Title: Fighting noise with topology

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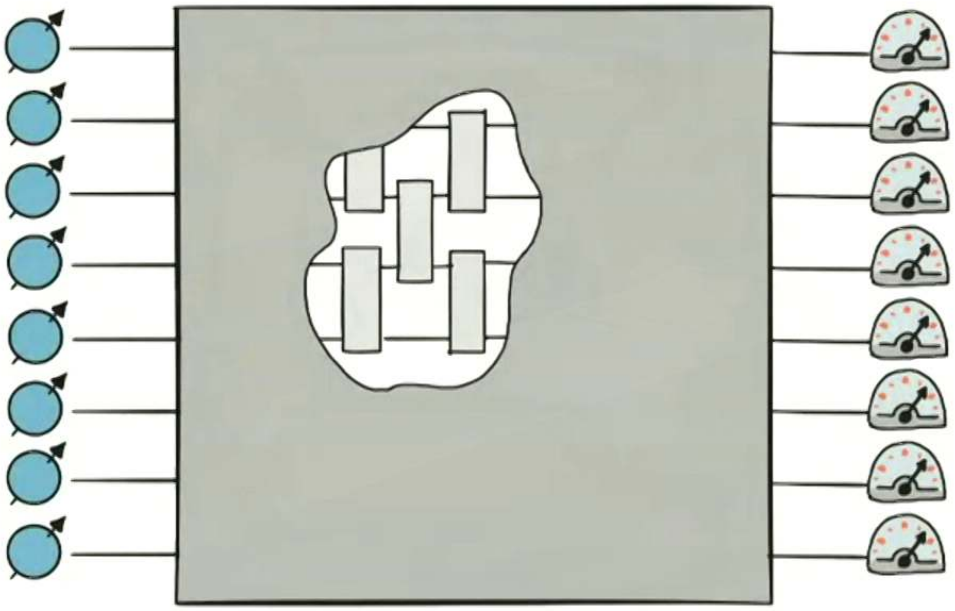
URL: http://pirsa.org/17030020

Abstract: As we get closer to build a quantum computer, the main remaining challenge is handling the noise that aflicts quantum systems.

Topological methods, in their various forms, have become the main contestants in the quest for succesfully overcoming noise. A good deal of their strength and versatility is due to their rather unique physical flavour, which keeps giving rise to surprising developments.

I will discuss the main driving forces behind my research on topological quantum error correction, as well as exciting recent directions, including unexpected connections with high energy physics.

What is quantum computation?



Why quantum computation?

- Feynman '81: Physical simulations
- Shor '94: Faster computation
- Preskill '12: Entanglement frontier

1
2
SNNPZ

Why quantum computation?

- Feynman '81: Physical simulations
- Shor '94: Faster computation
- Preskill '12: Entanglement frontier

- Mallory: Because it's there

1
2
SNNPZ

need: coherence + control

active | passive

fault-tolerant QC	self-correction
extract S with measurements	$F = E - TS$
threshold theorems	high d, e.g. d=6

1
2
SNNPZ

need: coherence + control

active / passive

fault-tolerant QC

extract S with measurements

threshold theorems

self-correction

$$F = E - TS$$

high d, e.g. d=6

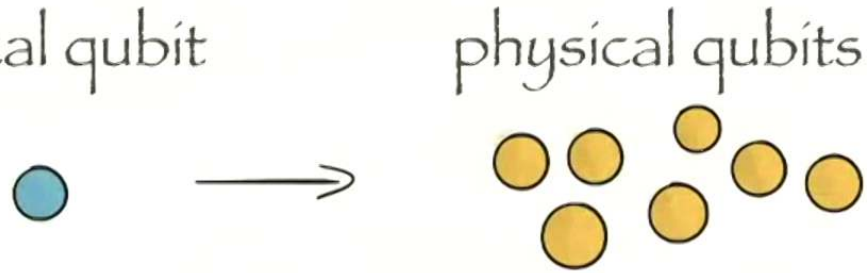
topological methods

1
2
SNNPZ

Topological codes

Error correction

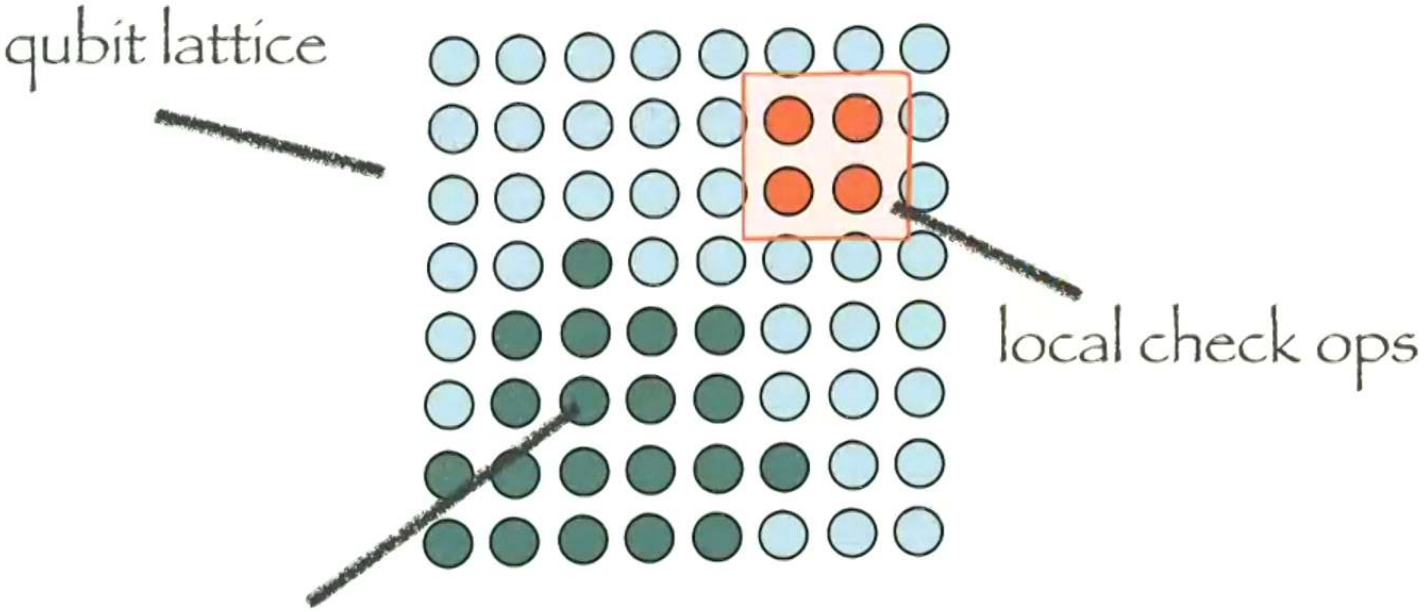
- redundancy:



extra d.o.f. → check ops
(error syndrome)

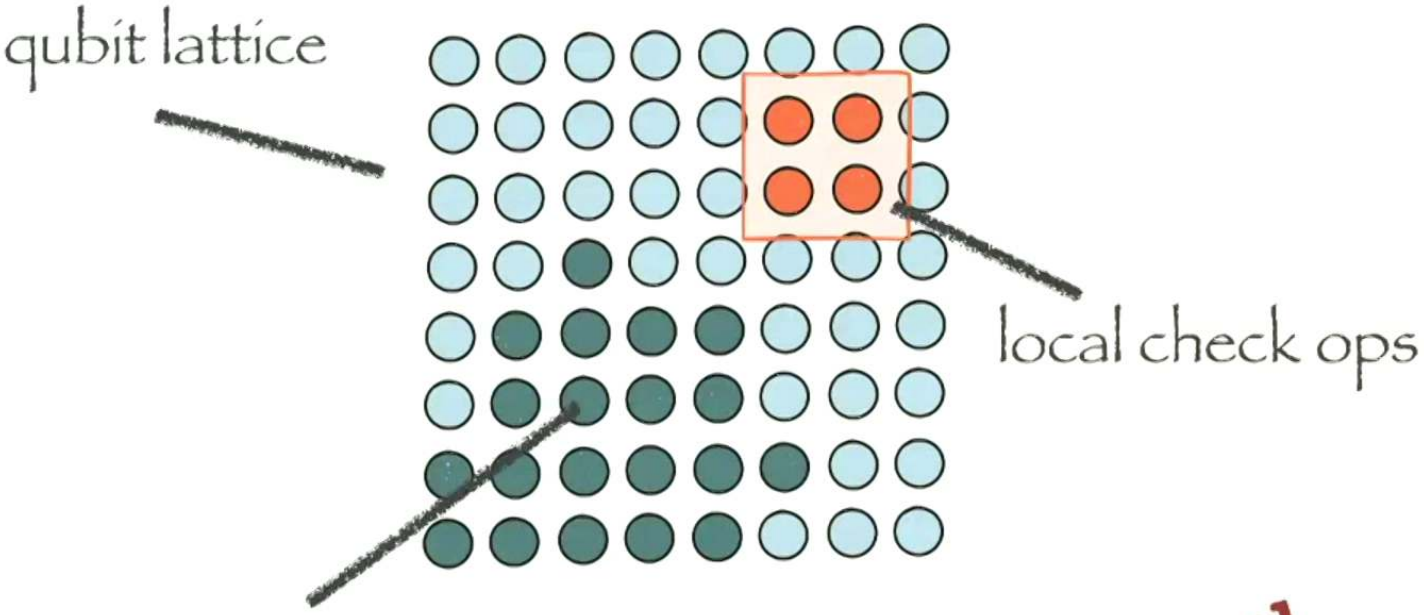
- noise structure (e.g. locality)

Topological codes



Kitaev '97

Topological codes

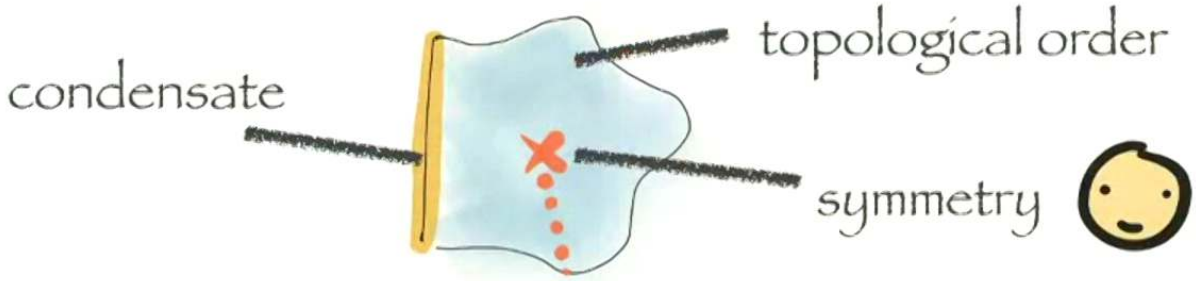


1. Practical

Kitaev '97

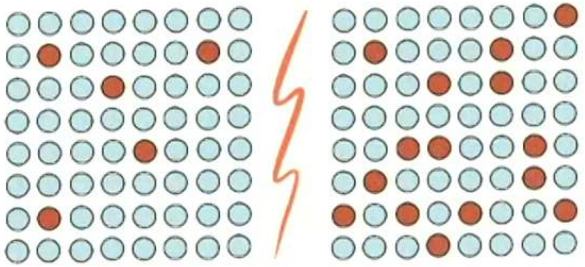
locality → physical 'flavor'

- condensed matter



- statistical physics

threshold as
phase transition



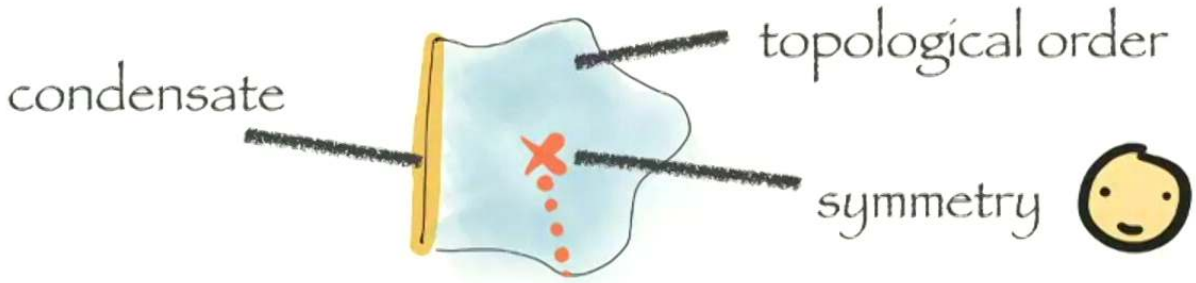
- ...

Dennis et al. '02

locality → physical 'flavor'

2. Interesting

- condensed matter



- statistical physics

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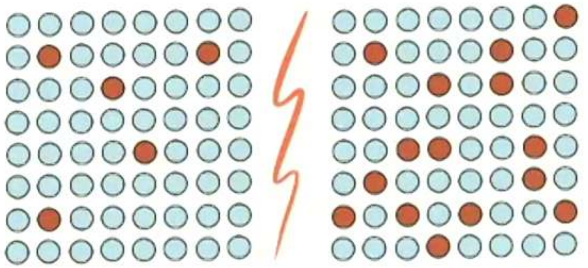
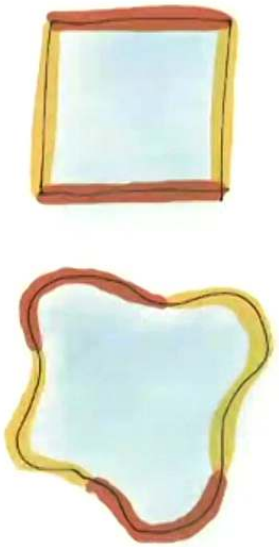


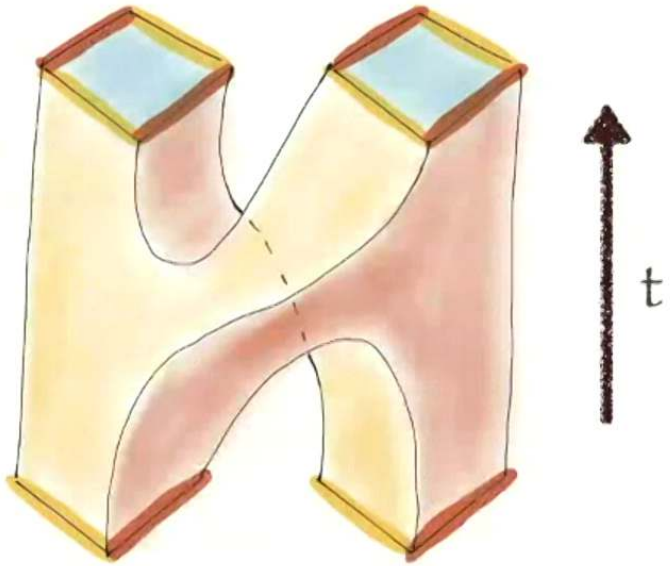
- …

topology?

logical qubits

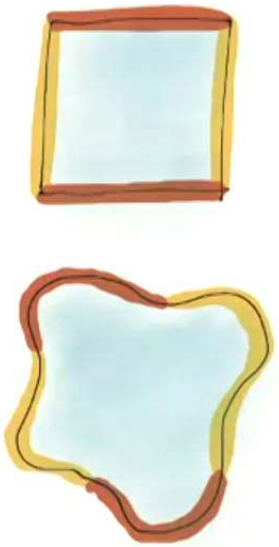


operations

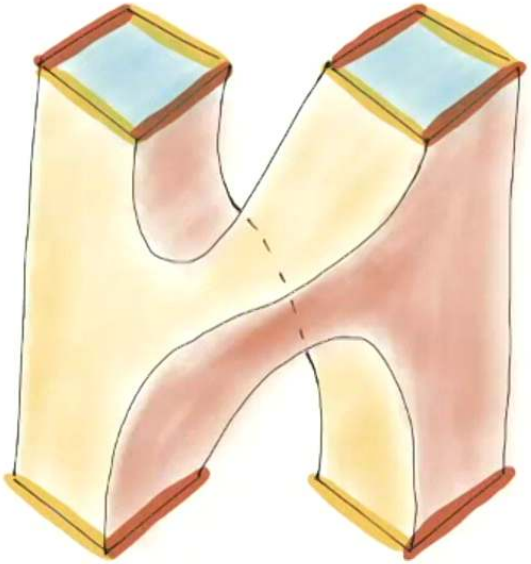


topology?

logical qubits



operations

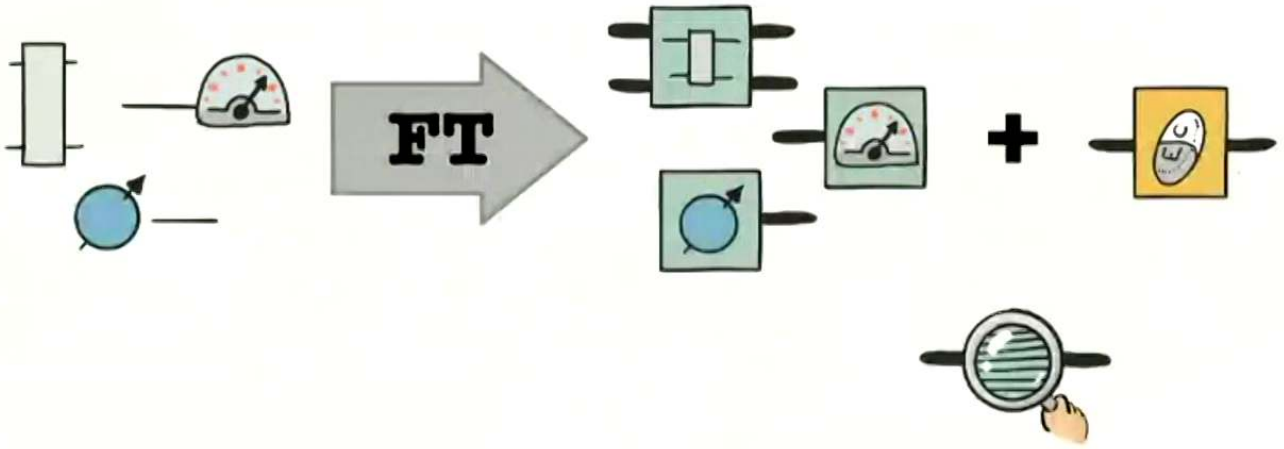


3. Fun!

Local operations &
color codes
1
2
SNNPZ

Fault-tolerant QC

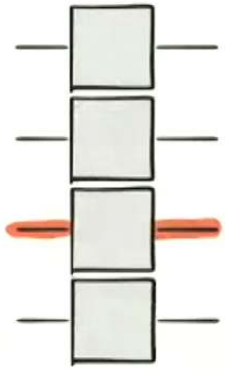
- information always encoded: gadgets
- error correction against noise accumulation
- operations preserve the structure of noise



Transversal gates

- optimal
- never universal

Eastin & Knill '09



transversality + topology = ?

Transversal gates

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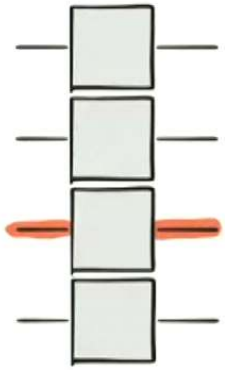
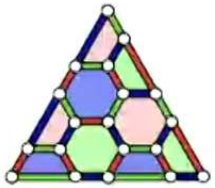
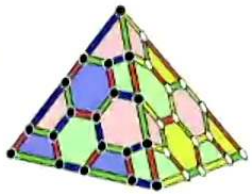


transversality + topology = color codes

d=2
universality
via distillation



d=3
universality
via error
correction
(d=4)

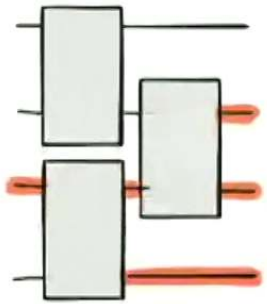


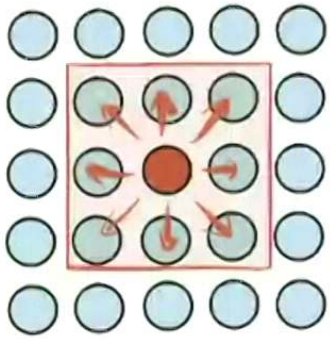
d>3
...

Local gates

- compatible with topological codes
- never universal?

  Bravyi & König '13
  Beverland et al. '14
  Pastawski & Yoshida '15





Local gates

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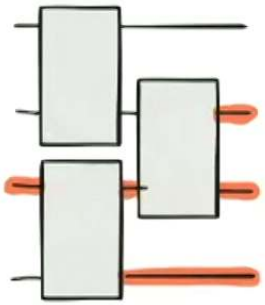
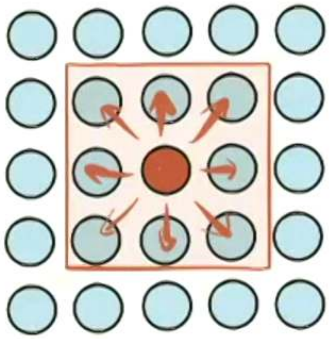
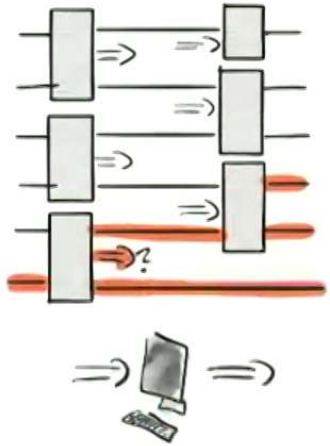
- color codes are optimal!





Quantum-local gates

local quantum ops +
(noiseless) global
classical computation



noise might
propagate badly!

Quantum-local gates

local quantum ops +
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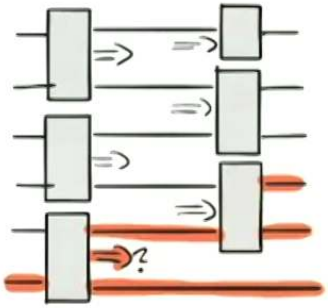
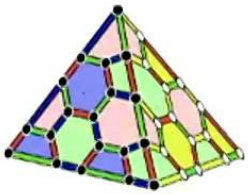
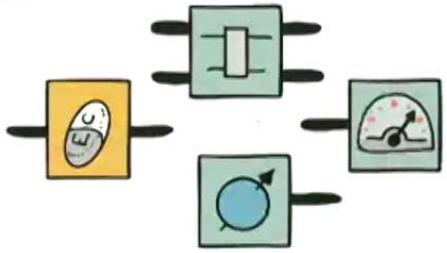


noise might
propagate badly!

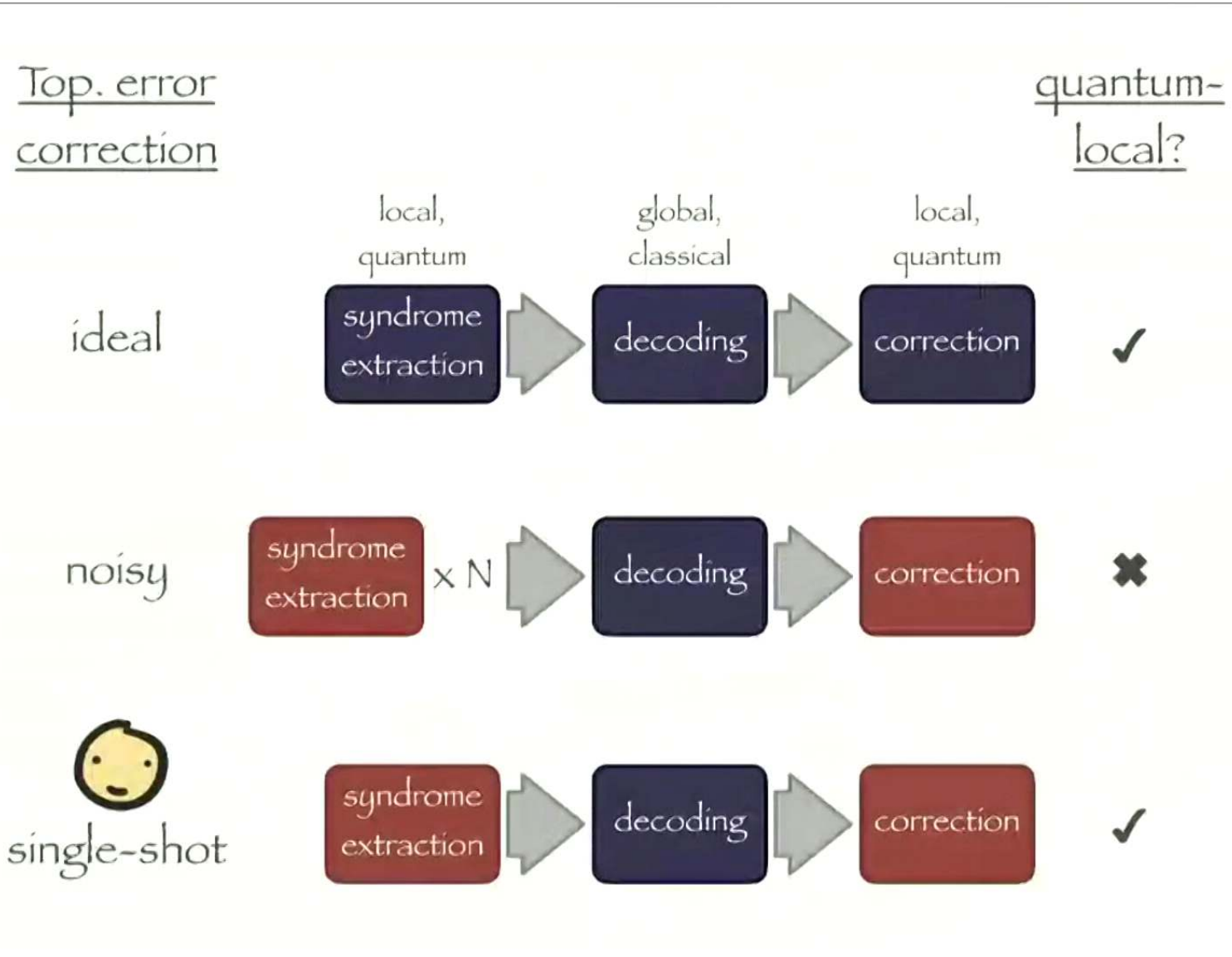
gauge color codes (d=3)





all gadgets
quantum-local!

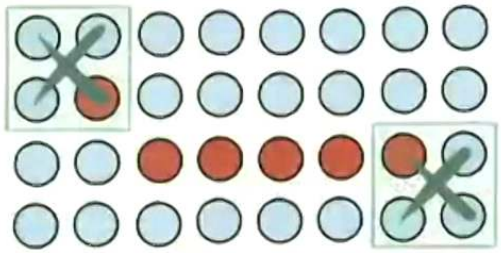
Single-shot error correction & gauge fields


Top. error correction
quantum-local?
local, quantum
global, classical
local, quantum
ideal
syndrome extraction
decoding
correction
noisy
syndrome extraction
x N
decoding
correction
single-shot
syndrome extraction
decoding
correction

d=2,3

errors ~ strings

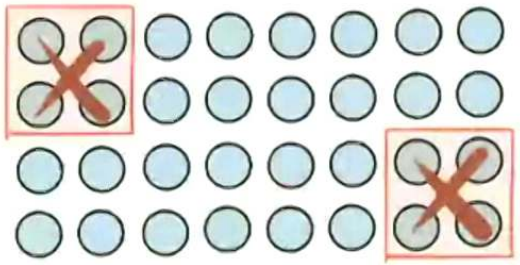
syndrome ~ endpoints



string error +

correct syndrome

?



no errors +

wrong syndrome

Subsystem codes

logical qubit → physical qubits

extra d.o.f. → check ops
(error syndrome)

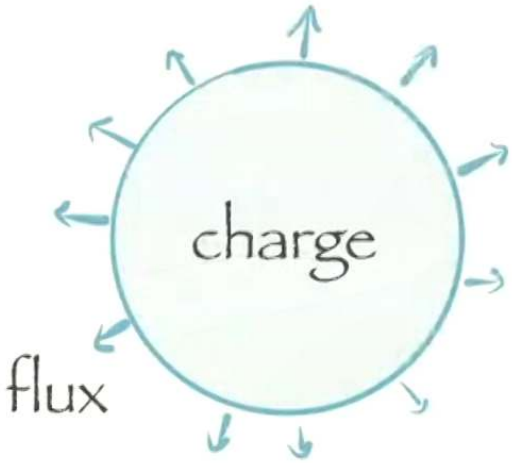
→ gauge d.o.f.
(gauge syndrome)

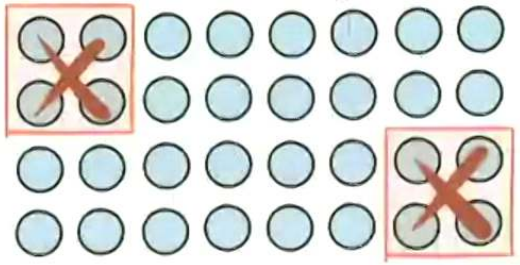
Gauss law

strings ~ errors

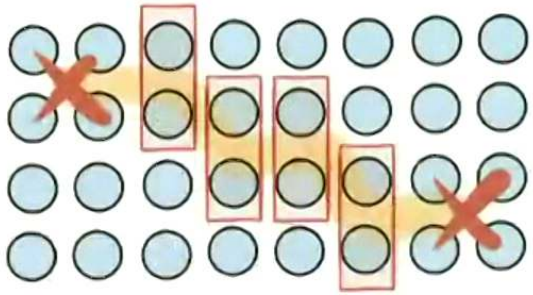
endpoints ~ syndrome ~ charge

gauge syndrome ~ field





syndrome



gauge syndrome:
confinement!

logical qubit

physical qubits

extra d.o.f. → check ops

→ gauge d.o.f.

$$\mathcal{H}_{\text{fixed synd.}} = \mathcal{H}_{\text{logical}} \otimes \mathcal{H}_{\text{gauge}}$$

$$H = \sum_i \lambda_i g_i = \bigoplus_{\text{synd.}} \mathbf{1} \otimes H_{\text{gauge}}^{(\text{synd})}$$

Gauge color codes

$\mathcal{H}_{\text{gauge}}$ (bulk) $\sim \mathbf{Z}_2^6$ LGT (3+1)

syndrome $\sim$ source configuration

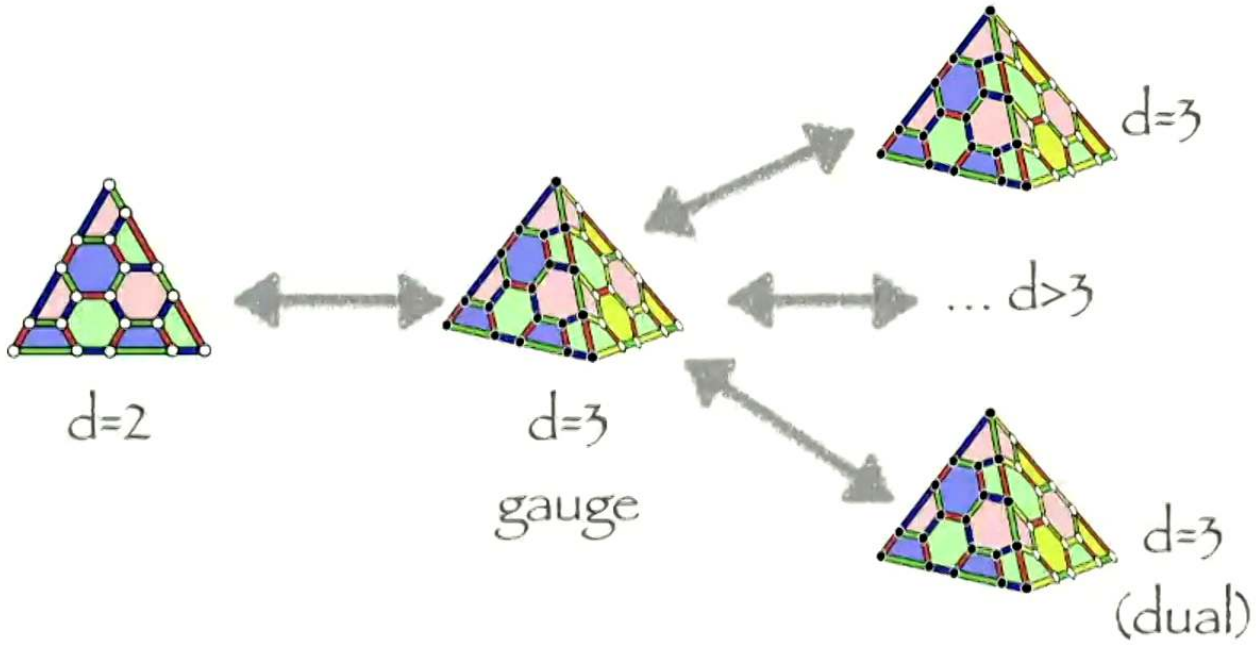
gauge d.o.f. $\sim$ gauge field

- interplay of boundaries and LGT phases?
- gapless phases? e.g. $\mathbf{Z}_n$
- self-correction?

1
2
SNNPZ

Gauge color codes

gauge fixed codes ~ phases of LGT



Other directions

- Beyond conventional fault-tolerance
- Taking advantage of specific features of implementation targets
- Local codes (beyond topological)

thank you