Title: Exactly Solvable Topological and Fracton Models as Gauge Theories 2

Speakers: Xie Chen

Collection: Online School on Ultra Quantum Matter

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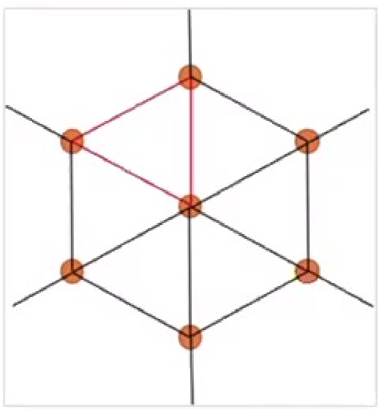
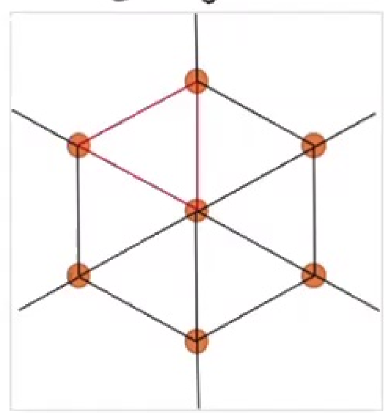
Exactly Solvable Topological and Fracton Models as Gauge Theories

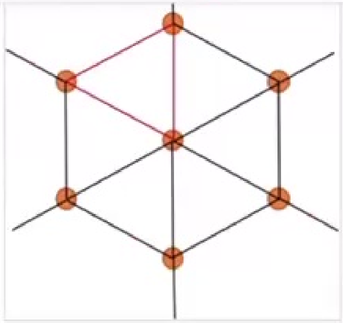
1. Toric Code
2. Toric Code as Gauge Theory
3. Toric Code from Gauging
4. Double Semion from Gauging
5. X-cube from Gauging

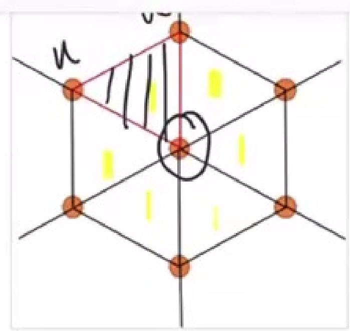
4. Double Semion from Gauging SPT.





$$H = -\sum \sigma_x$$





$$H_0 = -\sum \sigma_x \qquad H_1 = -\sum \sigma_x \prod_{\Delta} i^{\frac{1-\sigma^z_u \sigma^z_{u'}}{2}}$$

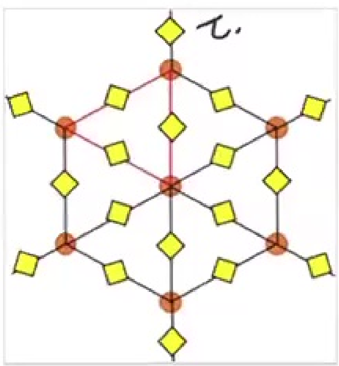
$$U = \prod \sigma_x .$$

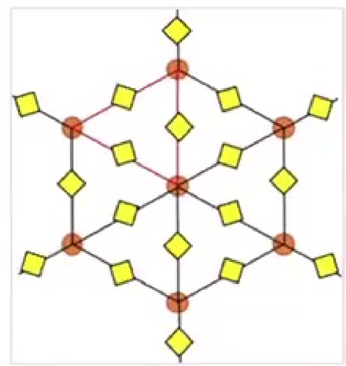
unique gapped ground state.

$$U = \prod U_x .$$

unique gapped ground state.

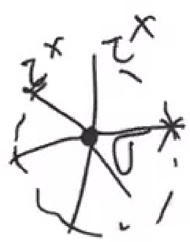
ising_tri





ising_tri

$$H_0^g = -\sum \sigma_x$$

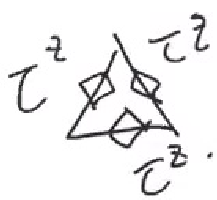


$$\sigma_x \prod \tau^x .$$

$$H_1 = -\sum$$

$$1 - \sigma^z ,$$

$$\sigma_x \prod_\Delta i$$



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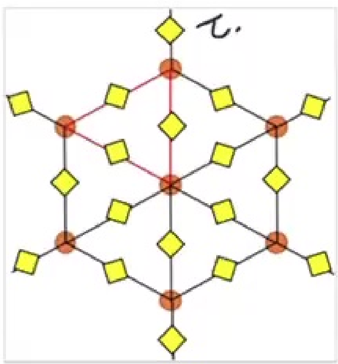
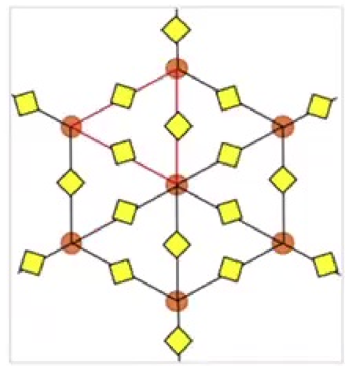
unique gapped ground state

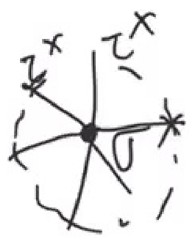
ising_tri

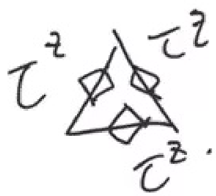
ising_tri





$$H_0^g = -\sum \sigma_x + G.S. + Flux.$$





$$\sigma_x \prod \tau^x.$$

$$H_1^g = -\sum \sigma_x \prod_{\triangle} i^{\frac{1-\sigma^z\tau^z\sigma^z}{2}} + G.S. + Flux.$$

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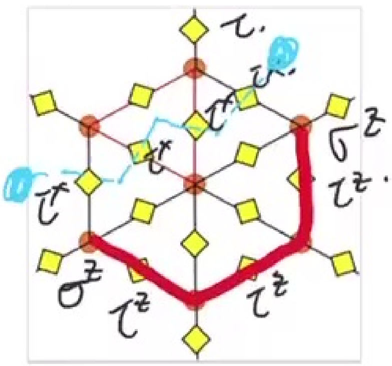
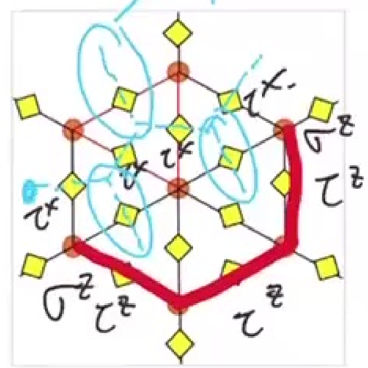
ising_tri

ising_tri

unique gapped g

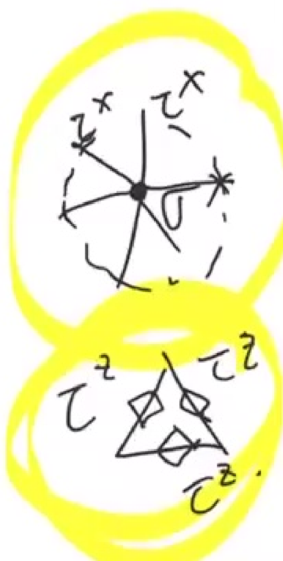
phase factors in τ^z basis.





$$H_0^g = -\sum \sigma_x$$

$+ G.S. + Flux.$



$$\sigma_x \prod \tau^x.$$

$$H_1^g = -\sum \sigma_x \prod_{i \in \triangle} \frac{1-\sigma^z\tau^z\tau^z}{2}.$$

$+ G.S. + Flux.$

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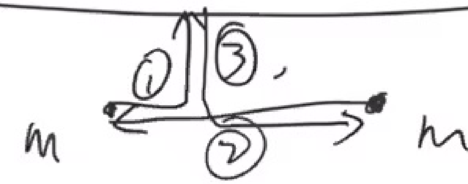
e : bosonic

m-e : -1 statistics.

m :  i. $\pi/2$.

1 : bosonic.

m : semion

em : semion -i.

Double semion.

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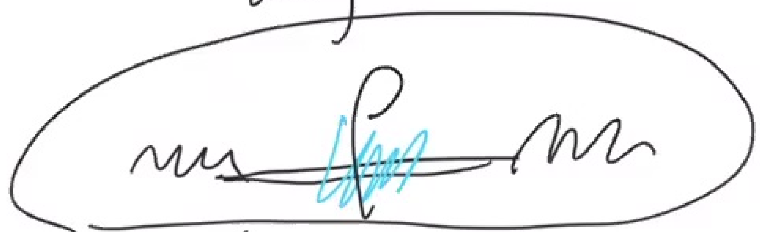
M : bosonic. M : semion em : semion

Double semion.

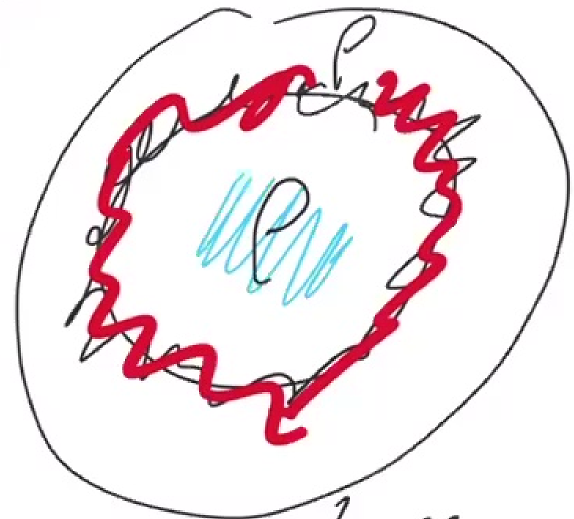
Symmetry Protected Topo Order.

Symmetry Protected Topo Order.

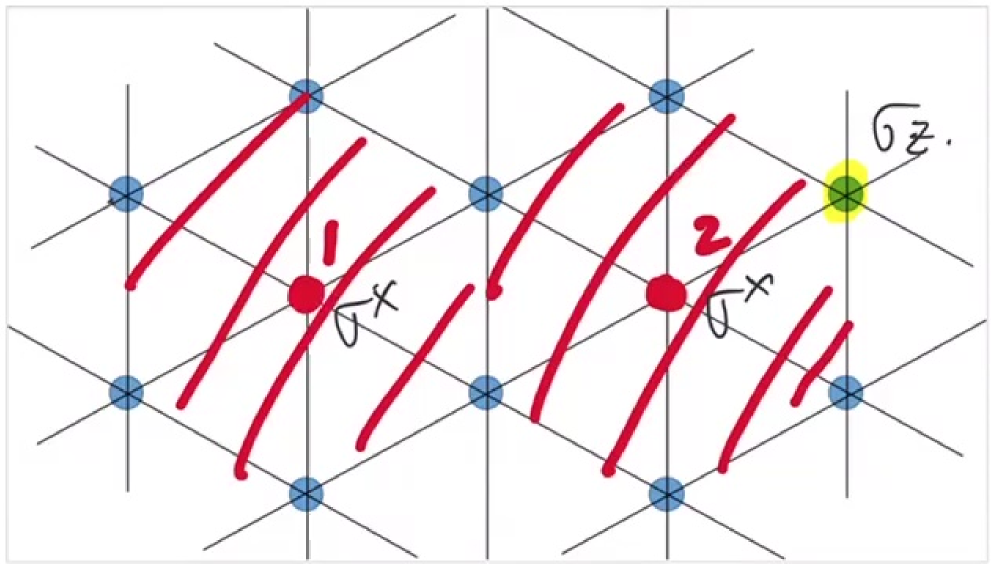
degenerate.



Edge State.



gapless.

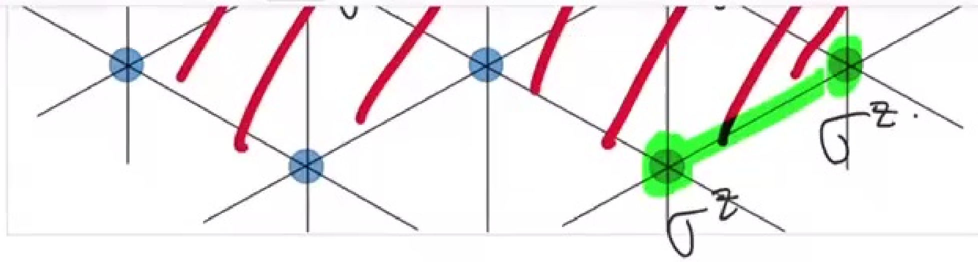


$H_0 = -\sum \sigma_x$.

no edge state.

$H_1 = h_1 + h_2$

① $-\sum \sigma_z$ explicit S.B.



$H_1 = h_1 + h_2$

$H_0 = -\sum \sigma_x$.

no edge state.

① $-\sum \sigma_z$ explicit S.B.

gap.

② $-\sum \sigma^z \sigma^z$. $\prod \sigma^z \sigma^z = I$

2-fold degenerate.

spo

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$H_0 = -\sum \sigma_x$.

no edge state.

$H_1 = h_1 + h_2$

① $-\sum \sigma_z$ explicit S.B. gap.

② $-\sum \sigma^z \sigma^z$. $\prod \sigma^z \sigma^z = I$

2-fold degenerate.

spontaneous S.B. gap.

$$\partial_\mu \phi \longrightarrow D_\mu \phi = \partial_\mu \phi + A_\mu$$

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no edge state.

① $-\sum \sigma_z$ explicit S.B. gap.

② $-\sum \sigma^z \sigma^z$. $\boxed{\prod \sigma^z \sigma^z = I}$

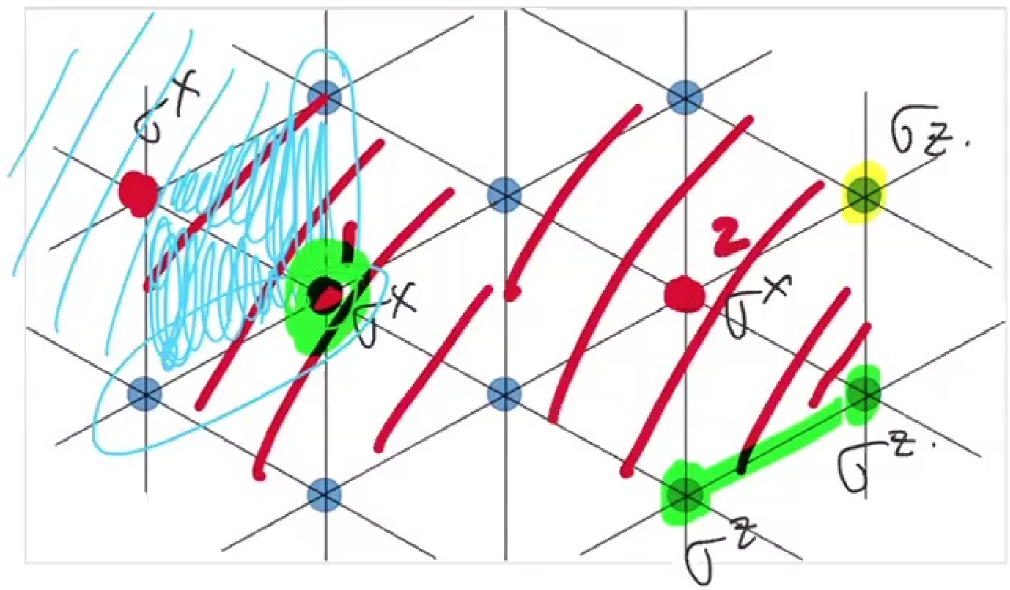
2-fold degenerate.
spontaneous S.B. gap.

$$\partial_\mu \phi \longrightarrow D_\mu \phi = \boxed{\partial_\mu \phi + A_\mu}$$

$$\boxed{\sigma_z \sigma_z \longrightarrow \sigma_z \tau_z \sigma_z}$$

Edge state

gapless



$H_0 = -\sum \sigma_x$.

no edge state.

$H_1 =$ $h_1 + h_2$

① $-\sum \sigma_z$ explicit S.B.

gap.

② $-\sum \sigma^z \sigma^z$. $\prod \sigma^z \sigma^z = I$

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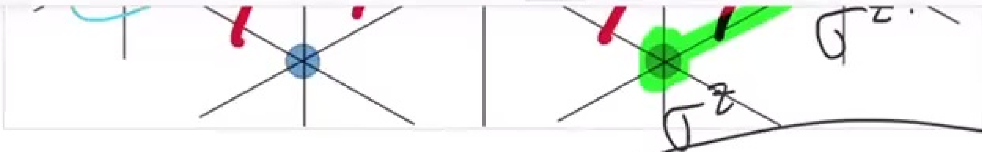


$_0 = -\sum \sigma_x$.

→ edge state.

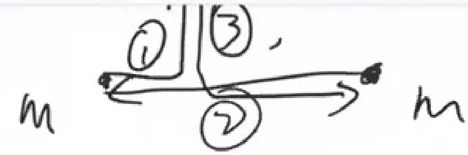
$H_1 = h_1 + h_2$

① $-\sum \sigma_z$ explicit S.B. gap.

② $-\sum \sigma^z \sigma^z$. $\prod \sigma^z \sigma^z = I$

2-fold degenerate.
spontaneous S.B. gap.

③ sym boundary terms.
gapless.

m :  i. $\pi/2$

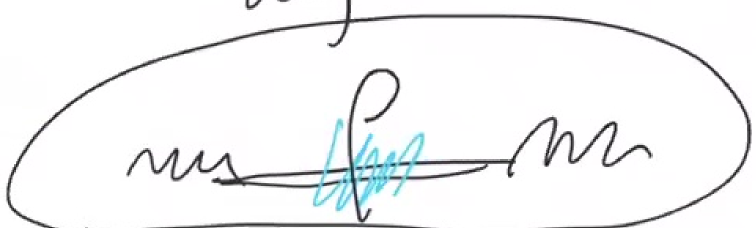
m : bosonic.

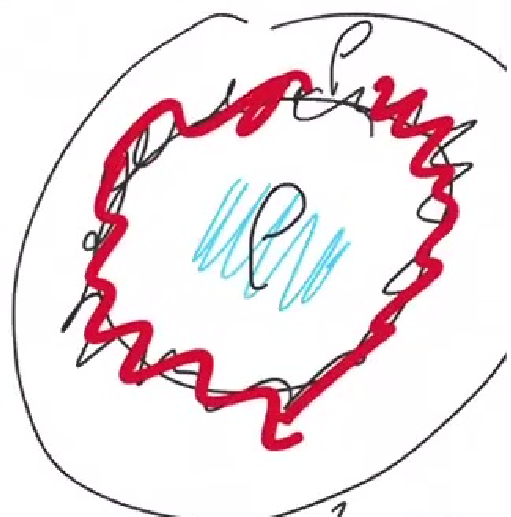
m : semion em : $\widetilde{\text{sem}}$

Double semion.

Symmetry Protected Topo Order.

degenerate.



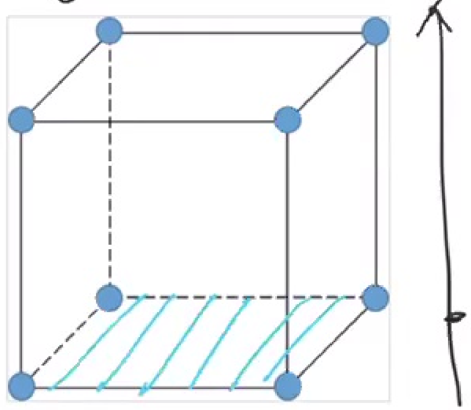


Edge State.

gapless.

5. X-cube from Gauging Subsystem Symmetry (Fracton).

σ



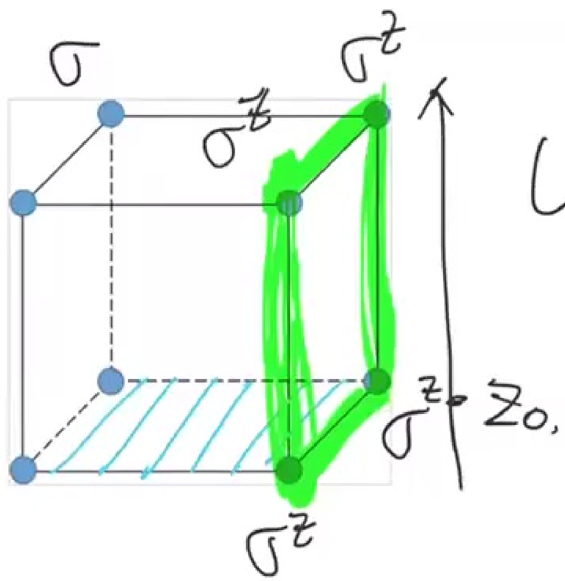
z_0.

$$H = -\sum \sigma^x.$$

$$U_{z_0} = \prod_{v \in P_{z_0}} \sigma_v^x, \quad U_{x_0}, \quad U_{y_0}.$$

higher-form symmetry.
higher-rank

(Fracton).

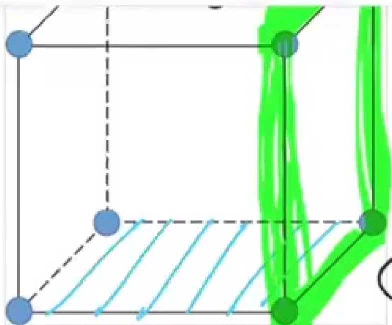


$$H = -\sum \sigma^x.$$

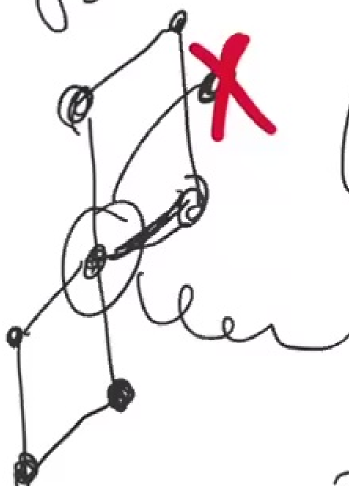
$$U_{z_0} = \prod_{v \in P_{z_0}} \sigma^x_v , \quad U_{x_0}, \quad U_{y_0}.$$

$$\boxed{\begin{array}{l}\text{higher-form symmetry.}\\ \text{higher-rank}\end{array}}$$

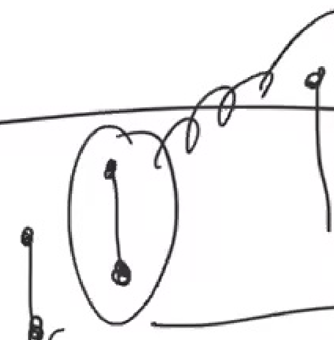
$U_{z_0} = \prod_{v \in P_{z_0}} U_v$, U_{x_0} , U_{y_0}.



higher-form symmetry.
higher-rank

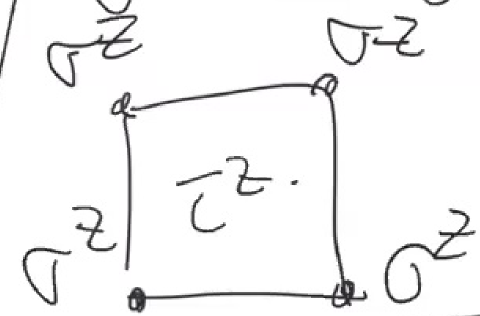


Fracton.



τ: gauge DoF qubit.

$\sigma^z \underline{\tau^z} \sigma^z$.



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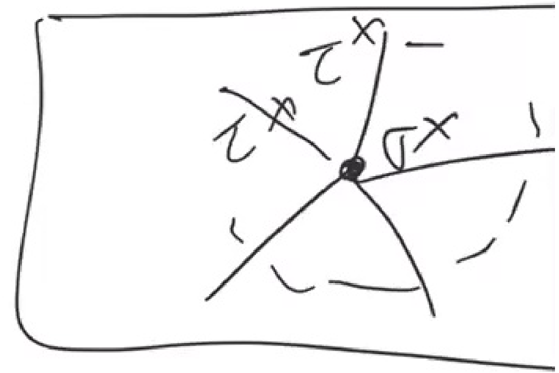
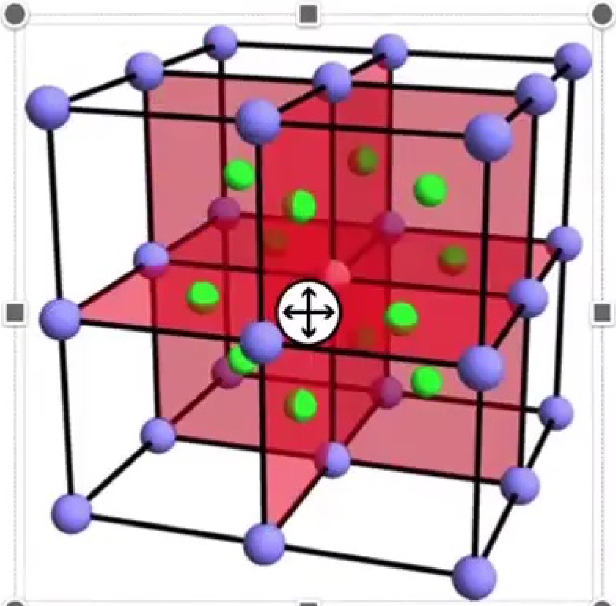
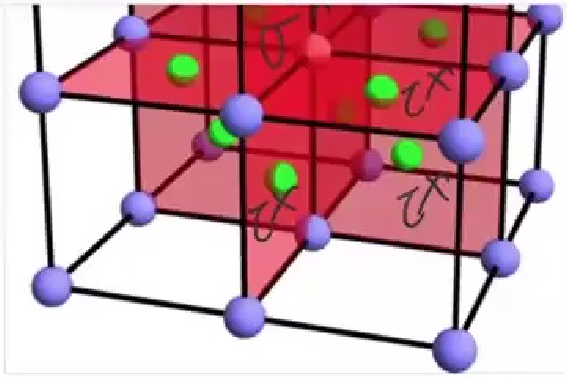
Gauge symmetry:

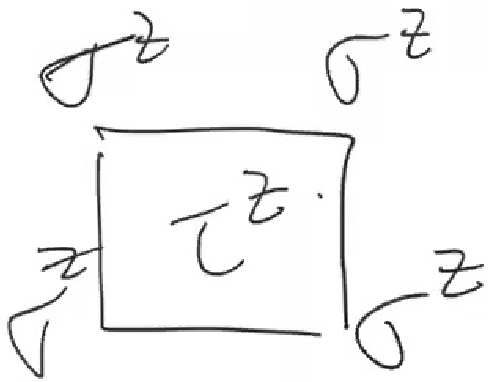




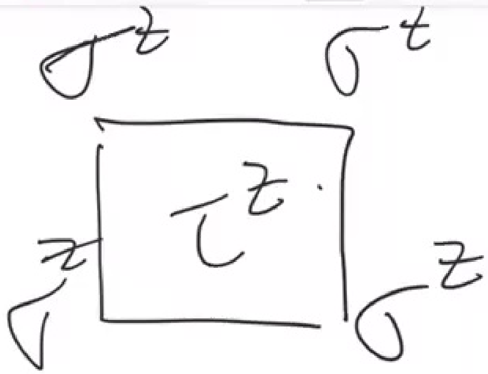
cubic2



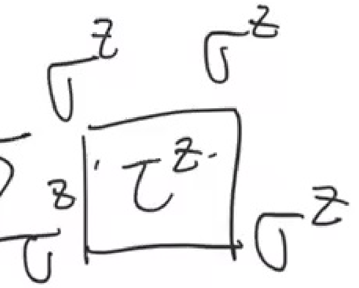
$\sigma^x \prod \tau$



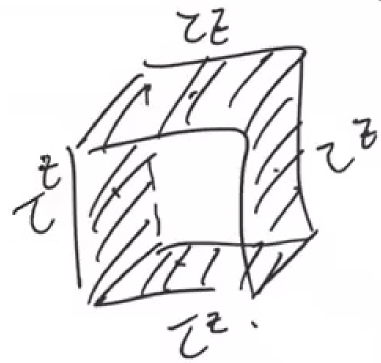
$$H_g = -\sum \sigma^x - \sum \sigma^x \prod \tau^x - J \sum$$

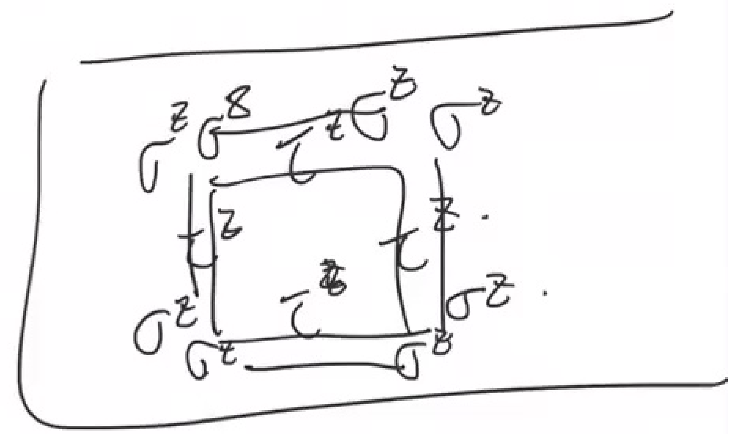


$$H_g = -\sum \sigma^x - \sum \sigma^x \prod \tau^x - J \sum_{\sigma}$$



$$-\sum$$





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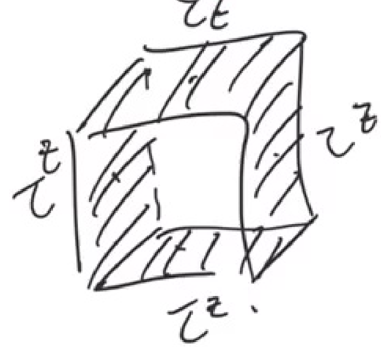
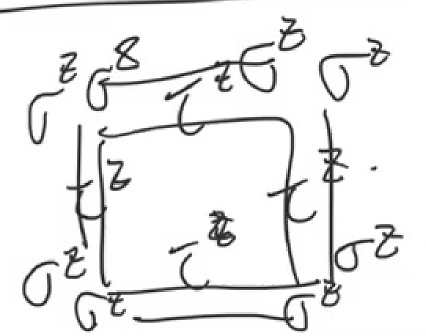
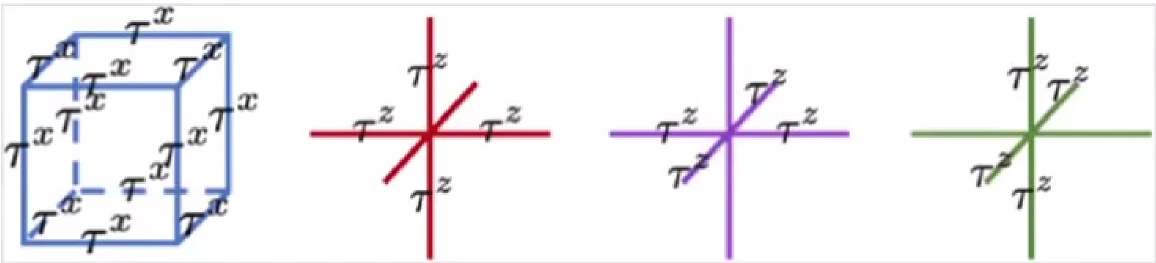
$$H_g = -\sum \cancel{\sigma^x} - \sum \cancel{\sigma^x} \prod \tau^x - J \sum_{\sigma}^{\sigma^z \quad \sigma^z} \boxed{\tau^z}_{\sigma^z} \sigma^z .$$

$$- \sum$$

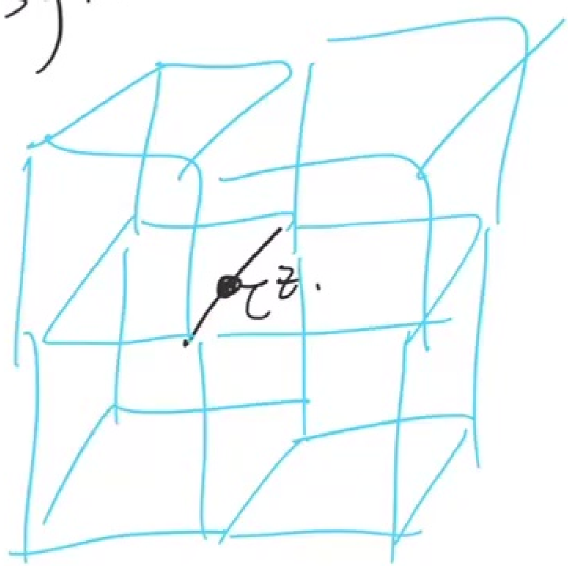


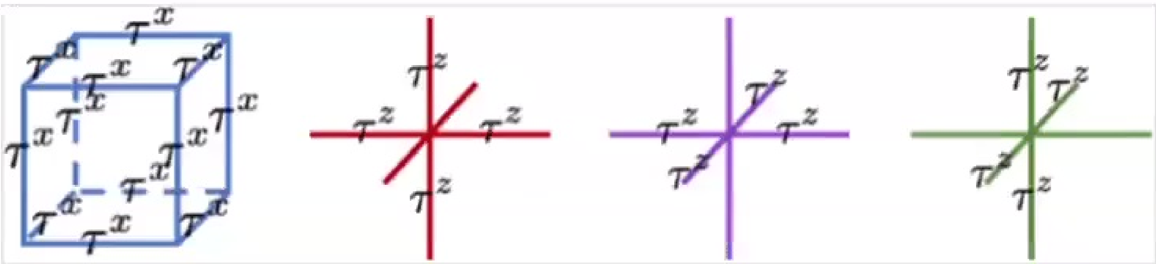
X-cube.



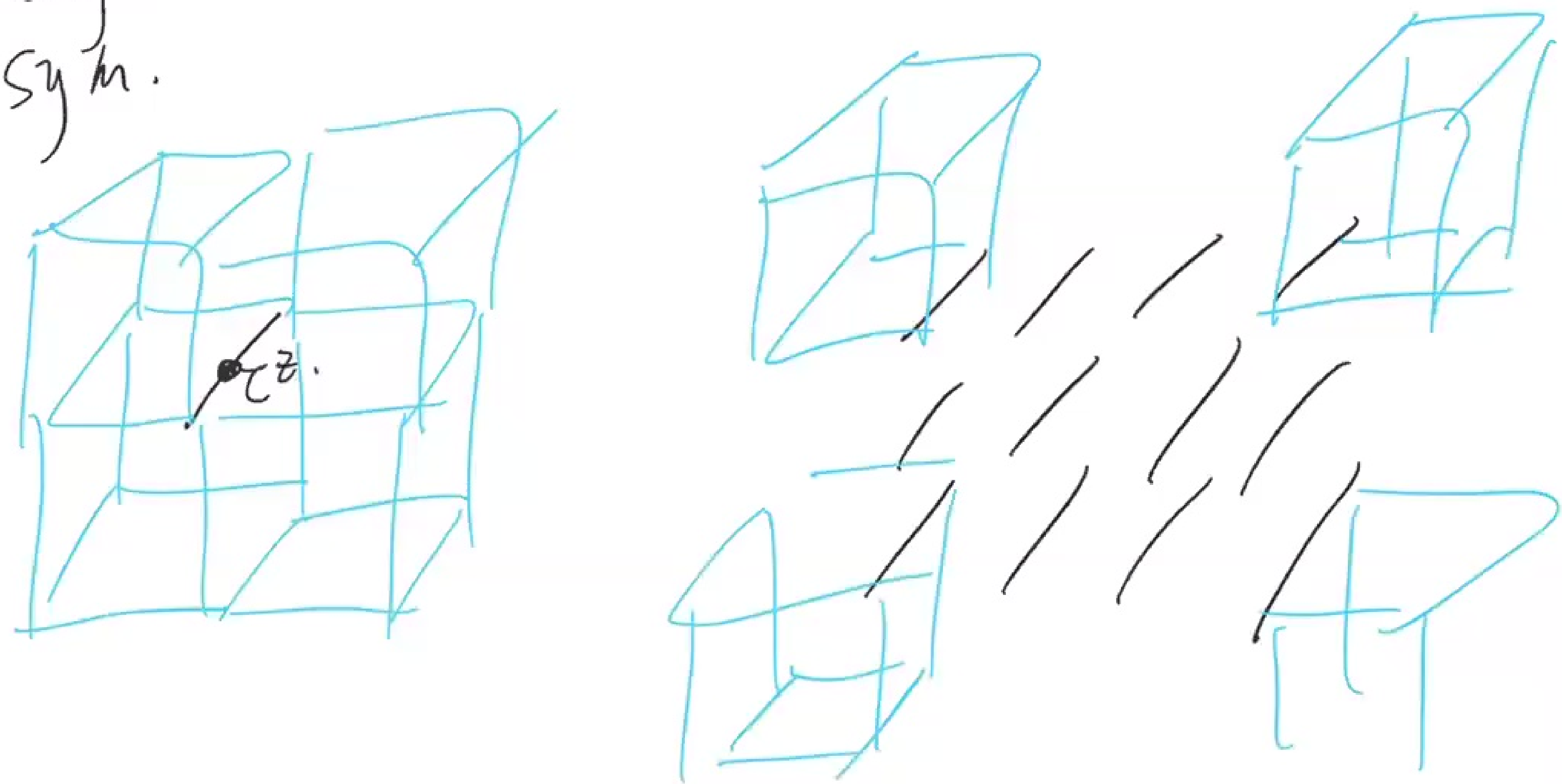


Gauge
Sym.





Gauge Sym.



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