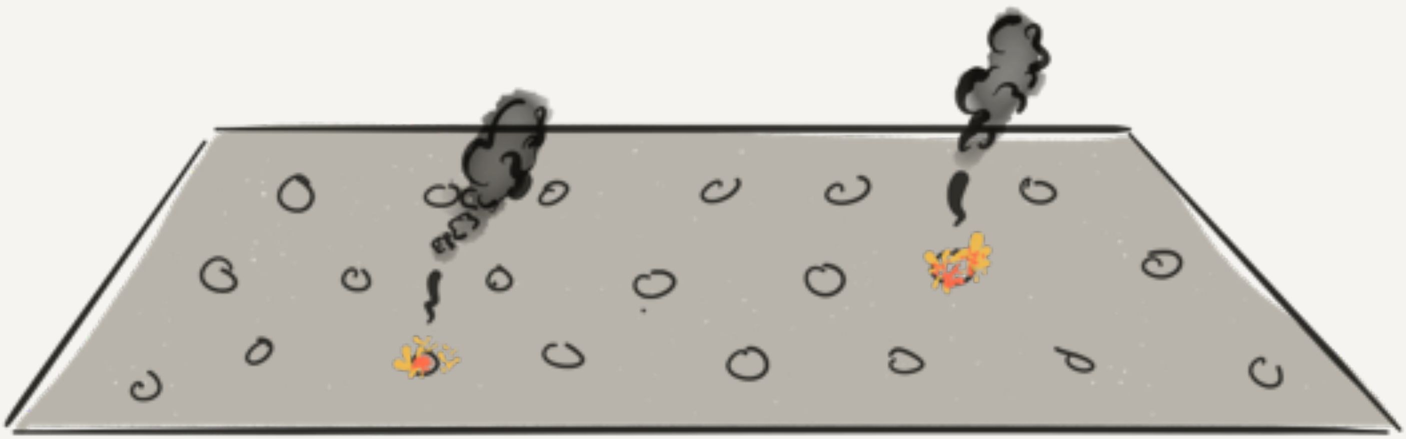
TIME-CORRELATED NOISE IN QUANTUM COMPUTATION

Motivation

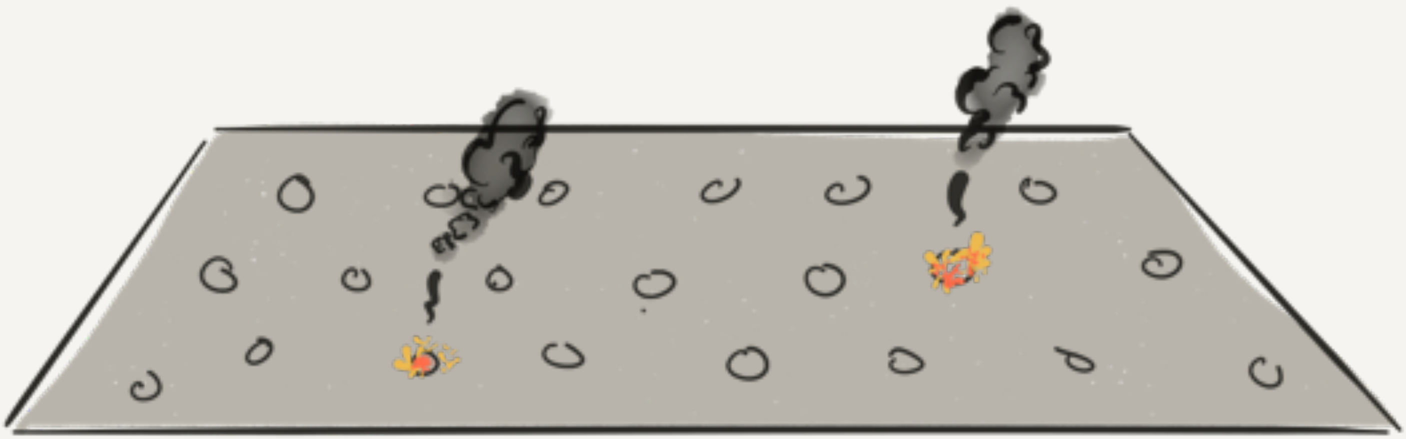
Fault-tolerant computation

- computing requires isolation & control
- maybe no such qubits occur "naturally"
- fault-tolerance: generic approach
- noise has to be weak & weakly correlated in spacetime
- here: arbitrary correlations in time

Fabrication faults



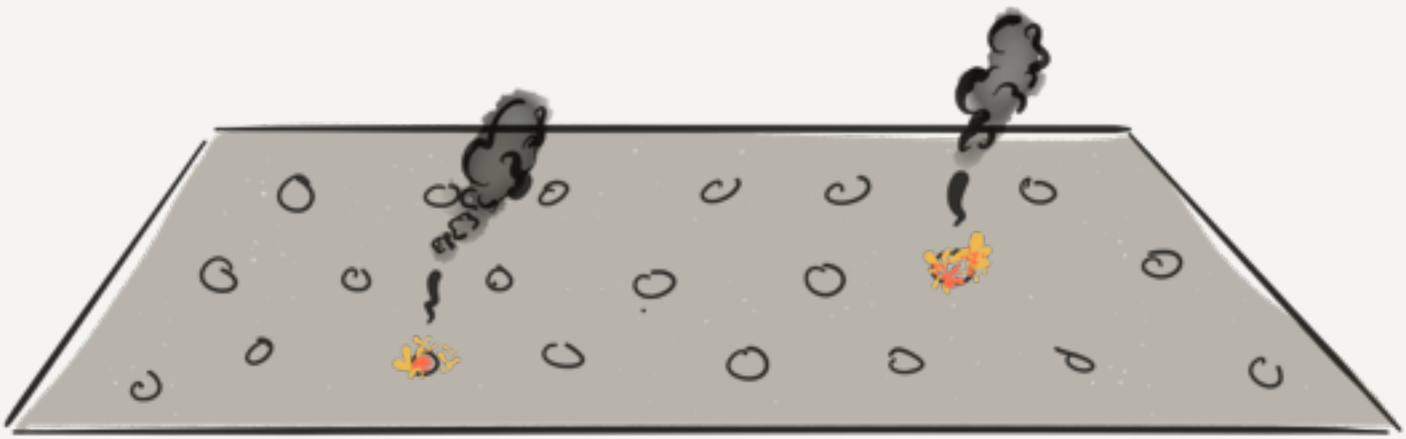
Fabrication faults



fabrication faults: <u>known</u> / unknown

operations: <u>flexible</u> / fixed

Fabrication faults

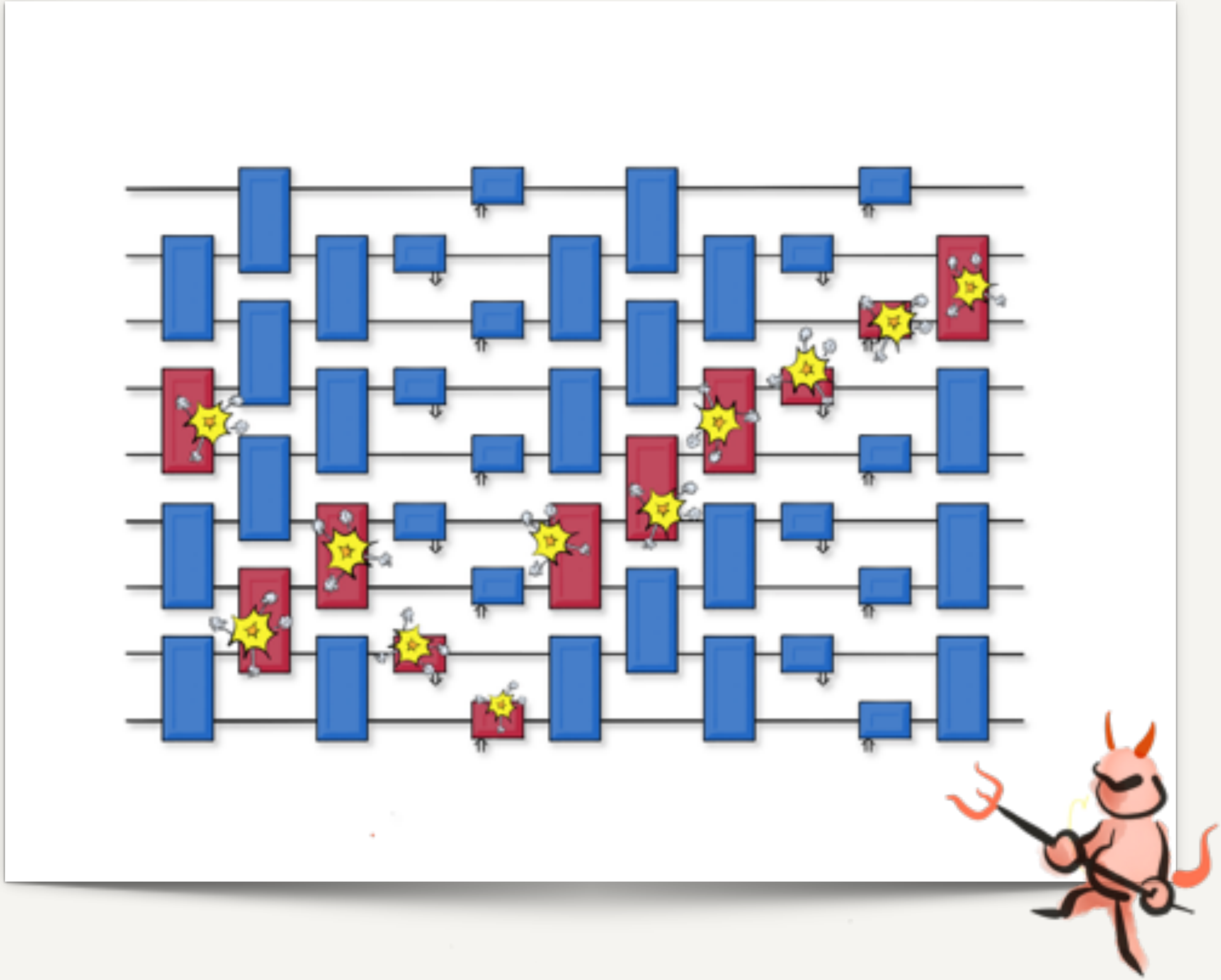


fabrication faults: known / <u>unknown</u>

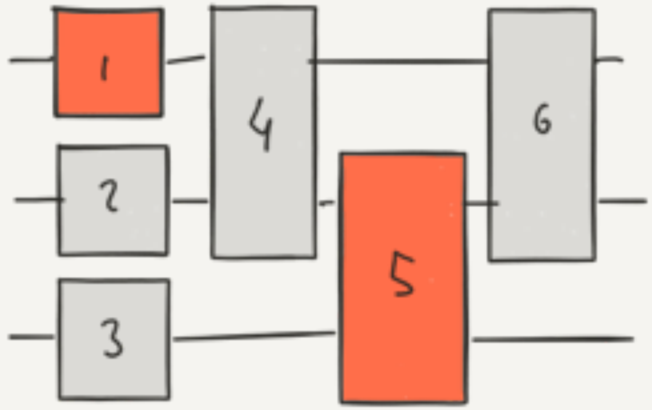
operations: flexible / <u>fixed</u>

Noise model

Stochastic noise

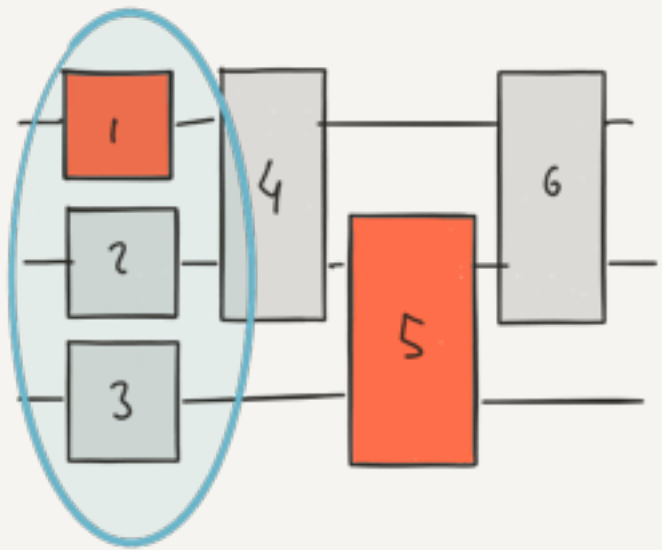


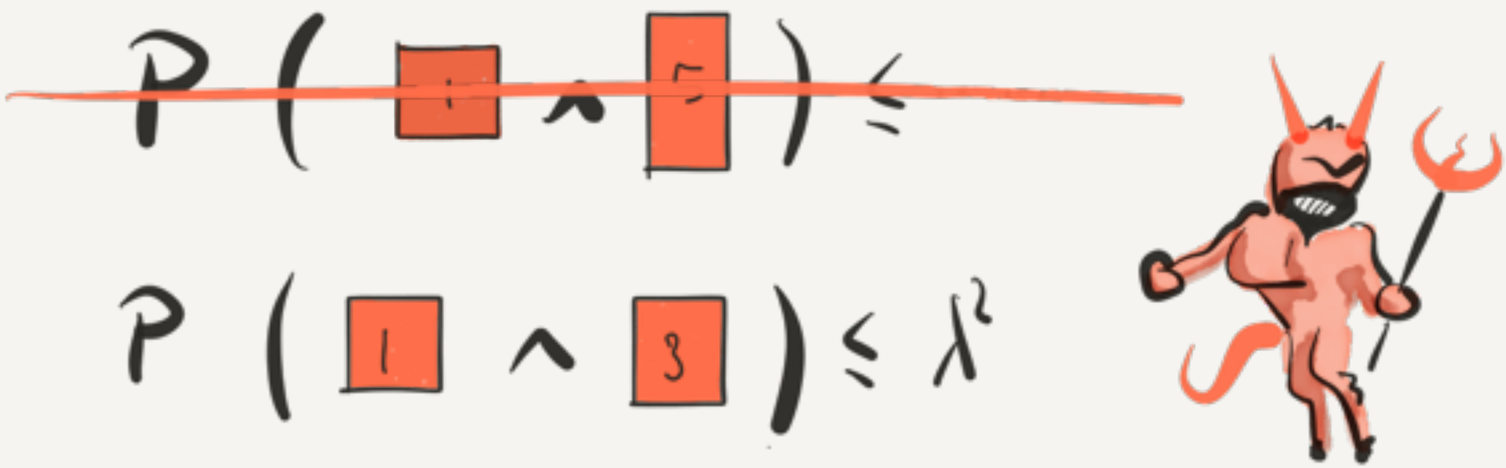
Local stochastic noise



$$P(\boxed{1} \wedge \boxed{5}) \leq \lambda^2$$

Spatially local stochastic noise

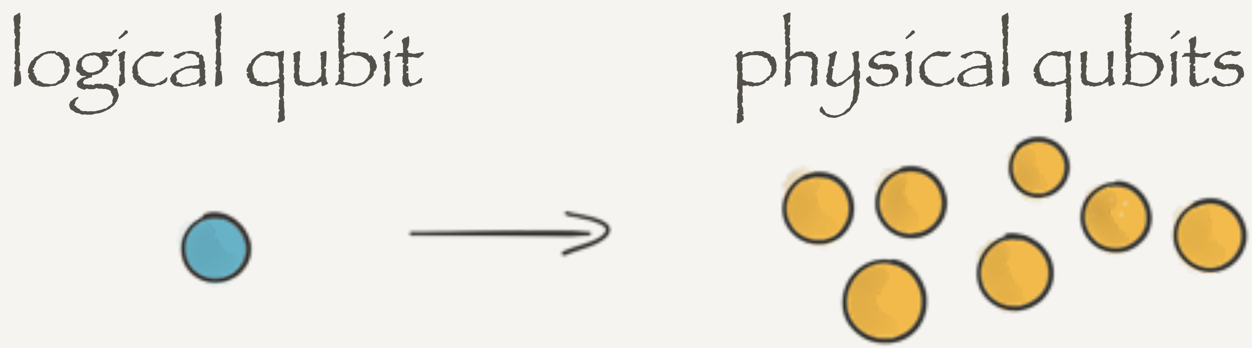




Quantum memories based on single-shot error correction exhibit an error threshold under spatially local stochastic noise

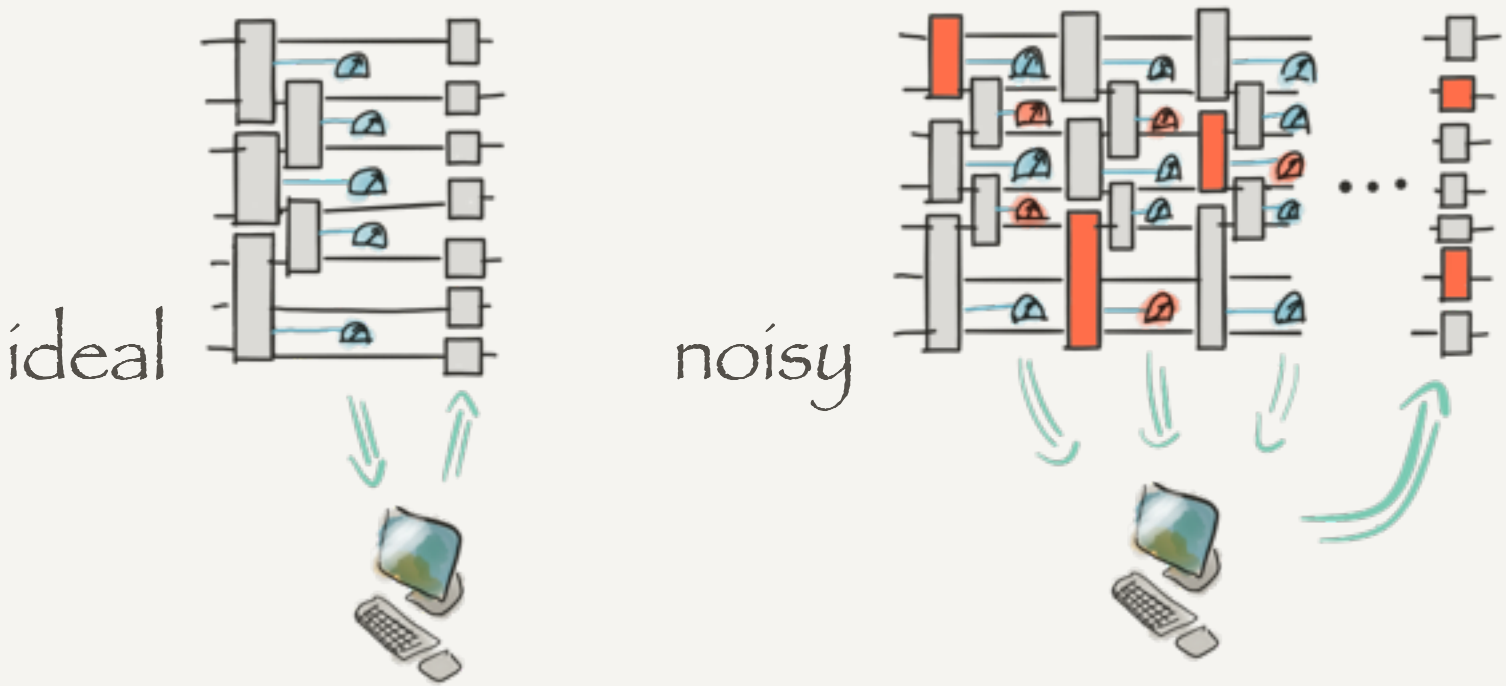
Single-shot error correction

Error correction

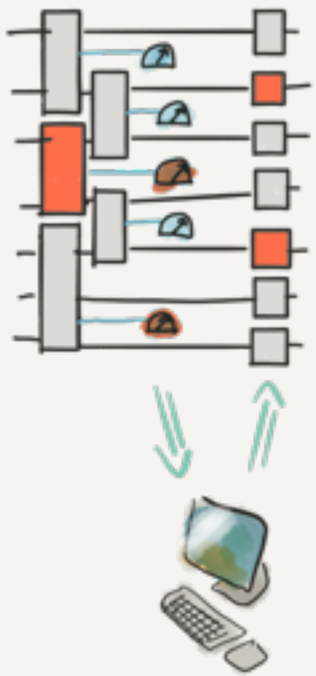


extra d.o.f. → check ops

Error correction

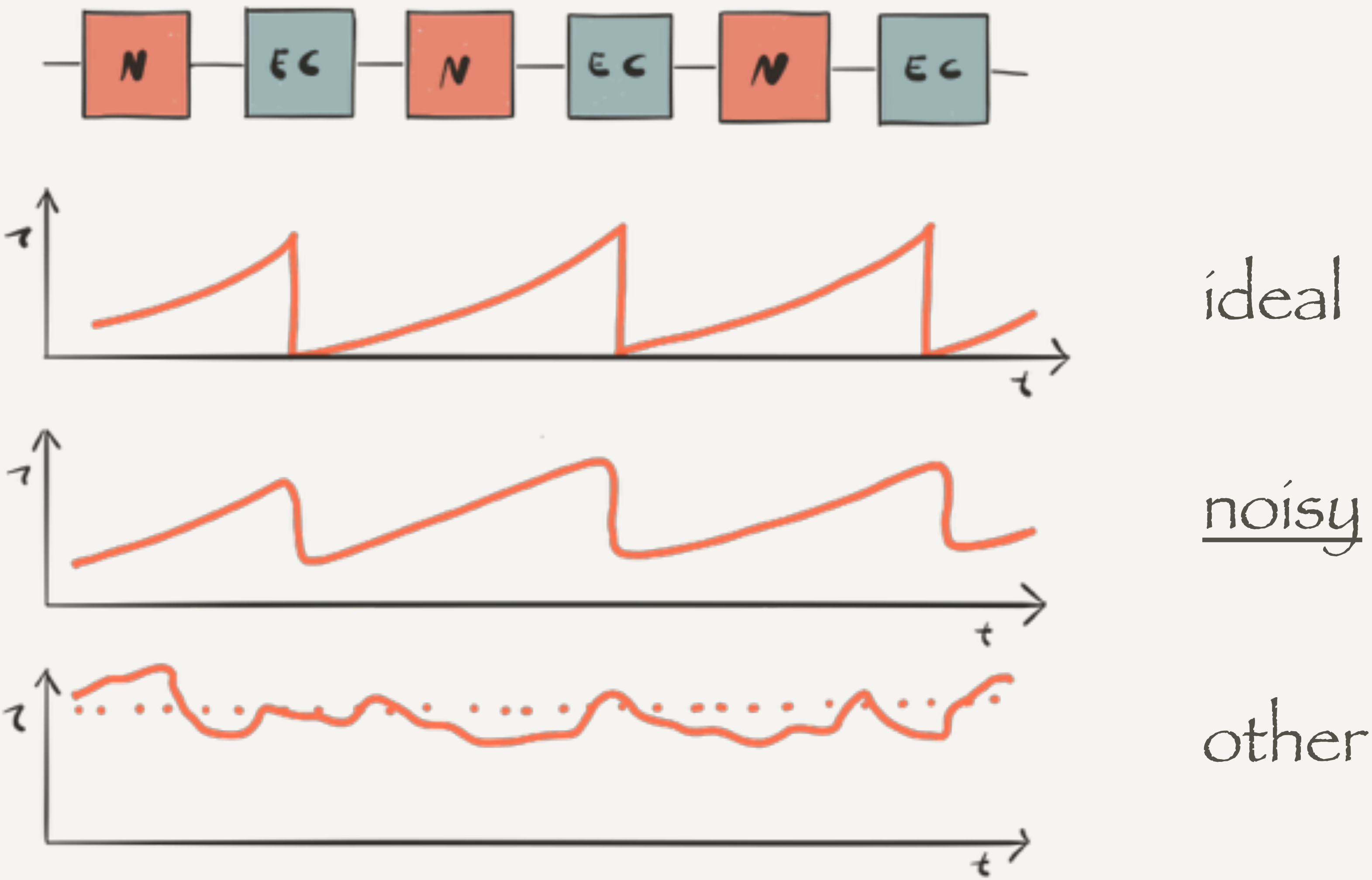


Error correction



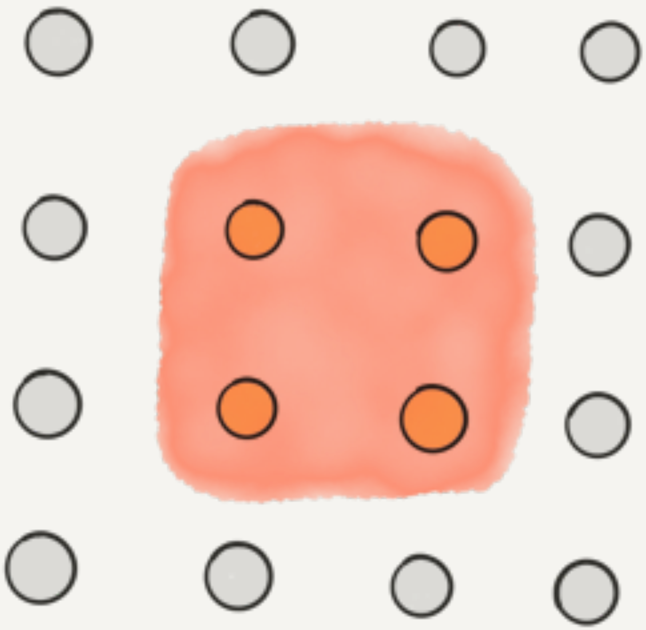
single-shot if
quantum-local
(analogous to LOCC)

Error correction



Topological codes

Topological codes



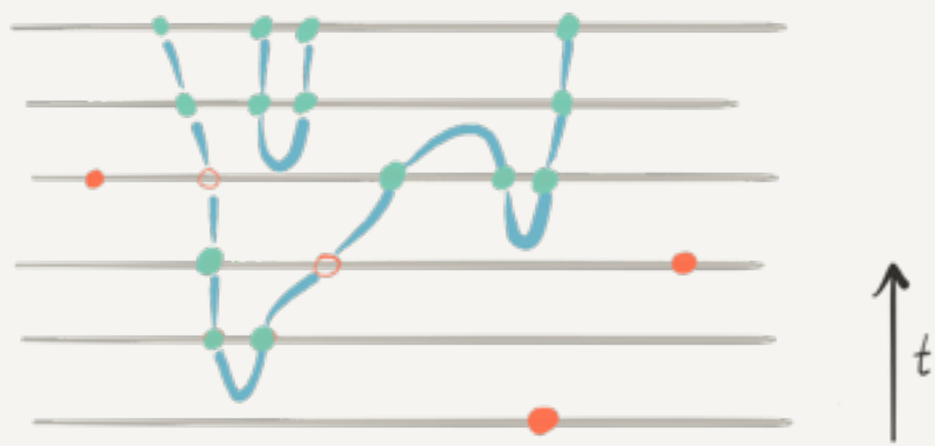
local check operators

local indistinguishability

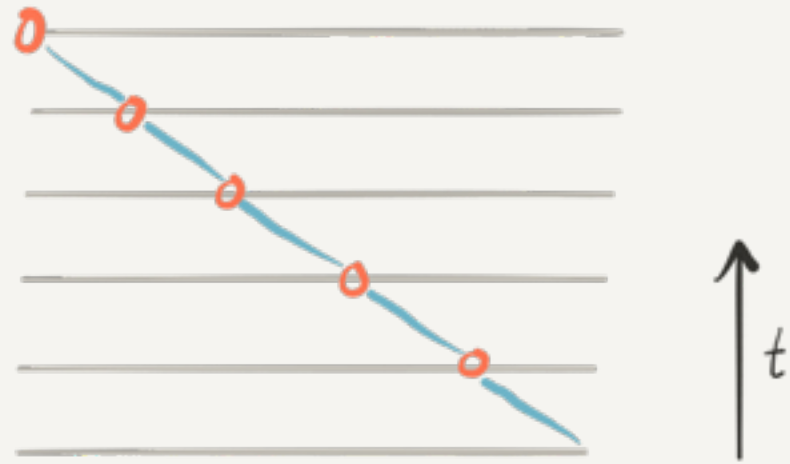
2D codes

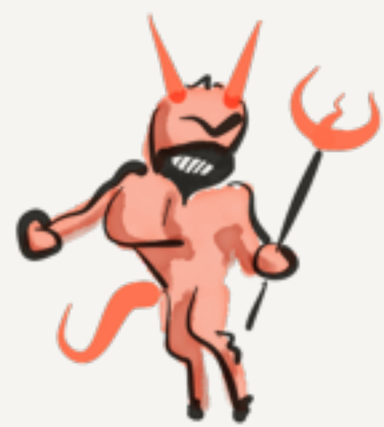
errors: strings

syndrome: endpoints

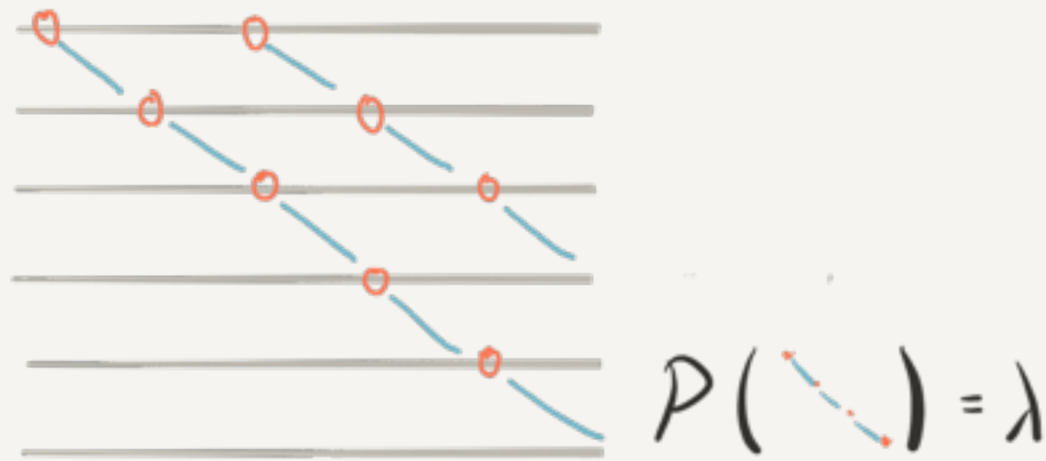


2D codes



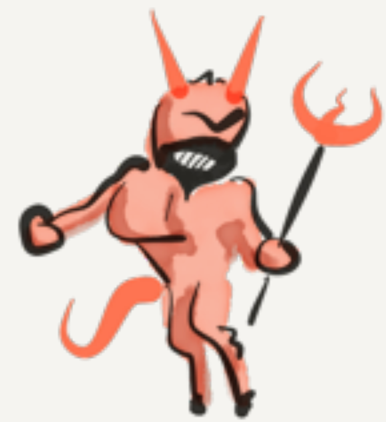


2D codes

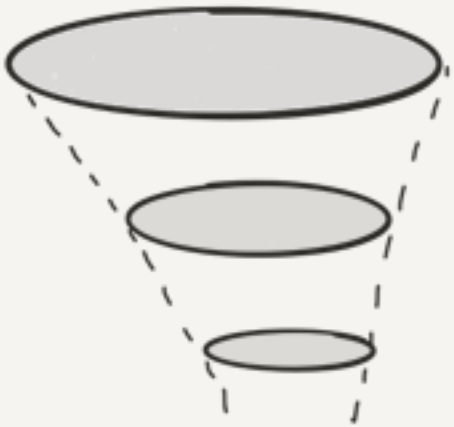


Spatially local (& Markovian), e.g.

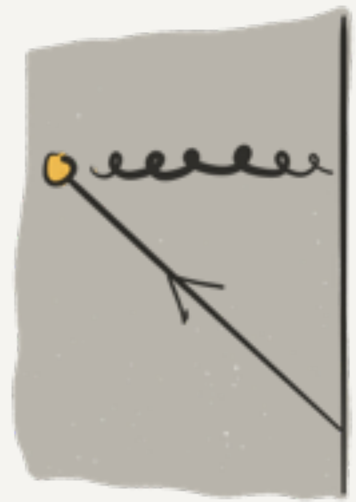
$$P(x_{1},t \wedge x_{2},t) = \lambda^2$$



Single-shot codes

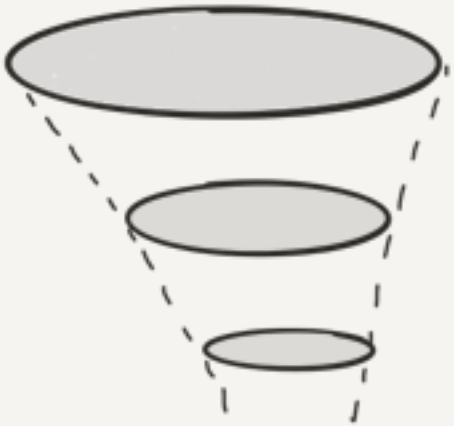


D = 4



D = 3

4D codes



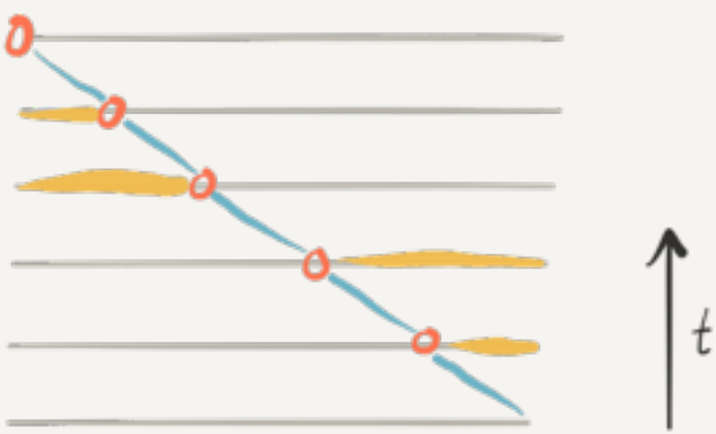
errors: membranes

syndrome: loops

3D codes

errors: strings
syndrome: endpoints

$$p\left(\overset{e}{\frown}\right) \leq \lambda^{e}$$

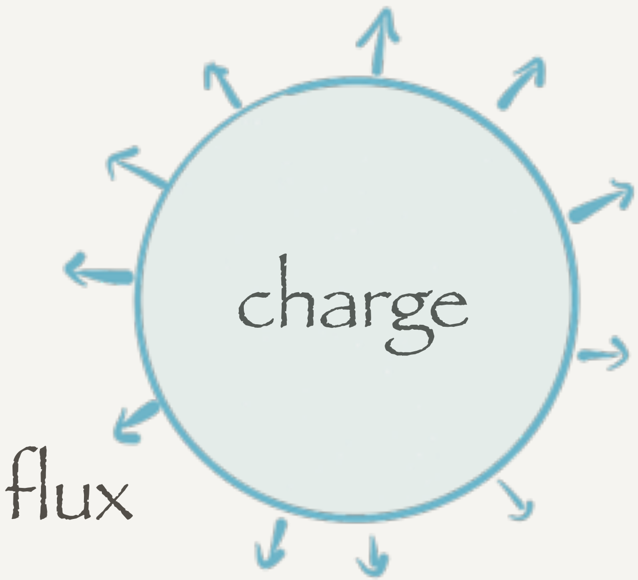


Subsystem codes

logical qubit → physical qubits

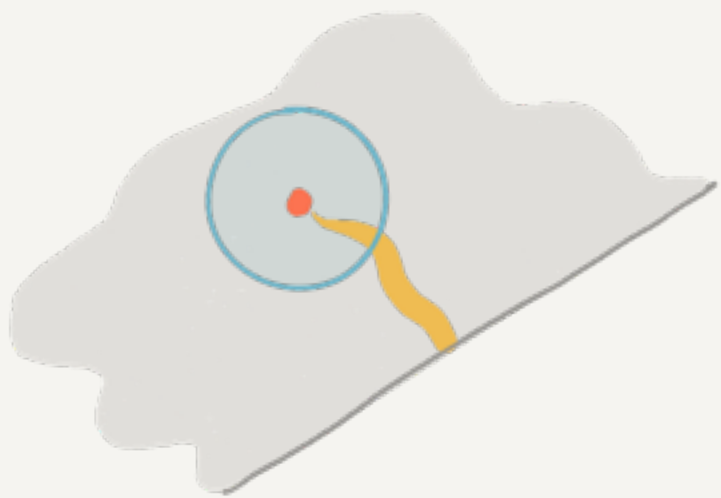
extra d.o.f. { check ops, gauge d.o.f.

Gauss law



charge → error syndrome

field → gauge syndrome



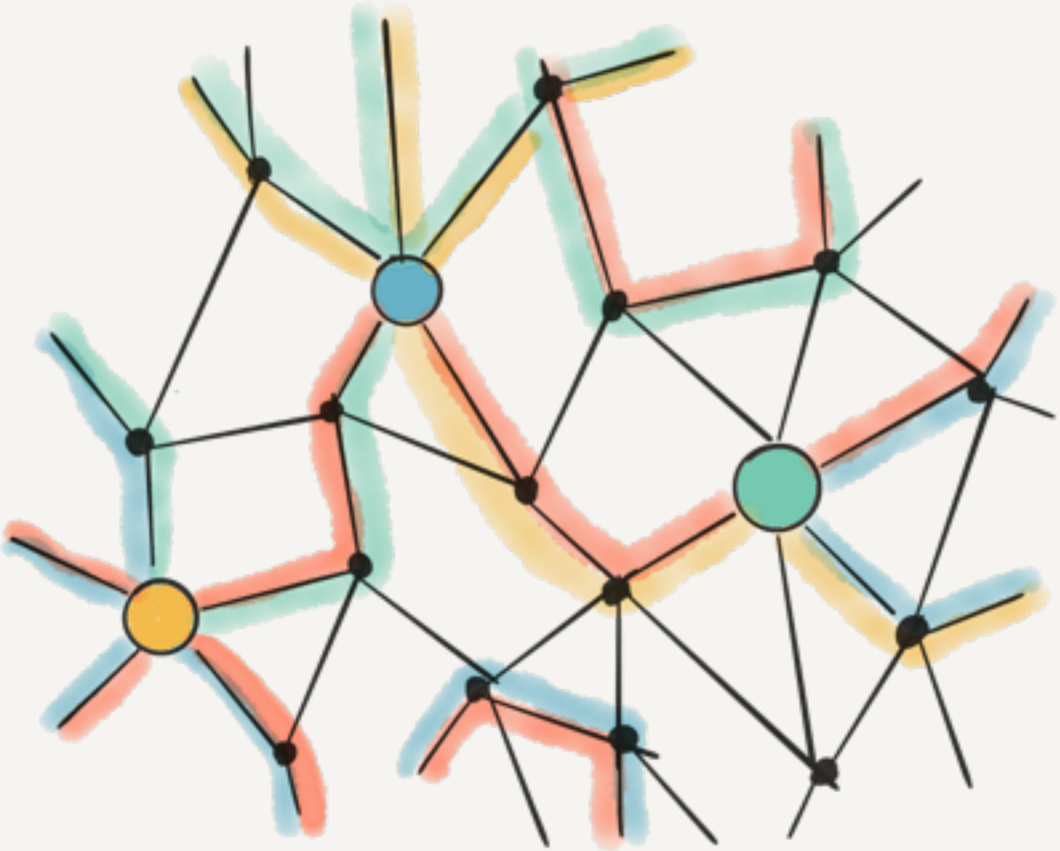
3D gauge color codes

tetrahedron = qubit

edge = gauge op

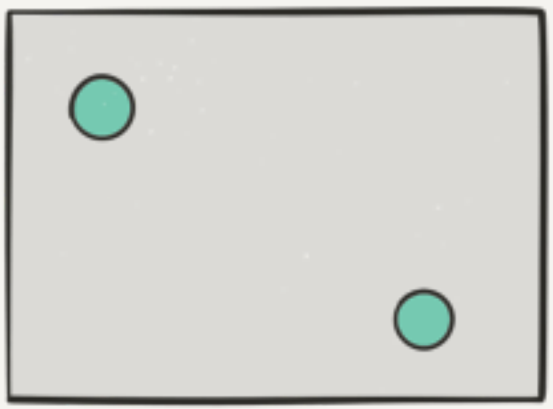
vertex = check op

X & Z type



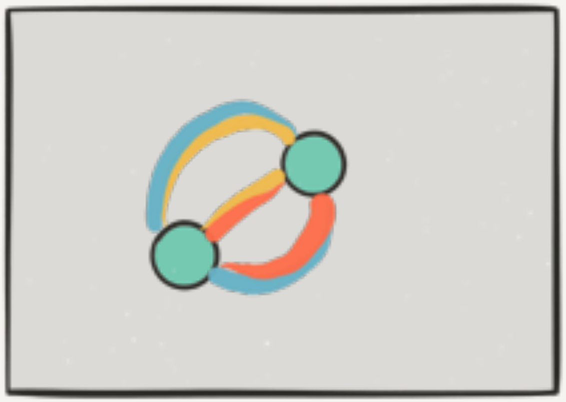
Confinement

check ops



unconfined

gauge ops



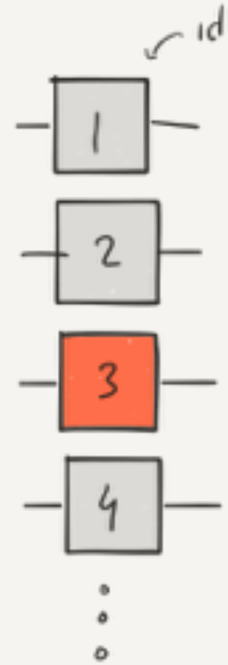
confined!

Result

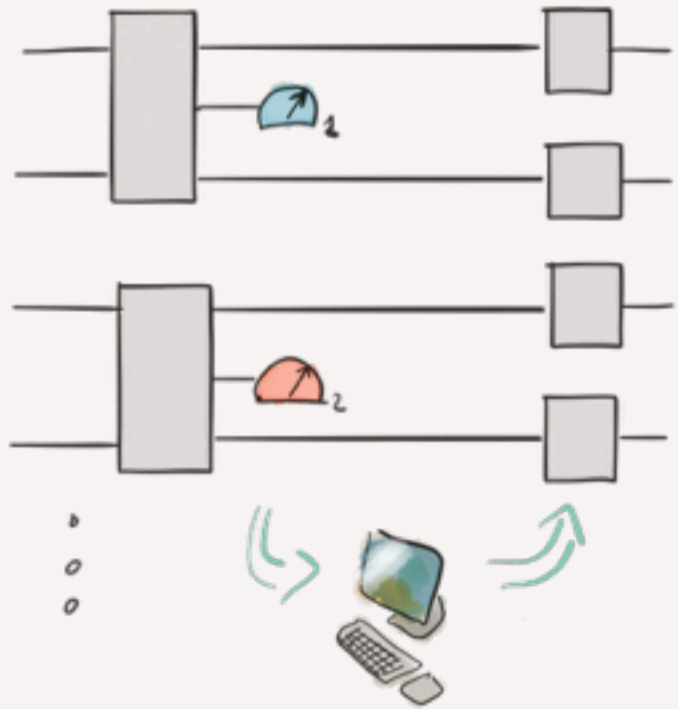
Quantum memory

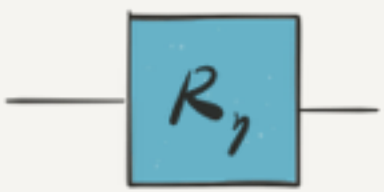
Perfect encoding and decoding to test the quality of the quantum memory: alternated noise and noisy error correction

Noise

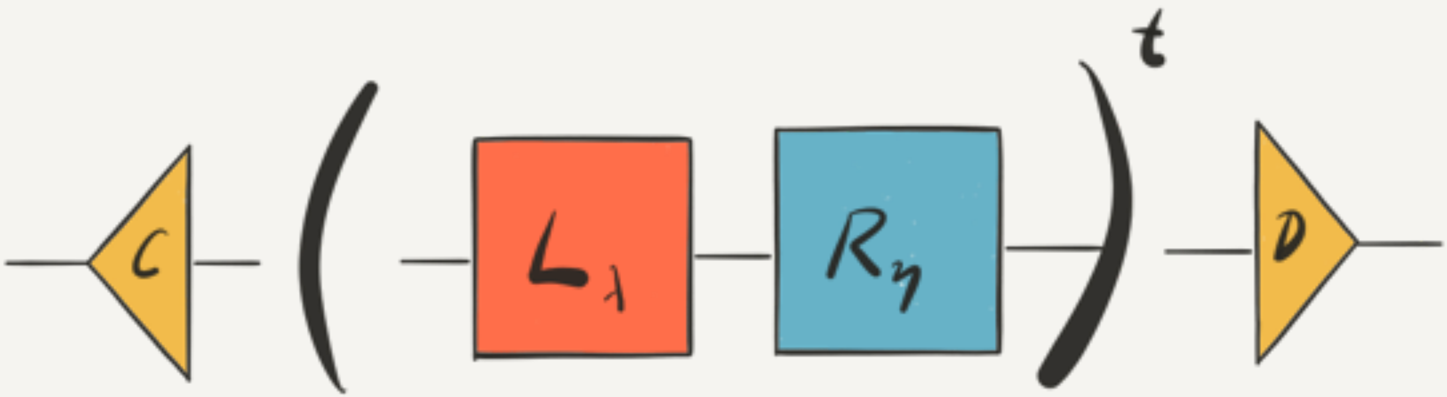


Noisy error correction





Quantum memory



For error rates below a threshold

$$p(\text{error}) \leq a\,t + b$$

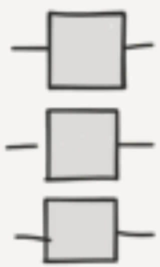
where a & b decrease exponentially with the system size.

DISCUSSION

- Universal computation probably straightforward
- $D < 3$
- Known fabrication faults
- Fully local (CA) error correction
- The physics of gauge color codes. Gapless phases? Confinement?

Local operations

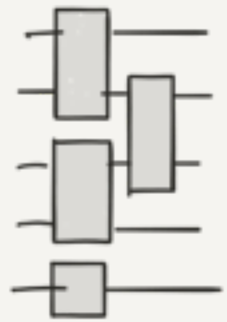
transversal



Not universal

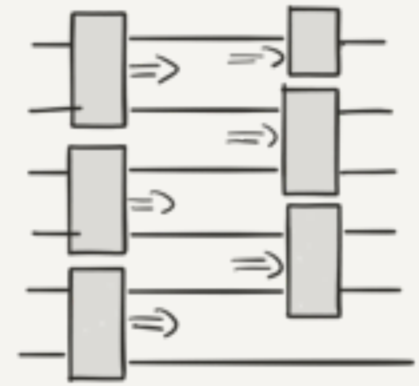
but  + EC = universal

local



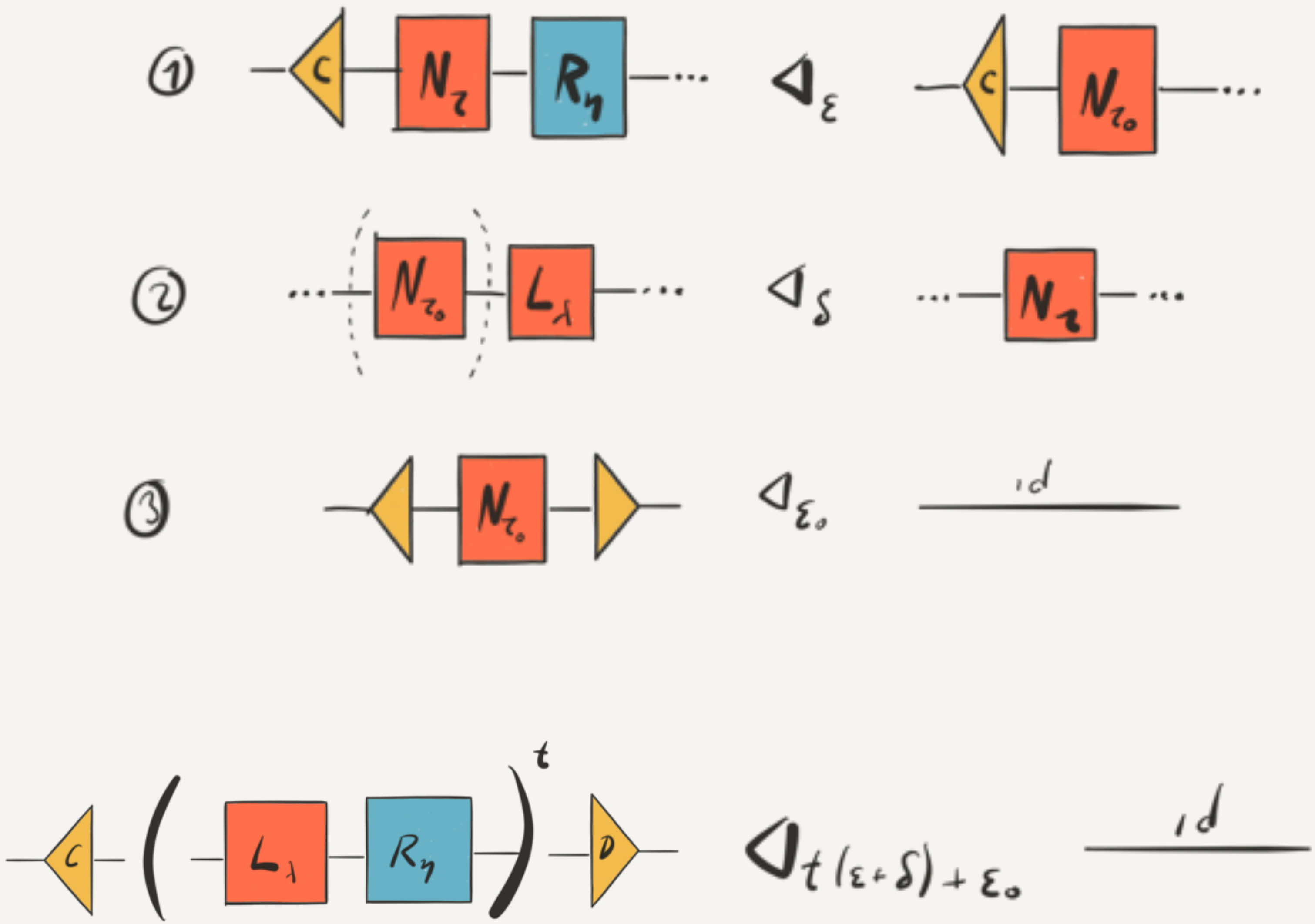
not universal ?

quantum-local



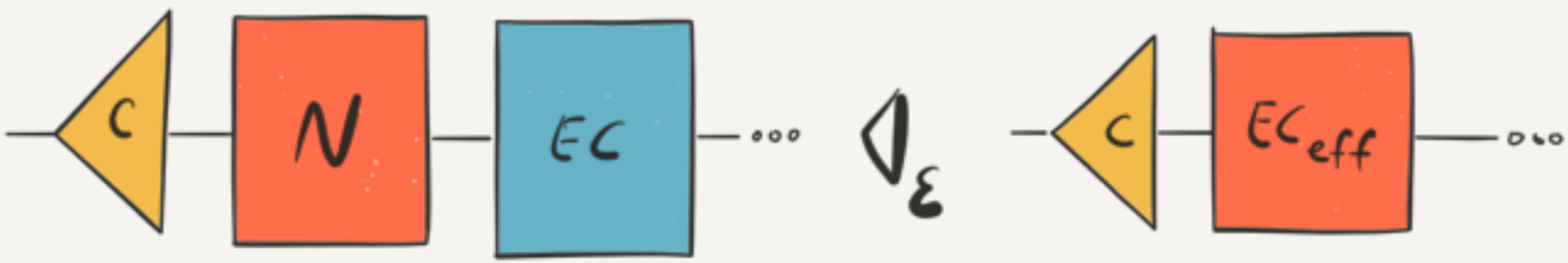
•  fault tolerance!

• Universal + EC

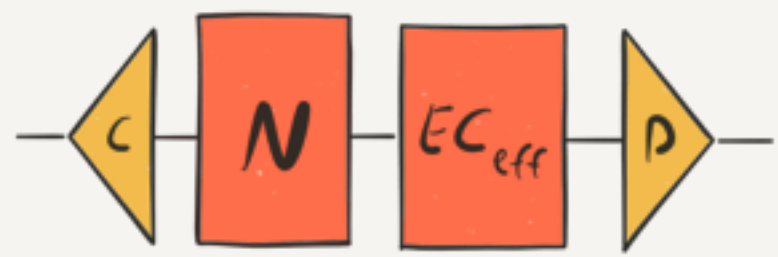


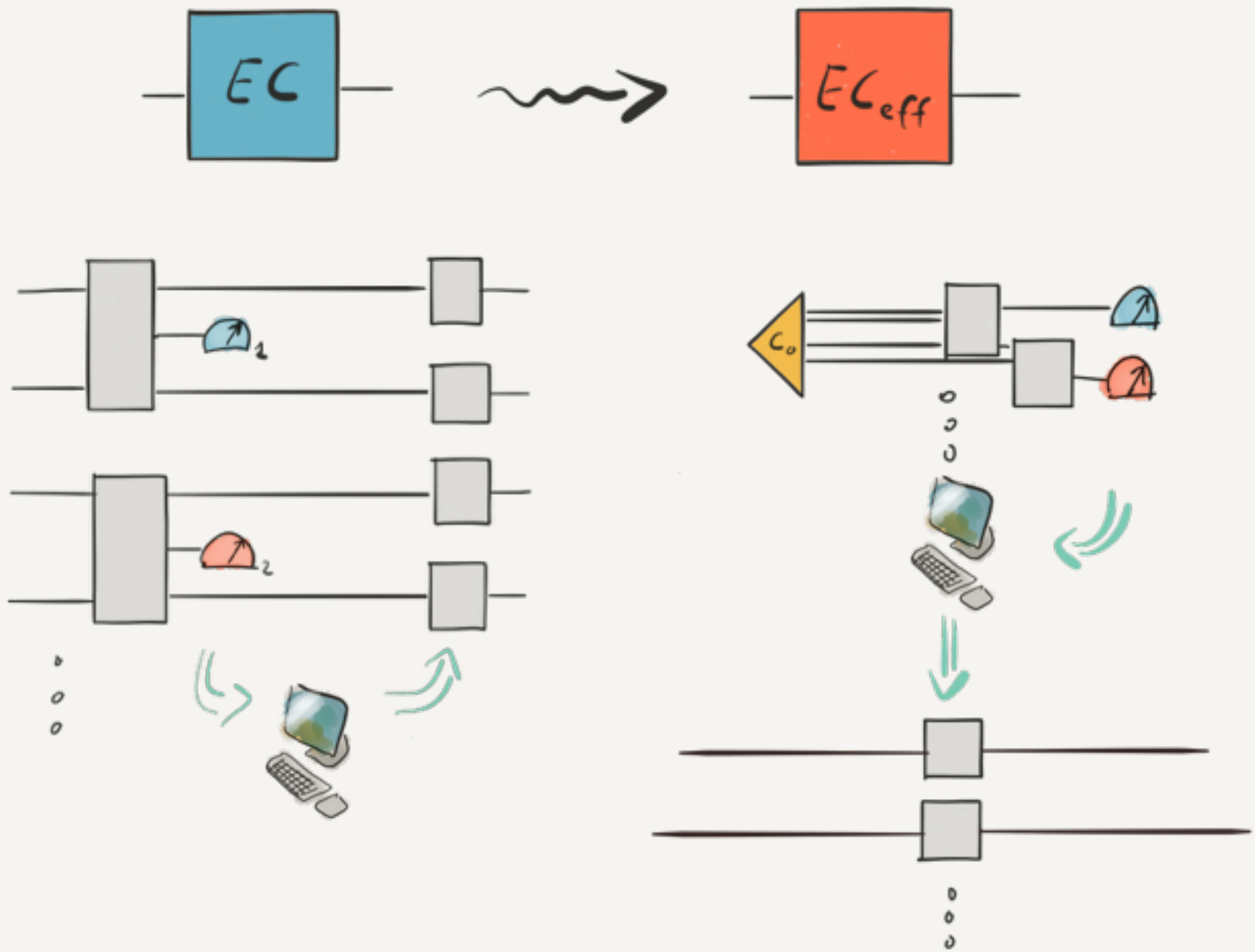
1
c
N_τ
R_η
⊲_ε
c
N_τ0
2
N_τ0
L_λ
⊲_δ
N_τ
3
N_τ0
⊲_ε0
id
c
L_λ
R_η
t
D
⊲_t(ε+δ)+ε0
id

Th.

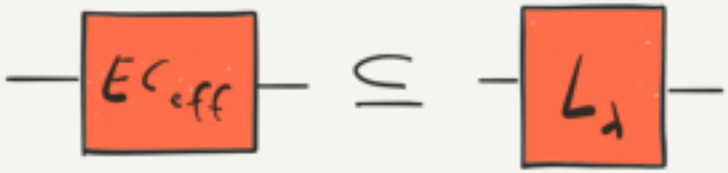


with ε the error rate of

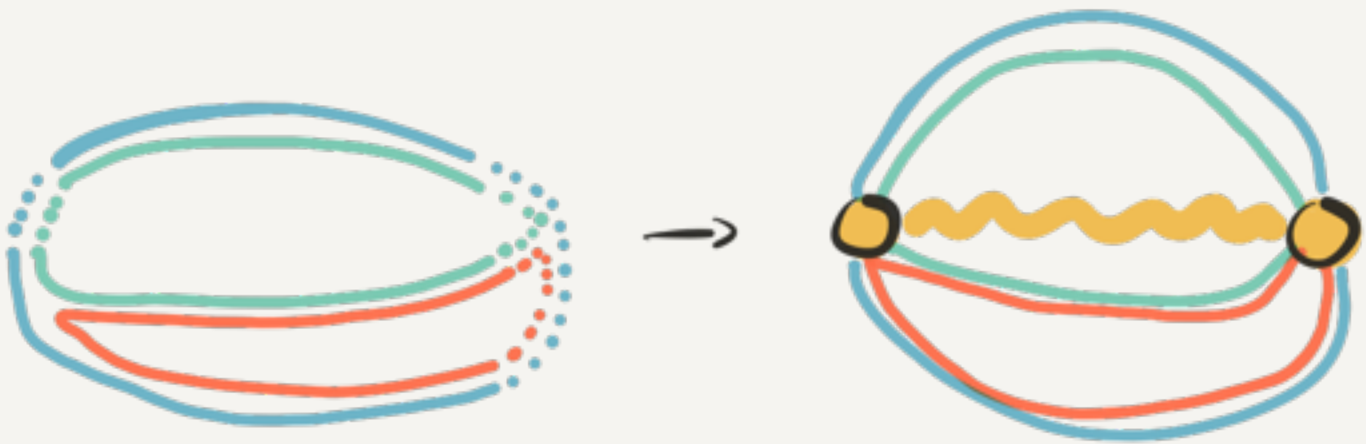




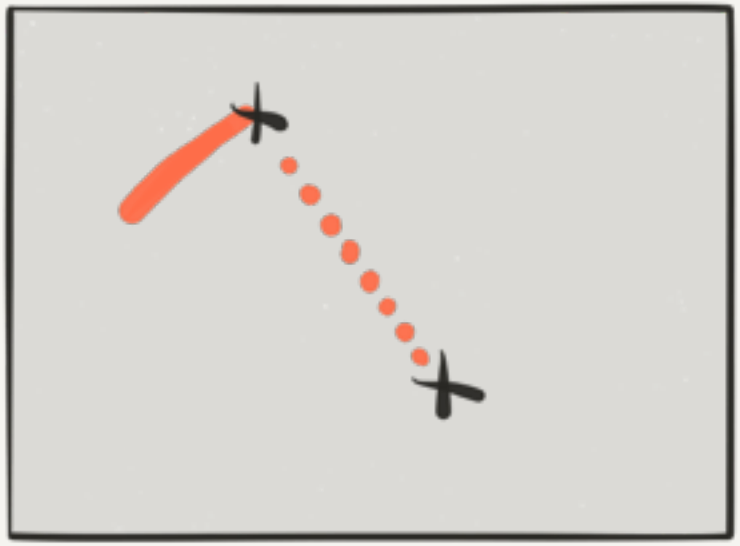
EC
ECeff
1
2
Co



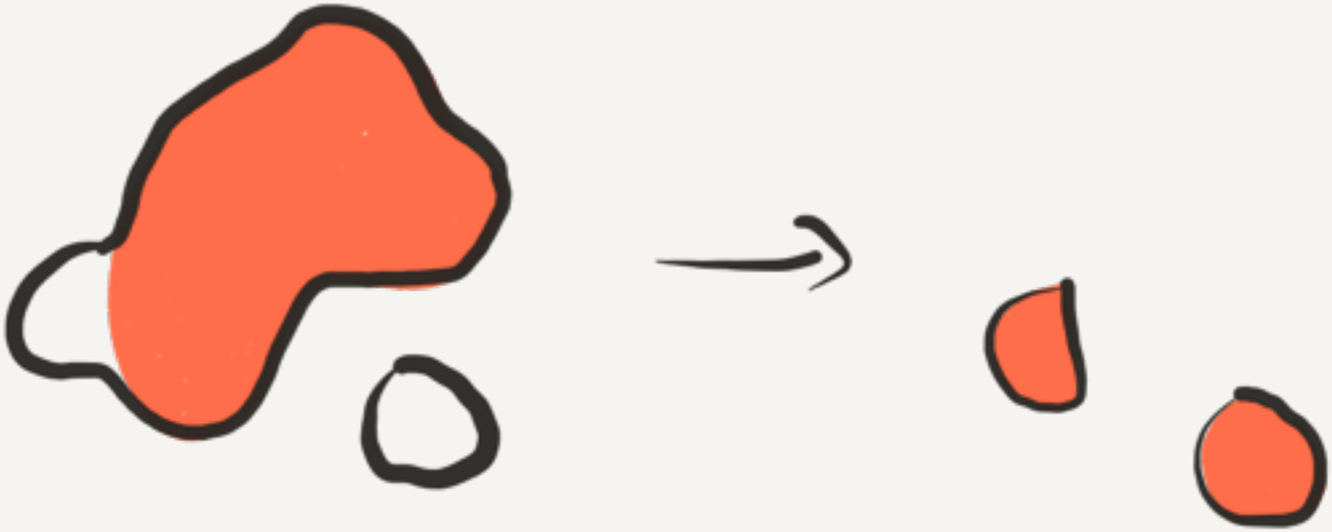
ECeff
⊆
Lλ



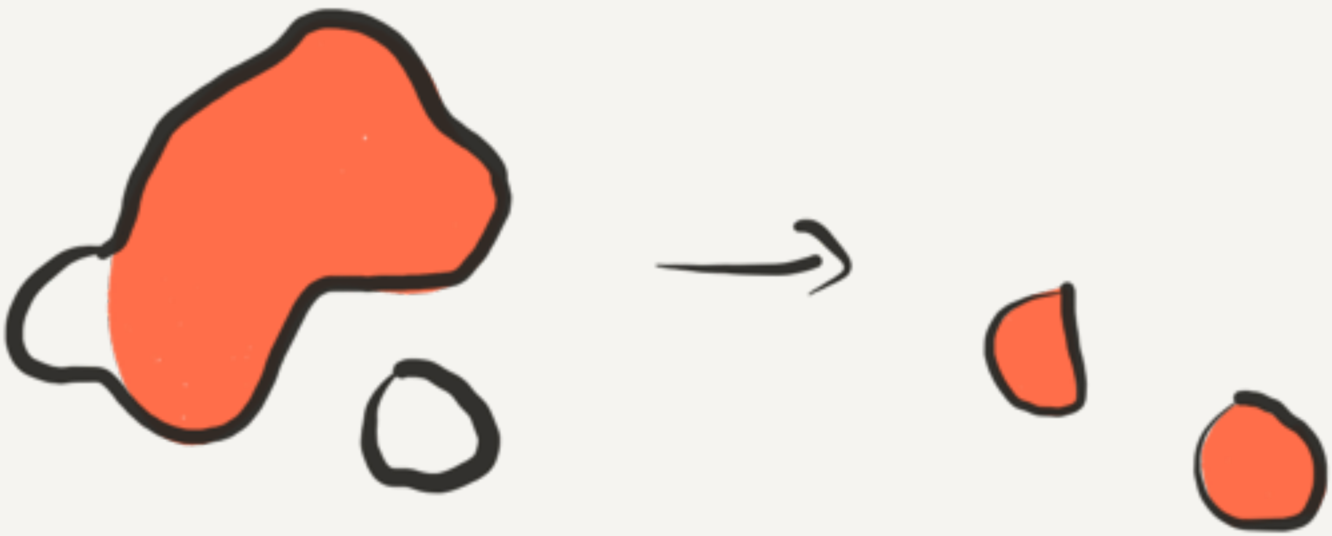
d = 2



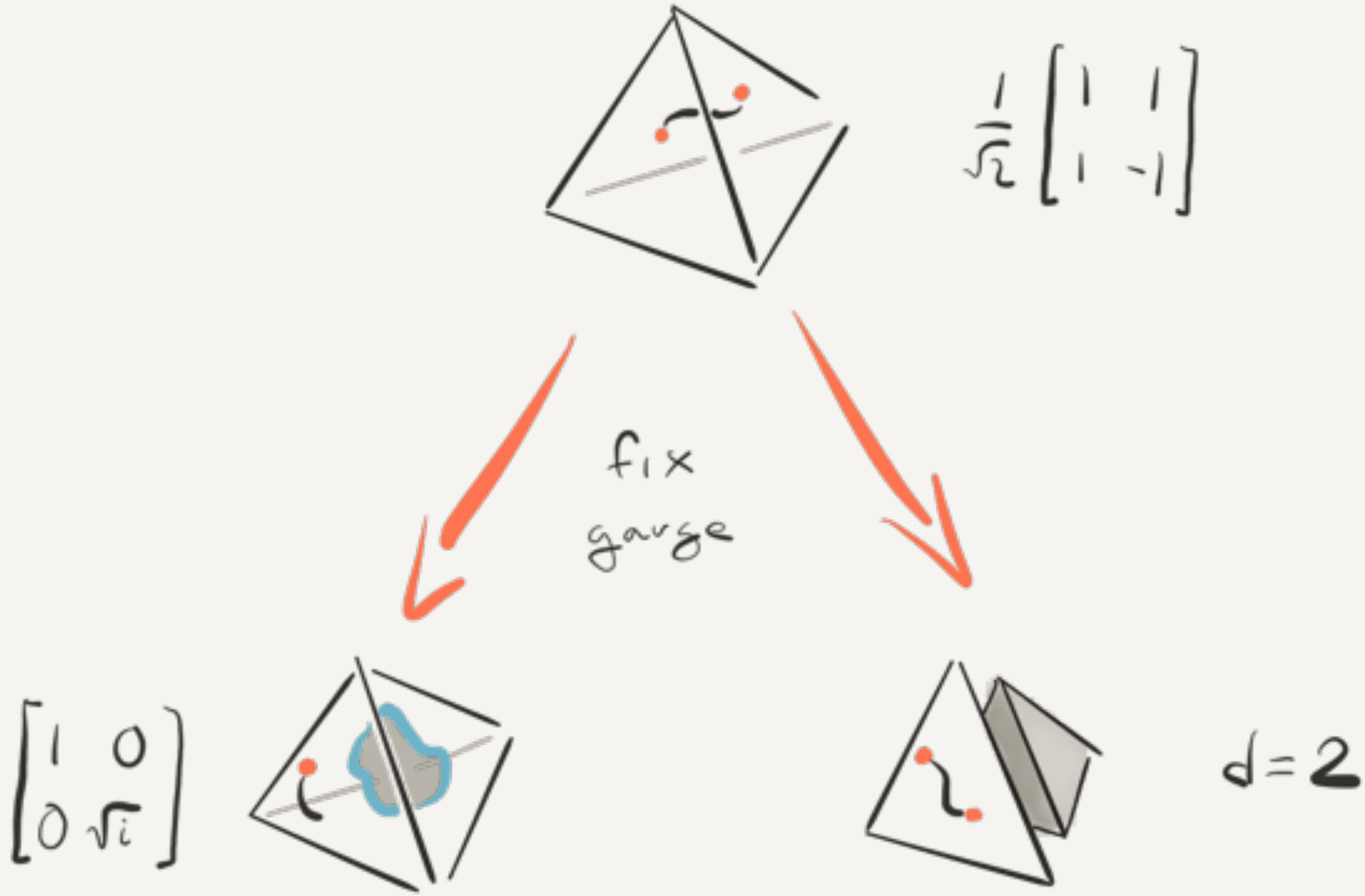
d = 4



d = 4

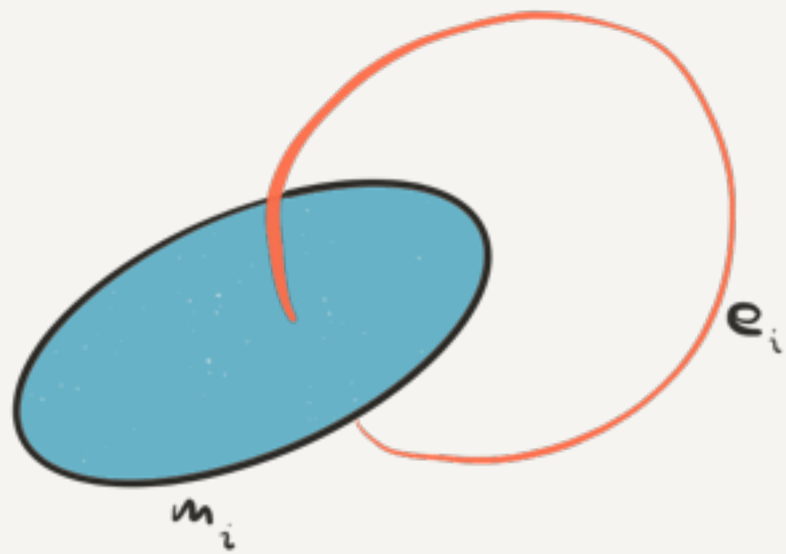


localized measurement errors yield localized residual noise

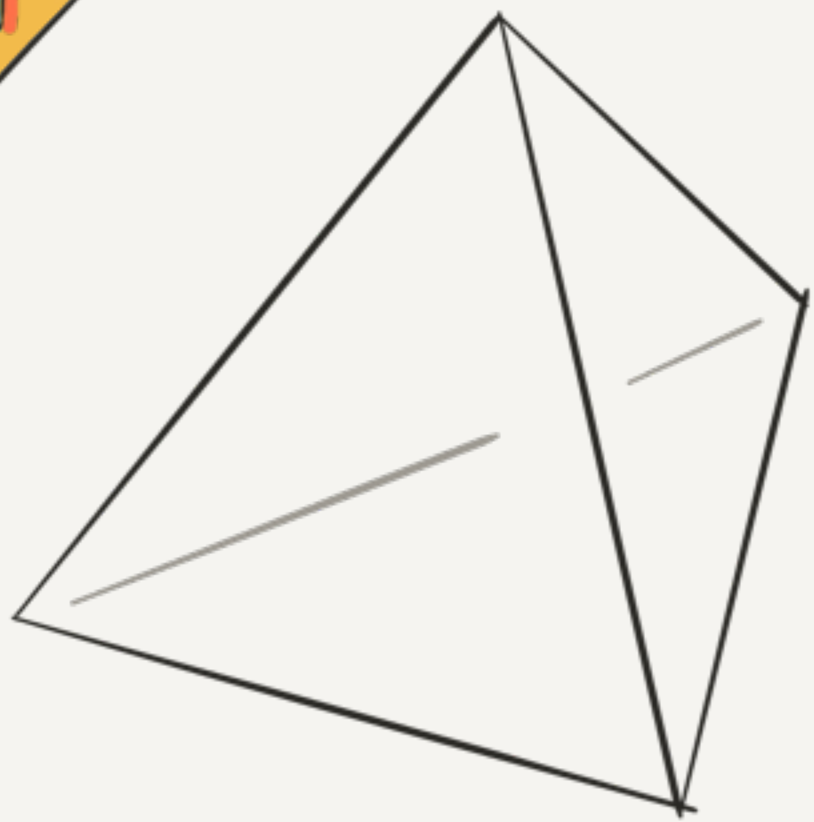


$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$
fix gauge
$\begin{bmatrix}1 & 0\\ 0 & \sqrt{i}\end{bmatrix}$
d=2

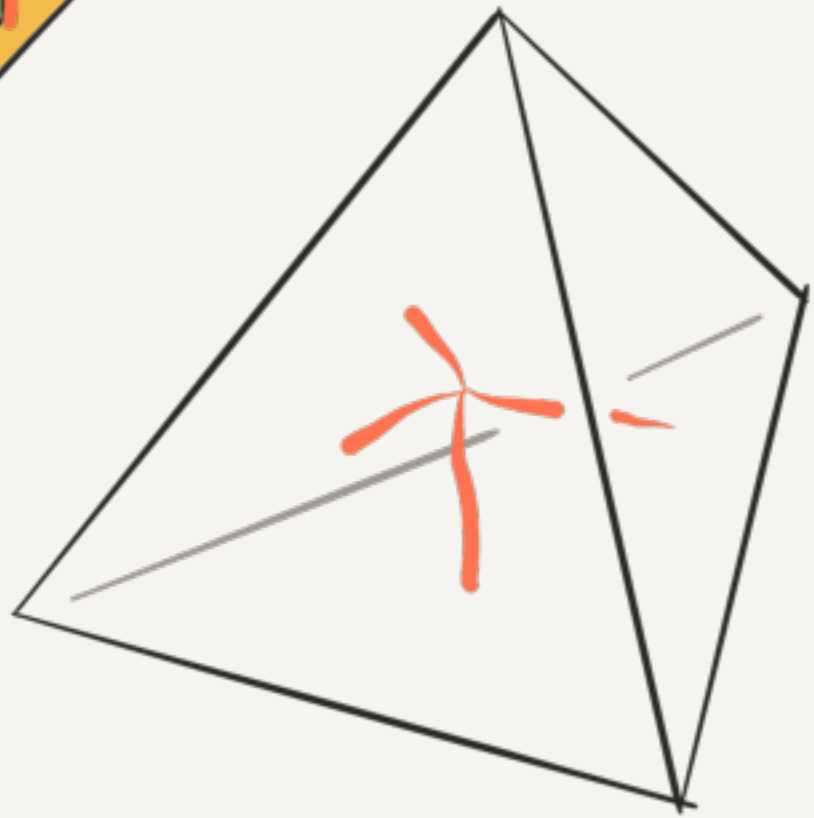
$\mathbb{Z}_2^6$



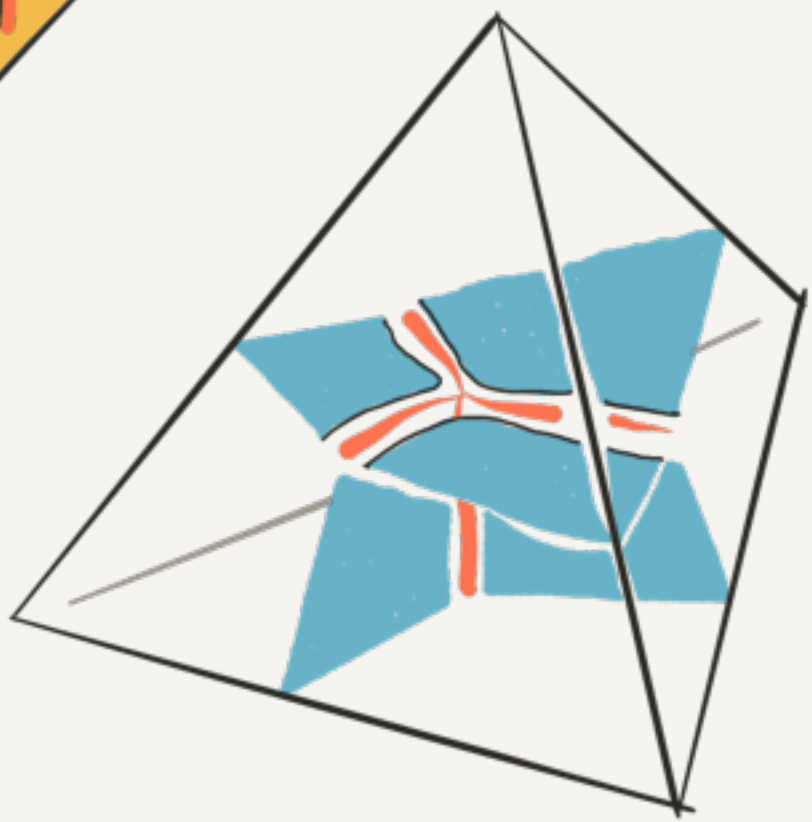

e.m




e.m




e, m




e, m