Entanglement Entropy with Non-Invertible Symmetries

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Región de Murcia

Ávila 16/11/2023

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Generalized Symmetries and Charges

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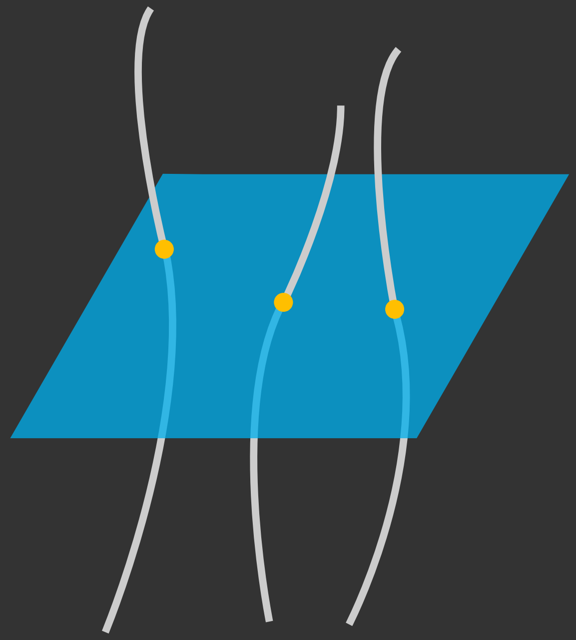
$$Q = \int_{\mathcal{M}_{d-p}} \star j_p$$



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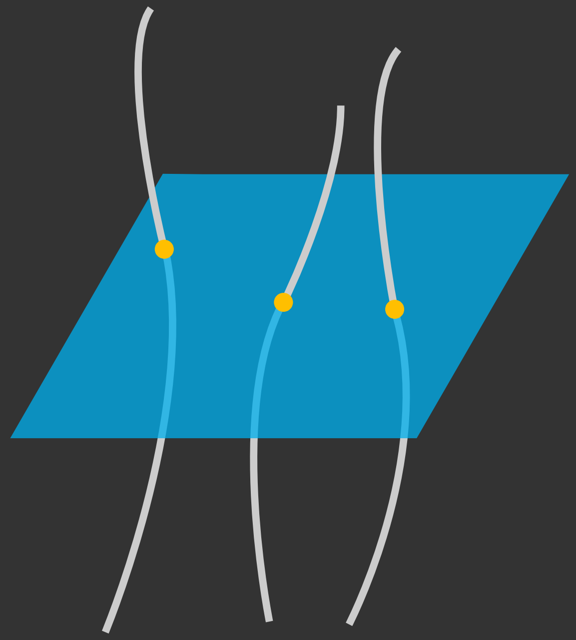

This defines a U(1)-valued topological operator:

$$U_\alpha(\mathcal{M}_{d-p}) = \exp\left(i\alpha \int_{\mathcal{M}_{d-p}} \star j_p \right)$$

Gaiotto, Kapustin,Seiberg, Willett, 2015

Chiral Anomaly

In 4-dimensional massless fermion theory, one can define 2 conserved currents associated to global symmetries:

$$S = \int d^4x \, \bar{\psi}(\partial\!\!\!/ + A\!\!\!/)\psi$$

$$j_V^\mu = \bar{\psi}\gamma^\mu\psi$$

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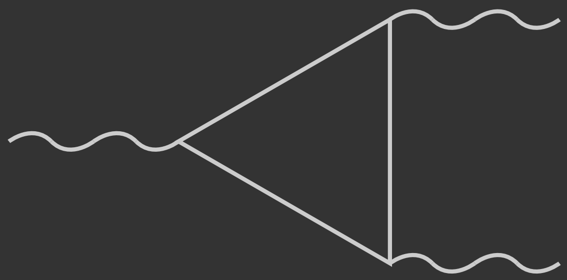
When the theory is quantized an extra term appears in the Ward Identity of the axial current, breaking its conservation. This is the chiral anomaly.

$$d \star j_V = 0$$

$$d \star j_A = F \wedge F$$



Axial charge is not conserved in the quantum theory!

Can we define a conserved charge associated to the axial current?

$$d\star j_A = F\wedge F = d(A\wedge F) \quad\Rightarrow\quad d\left(\star j_A - A\wedge F\right) = 0$$

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But we lose gauge invariance!

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But we lose gauge invariance!

A way to restore it is adding an extra field. We introduce a compact scalar field $\theta(x)$ on $\mathcal{M}_3$:

García-Etxebarria and Iqbal, 2023

$$A \to A + d\Lambda \qquad\qquad \theta \to \theta + \Lambda$$

$$\star j_A - A \wedge F + d\theta \wedge F$$

$$U_\alpha(\mathcal{M}_3) = \int \mathcal{D}\theta \exp i\alpha \left(\int_{\mathcal{M}_3} \star j_A - (A - d\theta) \wedge F \right)$$

But now the operator is non-invertible → Non-Invertible Symmetry

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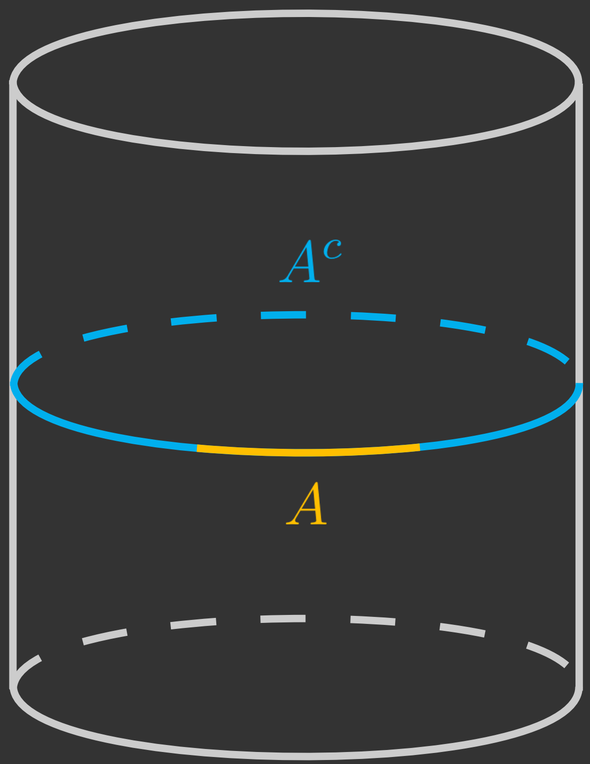
Symmetry Resolved Entanglement Entropy

Entanglement entropy measures the entanglement between two subsystems. It is defined as the von Neumann entropy of the density matrix after tracing out the complementary surface.

$$\rho_A = \mathrm{Tr}_{A^c} |\psi\rangle \langle\psi|$$

$$S_{vN} = -\,\mathrm{Tr}\left(\rho_A \log \rho_A\right)$$



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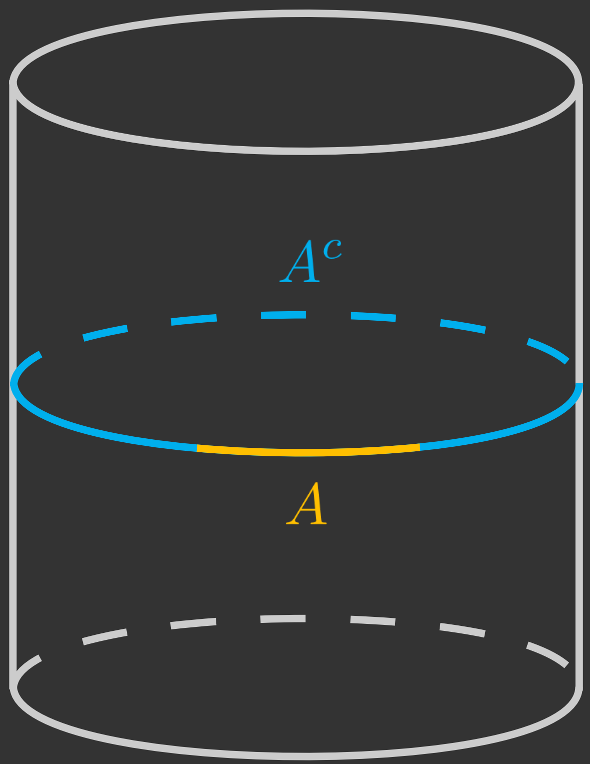

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Goldstein and Sela, 2018

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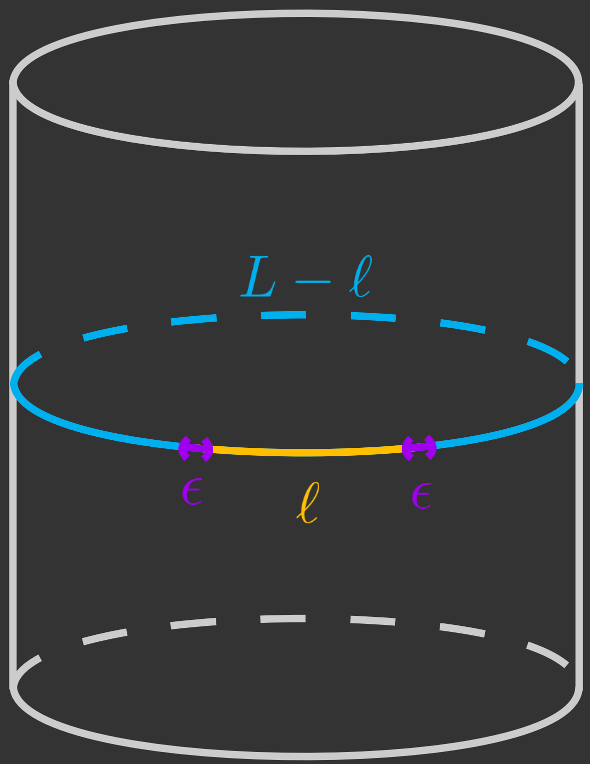

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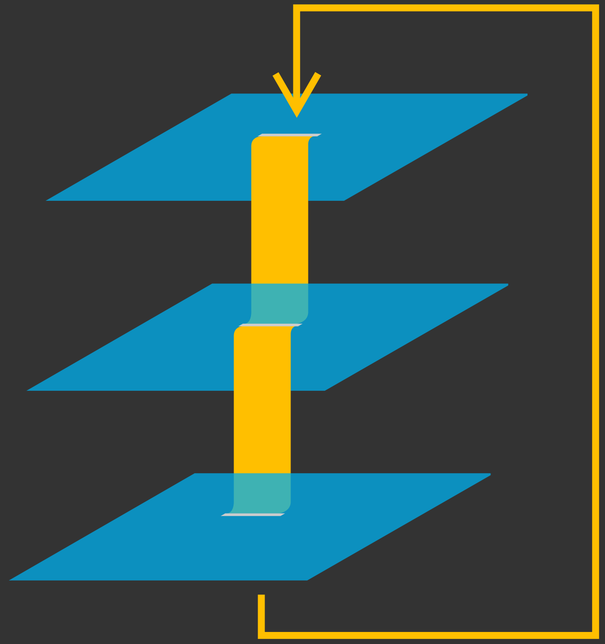
Entanglement entropy is UV divergent, we need a cutoff ϵ.

SREE with Replica Trick

SREE can be computed using the replica trick

$$S_{SREE}(q,r) = \lim_{n\to 1} \frac{1}{1-n} \log \frac{Z(q^n, r)}{(Z(q,r))^n}$$

$$q = e^{-\pi^2/\log(\ell/\epsilon)}$$



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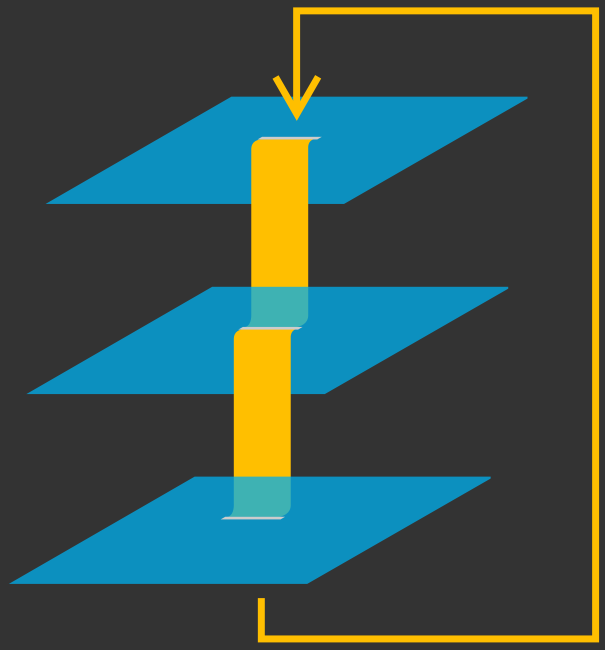
The partition function for some irrep is:

$$Z(q^n, r) = \frac{d_r}{|G|} \sum_{g\in G} \chi_r^*(g) \frac{Z(q^n, g)}{(Z(q))^n}$$

With:

$$Z(q) = \mathrm{Tr}\, q^{L_0 - \frac{c}{24}}$$

$$Z(q^n, g) = \mathrm{Tr}\left(U^A(g) q^{n\left(L_0 - \frac{c}{24}\right)}\right)$$



Kusuki, Murciano, Ooguri, Pal, 2023

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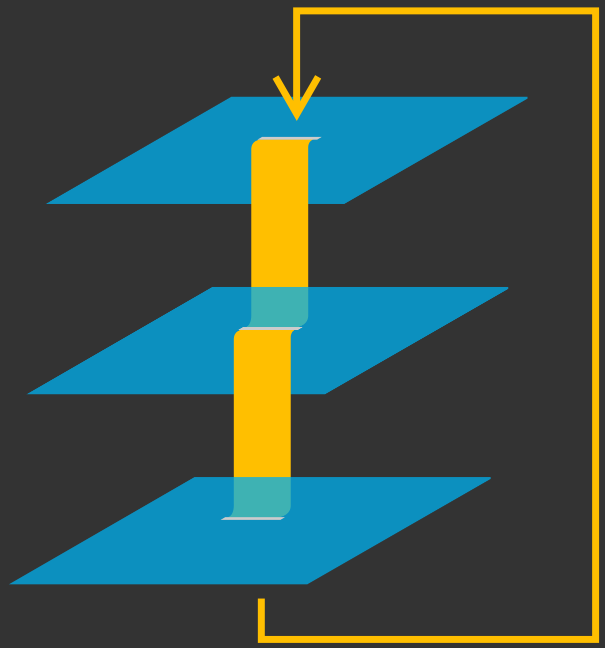

Kusuki, Murciano, Ooguri, Pal, 2023

Symmetry Operator

Charged moment

Under the modular transformation $q \to \tilde{q} = e^{-4\log(\ell/\epsilon)}$ the charged moment:

$$Z(q^n, g) = {}_g\langle a_1 | \, \tilde{q}^{\frac{1}{n}\left(L_0 - \frac{c}{24}\right)} \, | a_2 \rangle_g$$

Kusuki, Murciano, Ooguri, Pal, 2023

We may demand our states to be symmetric under the action of every element of the group.

$$U^A(g) \, |a\rangle = \langle U^A(g) \rangle \, |a\rangle$$

Strongly Symmetric

$$U^A(g) \, |a\rangle = |a\rangle + \ldots$$

Weakly Symmetric

Choi, Rayhaun, Sanghavi, Shao, 2023

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Choi, Rayhaun, Sanghavi, Shao, 2023

The operator implementing the symmetry is a topological co-dimension 1 operator.

$$U^A_\alpha(\mathcal{M}_{d-1}) = \exp\left(i\alpha \int_{\mathcal{M}_{d-1}} \star j \right)$$

For d = 2 they are lines

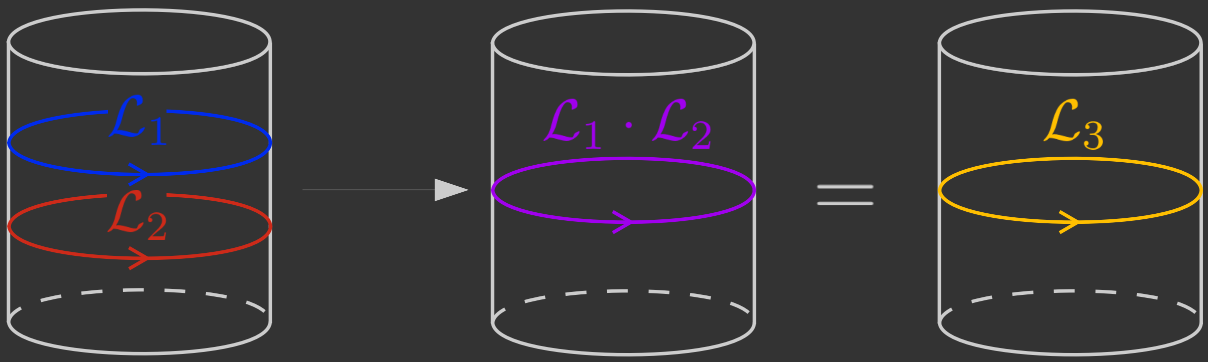
$\Downarrow$

Verlinde Lines

Verlinde Lines

Verlinde lines are topological 1-dimensional operators. They have a denifed product over them called fusion.

Verlinde, 1988



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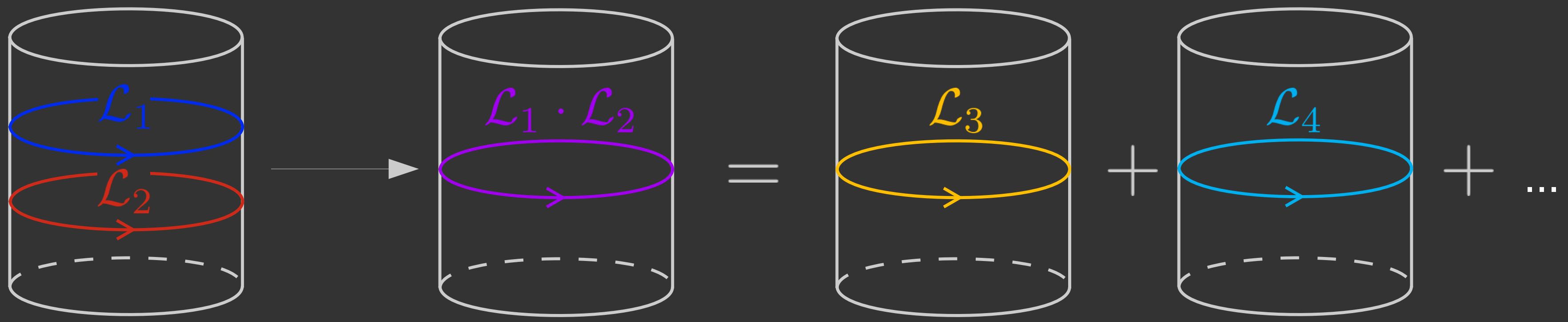

The product may not be one of a group but something wider: Fusion Category.

Some elements of the category may not have an inverse: non-Invertible lines!

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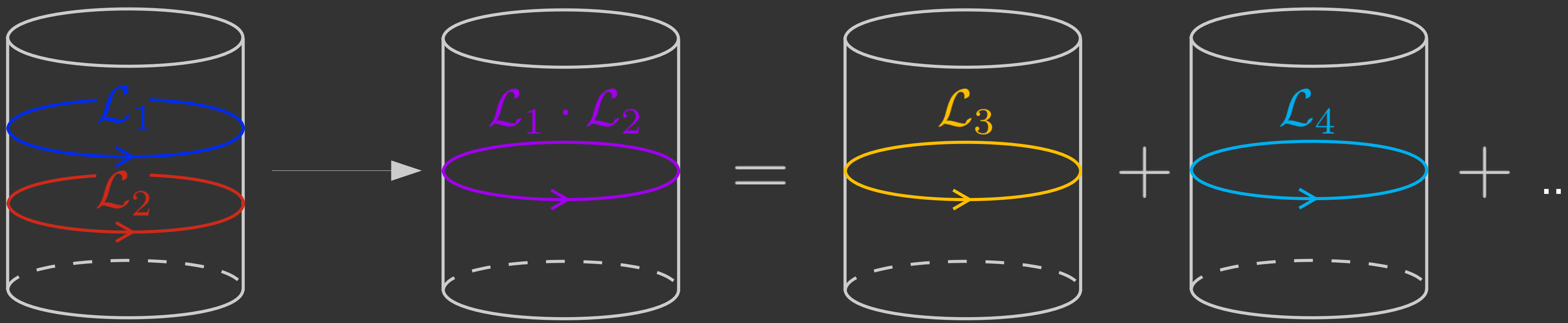

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$$\Downarrow$$

We can compute SREE for non-Invertible symmetries with Verlinde Lines.

General Result for Finite Groups

Verlinde lines are also useful to compute SREE for groups.

For finite groups, the identity sector dominates over the other elements of the group in the small cutoff limit:

$$\lim_{\tilde{q}\to 0} \frac{Z(q^n, g)}{Z(q^n, e)} = \delta_{g,e}$$

Furthermore, the leading contribution comes from the ground state:

Kusuki, Murciano, Ooguri, Pal, 2023

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Representation part

Model-dependent part

Boundary part

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Critical Ising Model

The Critical Ising Model $\left(c = \frac{1}{2}\right)$ has three primaries and three lines

$$\begin{array}{cccc} & \mathbb{1} & \varepsilon & \sigma \\ \widehat{\mathbb{1}}: & 1 & 1 & 1 \\ \widehat{\eta}: & 1 & 1 & -1 \\ \widehat{N}: & \sqrt{2} & -\sqrt{2} & 0 \end{array}$$

$$\varepsilon: \quad energy \;\; operator$$

$$\sigma: \quad spin \;\; operator$$

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$\varepsilon:\ \ energy\ \ operator$

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The fusion rules:

$$\eta^2=\mathbb{1} \qquad N^2=\mathbb{1}+\eta \qquad \eta N=N\eta=N$$

The lines $\{\mathbb{1},\eta\}$ implement the group-like $\mathbb{Z}_2$ symmetry of the model. The N line is non-invertible and it implements the Krammers-Wannier duality.

One can find three simple boundary states in the model:

$$|\uparrow\rangle = \frac{1}{\sqrt{2}}|\mathbb{1}\rangle\rangle + \frac{1}{\sqrt{2}}|\varepsilon\rangle\rangle + \frac{1}{2^{1/4}}|\sigma\rangle\rangle$$

$$|\downarrow\rangle = \frac{1}{\sqrt{2}}|\mathbb{1}\rangle\rangle + \frac{1}{\sqrt{2}}|\varepsilon\rangle\rangle - \frac{1}{2^{1/4}}|\sigma\rangle\rangle$$

$$|f\rangle = |\mathbb{1}\rangle\rangle - |\varepsilon\rangle\rangle$$

Kusuki, Murciano, Ooguri, Pal, 2023

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Kusuki, Murciano, Ooguri, Pal, 2023

Only the last one is invariant under the action of the $\mathbb{Z}_2$ group:

$$\eta\,|\uparrow\rangle = |\downarrow\rangle \qquad \eta\,|\downarrow\rangle = |\uparrow\rangle \qquad \eta\,|f\rangle = |f\rangle$$

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However, under the non-invertible line $N\,|f\rangle = |\uparrow\rangle + |\downarrow\rangle$

It is not possible to compute SREE for the category of Critical Ising model.

Tricritical Ising Model

The Tricritical Ising Model $\left(c = \frac{7}{10}\right)$ has six primary operators:

$$\begin{array}{lcccccc} & \mathbb{1} & \varepsilon & \varepsilon' & \varepsilon'' & \sigma & \sigma' \\ \widehat{\eta}: & 1 & 1 & 1 & 1 & -1 & -1 \\ \widehat{N}: & \sqrt{2} & -\sqrt{2} & \sqrt{2} & -\sqrt{2} & 0 & 0 \\ \widehat{W}: & \varphi & -\varphi^{-1} & -\varphi^{-1} & \varphi & -\varphi^{-1} & \varphi \end{array} \qquad \varphi = \frac{1+\sqrt{5}}{2}$$

We recognize η and N lines like in the Critical Ising Model.

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$$\varphi = \frac{1+\sqrt{5}}{2}$$

We recognize η and N lines like in the Critical Ising Model.

We can also notice a new non-Invertible line:

$$W^2 = \mathbb{1} + W$$

The lines $\{\mathbb{1}, W\}$ form a subcategory within the whole category: Fibonacci Category. We can compute SREE using this subcategory.

For the Fibonacci subcategory one can find three (weakly) symmetric boundary states.

$$W\,|W\rangle = |W\rangle + |\mathbb{1}\rangle \qquad W\,|\eta W\rangle = |\eta W\rangle + |\eta\rangle$$

$$W\,|NW\rangle = |NW\rangle + |N\rangle$$

Choi, Rayhaun, Sanghavi, Shao, 2023

SREE can be computed for a subcategory containing a non-Invertible line!

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At leading order, with boundary conditions $\langle NW|$ and $|NW\rangle$:

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Boundary part

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- For the ones we can compute SREE the result is the same as the ordinary symmetry one. So to this quantity they behave exactly as ordinary symmetries.
  - What are the irreps of a fusion category? What are their dimensions? (WIP)
- There were some lines for which SREE cannot be computed:
  - Does this mean that SREE is ill-defined in some cases?
  - On the other hand, this quantity is intimately related to the notion of conserved charge. Could the impossibility of computing SREE for some lines mean there is no good definition of charge in those cases? (WIP)
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THANK YOU!