arXiv:1505.07432

Classical Verification of Quantum Proofs

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IQC, UWaterloo

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QCIS, UTS

Classical and quantum proof verification

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- Proof verification is a central concept in computer science
  - **NP**, **IP**, **MIP**, **PCP**, …

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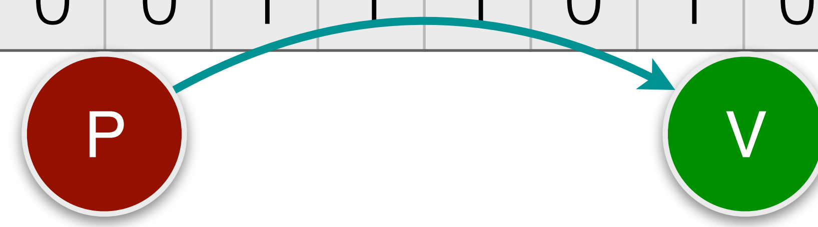
1	0	0	1	1	1	0	1	0	$\dots$



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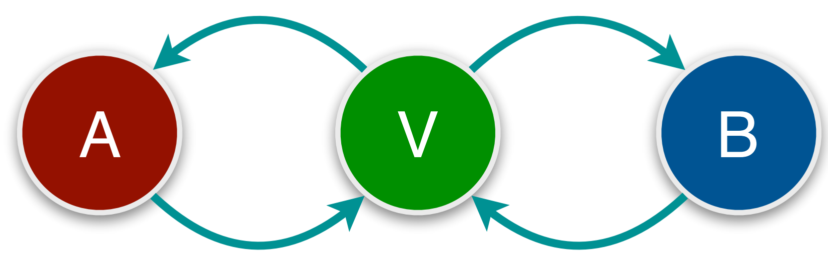

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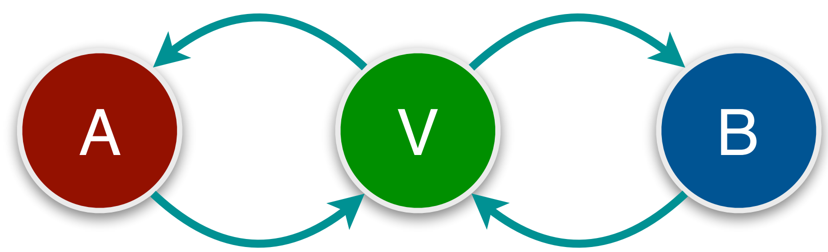

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  - 3-SAT, G3C, Ising

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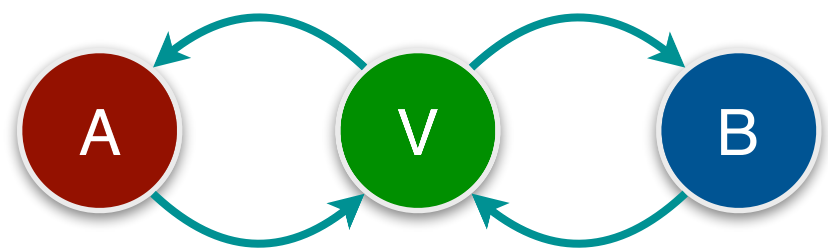

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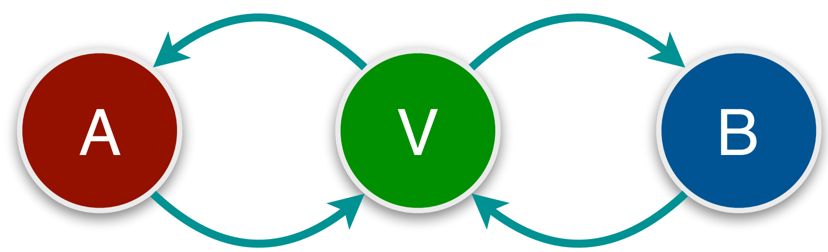

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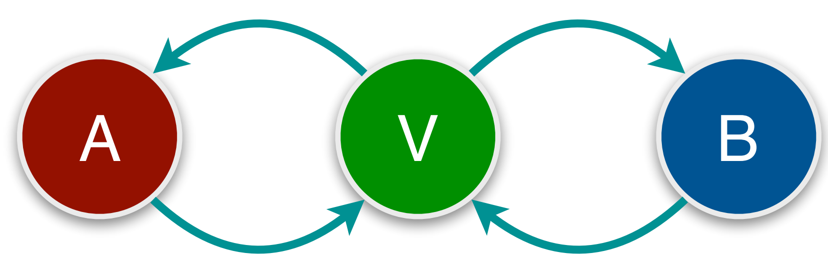

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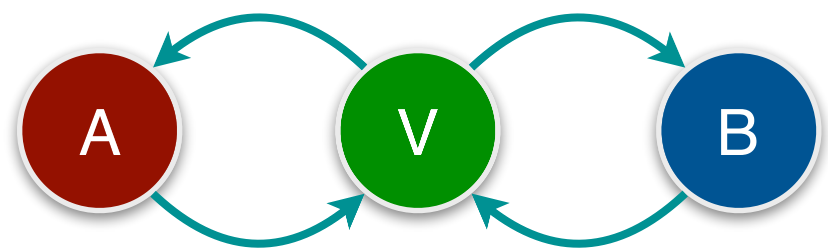

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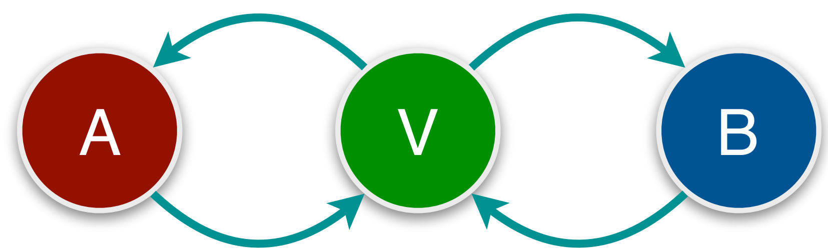

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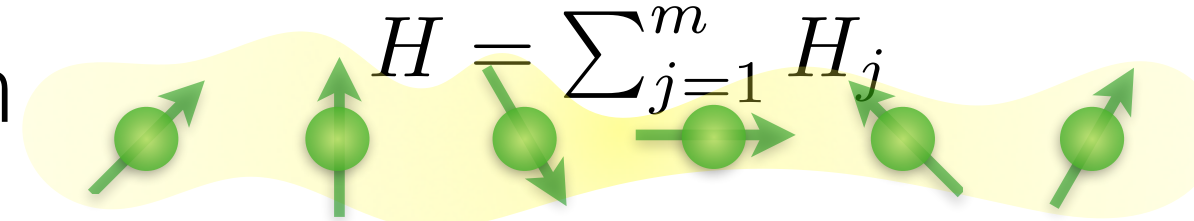

Multi-player one-round games for NP

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- Proof verification without seeing the whole proof

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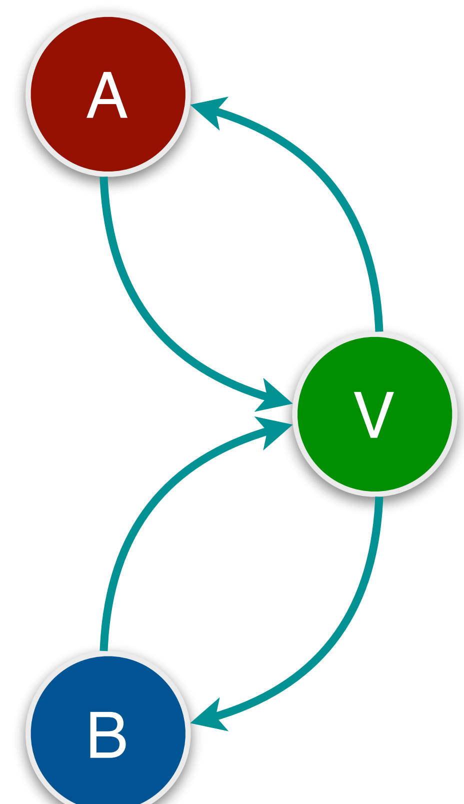

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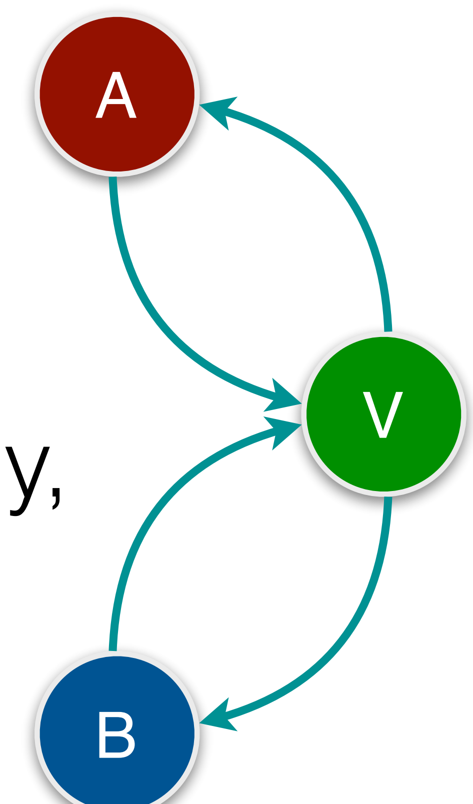
  - Query a variable in the clause randomly, check consistency (oracularization)



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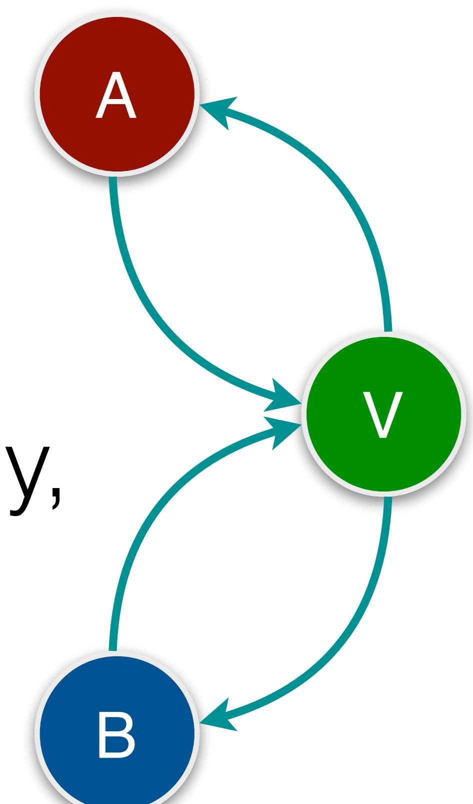
- **NP**-hardness of multi-player games



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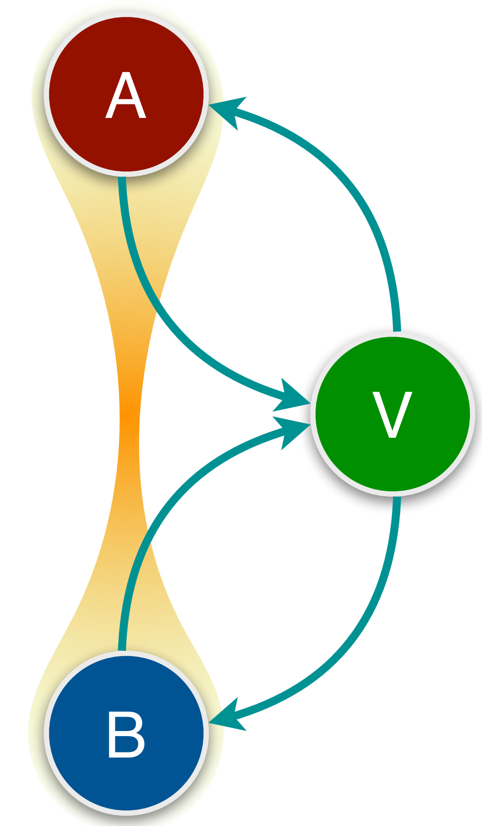
- Bell inequalities
- Entanglement can either weaken or strengthen the expressive power

[Cleve et al. 04]



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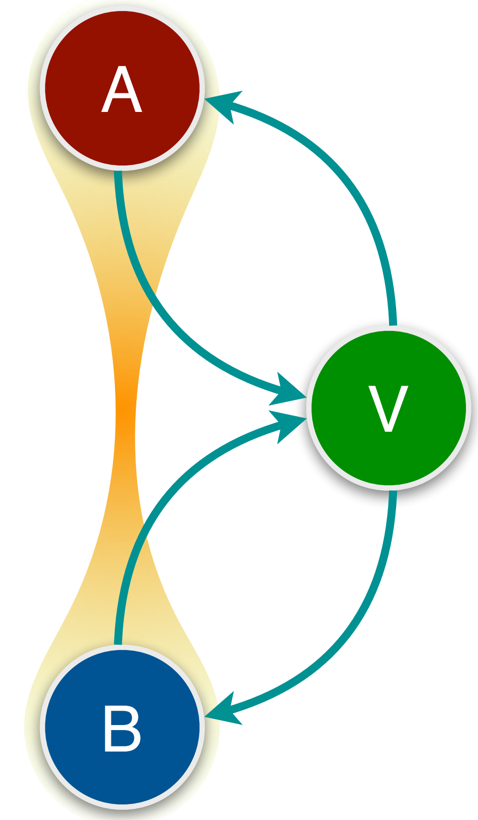

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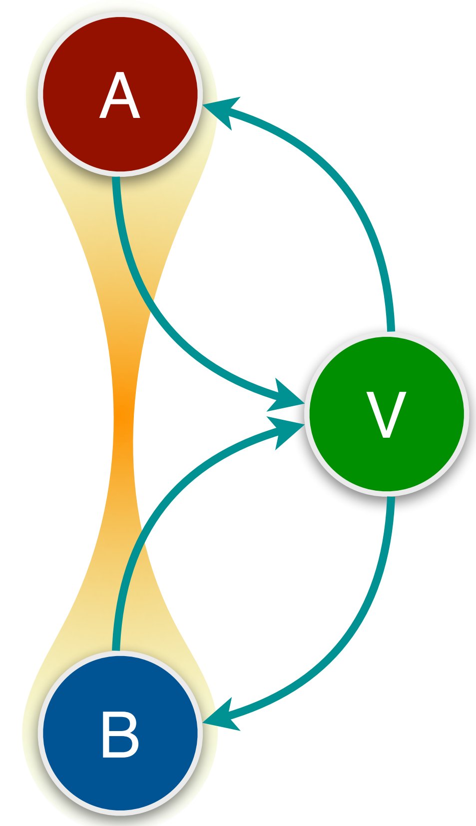

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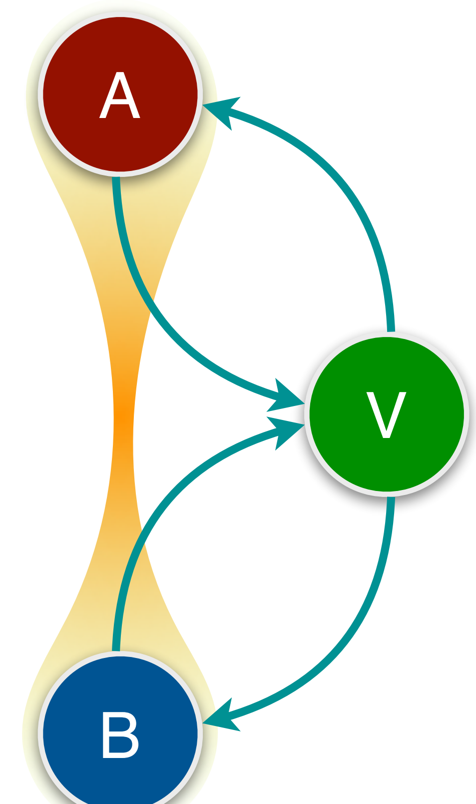
“Quantum hardness” for entangled games?



Multi-player games for QMA

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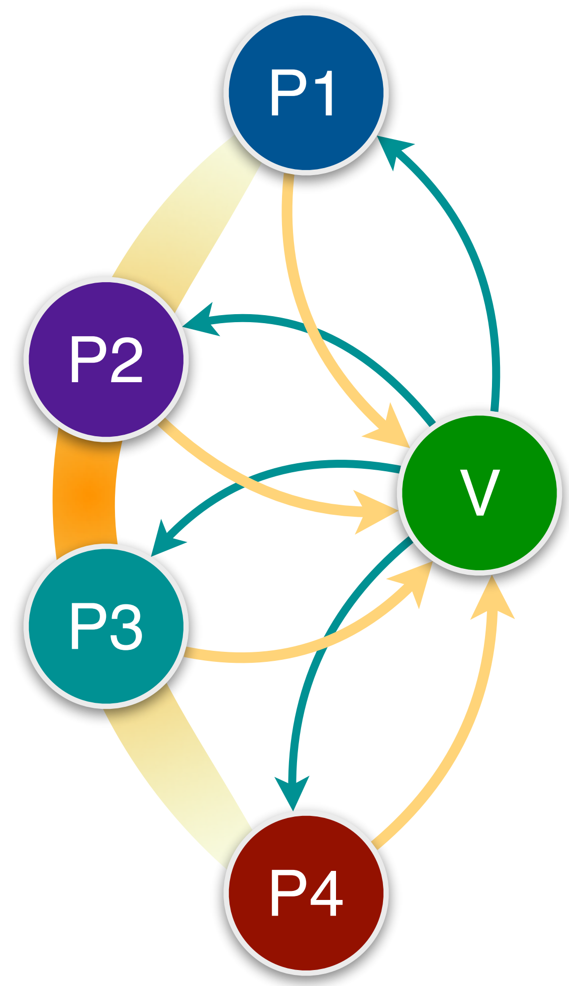

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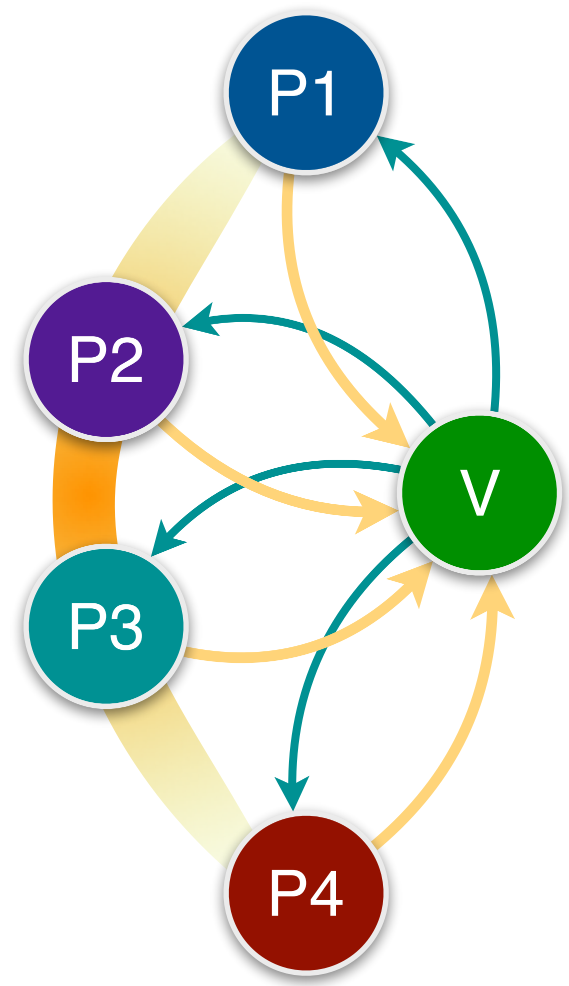
  - Perform the encoding check
  - Perform the energy check



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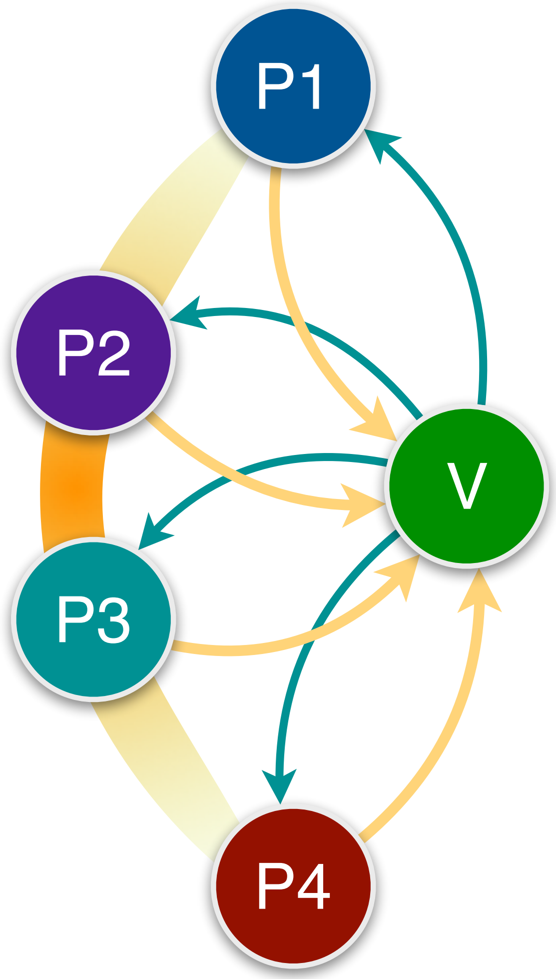
- Quantum oracularization
  - Classical oracularization as an error detecting code

$0 \mapsto 00,\ 1 \mapsto 11$



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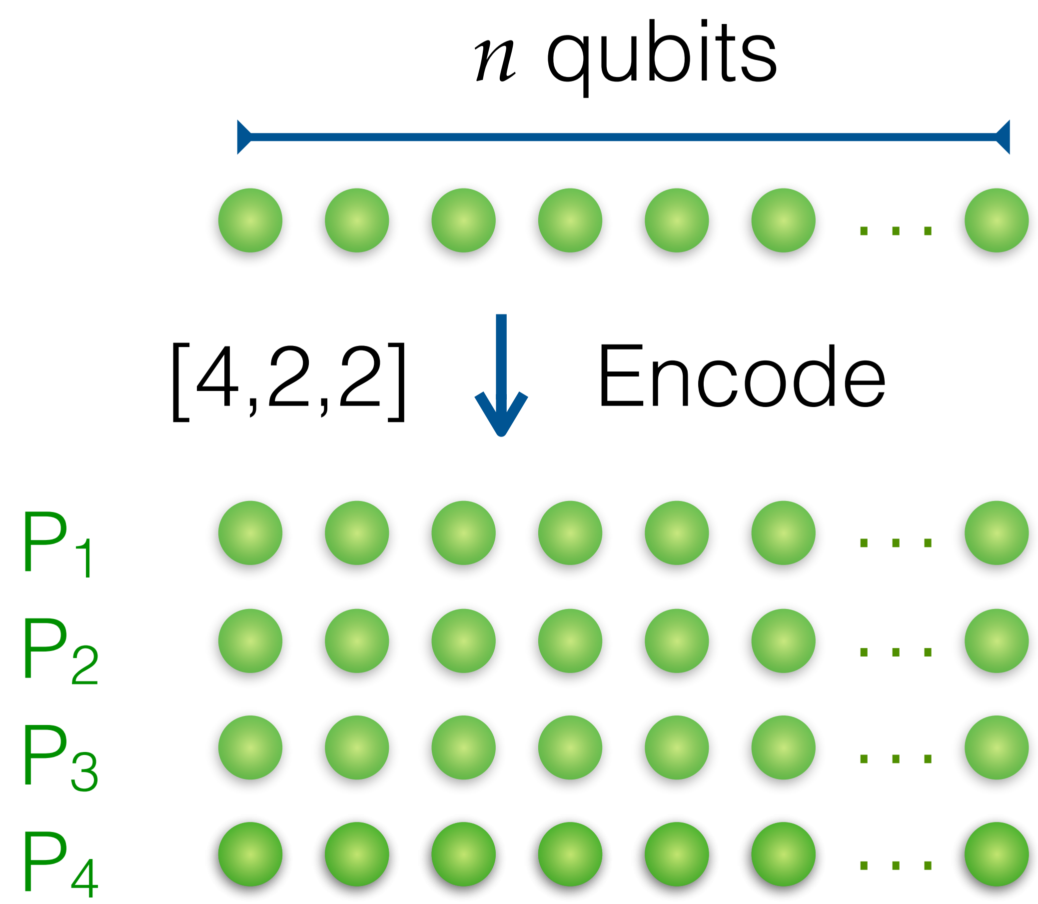
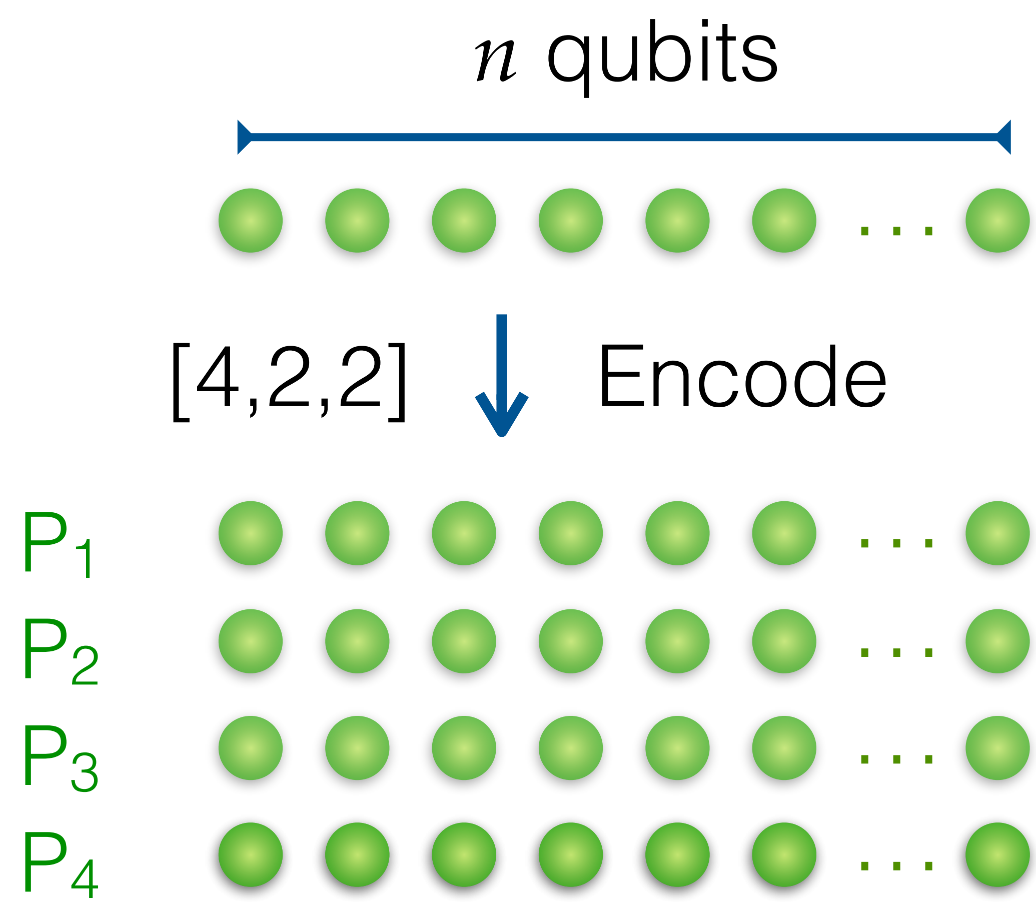


Fitzsimons-Vidick protocol

- Encode and distribute among the four provers



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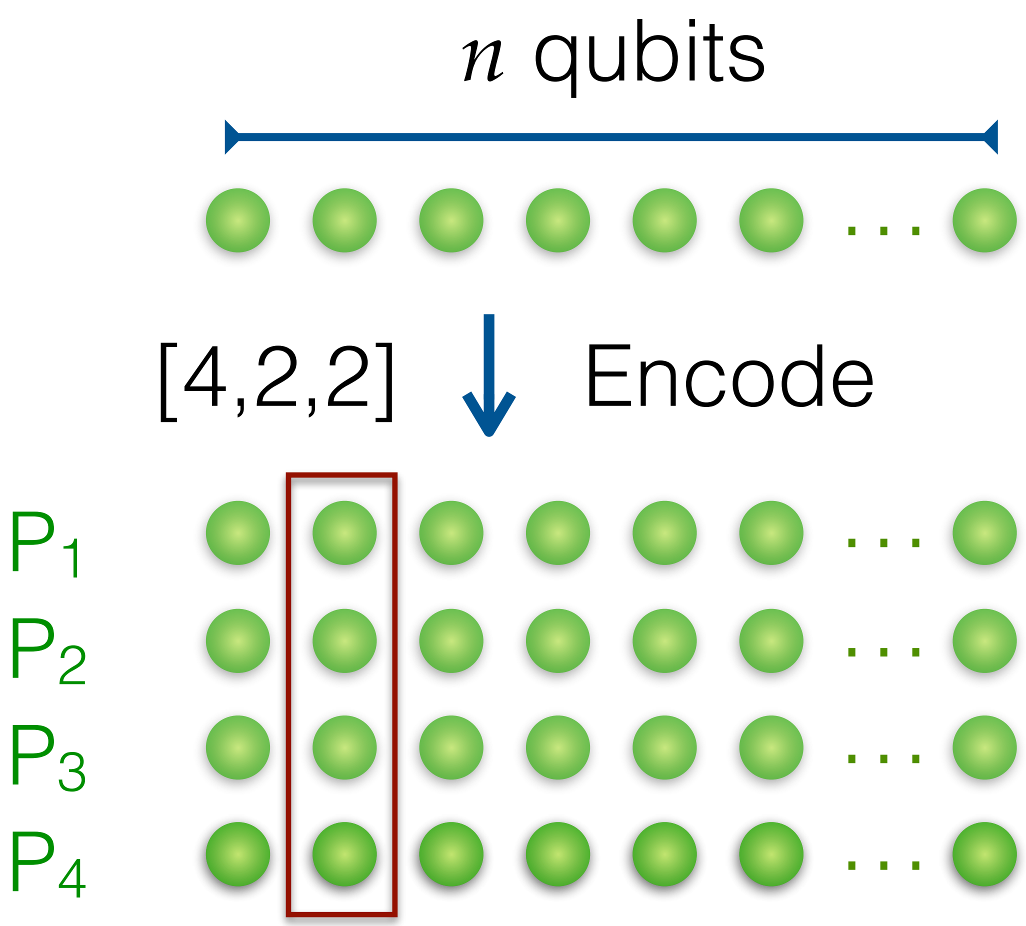

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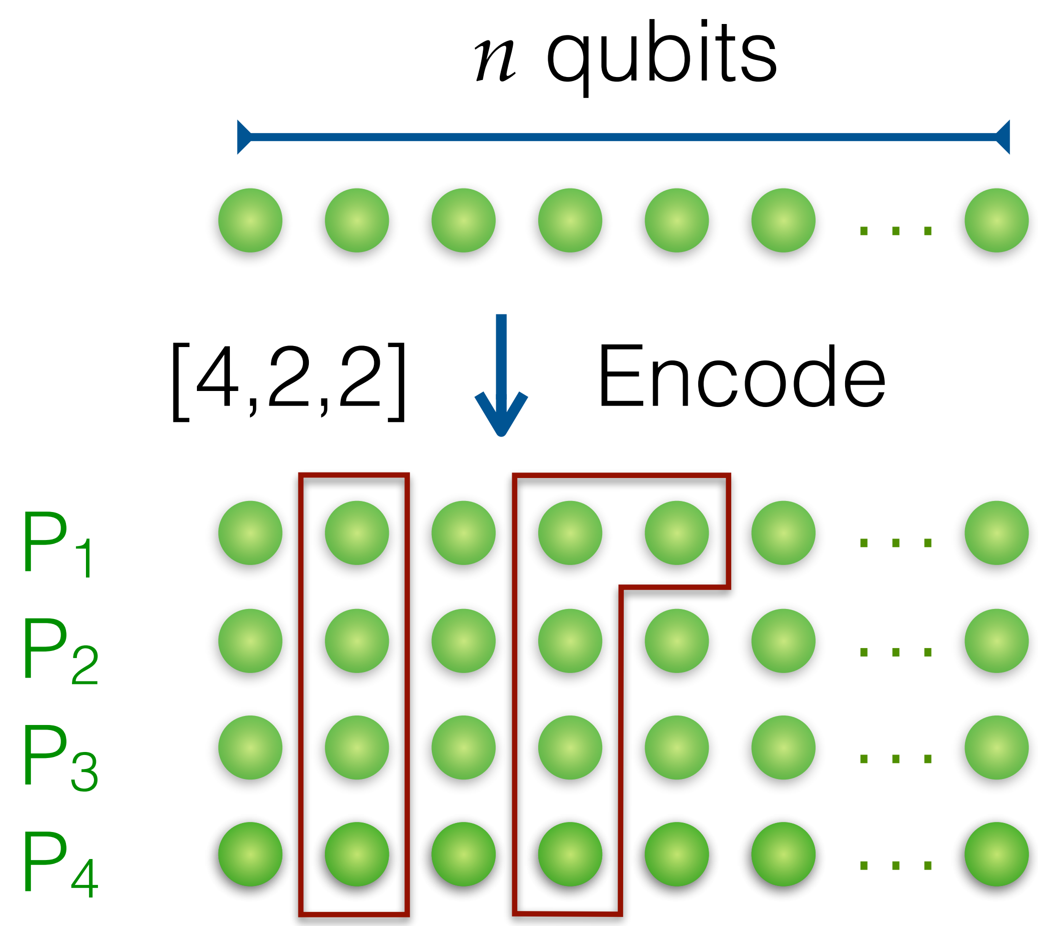

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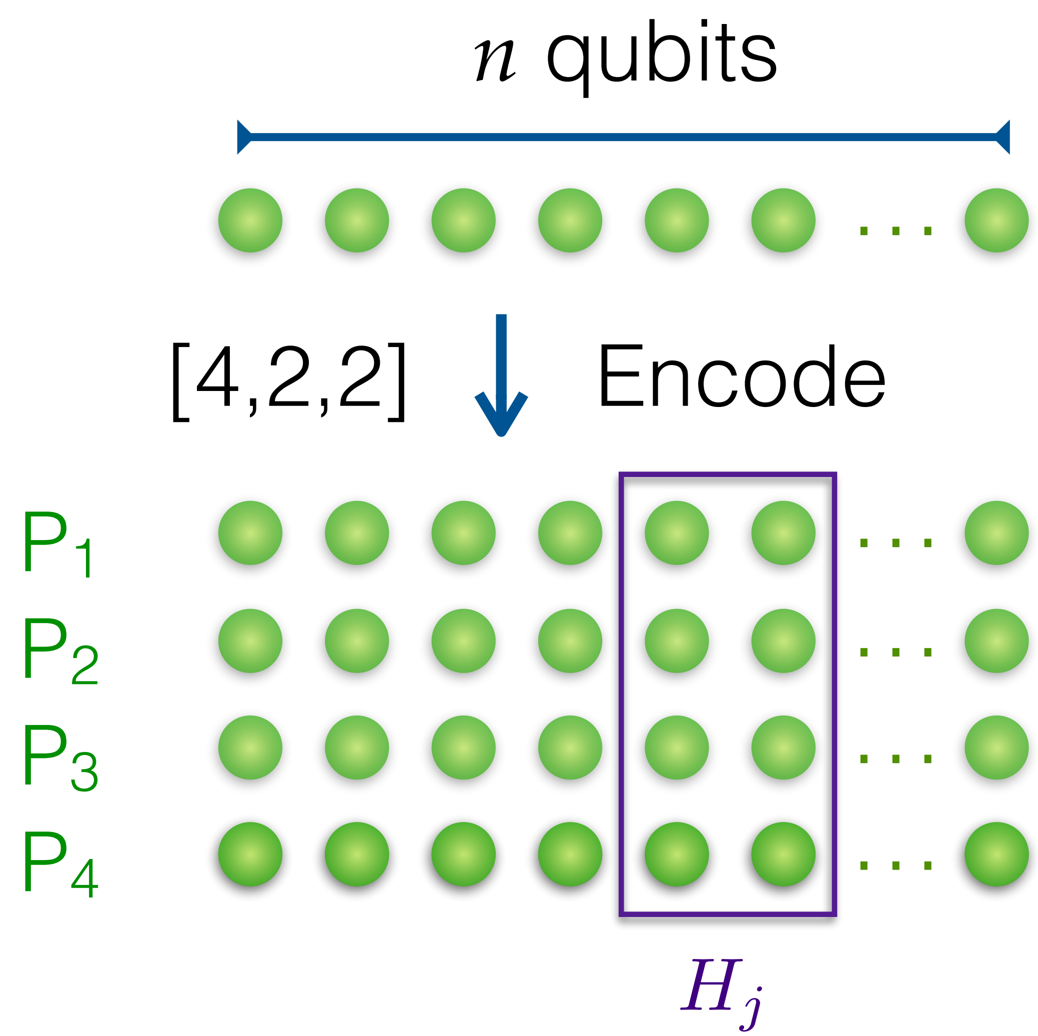

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- Questions: $O(\log n)$ bits
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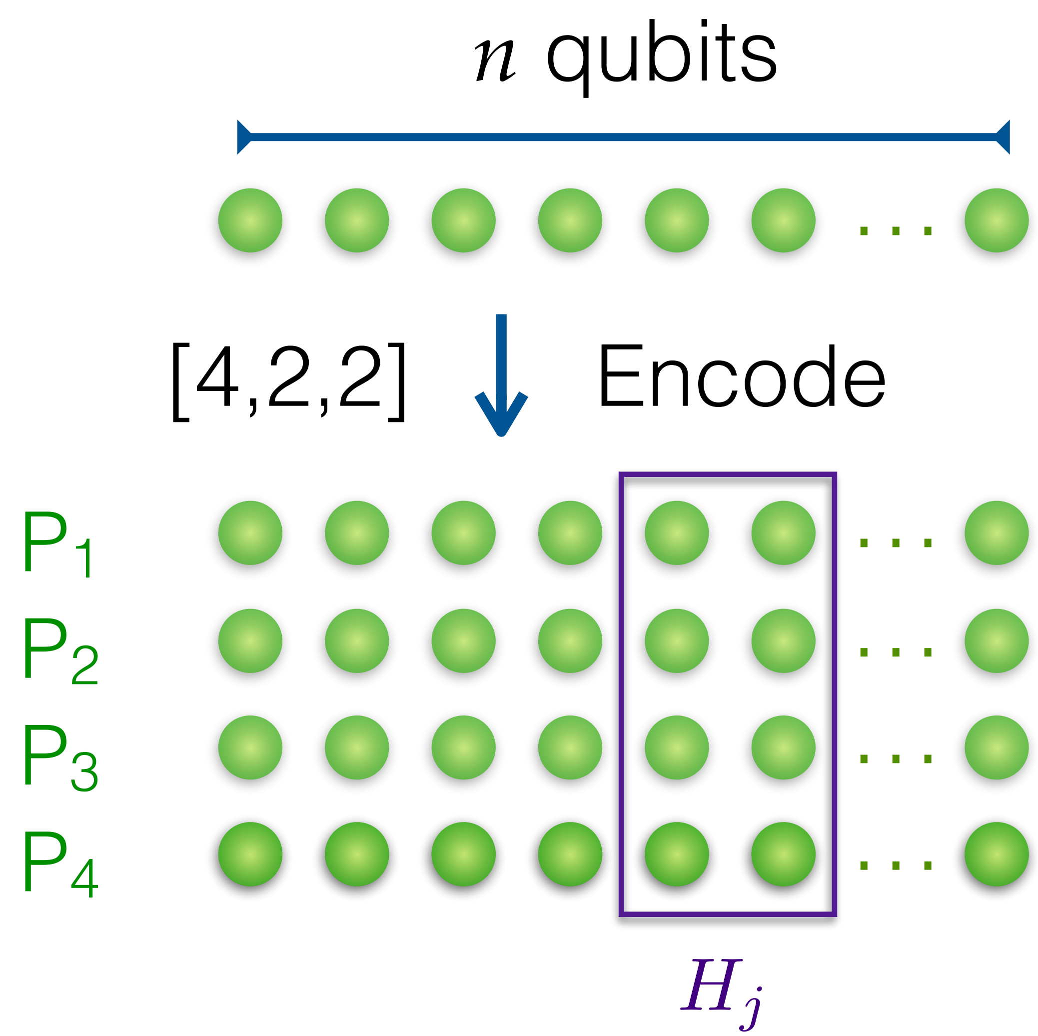

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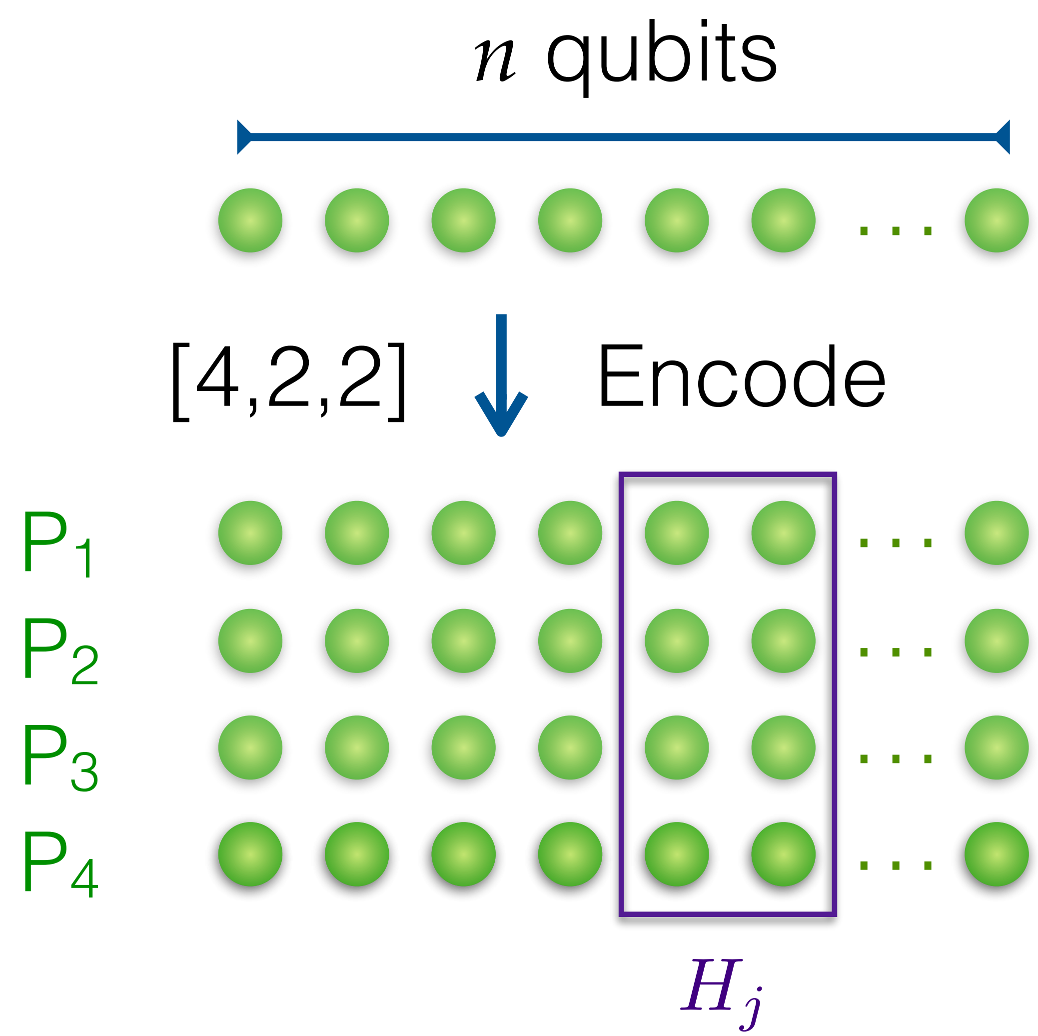

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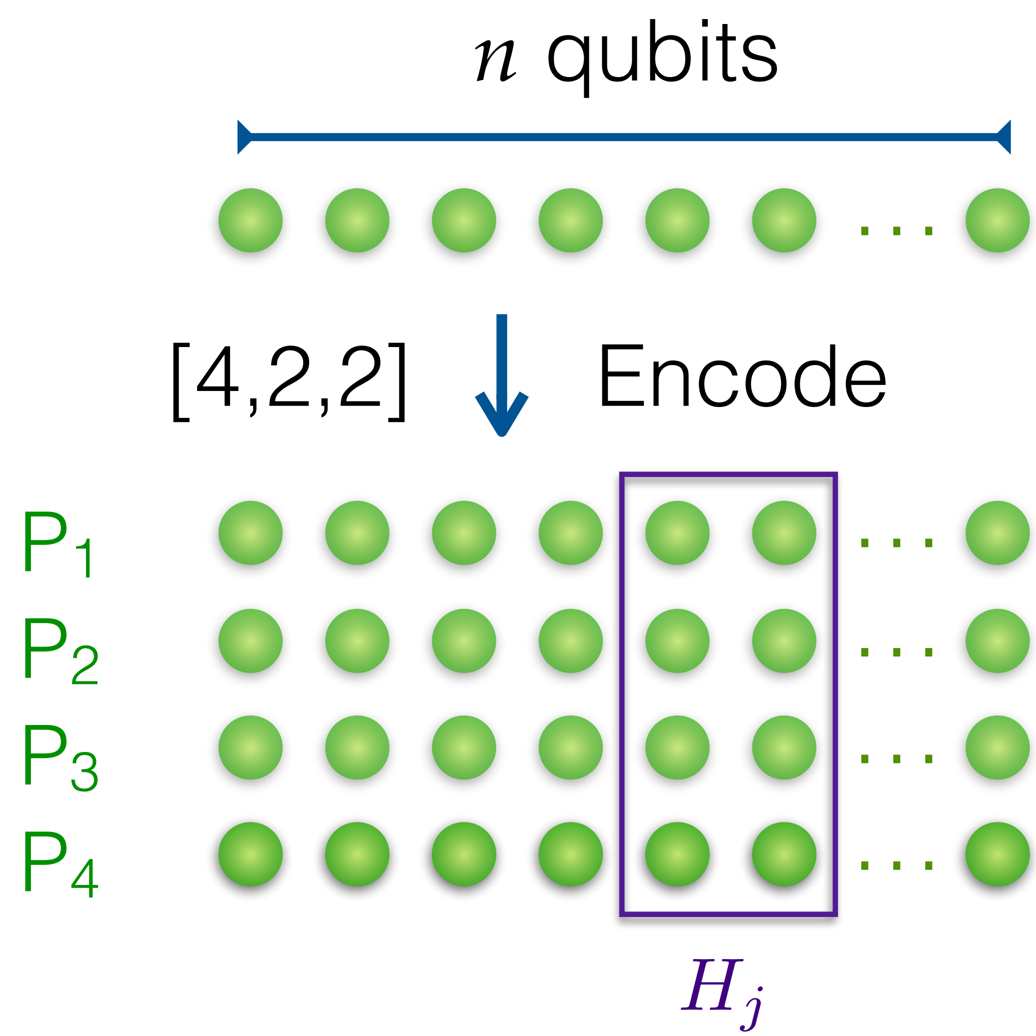
- De-quantization of both the answer messages and verifier



Main results

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- A 4-player protocol for the local Hamiltonian problem

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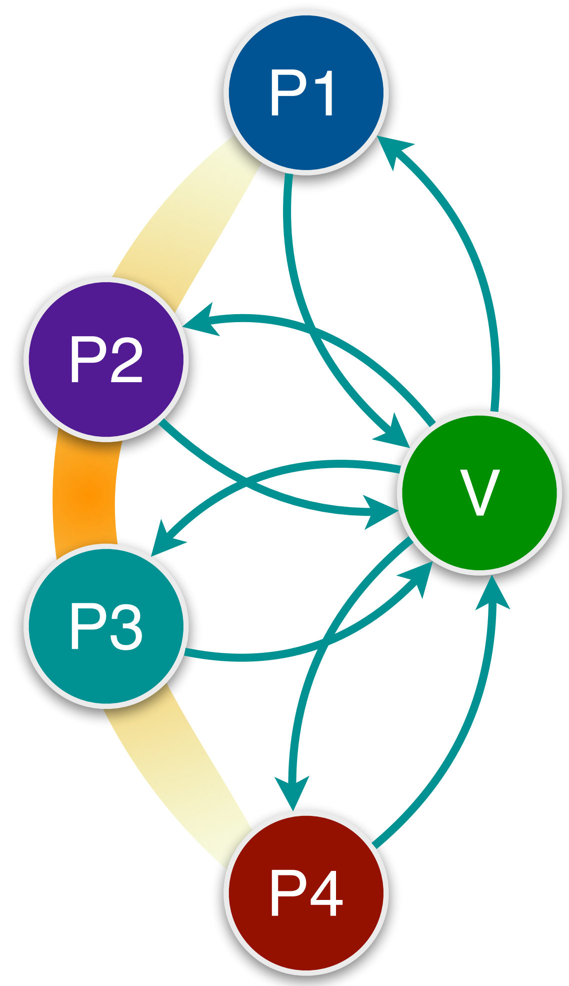

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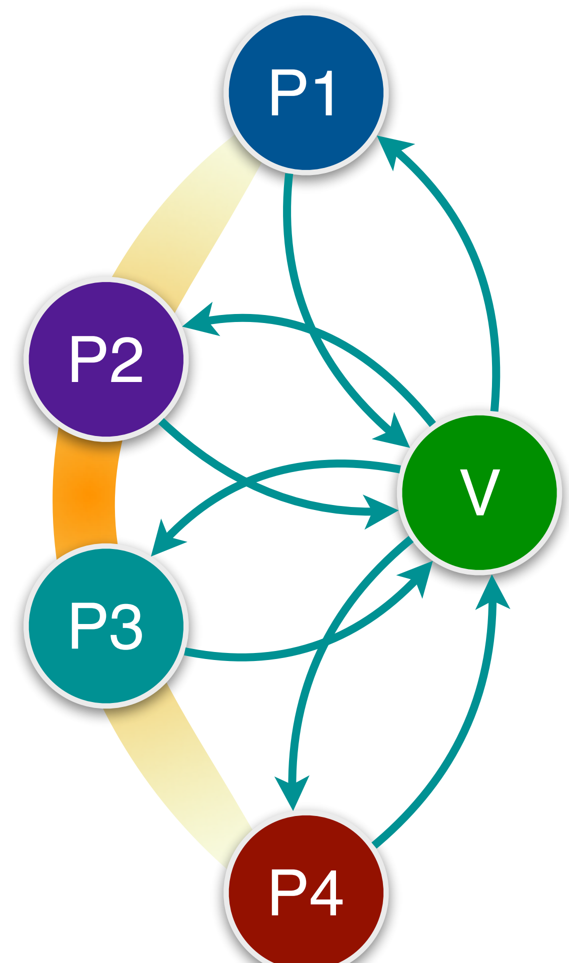

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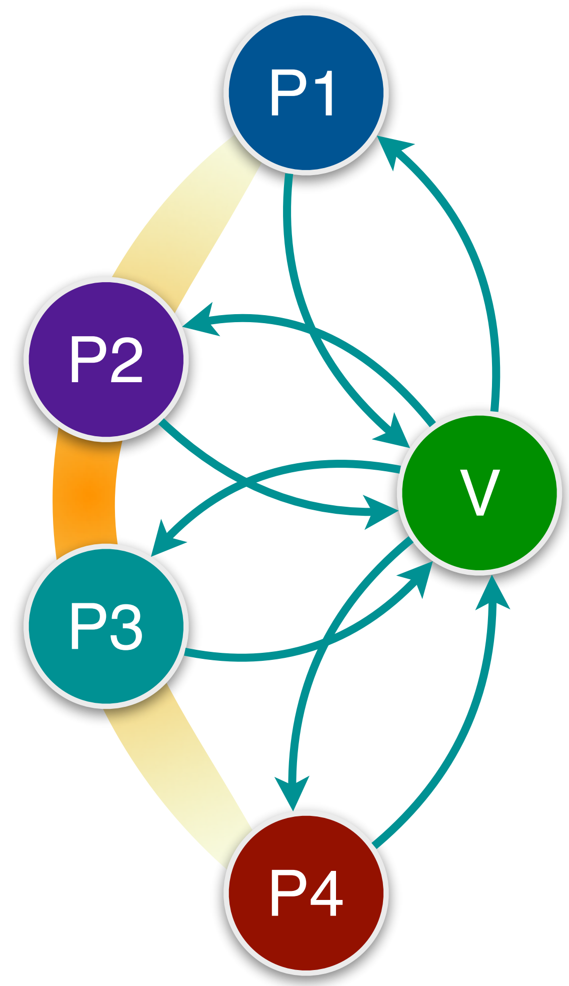

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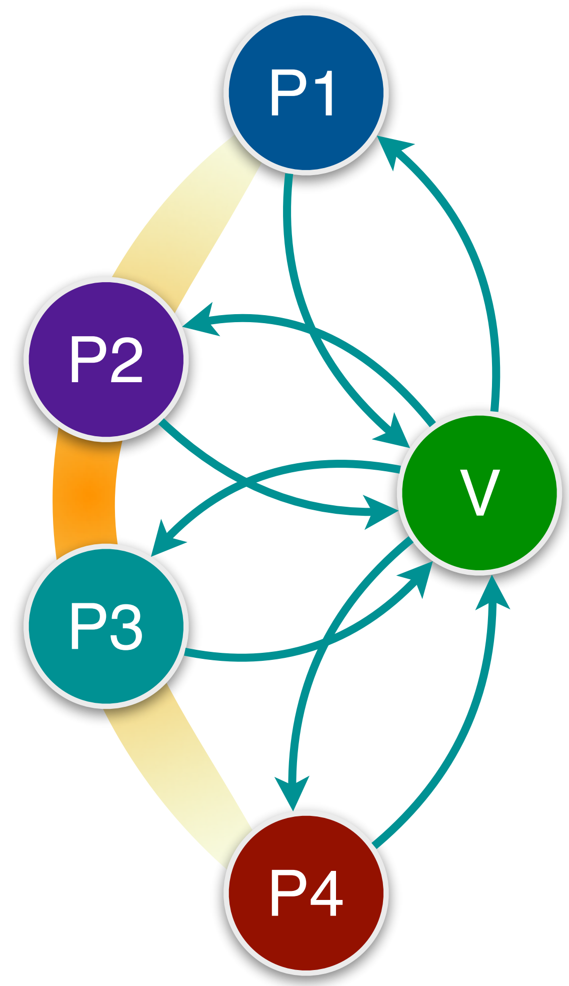
- For exponentially small gapped c,s, **MIP**$\subsetneq$**MIP***(4,1,c,s) under assumptions



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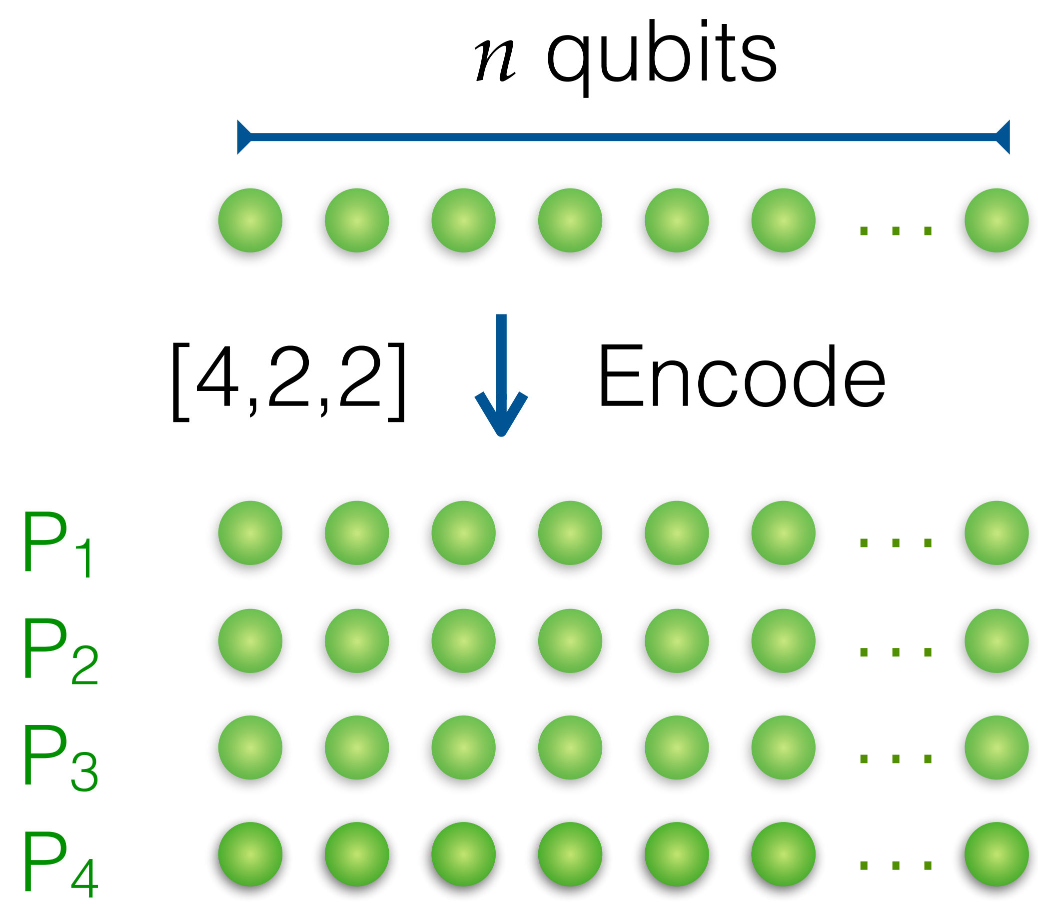

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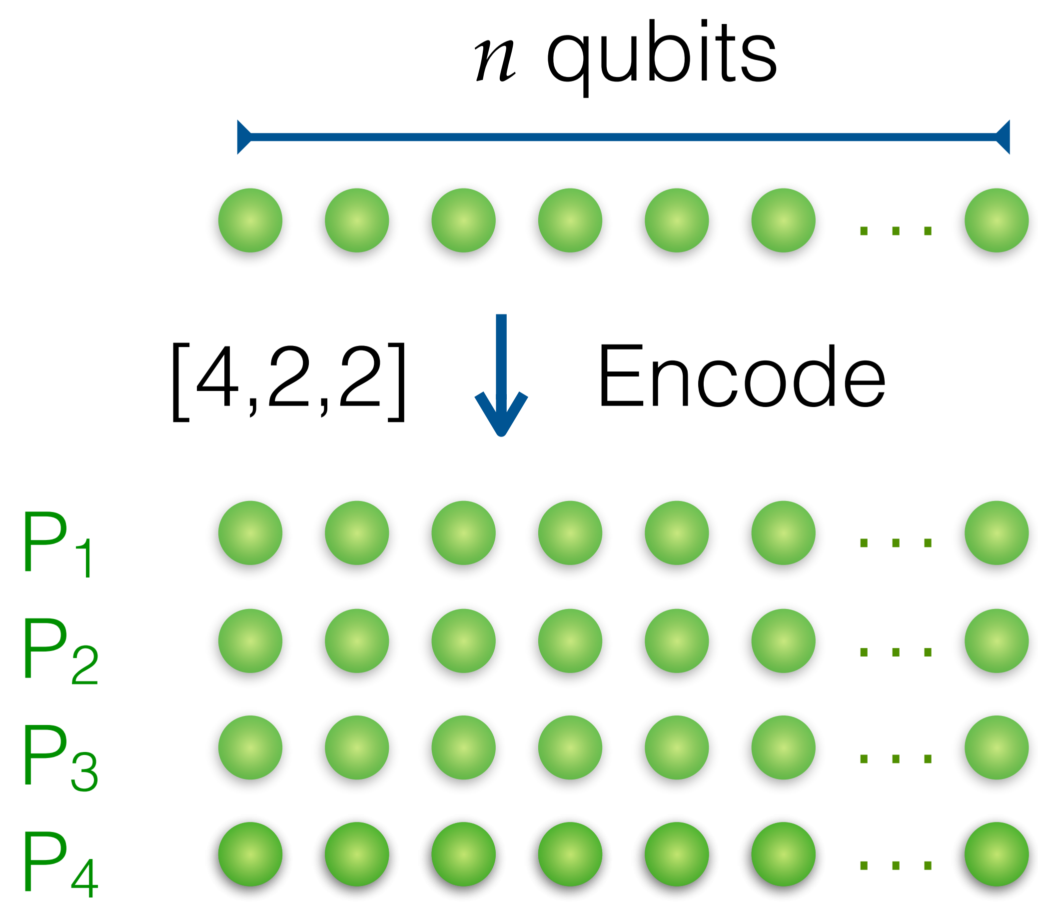

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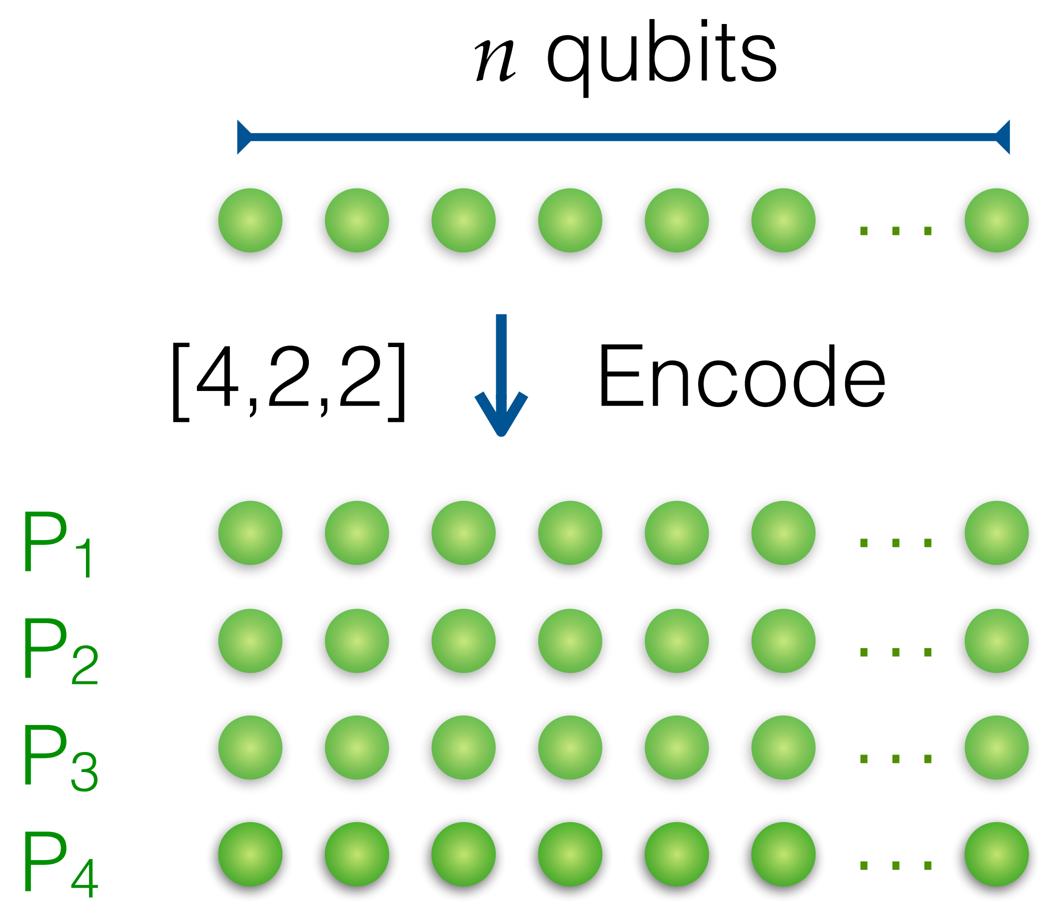

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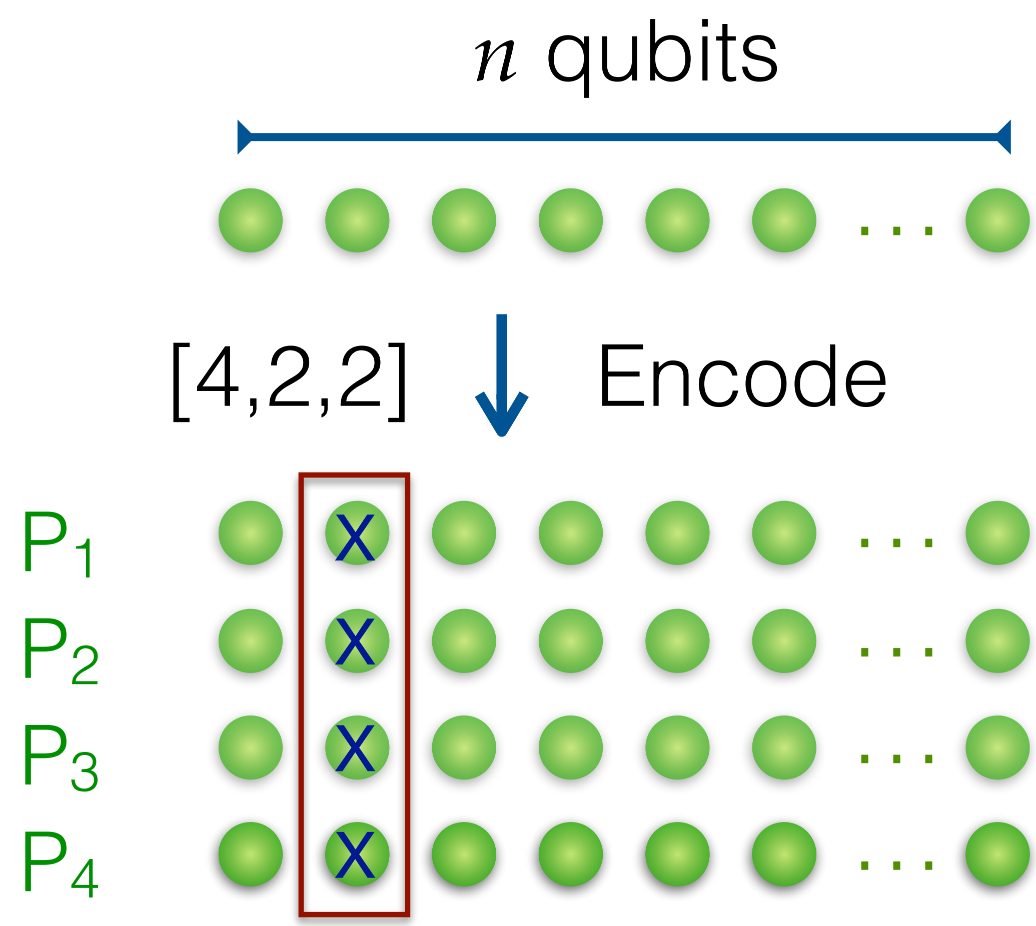

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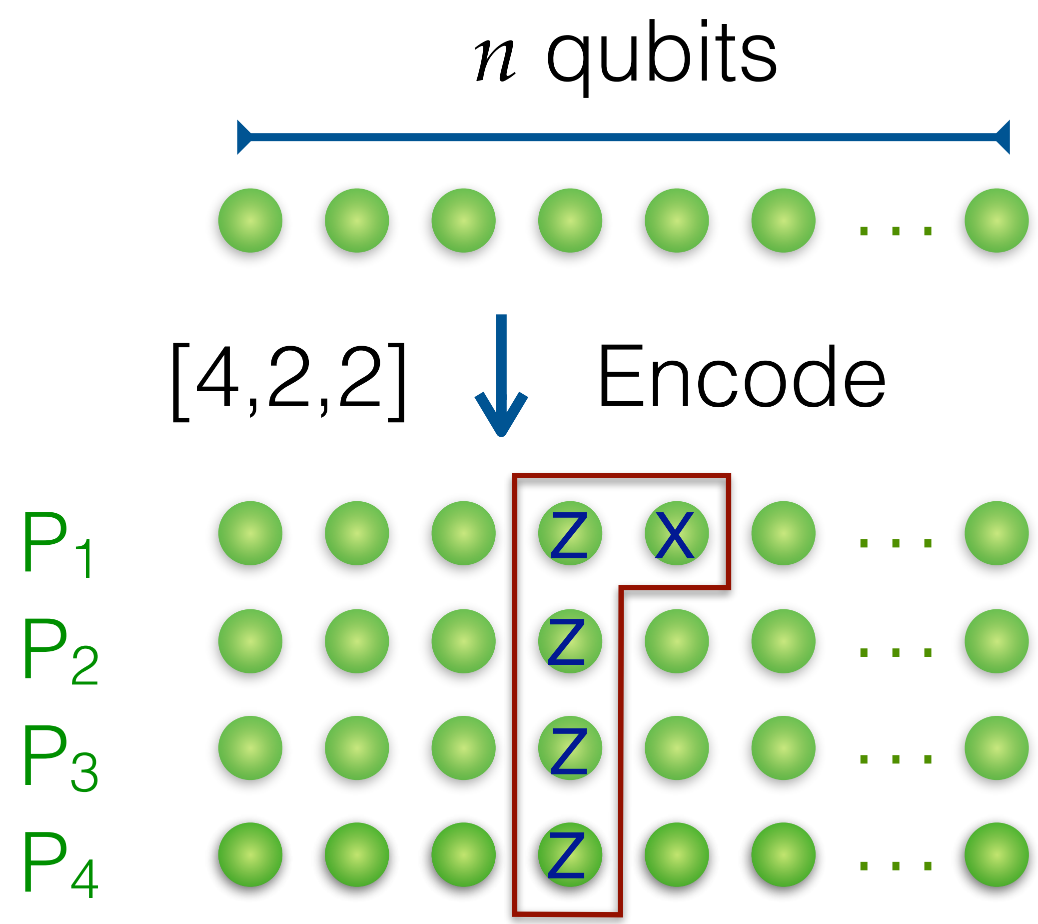

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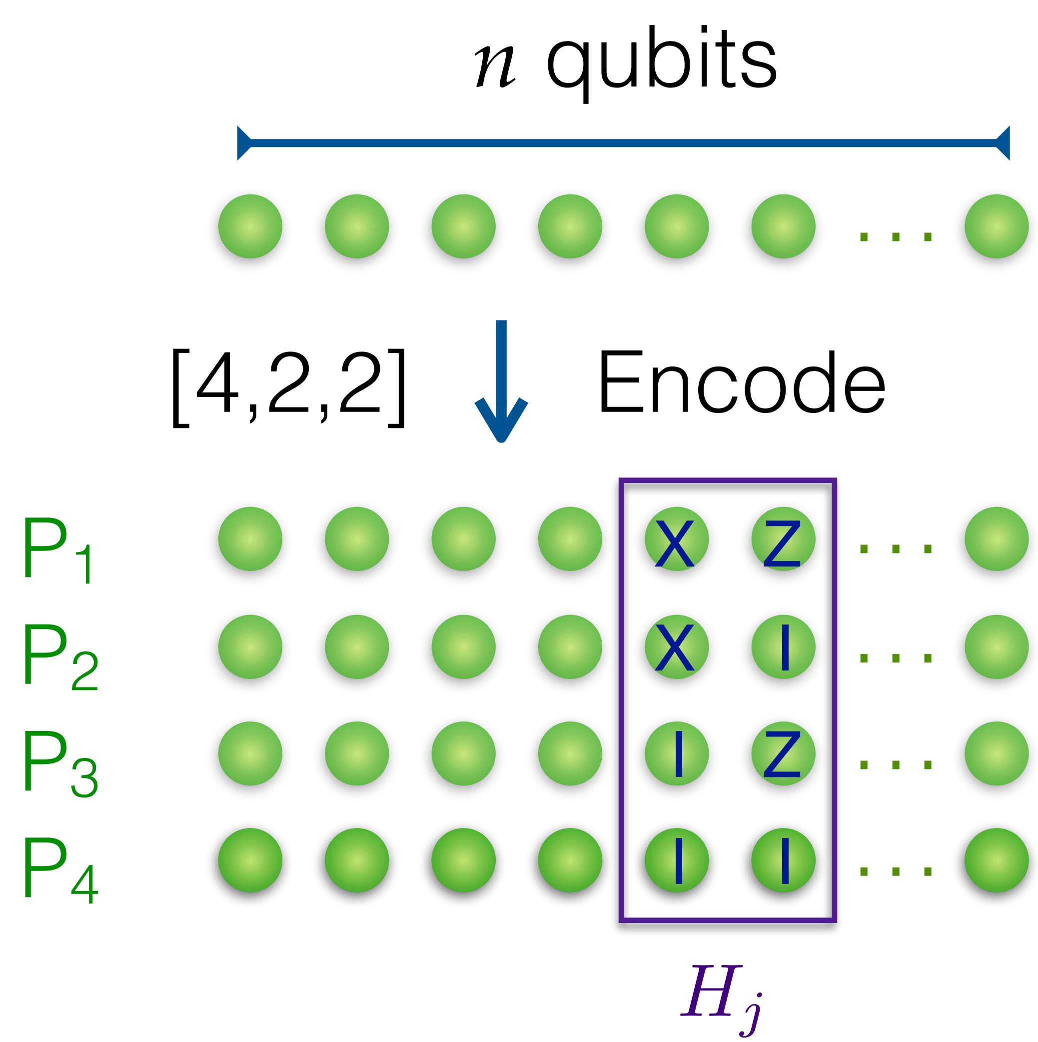

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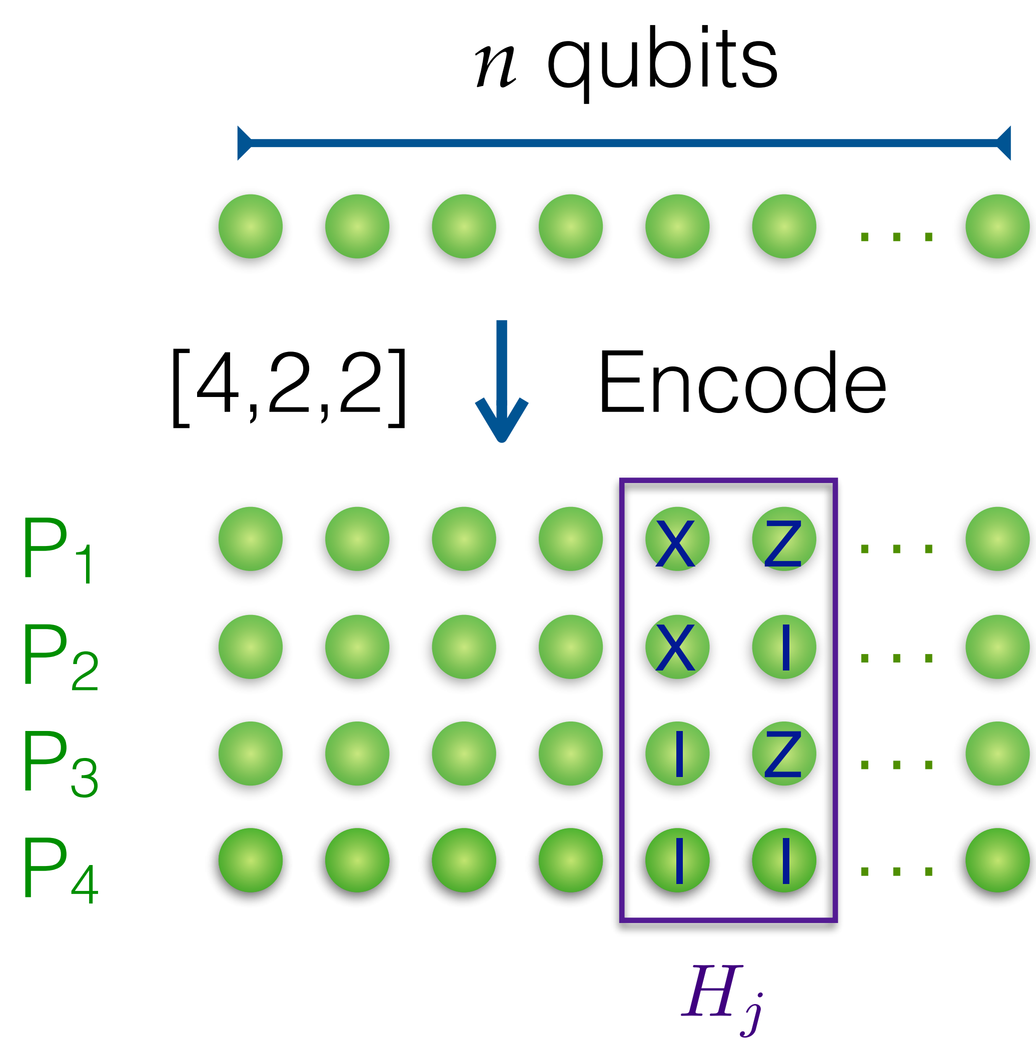
- How can we trust the provers?



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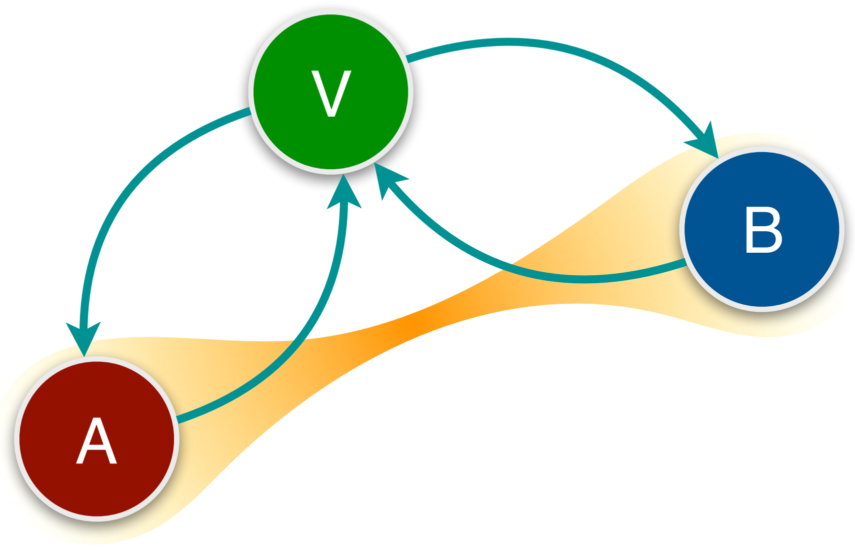

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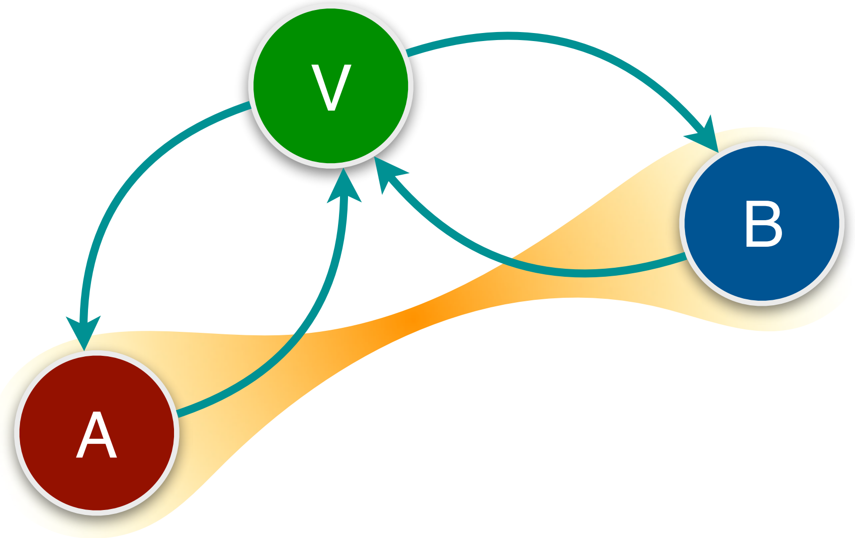

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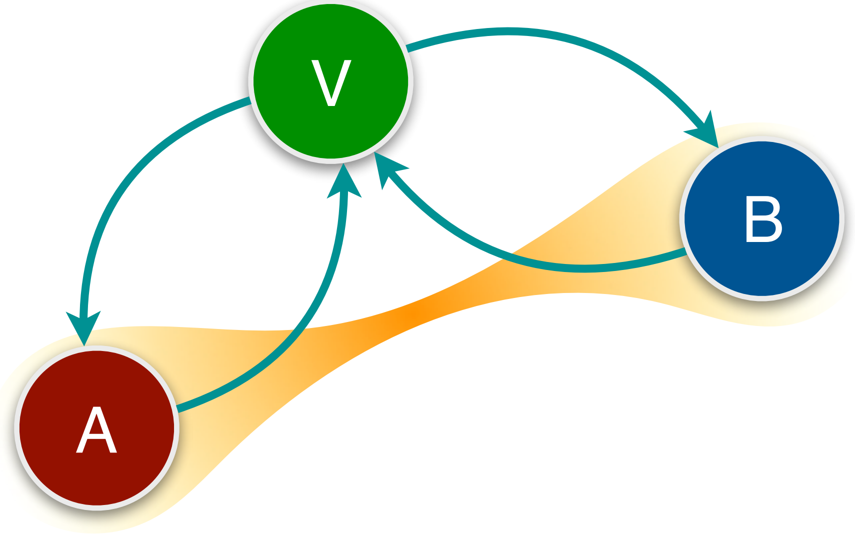

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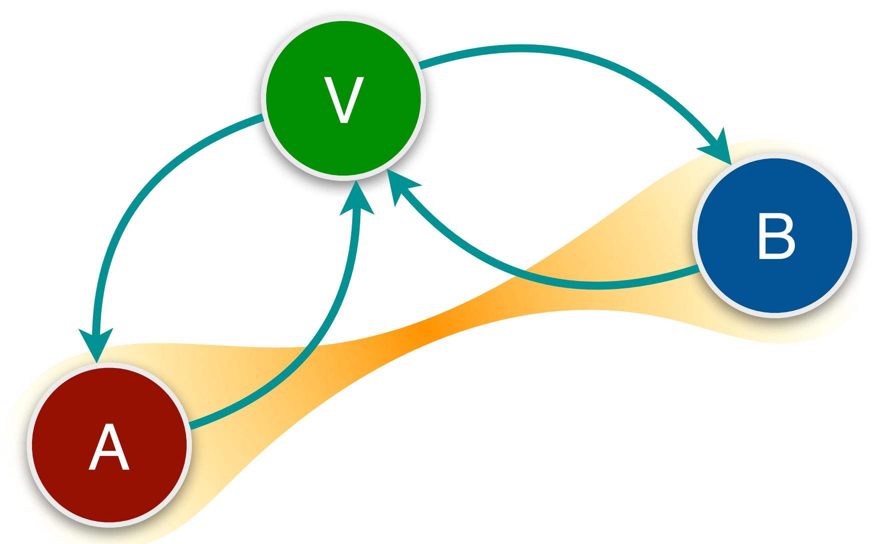

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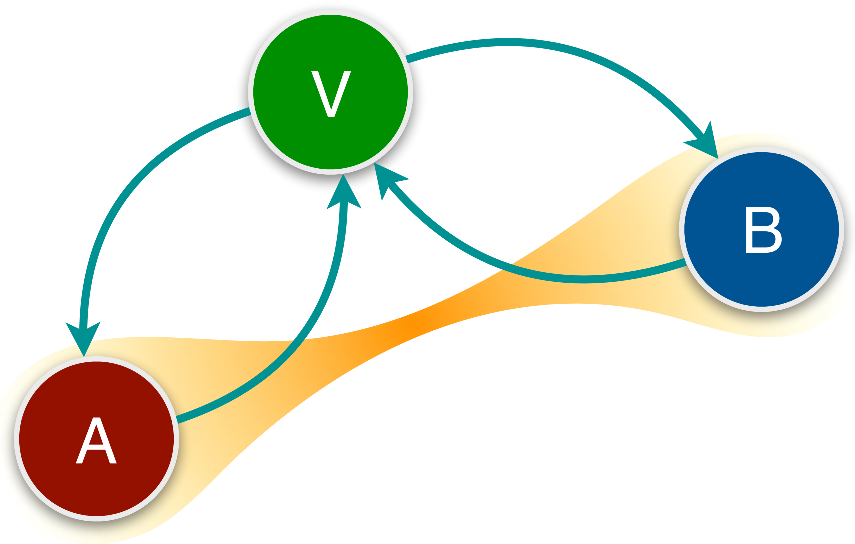
  - Impossible!

[Werner 89]



Where are the qubits?

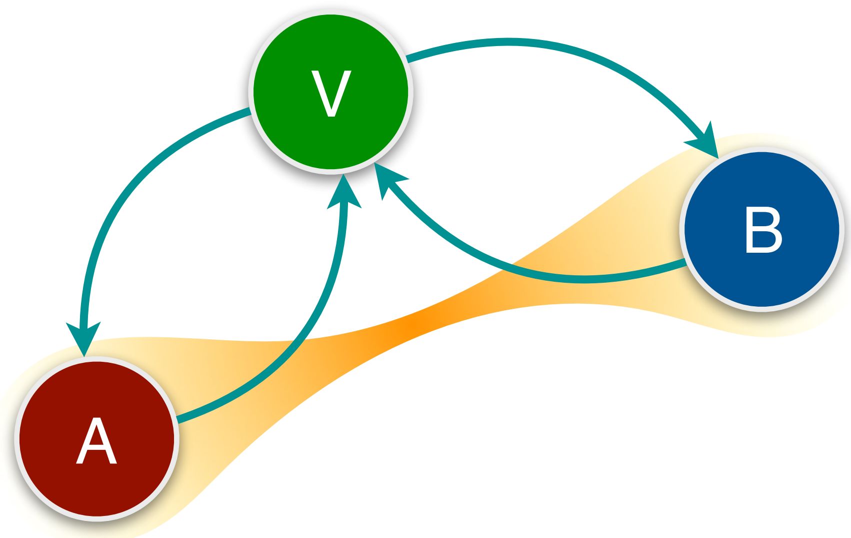
- The classical verifier can only collect information about Pr[answers $a,b,c,\ldots$ | questions $s,t,u,\ldots$]
- Alice and Bob want to prove that they have jointly prepared a quantum state
- Example I: EPR
  - Use CHSH rigidity

[Reichardt, Unger, Vazirani 13]

- Example II: Werner states
  - Impossible!

[Werner 89]

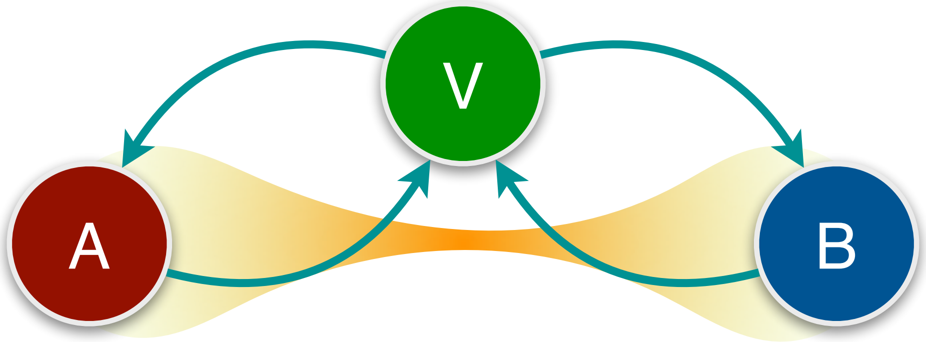
- Stabilizer games



CHSH game in terms of stabilizers

CHSH game in terms of stabilizers

CHSH: $a \oplus b \stackrel{?}{=} s \wedge t$

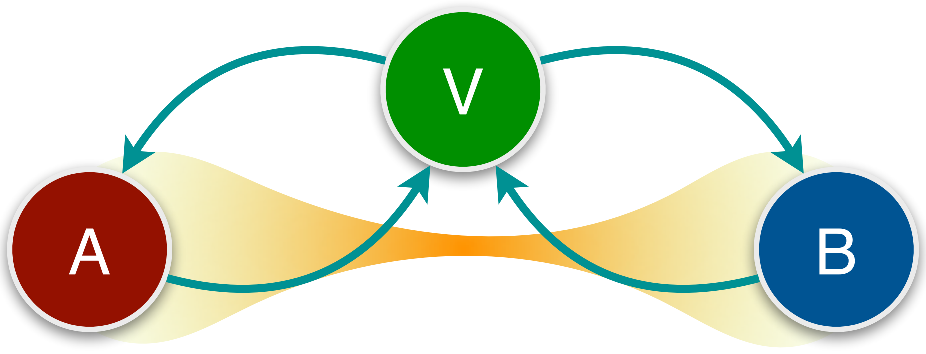


CHSH game in terms of stabilizers

- The EPR state as a stabilizer

X	X
Z	Z

CHSH: $a \oplus b \stackrel{?}{=} s \wedge t$



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X	X
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$$\langle XX + ZZ \rangle = 2$$

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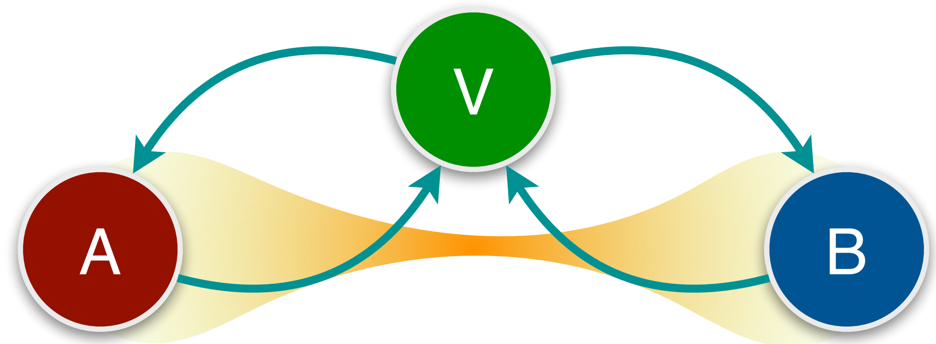


CHSH game in terms of stabilizers

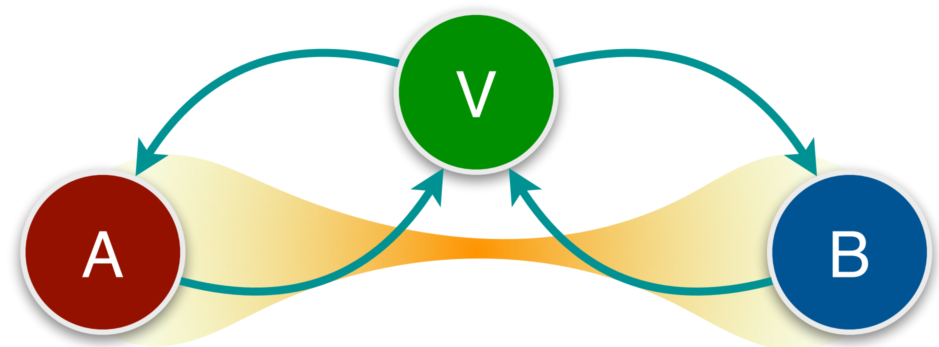
- The EPR state as a stabilizer

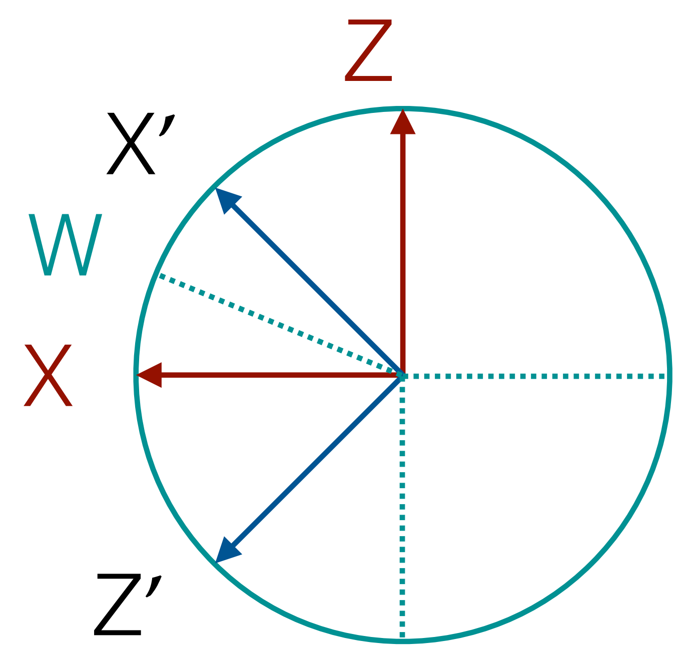
X	X
Z	Z

$$\langle XX + ZZ \rangle = 2$$

$$X = \frac{X' + Z'}{\sqrt{2}} \qquad Z = \frac{X' - Z'}{\sqrt{2}}$$

CHSH: $a \oplus b \stackrel{?}{=} s \wedge t$





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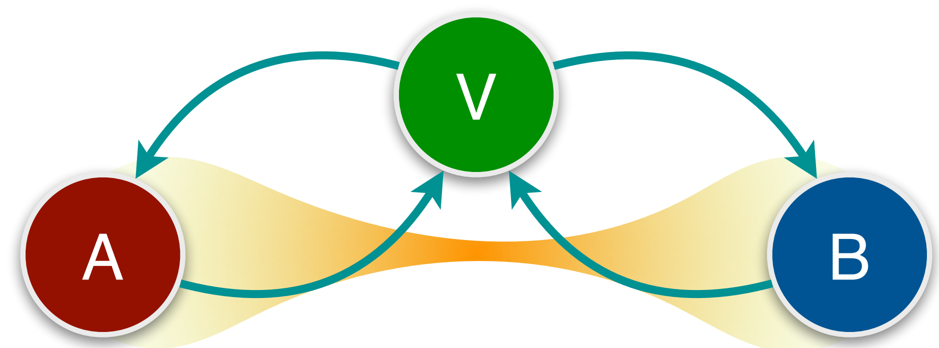

X	X
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$$\langle XX + ZZ \rangle = 2$$

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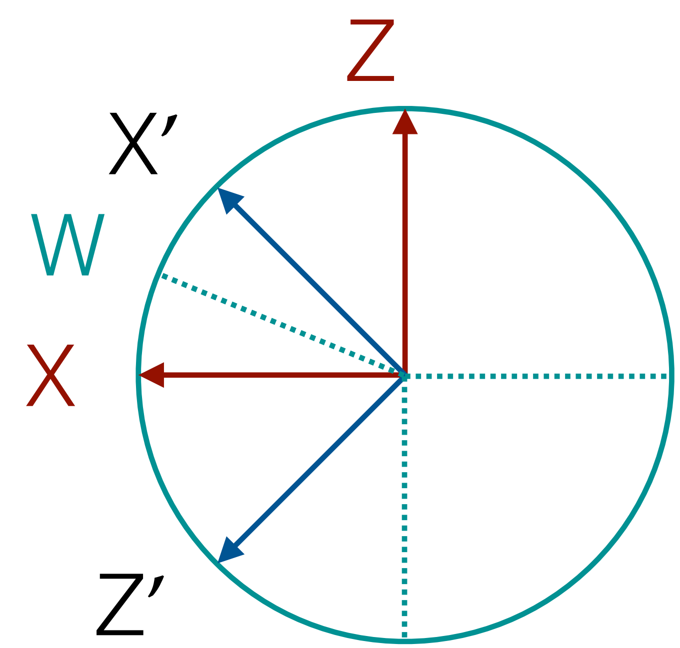
$$\langle XX' + XZ' + ZX' - ZZ' \rangle = 2\sqrt{2}$$

$$\langle X(X' + Z') + Z(X' - Z') \rangle \leq 2$$



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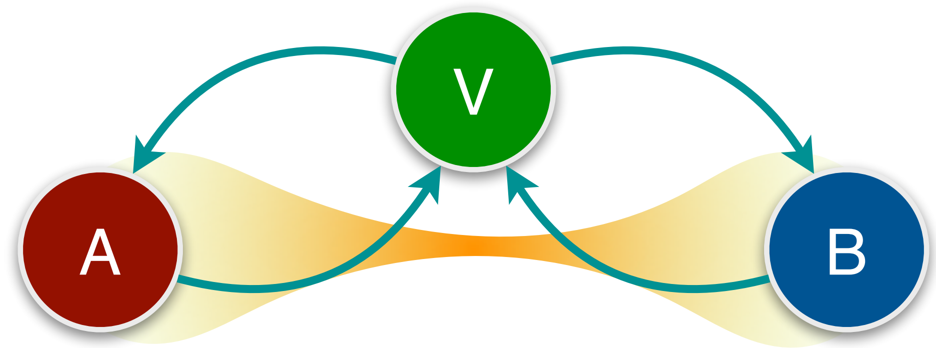

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$$\langle X(X' + Z') + Z(X' - Z') \rangle \leq 2$$

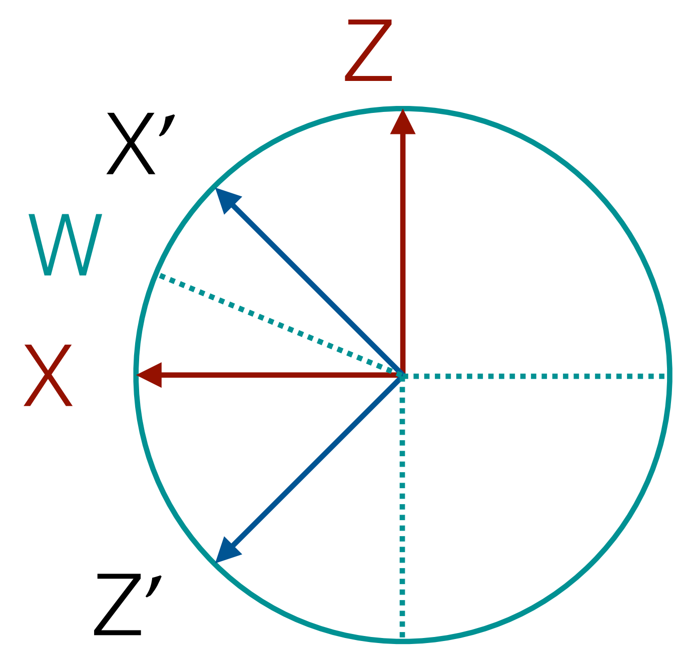
X	X
Z	Z

$\longrightarrow$

+	X	X'
+	X	Z'
+	Z	X'
-	Z	Z'

$\longrightarrow$

+	0	0
+	0	1
+	1	0
-	1	1



Stabilizer games with a special player

Stabilizer games with a special player

- Apply the 45-degree rotation trick to the stabilizers of the [4,2,2] code

X	X	X	X
Z	Z	Z	Z

$\longrightarrow$

+	X	X	X	X’
+	X	X	X	Z’
+	Z	Z	Z	X’
-	Z	Z	Z	Z’

Stabilizer games with a special player

- Apply the 45-degree rotation trick to the stabilizers of the [4,2,2] code

X	X	X	X
Z	Z	Z	Z

→

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+	X	X	X	Z’
+	Z	Z	Z	X’
-	Z	Z	Z	Z’

→

+	0	0	0	2
+	0	0	0	3
+	1	1	1	2
-	1	1	1	3

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Z	Z	Z	Z

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+	X	X	X	Z’
+	Z	Z	Z	X’
-	Z	Z	Z	Z’

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Parity Questions

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Parity Questions

- Special player: the 4-th player

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X	X	X	X
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→

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→

+	0	0	0	2
+	0	0	0	3
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Parity Questions

- Special player: the 4-th player

- No full rigidity, but partial rigidity: the special player must measure honestly

Partial rigidity of the special player stabilizer game

Lemma (Partial Rigidity). For any strategy $\mathcal{S} = (\rho, \{R_w^{(i)}\})$ of the special player stabilizer game whose value is at least $\omega_{\rm sps}^* - \varepsilon$ there exists an isometry $V : \mathcal{H}_4 \to \mathbb{C}^2 \otimes \hat{\mathcal{H}}_4$ such that

$$R_3^{(4)} = V^\dagger (Z' \otimes I) V,$$

$$R_2^{(4)} \approx_{\sqrt{\varepsilon}} V^\dagger (X' \otimes I) V.$$

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Proof of the lemma uses the Jordan's lemma and a proof technique for the CHSH rigidity from [Reichardt, Unger, Vazirani 13]

Stabilizer games

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- The stabilizer game is a 4-player game with 2-bit questions and single-bit answers

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+	0	0	2	0
+	0	0	3	0
+	1	1	2	1
-	1	1	3	1

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- The stabilizer game is a 4-player game with 2-bit questions and single-bit answers
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- Encoded Werner states are certifiable!

+	0	0	2	0
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Rigidity of the stabilizer game

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$$
\begin{aligned}
R_3^{(i)} &= V_i^\dagger (Z' \otimes I) V_i, \\
R_2^{(i)} &\approx_{\sqrt{\varepsilon}} V_i^\dagger (X' \otimes I) V_i, \\
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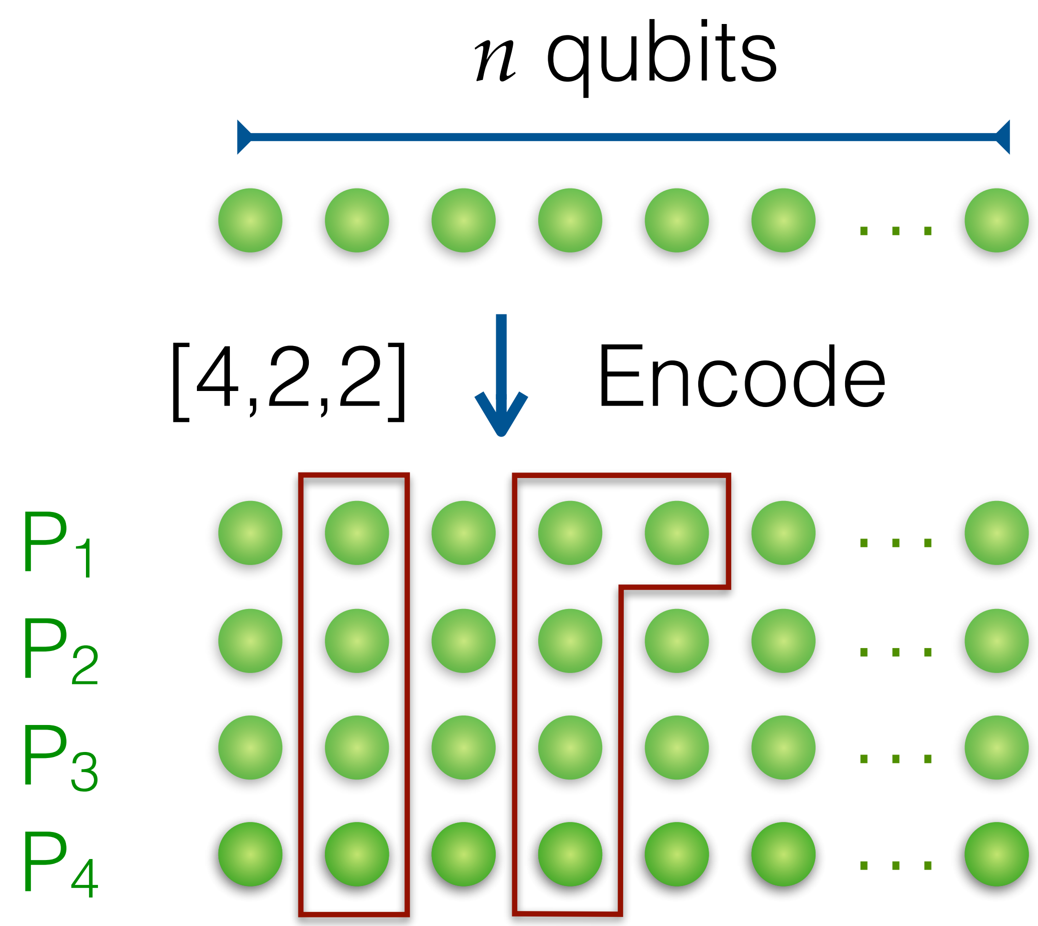
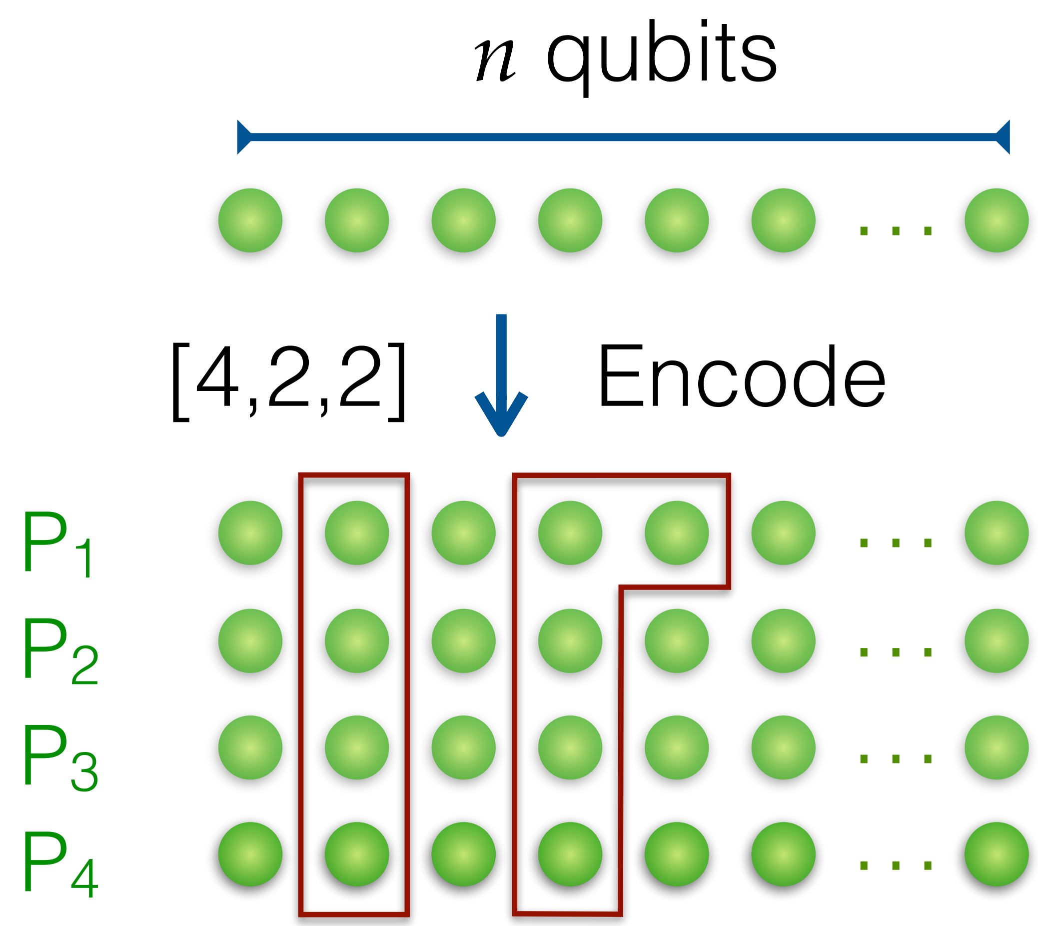
The proof uses the consistency properties of the game

Multi-qubit stabilizer game



Multi-qubit stabilizer game

- For both types of the encoding checks, the verifier plays the corresponding stabilizer game



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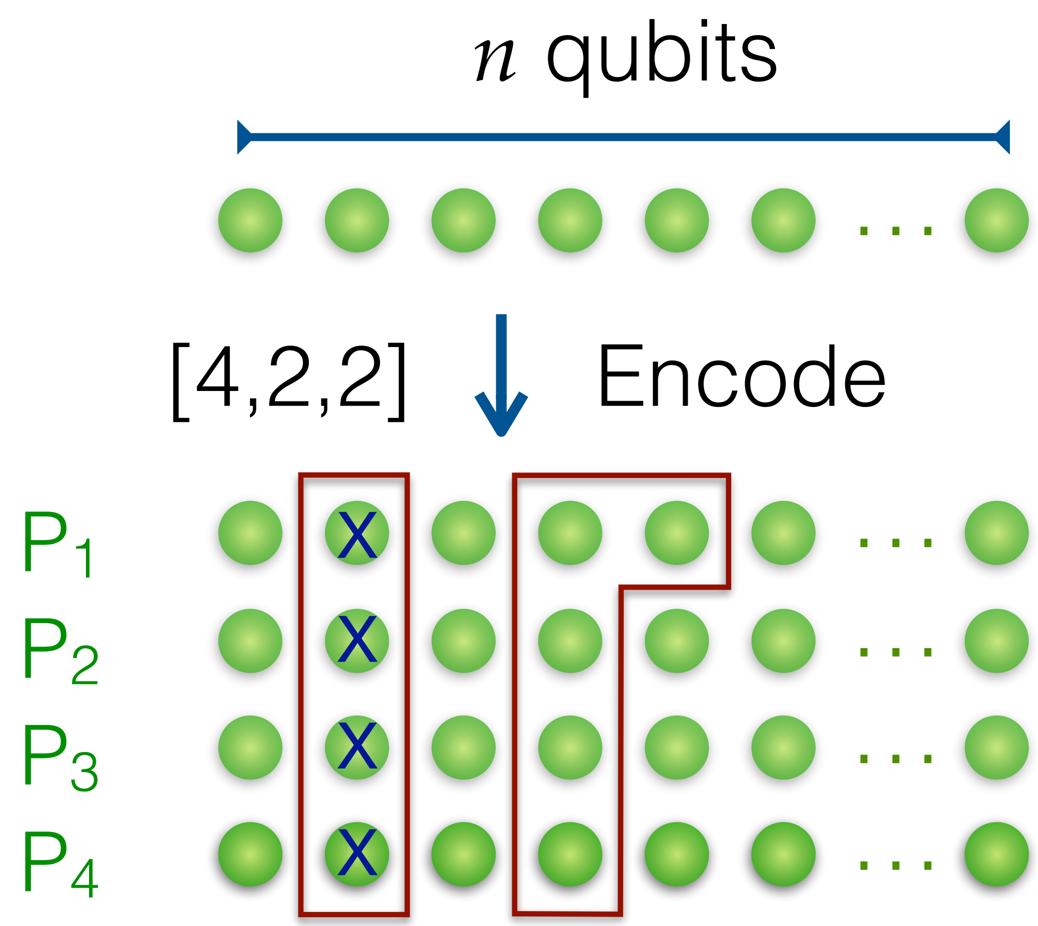

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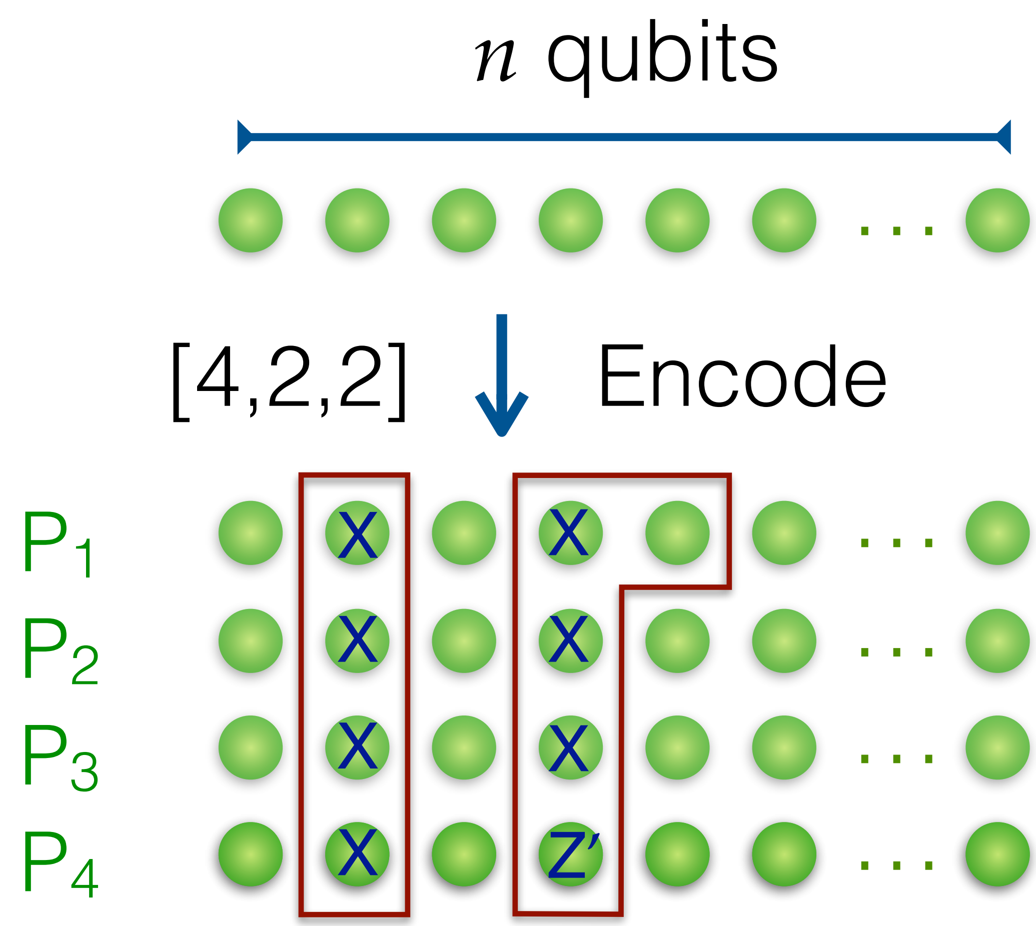

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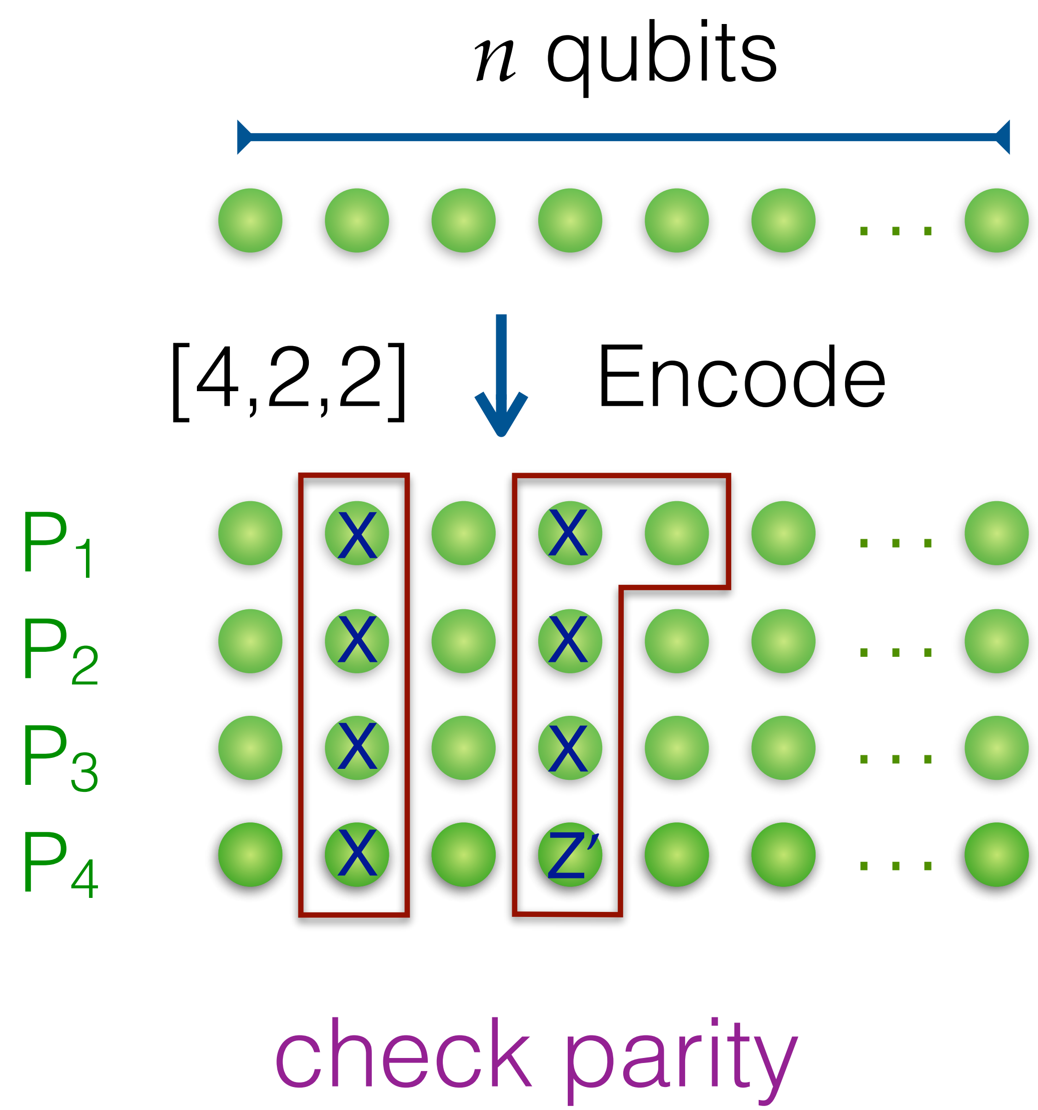

Multi-qubit stabilizer game

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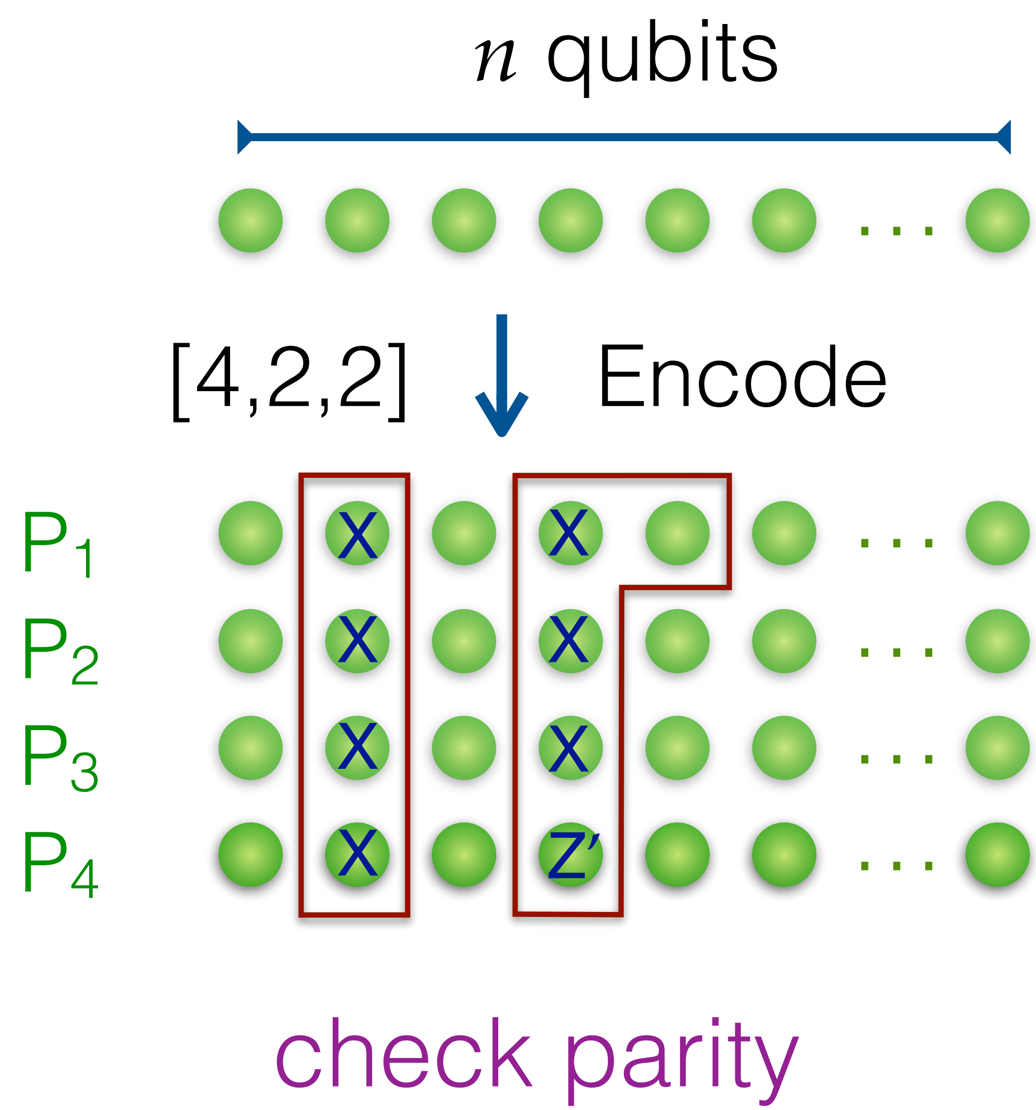
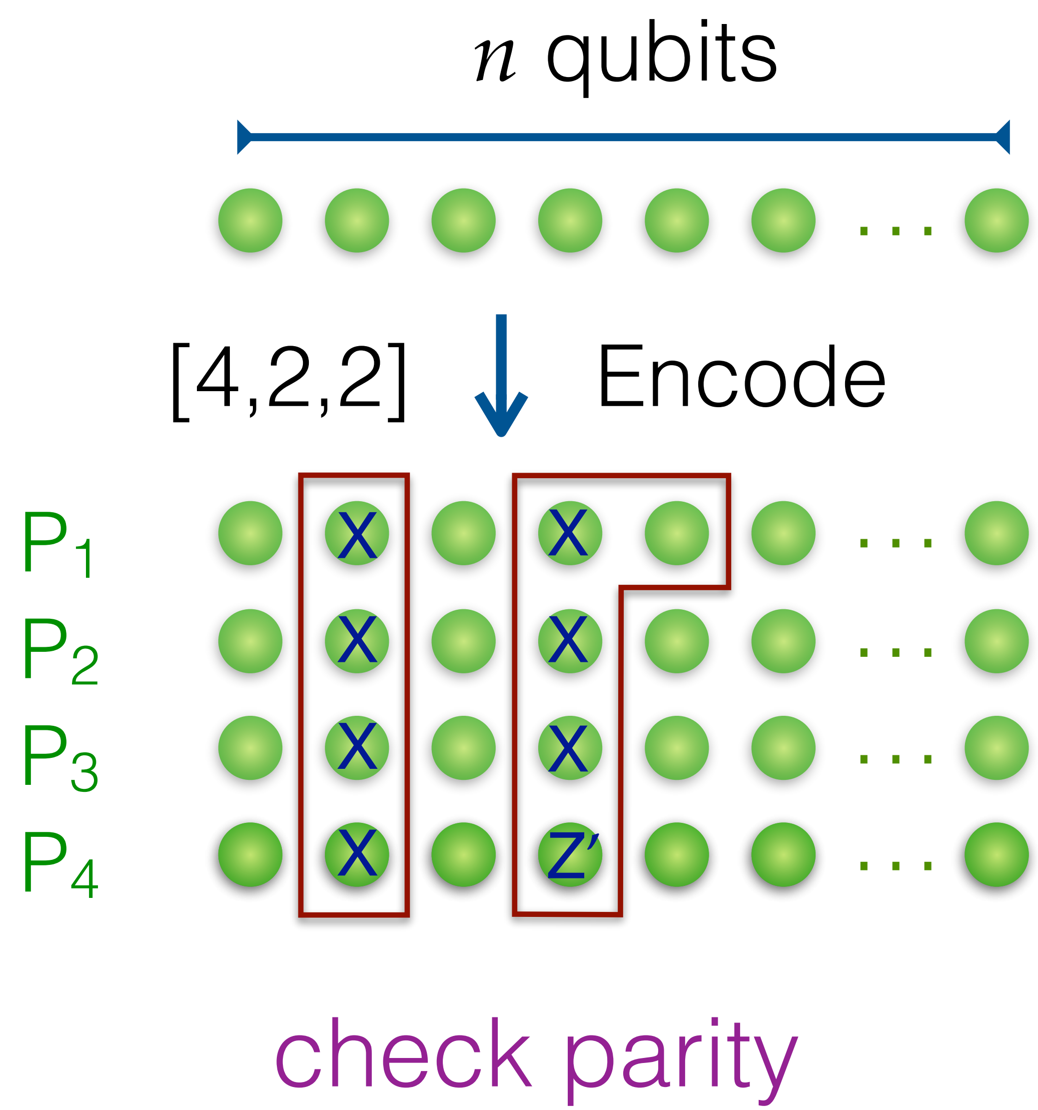
- Full rigidity

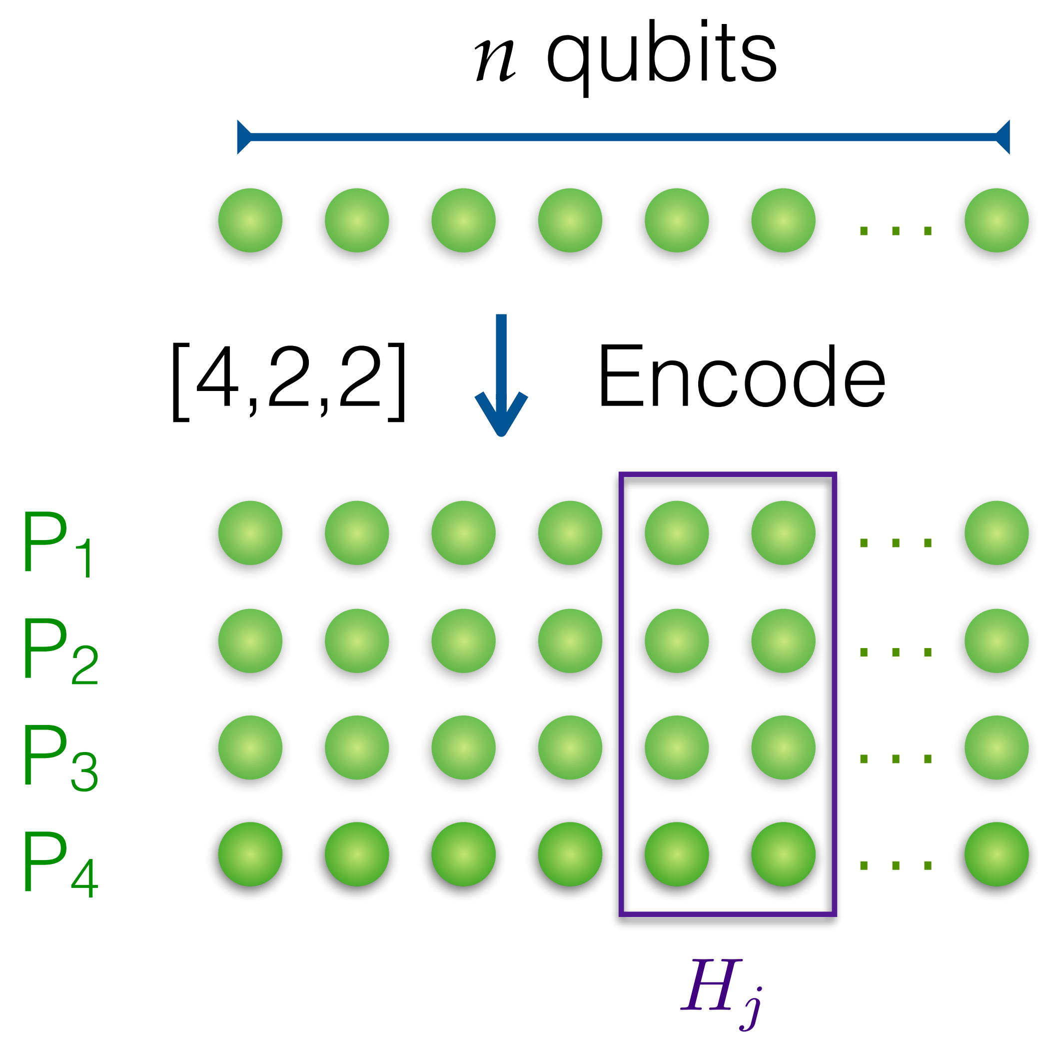


Multi-qubit stabilizer game

- For both types of the encoding checks, the verifier plays the corresponding stabilizer game
- Full rigidity
- “Locates” the n qubits in a sequential way



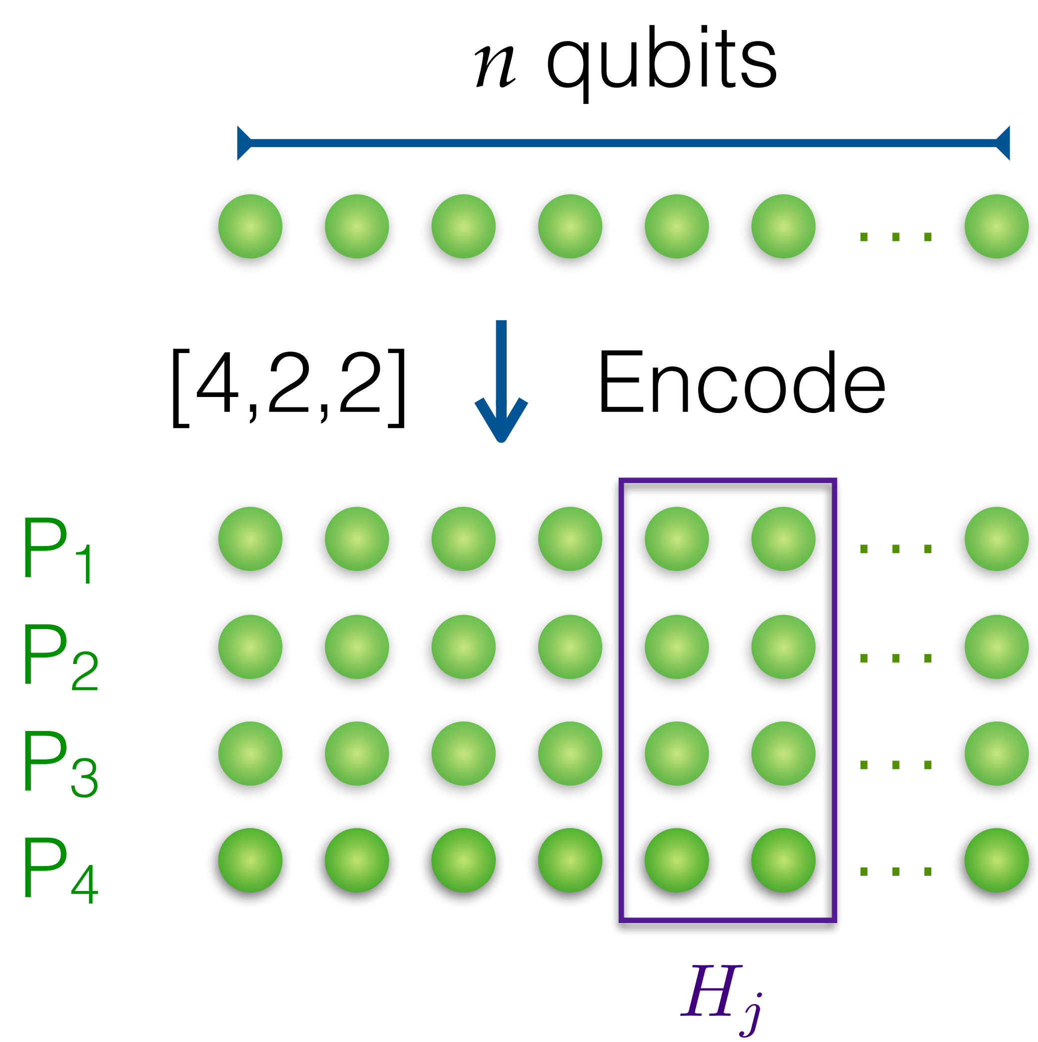
Energy measurement



Energy measurement

- Hamiltonians with XZ interactions remain **QMA**-complete

  [Cubitt, Montanaro 14]



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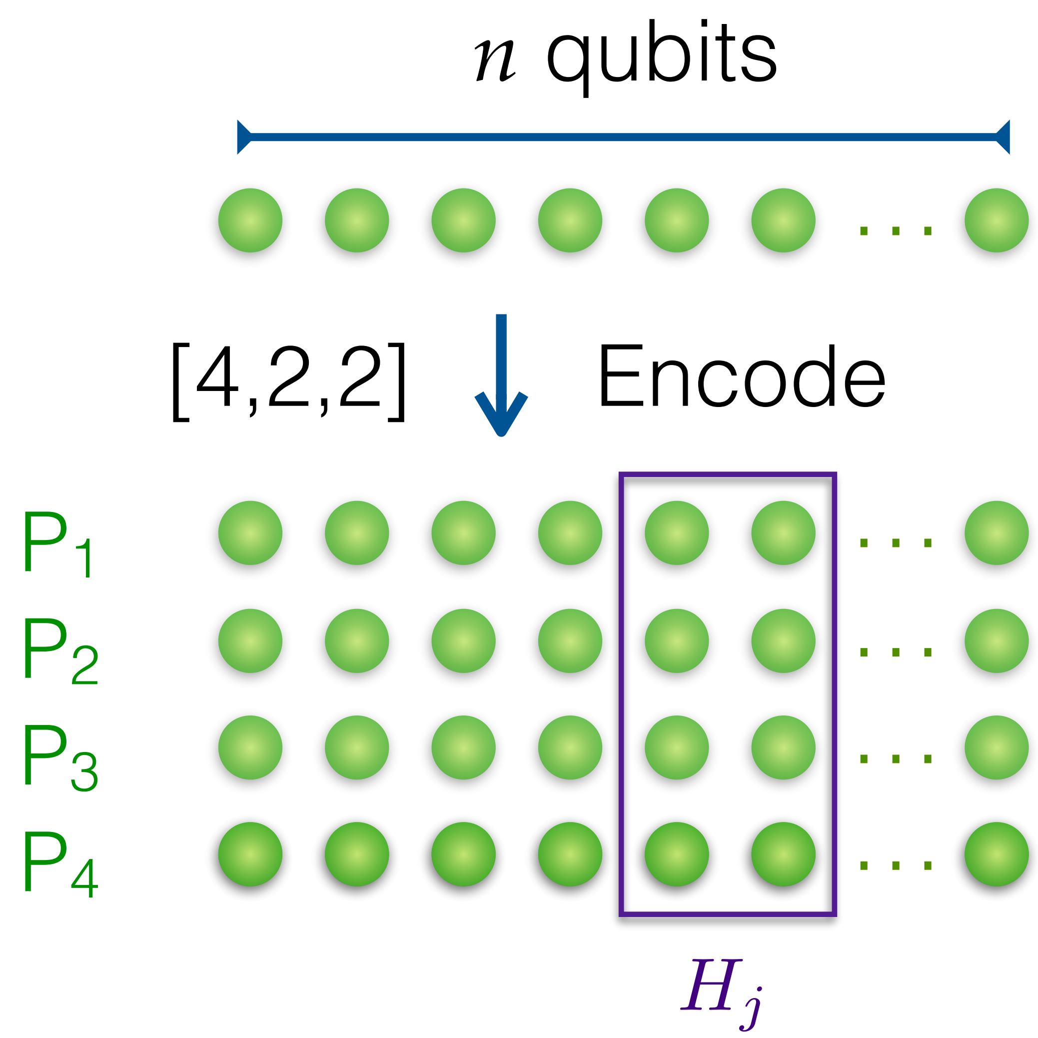
- Send measurement specifications of the logical X and logical Z operators



Energy measurement

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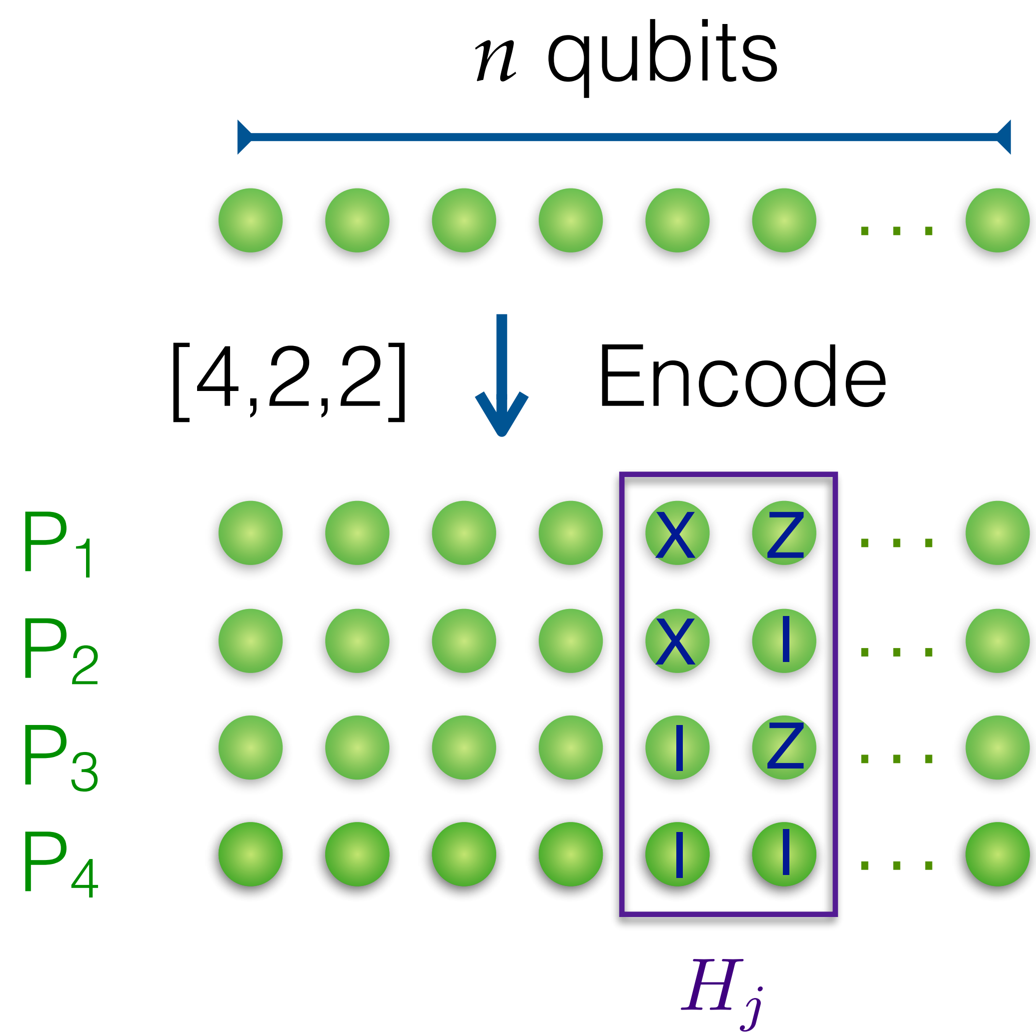
- Send measurement specifications of the logical X and logical Z operators

X	X	I	I
Z	I	Z	I



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[Anand, Vidick 15]

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  [Anand, Vidick 15]
- Can we reduce the number of players down to 2?
- Beyond **QMA**-hardness?

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12012[illegible]02[illegible]1203123030231231023123033023321020303032
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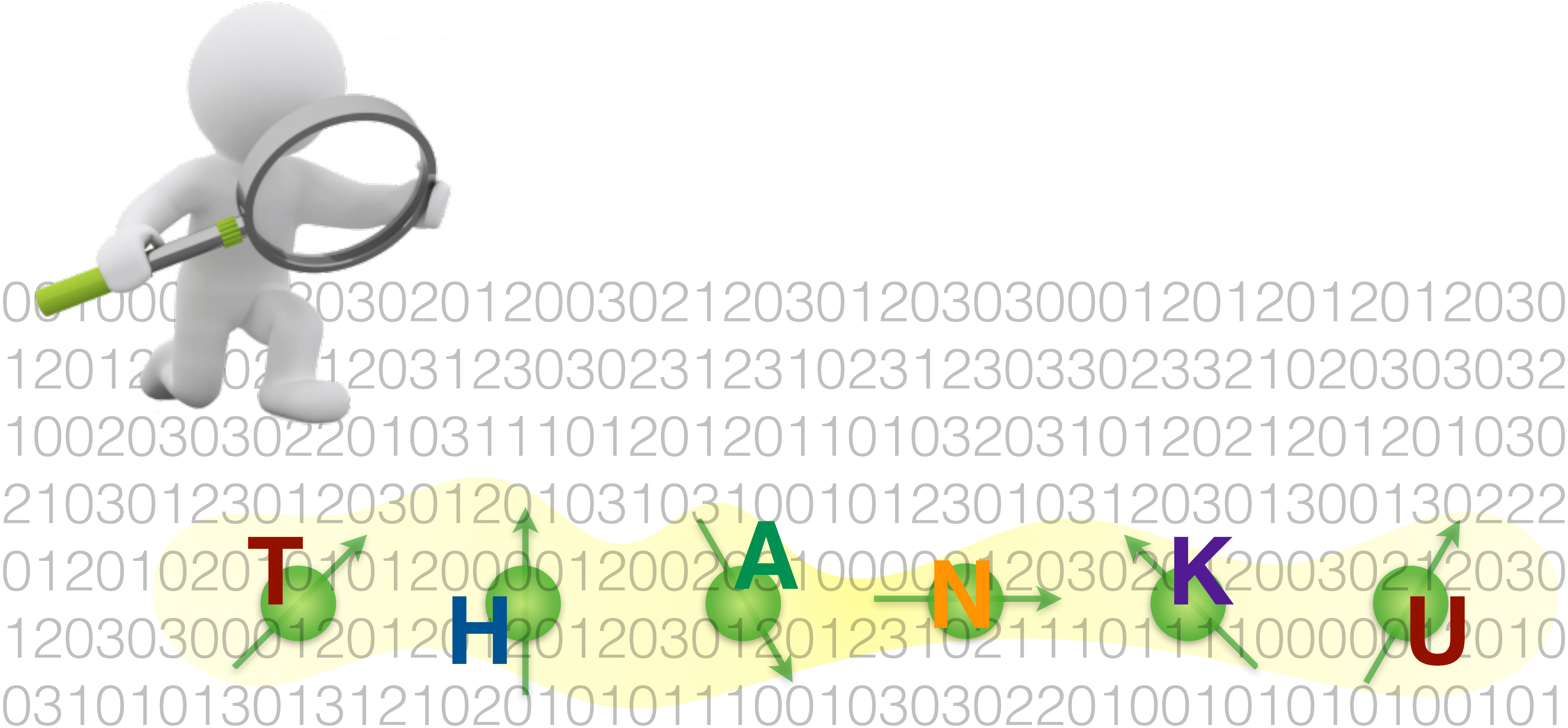
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