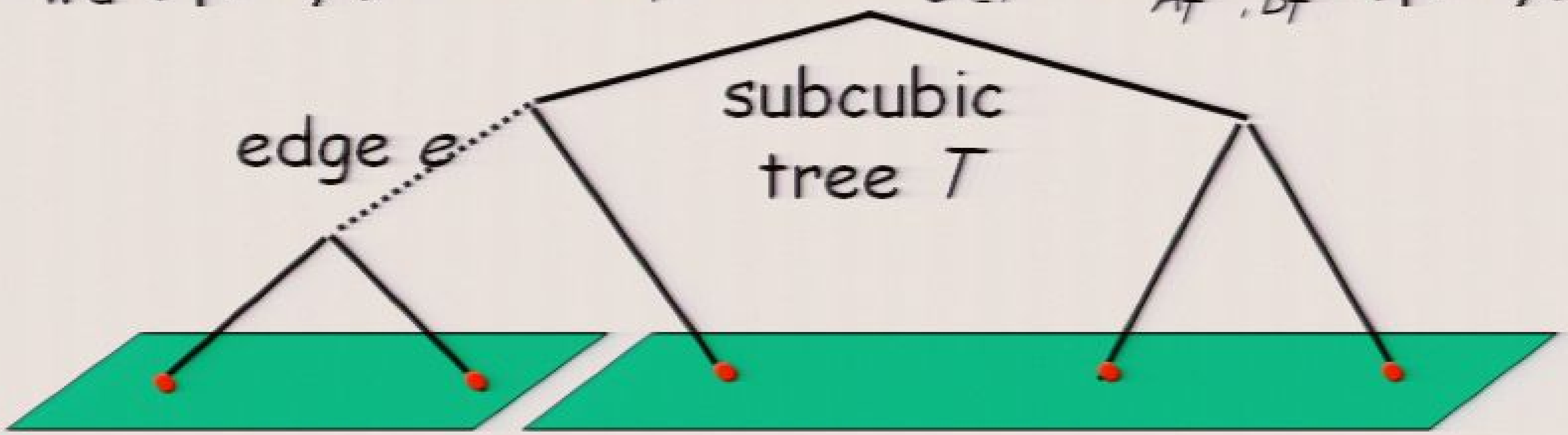

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2D cluster states show the divergence such as $E_{wd}(|C_N\rangle) \geq O(\sqrt{N})$

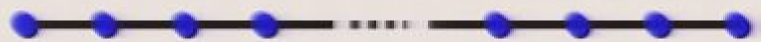
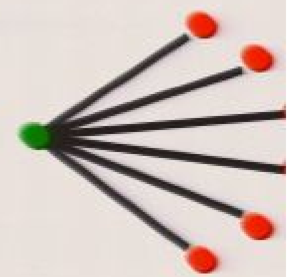
Any (efficient) universal resource must have a diverging entanglement width which scales faster than logarithmic in N

Non-universal graph states

Theorem 1:

ny set of the graph states whose entanglement width is at nost polylogarithmic in the number of qubits N is not an fficient universal resource.

"interaction geometry determines the value as a resource"

- 1D cluster states ($E_{wd} = 1$) 
- GHZ (tree) states, fully connected graphs 
- graphs with bounded tree-width or clique-width

fficient classical simulation of QC:

or graph states, if $E_{wd} =< \text{polylog}(N)$, then measurement-ased QC is effciently simulatable by classical computers

One-way computation on 1D cluster states and GHZ states:

[Nielsen 05; Markov & Shi 05; Jozsa 06; Van den Nest et al. 06; Yoran & Short 06; Bravyi & Raussendorf 07; ...]

"Universe" of entanglement resources

The amount of entanglement must scale fast unboundedly!

ntropic
ntanglement width

?

maximum size of
unit localizable
entanglement

ichmidt-rank
idth

universal resource families

$O(\text{polylog}\, N)$ $O(N) \rightarrow \infty$

**classically
efficiently
simulatable**

Schmidt measure

geometric
measure

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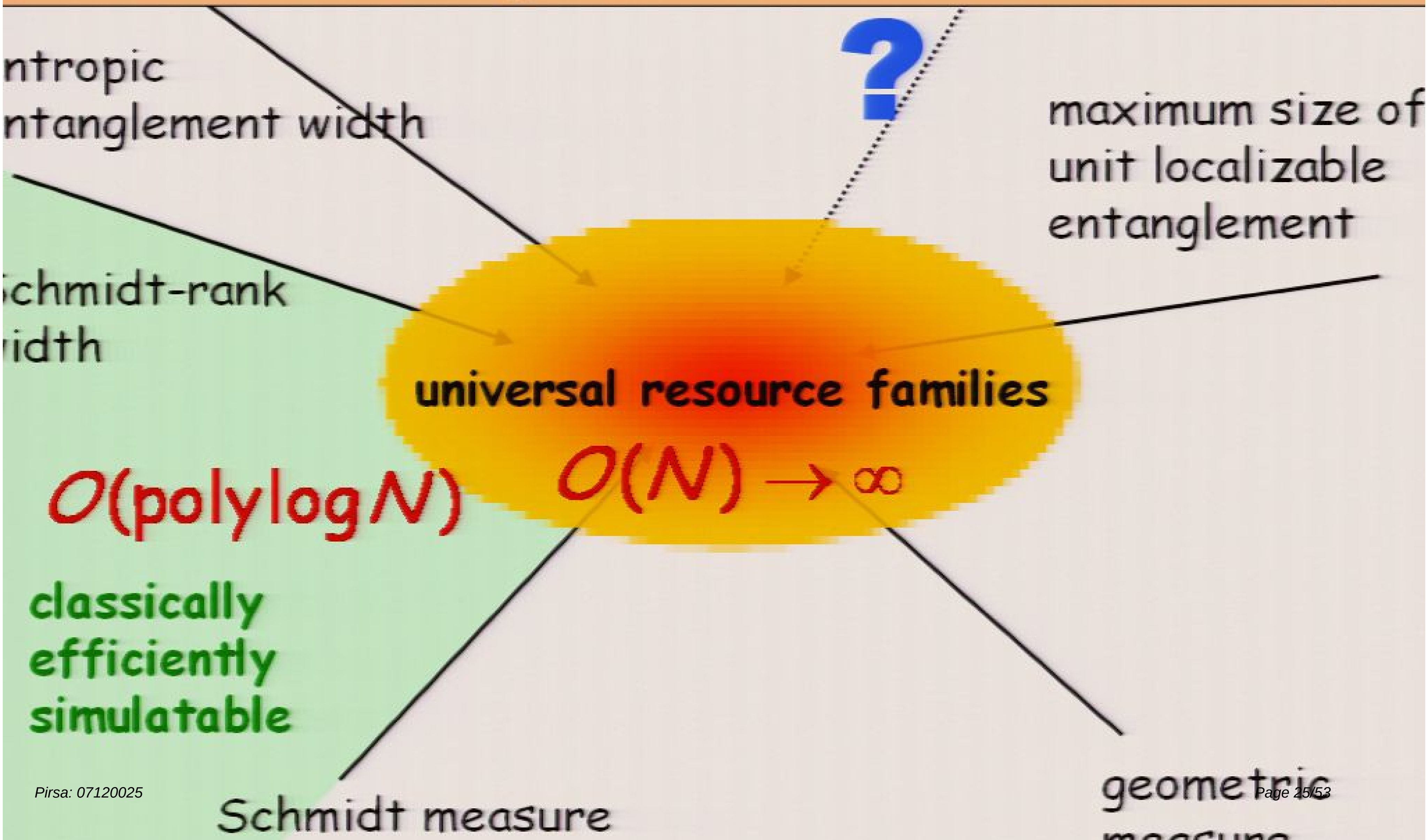

Blowing-up universal resource states

Observation:

A set of states Ψ is a universal resource for one-way QC, if and only if $\Psi \geq_{LOCC} |C_n\rangle$ for every n.

2D cluster states

other universal resource states

single-qubit measurements

$$\{\ldots, |C_n\rangle, \ldots, |C_N\rangle, \ldots\} \qquad \Psi = \{\ldots, |\psi_n\rangle, \ldots, |\psi_N\rangle, \ldots\}$$

efficient $N = poly(n)$

show equivalence between two families of entanglement resource states under LOCC (constructive proof).

note: it is often easier than proving universality with other (e.g. circuit) universal models, as seen soon

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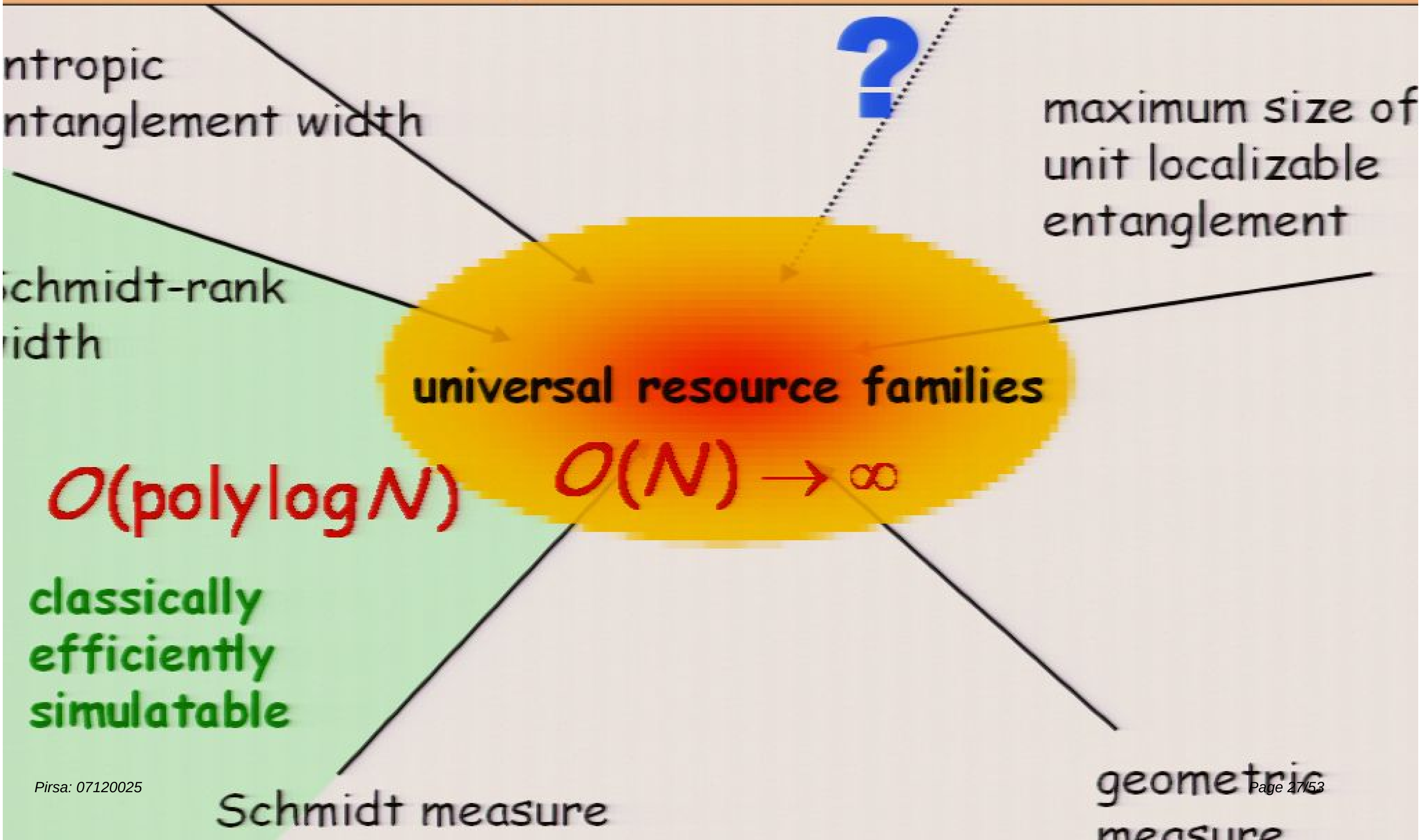

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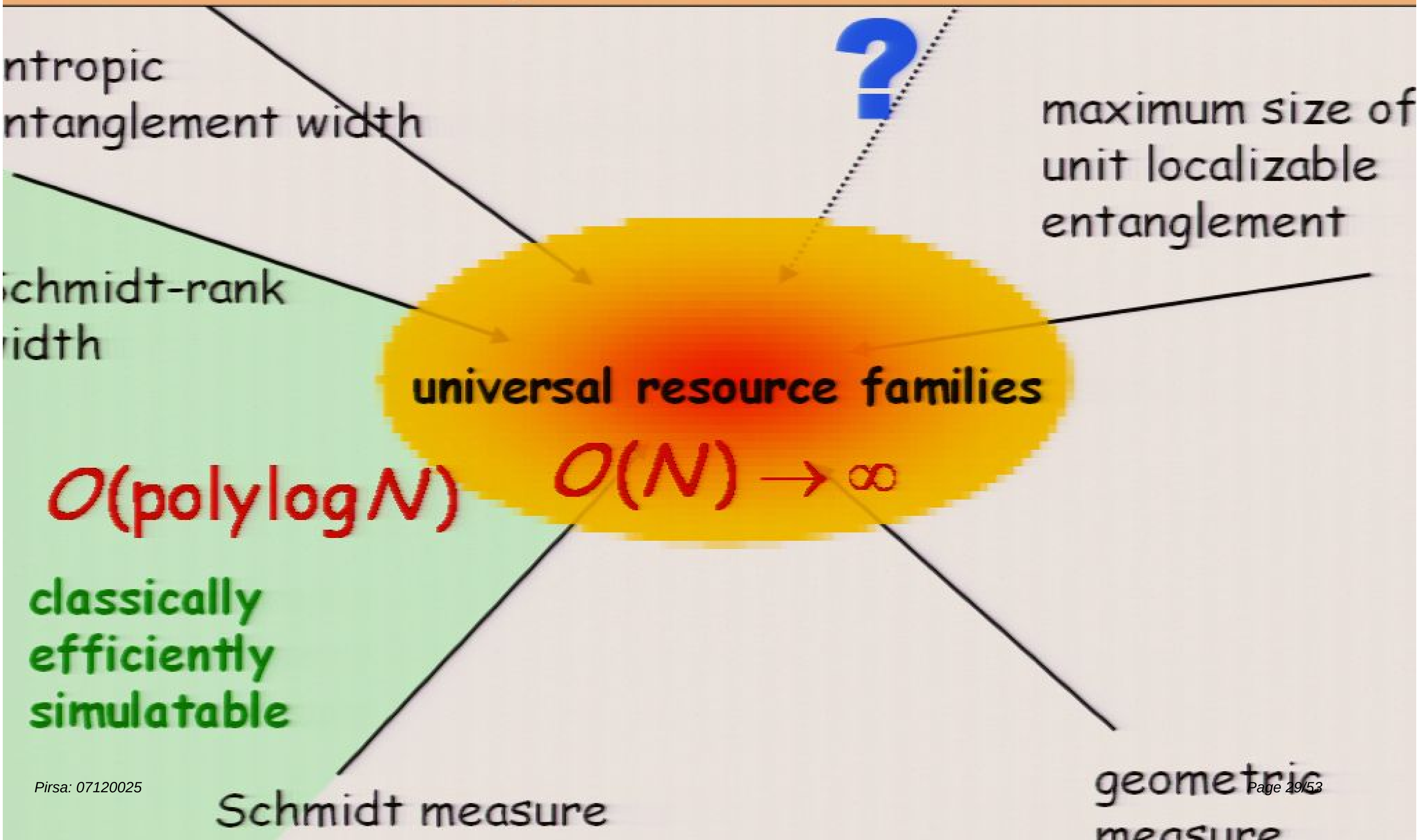

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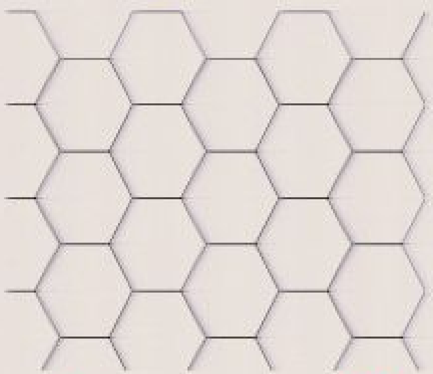
Examples of universal resources

Theorem2:

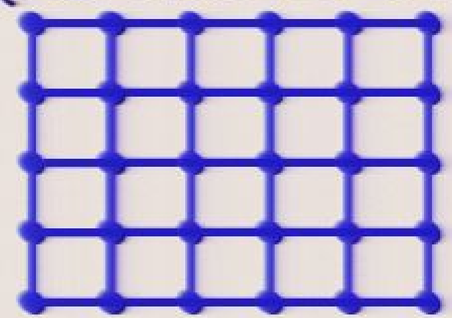
ll graph states by 2D regular lattices are universal resources.

hexagonal lattice



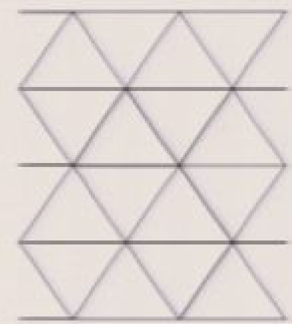
degree = 3

square lattice
(2D cluster state)



degree = 4

triangular lattice



degree = 6

minimum possible degree for
iiform lattices to be universal

ierits of the lower degree

- increased robustness for local decoherence
- convenience for bottom-up methods (ex. by polarizing beam
plitters in Linear Optics QC, matter-photon hybrid approach)

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5. Summary

Motivating observations

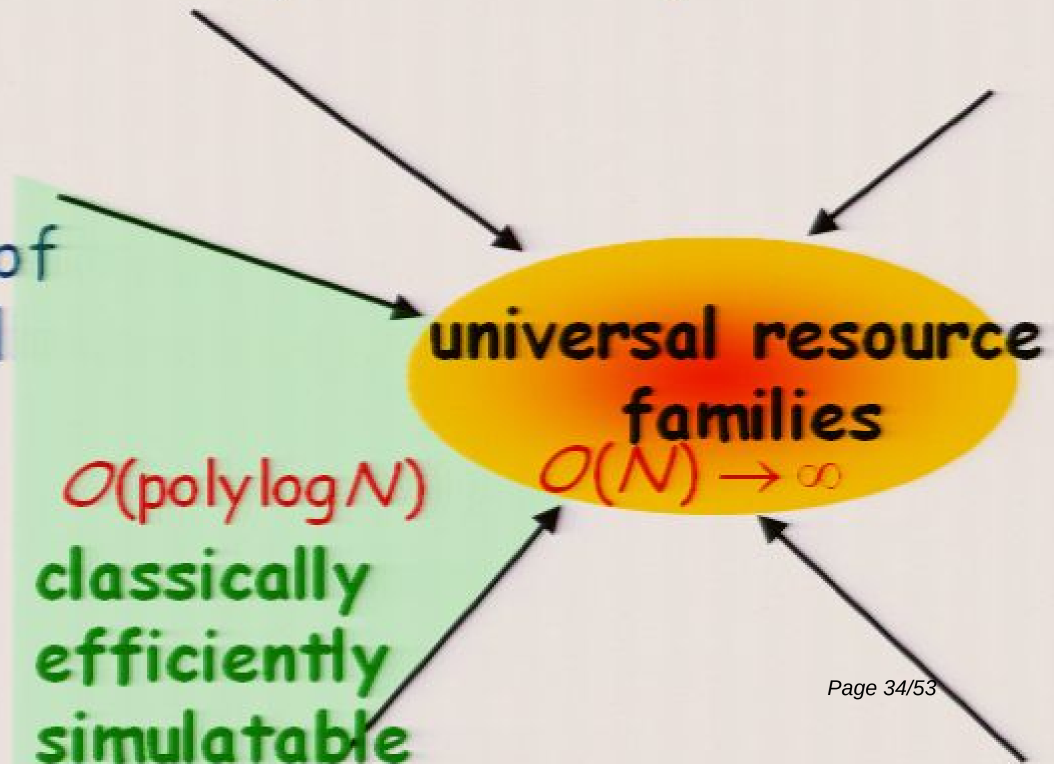
- dimensionality was a key for computational power

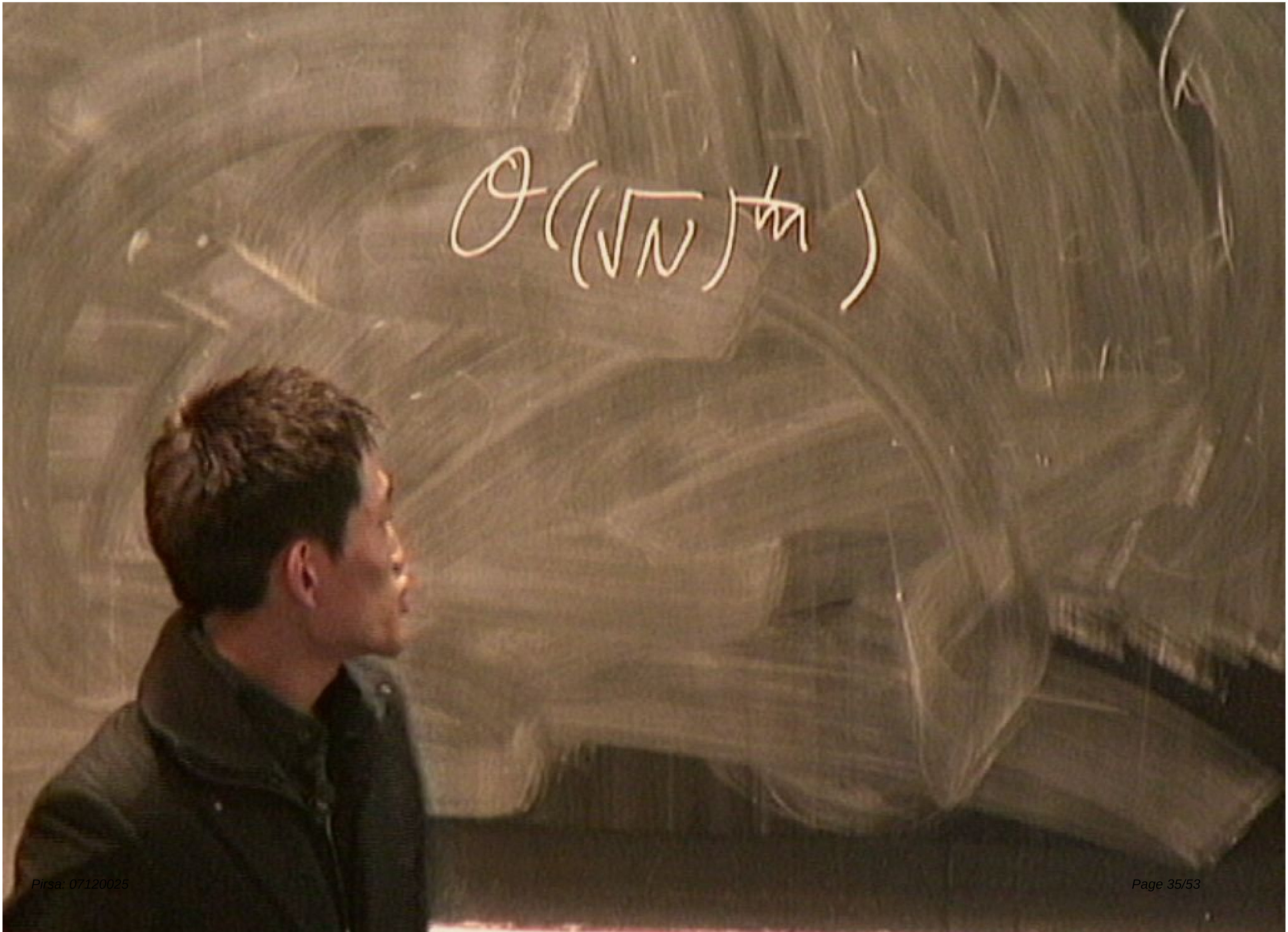
  - all 2D regular lattices: efficiently universal $E_{wd} \ge O(\sqrt{N})$

  - 1D chain: non-universal, & classically simulatable $E_{wd} = 1$

What will happen at an "intermediate" (fractal-like) dimension?

- Is the change ("boundary") of computational power gradual physically?





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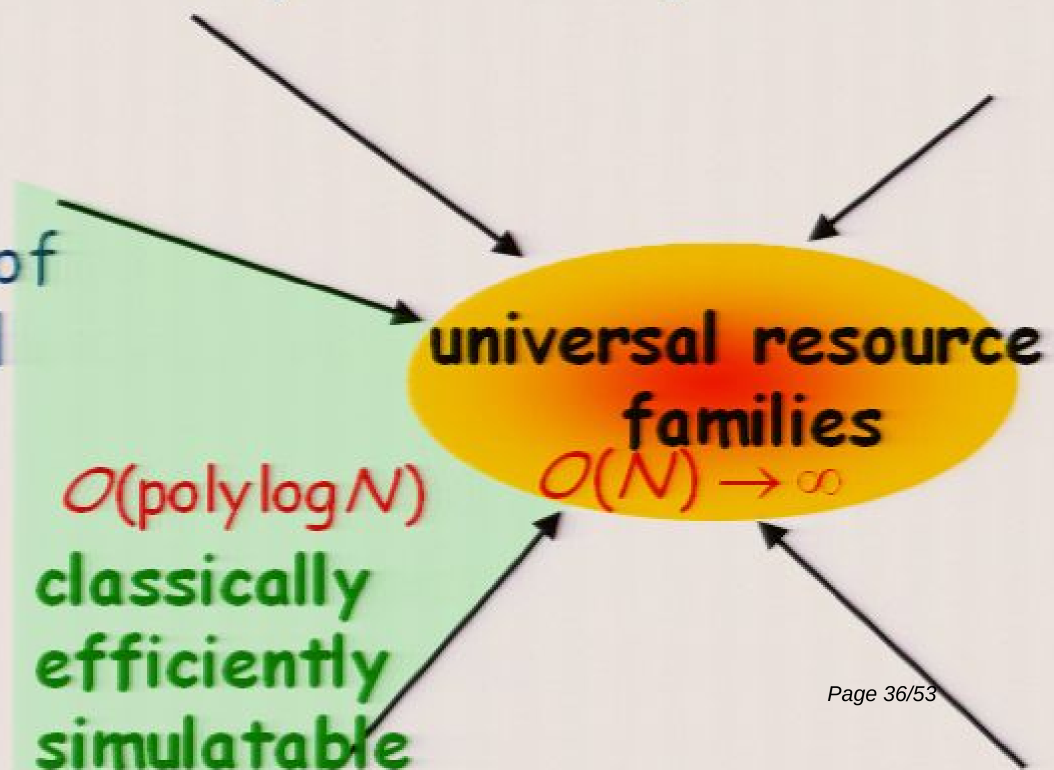
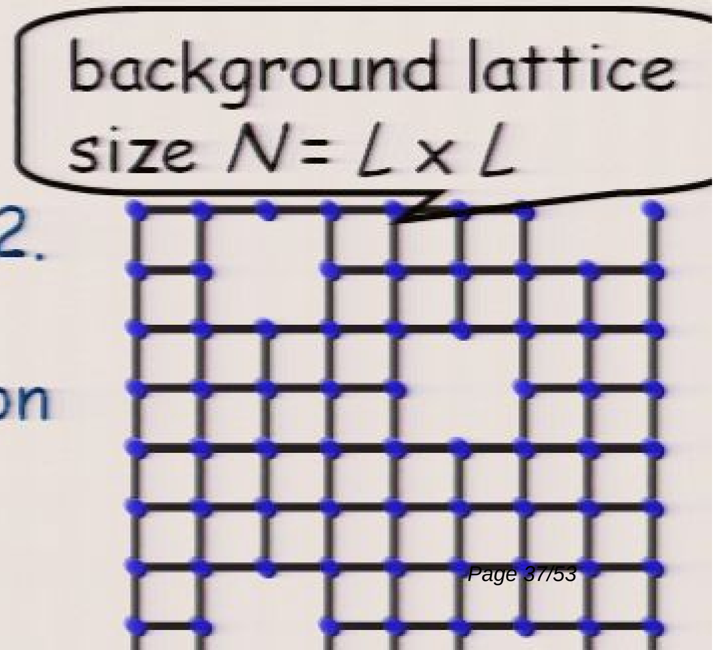


Simple model with phase transition

2D square lattice with holes

(cf. physical implementation by the cold atoms stored in the optical lattice in the Mott-insulator regime)

every site is occupied independently with probability p_{site}, followed by the controlled-phase operations.
(empty site becomes a "hole" without adjacent edges)
the locations of holes are heralded.



effective dimension is decreasing from 2.

p_{site} corresponds to physical imperfection in filling the 2D square lattice.
"Is the value as the resource getting worse gradually?" --- NO!

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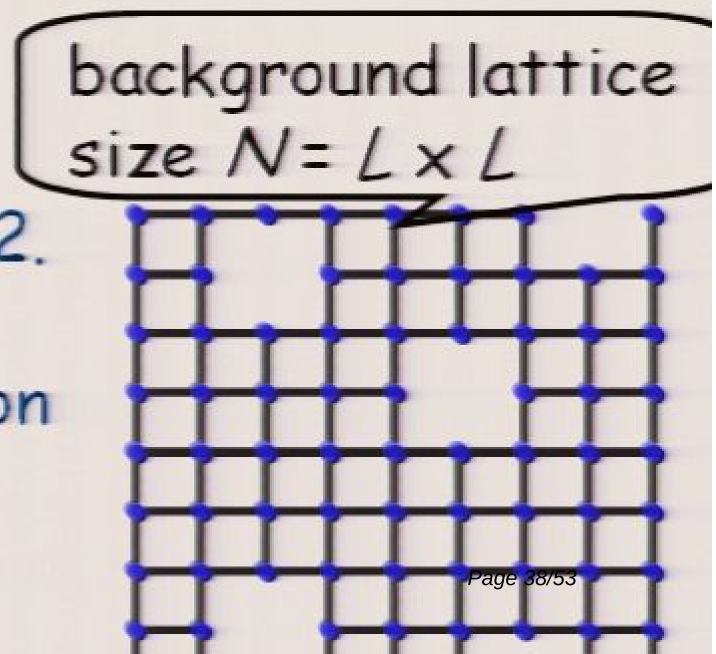

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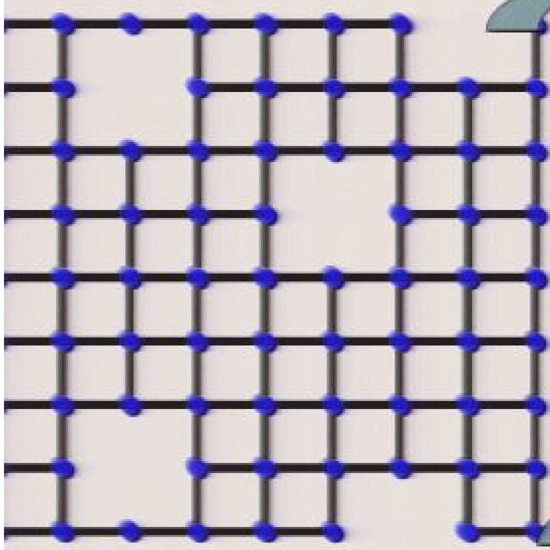
Percolation

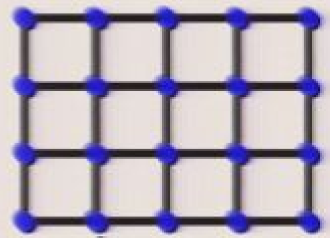
ercolation (existence of $O(N)$ giant cluster) above $p_{th} = 0.592$.

Jote: the $O(N)$ connected giant graph state is not necessarily niversal (cf. 1D cluster and tree graphs with size N).

poly-time classical and quantum algorithm



$p_{site} > p_{th}$

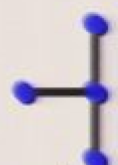


$E_{wd} \geq O(\sqrt{N})$

$O(N)$-qubit universal resource state (with a constant overhead depending on p_{site})

any LOCC

$p_{site} < p_{th}$



$E_{wd} \leq O(\log N)$

not efficiently universal (one-way QC is classically simulatable efficiently)

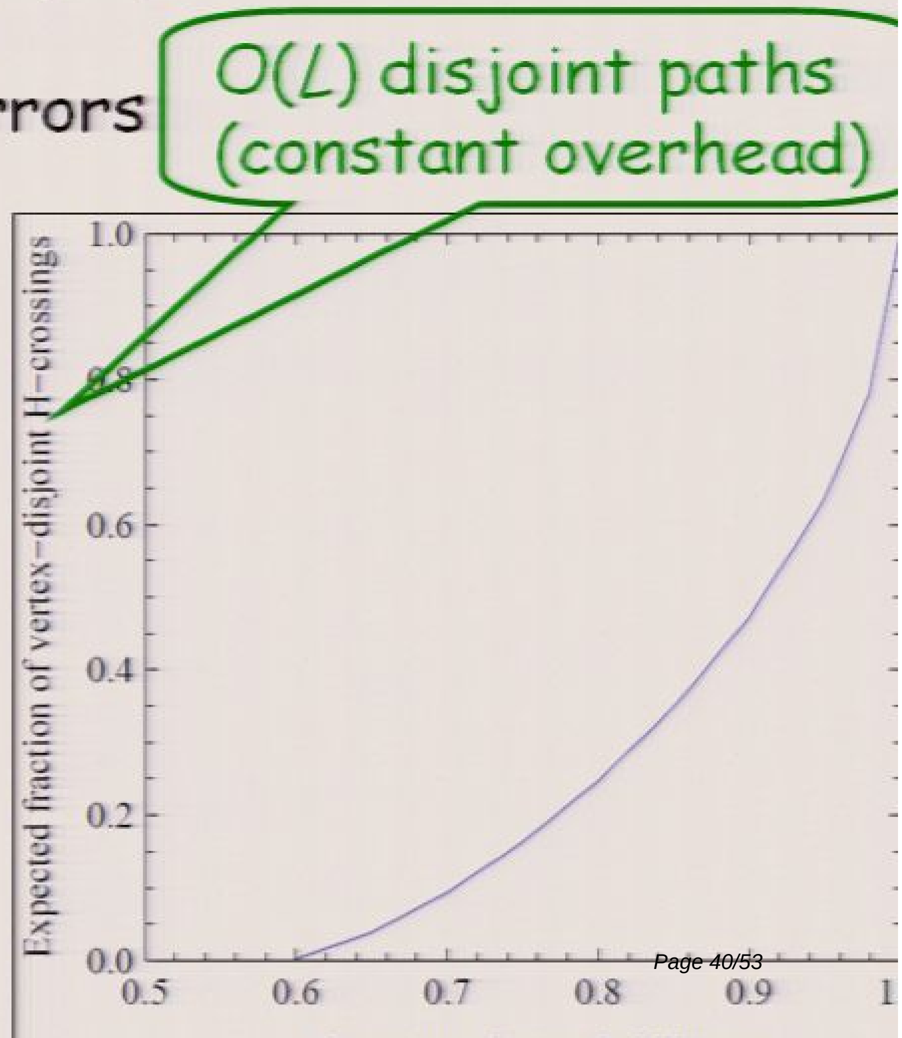
$p_{site} > p_{th}$

Supercritical phase

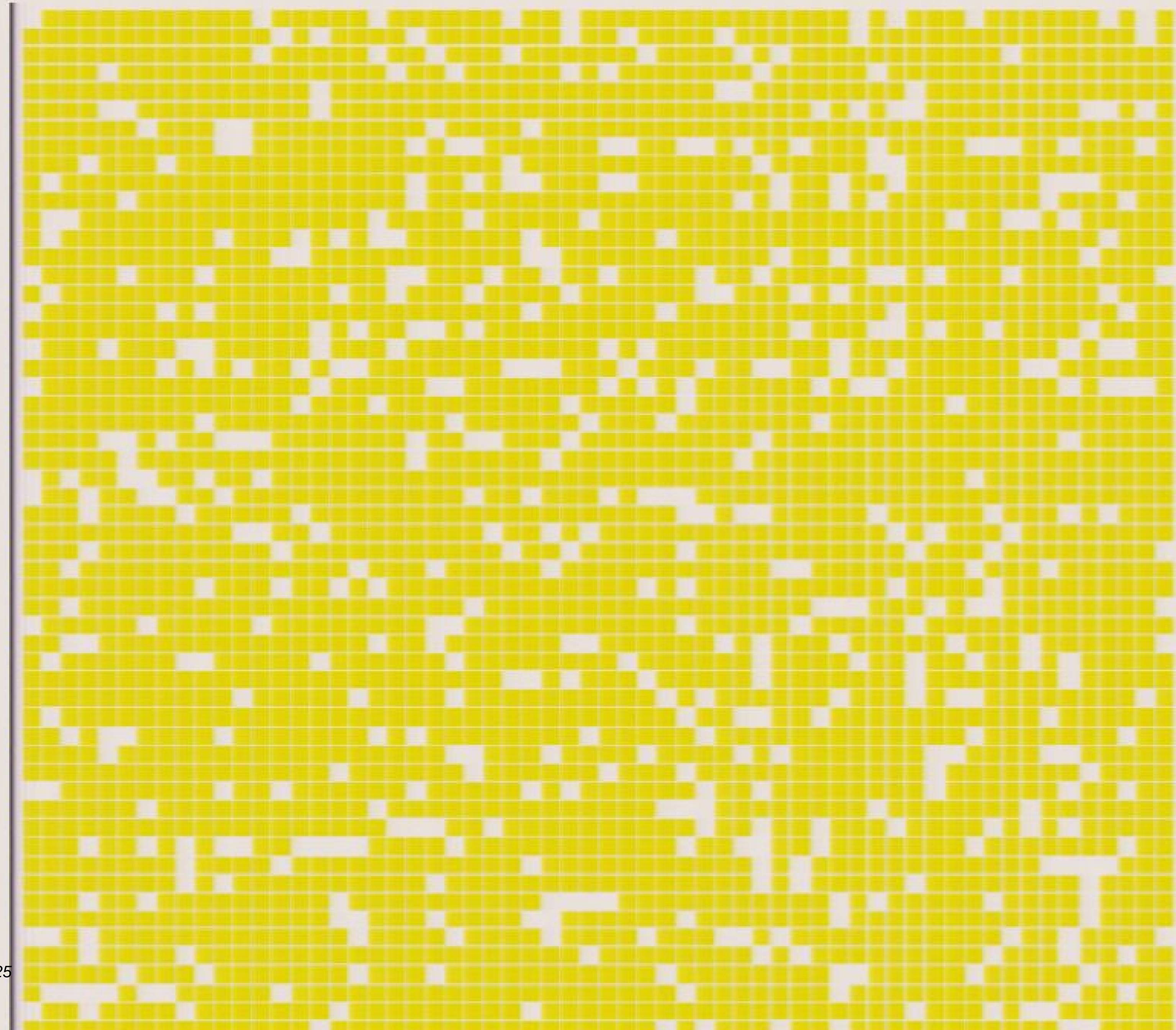
olynomial-time (quasi-deterministic) algorithm to concentrate erfect 2D cluster state with a constant overhead c

1) Lattice identification by classical poly-time algorithm
   - identification of disjoint paths
   - localization and correction of errors

2) Lattice contraction by quantum measurements



Concentration algorithm at p=0.85



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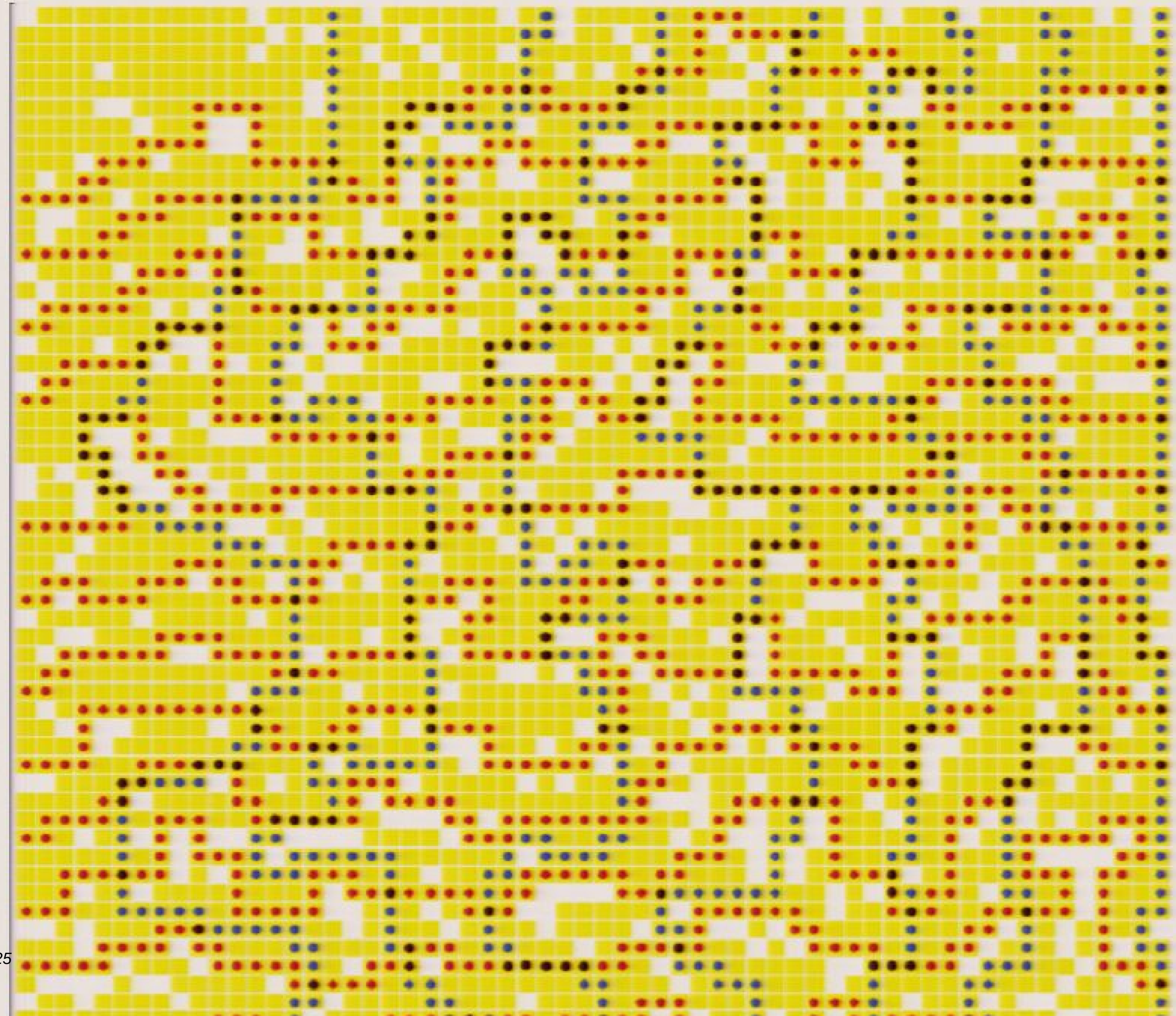
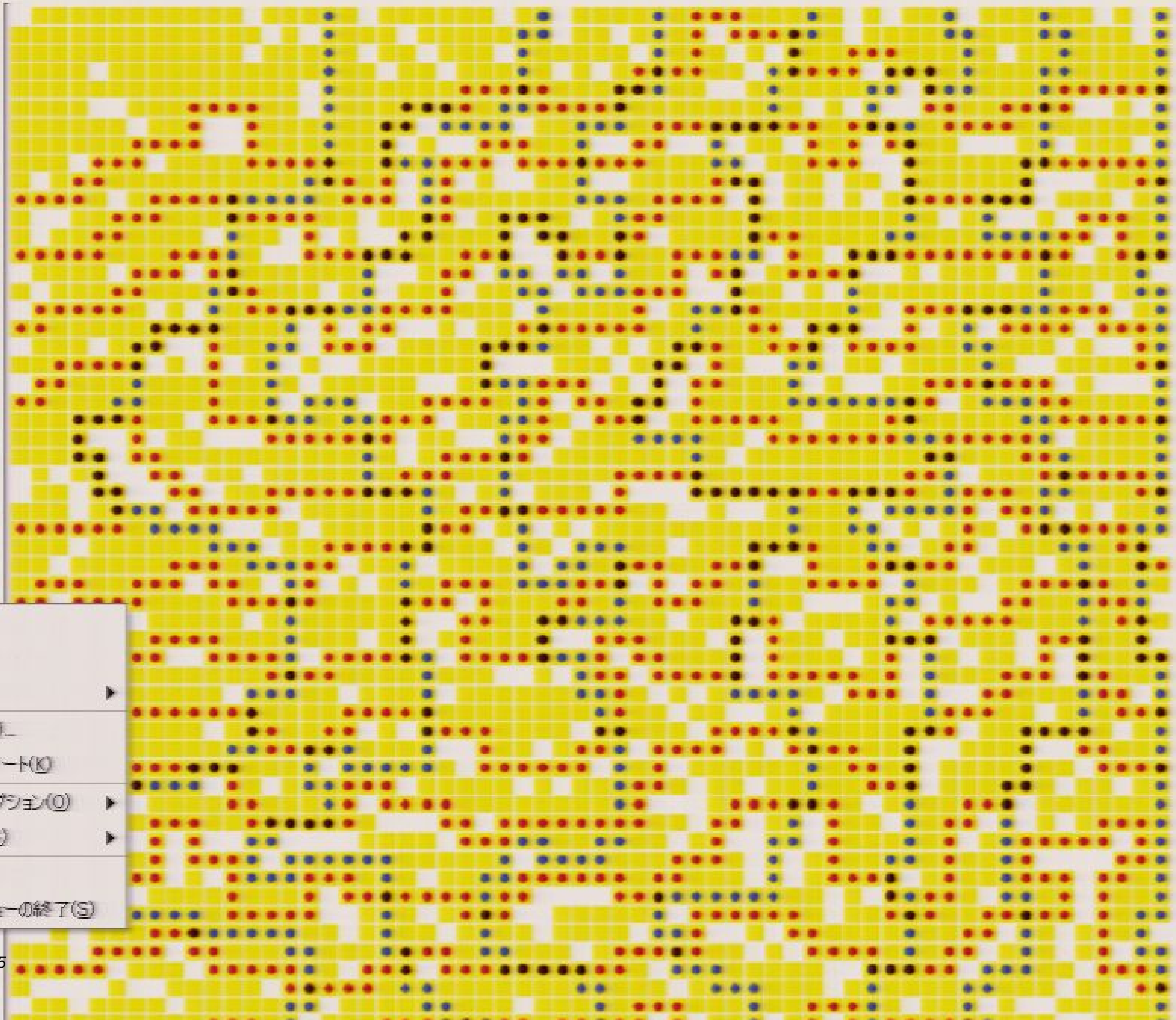
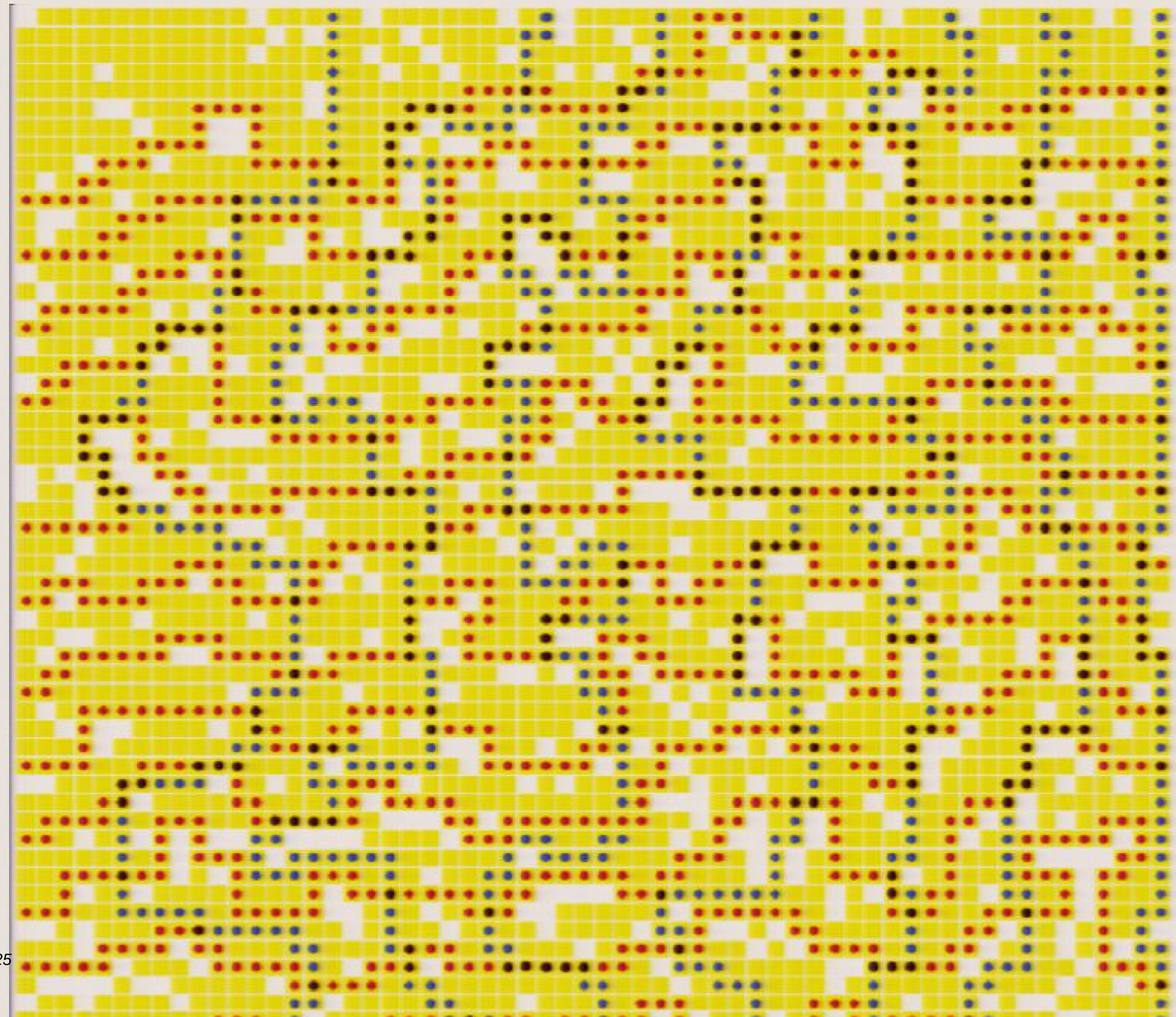


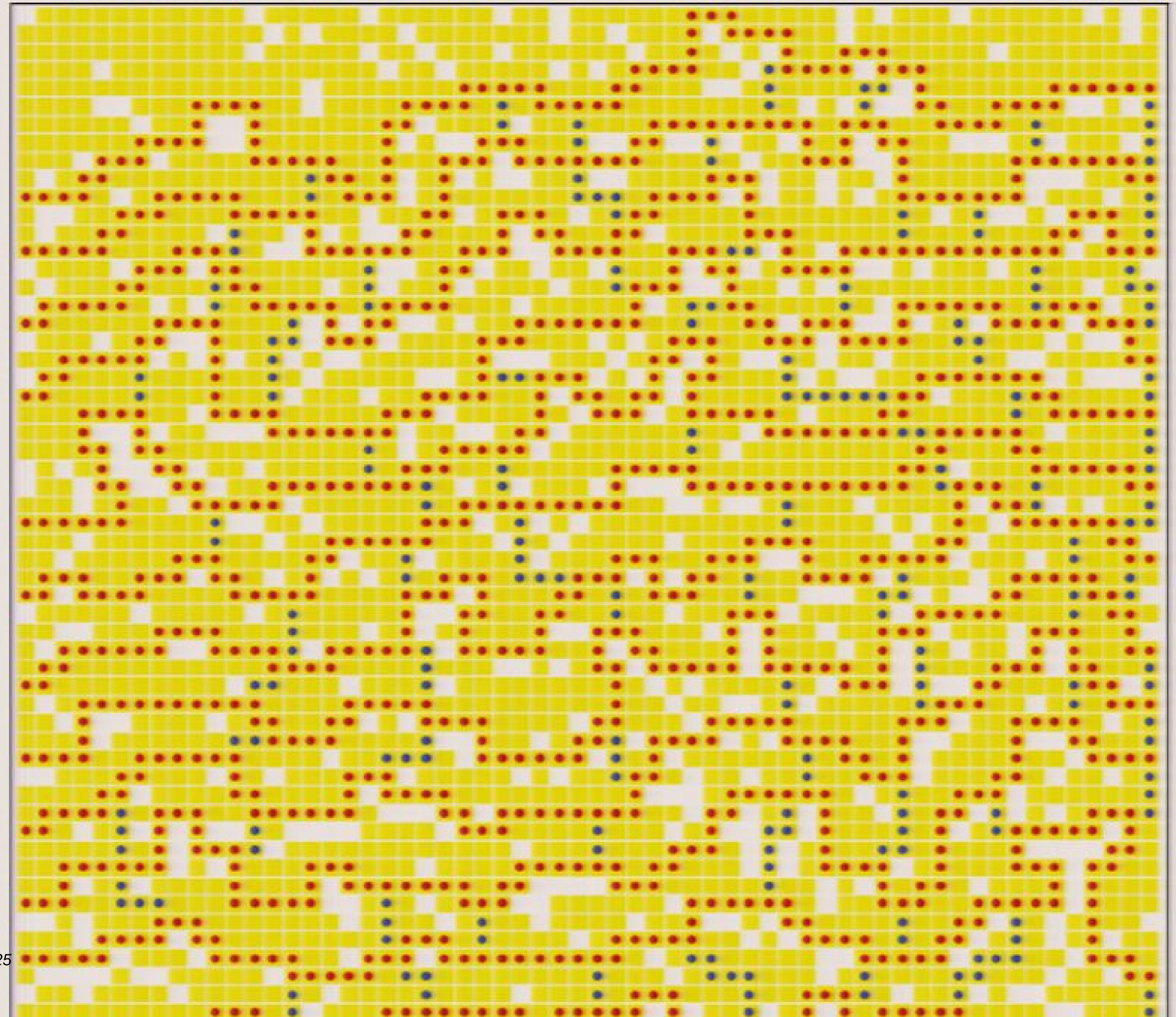
Concentration algorithm at p=0.85



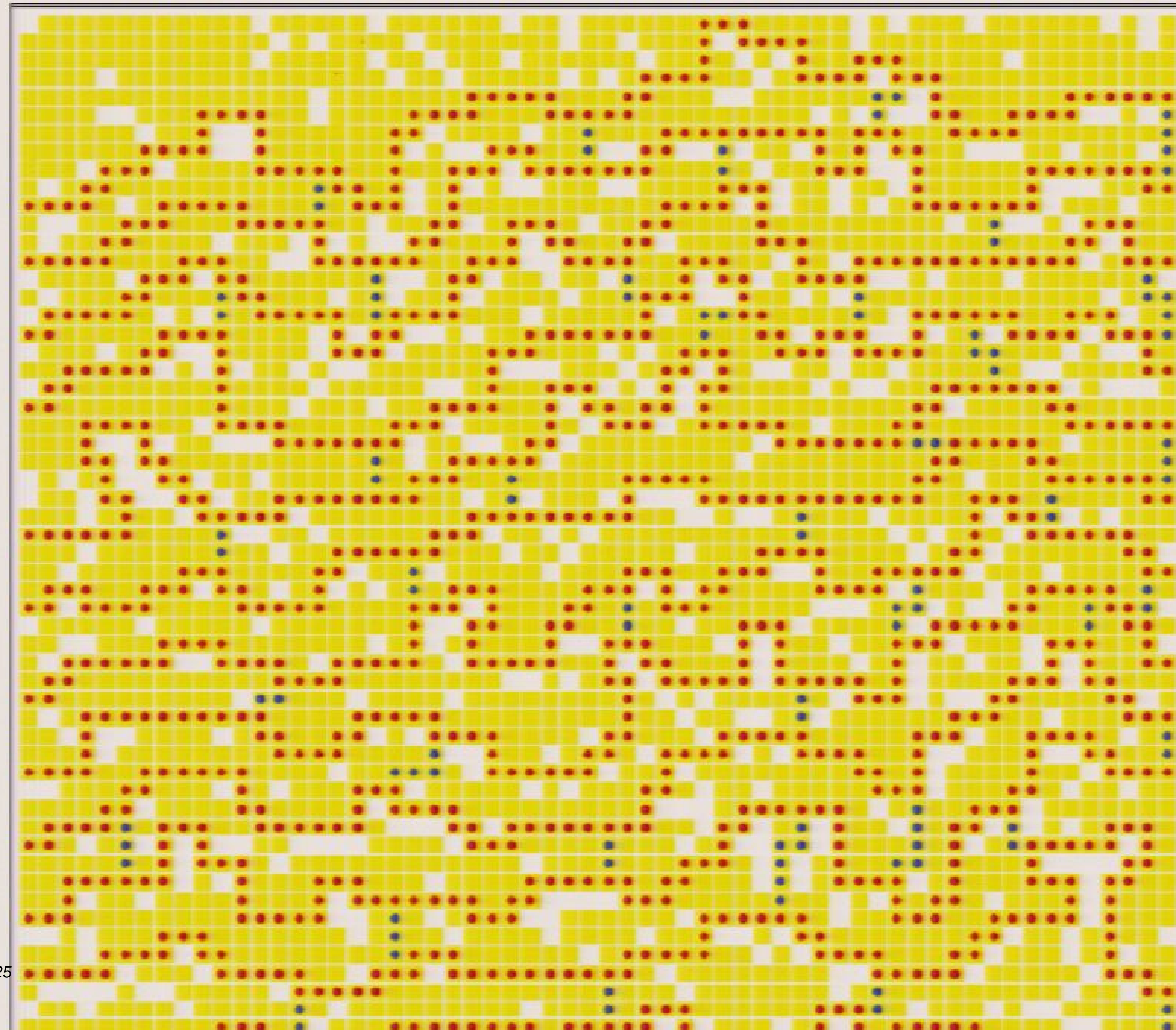
Concentration algorithm at p=0.85



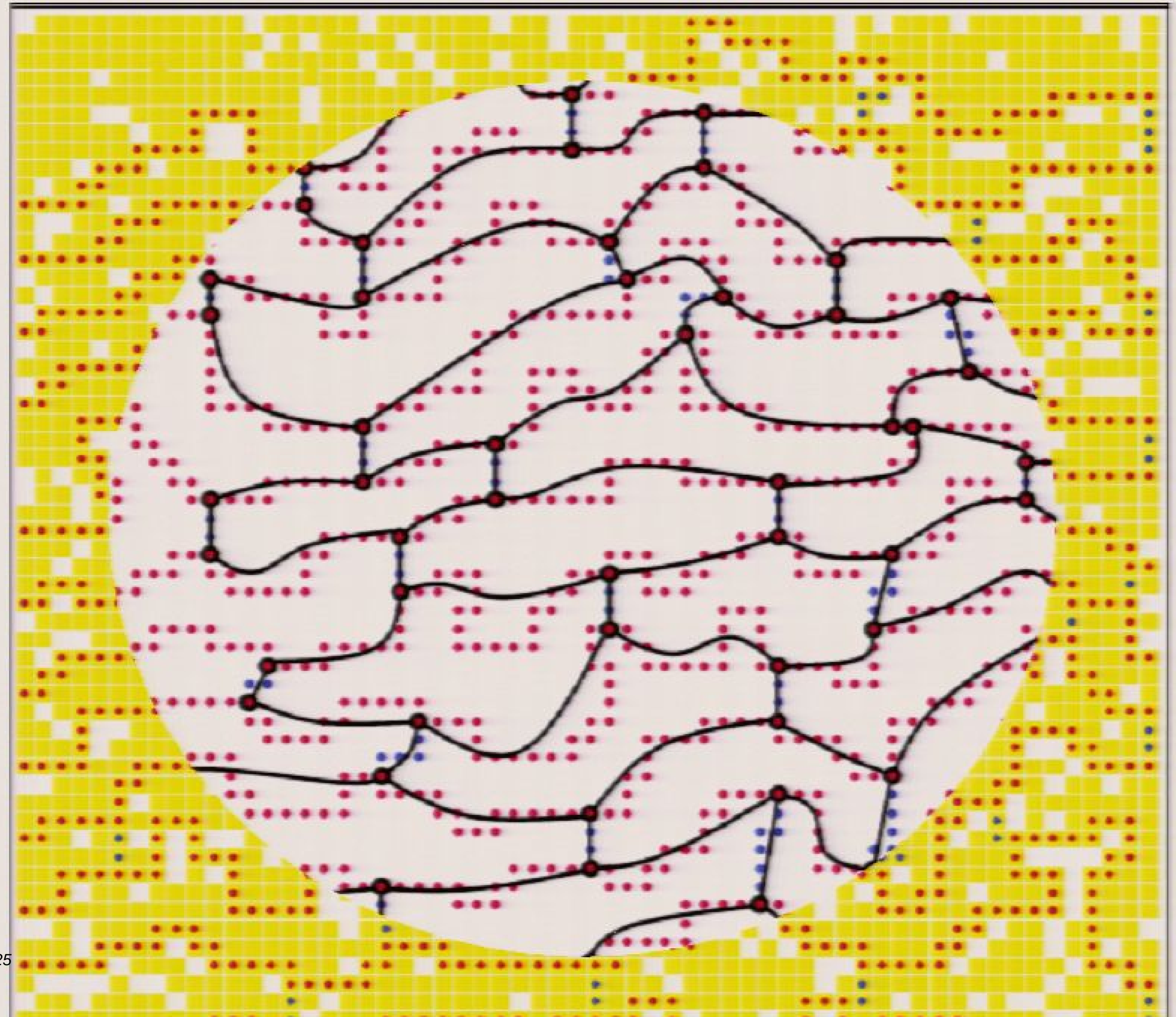
Concentration algorithm at p=0.85



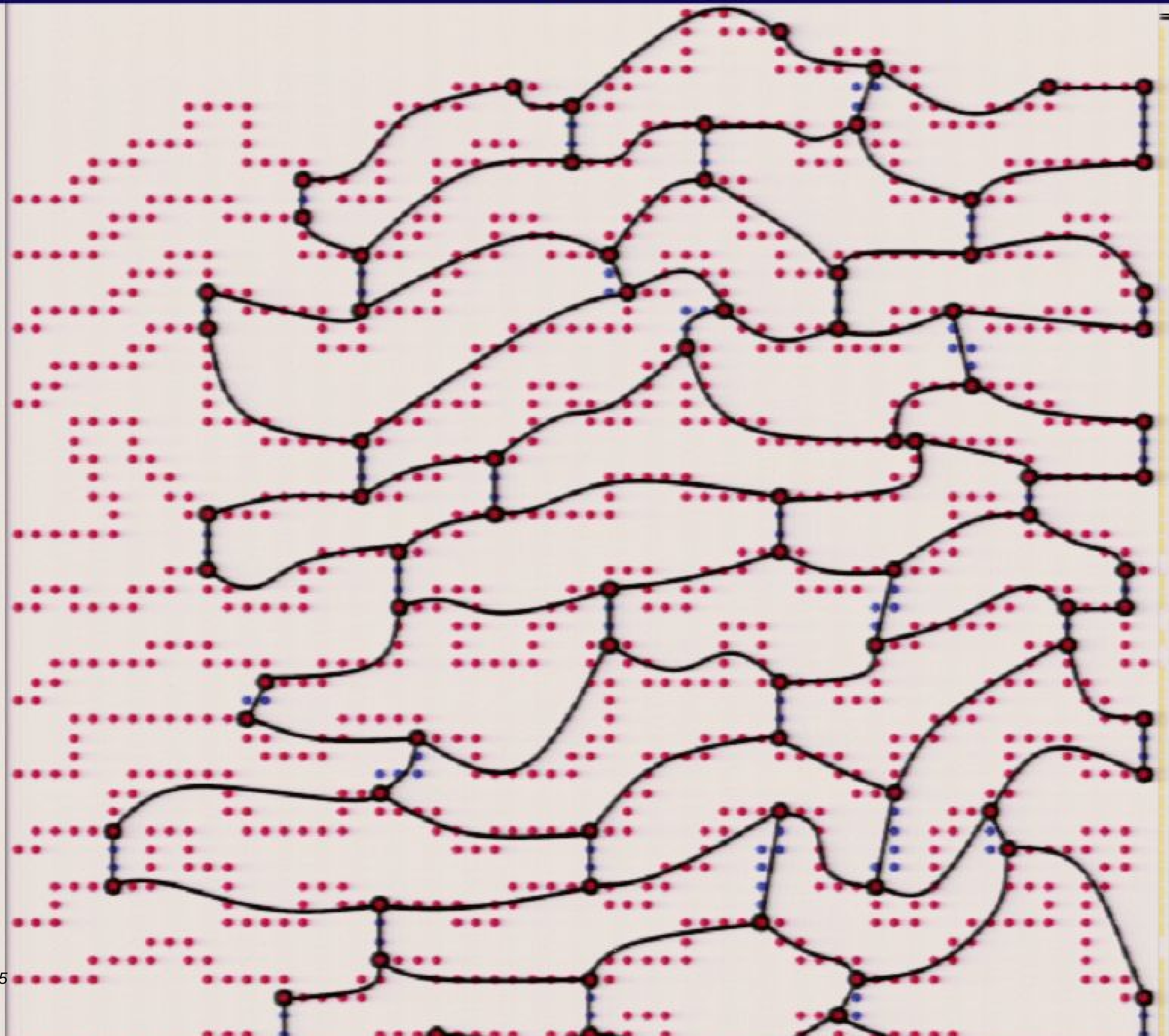
Concentration algorithm at p=0.85



Concentration algorithm at p=0.85



Concentration algorithm at p=0.85



$p_{site} > p_{th}$

Supercritical phase

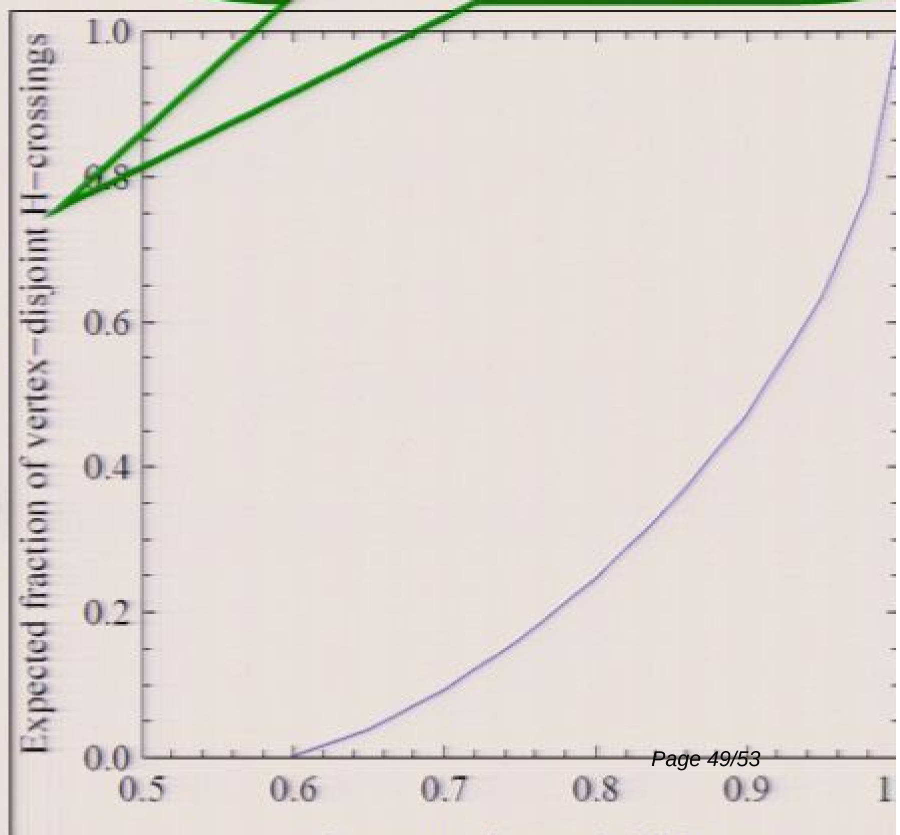
olynomial-time (quasi-deterministic) algorithm to concentrate erfect 2D cluster state with a constant overhead c

1) Lattice identification by classical poly-time algorithm

- identification of disjoint crossings
- localization and correction of errors

$O(L)$ disjoint paths (constant overhead)

2) Lattice contraction by quantum measurements



$E_{wd}(\textit{faulty lattice with size } N)$

$E_{wd}(\textit{perfect 2D cluster with size } cN)$

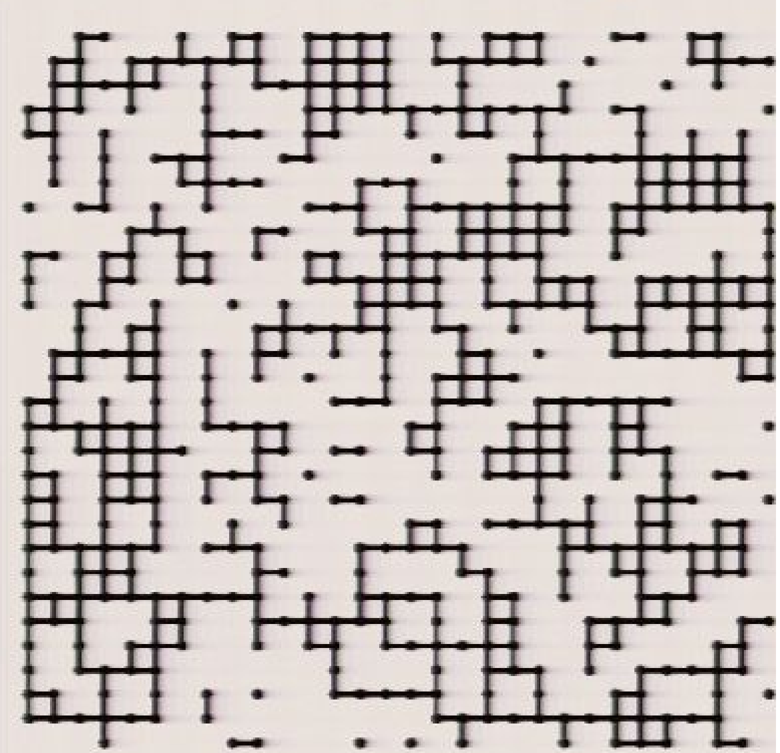
$O(\sqrt{N})$

Subcritical phase

$p_{site} < p_{th}$

largest component is almost surely $O(\log N)$

$$E_{wd}(\otimes_j |G_j\rangle) = \max_j E_{wd}(|G_j\rangle)$$
$$\leq O(\log N)$$



The total amount of entanglement is determined by that of the most entangled connected component.

uantum computational power is not simply additive!"

he computational power is not efficiently universal, and ctually any measurement-based computation on it is fficiently simulatable by classical computer.

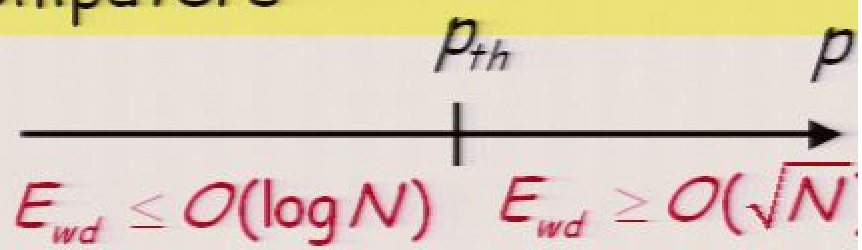
Phase transition of computational power

2D square lattice with holes

The 2D cluster state with holes undergoes the phase ransition in its computational power at the percolation hreshold $p_{\rm th} \sim 0.5927....$

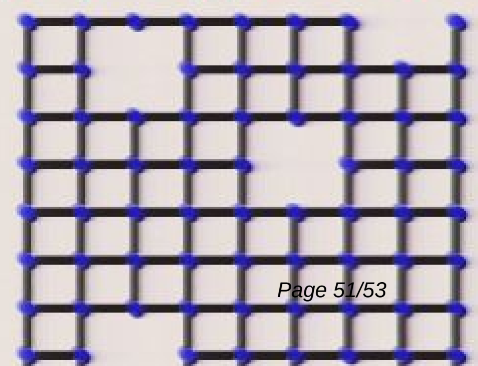
$p_{\rm site} > p_{\rm th}$: it is as efficiently universal as the perfect 2D cluster with size N

$p_{\rm site} < p_{\rm th}$: measurement-based QC on it is efficiently simulatable by classical computers



entanglement as an order parameter

amount of entanglement measured by entanglement width changes exponentially at the threshold



Summary

rom which entanglement feature and how does the
easurement-based quantum computer obtain its superior
omputational power compared with the classical computer?

- scaling of entanglement reflects computational power
- phase transition (exponential change of entanglement)

- Van den Nest, Miyake, Dür, & Briegel,
Phys. Rev. Lett. **97**, 150504 (2006).

- Van den Nest, Dür, Miyake, & Briegel,
New J. Phys. **9**, 204 (2007), in the special issue on the
measurement-based quantum information processing.

- Browne, Elliott, Flammia, Merkel, Miyake, & Short,
arXiv:0709.1729

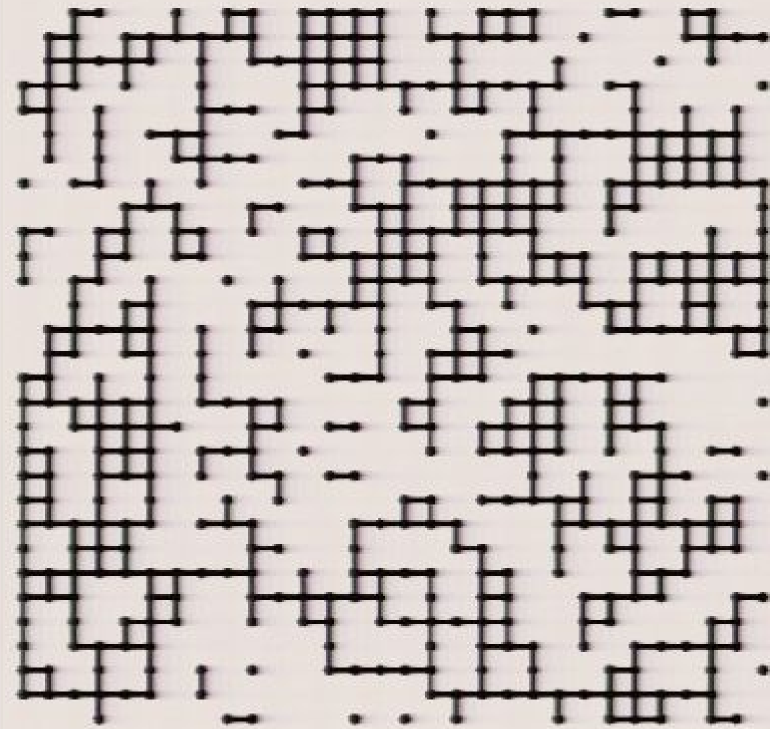
Subcritical phase

$p_{site} < p_{th}$

largest component is almost surely $O(\log N)$

$$E_{wd}(\otimes_j |G_j\rangle) = \max_j E_{wd}(|G_j\rangle) \leq O(\log N)$$

The total amount of entanglement is determined by that of the most entangled connected component.



quantum computational power is not simply additive!"

The computational power is not efficiently universal, and
actually any measurement-based computation on it is
efficiently simulatable by classical computer