On Three-Dimensional Mirror Symmetry

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$D = 3$, $\mathcal{N} = 4$ Supermultiplets and R-Symmetry

- $\mathcal{N} = 4$ supersymmetry in $D = 3$ has 8 real supercharges, which are doublets of $Spin(2,1) \sim SL(2,\mathbb{R})$ and transform as $(2,2)$ under the R-symmetry group, $SU(2)_L \times SU(2)_R$.

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  Vector multiplet:$(3 \oplus 1, 1) + (\mathbf{2}, \mathbf{2})$
  Half-hyper multiplet:$(1, 2) + (\mathbf{2}, \mathbf{1})$
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  The half-hypers transform in pseudo-real representation of the gauge group. A $\mathcal{N} = 4$ hypermultiplet in three dimensions consists of two copies of half-hypers.
- Matter content in these supermultiplets is not symmetric with respect to the exchange $SU(2)_R \leftrightarrow SU(2)_L$ – "twisted" multiplets where $SU(2)_R$ and $SU(2)_L$ are exchanged.

Mirror Symmetry

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- The precise transformation is captured in a linear map - **mirror map**

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- A large class of such boundary conditions can be understood as D3 branes ending on NS5 or D5 branes and/or orbifold/orientifold 5-planes.
- Mirror Symmetry $\iff$ S-duality of boundary conditions $\implies$ Exchange of NS5 and D5 branes, D3 invariant.

M-Theory Description

- k M2 branes in the background geometry $M : \mathbb{R}^{2,1} \times \mathbb{C}^2/\Gamma_1 \times \mathbb{C}^2/\Gamma_2$. $\Gamma_{1,2}$ are discrete subgroups of $SU(2)$ and have an $A - D - E$ classification.

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- $M \to M_1 : \mathbb{R}^{2,1} \times ALF_1 \times \mathbb{C}^2/\Gamma_2$
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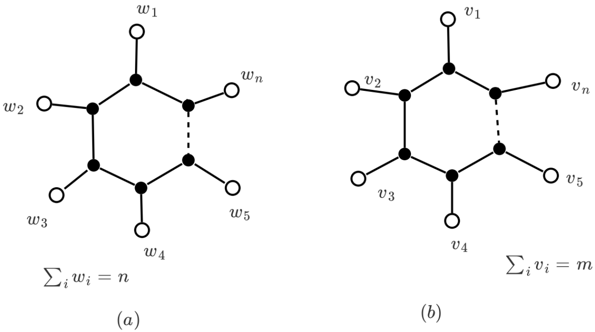
- In the IR limit, when $g^A_{YM}, g^B_{YM} \to \infty$, A and B are described by the same M-theory background $\mathcal{M} : \mathbb{R}^{2,1} \times \mathbb{C}^2/\Gamma_1 \times \mathbb{C}^2/\Gamma_2$. This is the statement of mirror symmetry.

$\Gamma_1 = \mathbb{Z}_n, \Gamma_2 = \mathbb{Z}_m$



- A Model: $U(k)^m$ gauge theory with bifundamental hypers and n fundamental hypers.

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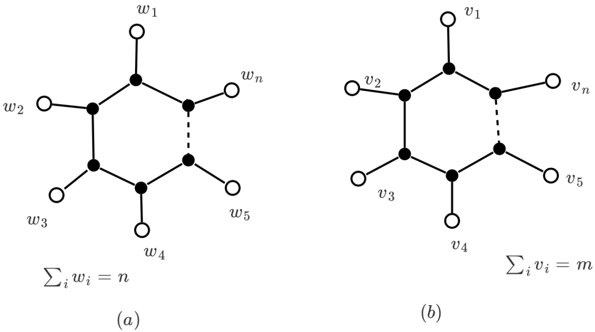

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- B Model: $U(k)^n$ gauge theory with bifundamental hypers and m fundamental hypers.

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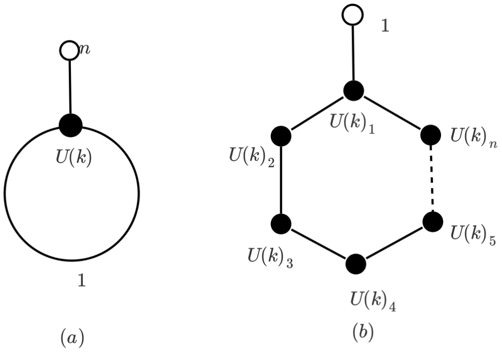

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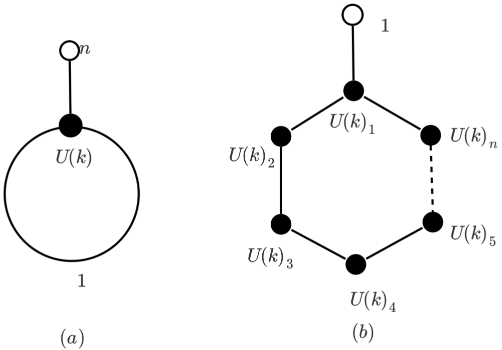

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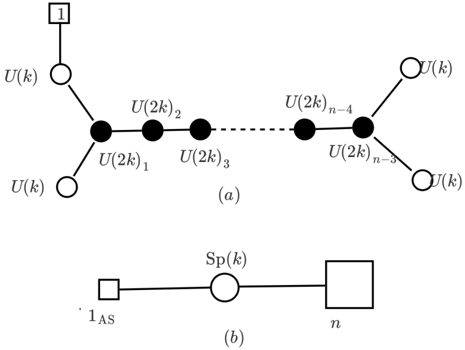

- A-model: $U(k)^4 \times U(2k)^{n-3}$ gauge theory with bifundamental hypers and 1 fundamental hypers.

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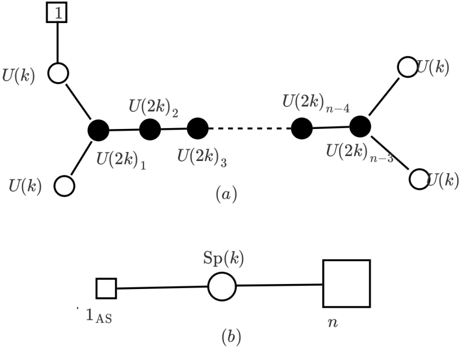

- A-model: $U(k)^4 \times U(2k)^{n-3}$ gauge theory with bifundamental hypers and 1 fundamental hypers.
- $Sp(k)$ gauge theory with n fundamental hypers and one hyper in the anti-symmetric representation of $Sp(k)$.

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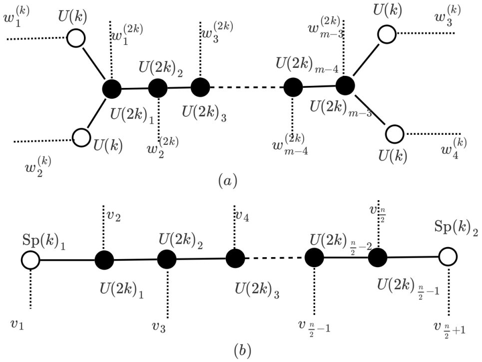

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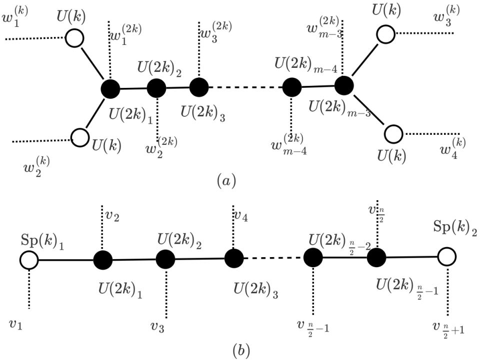

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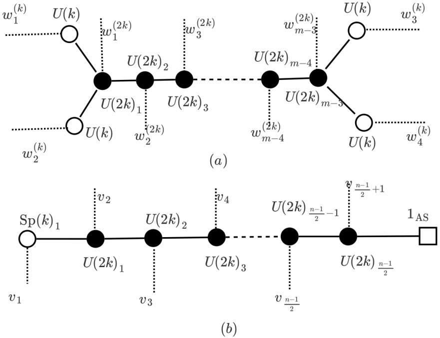

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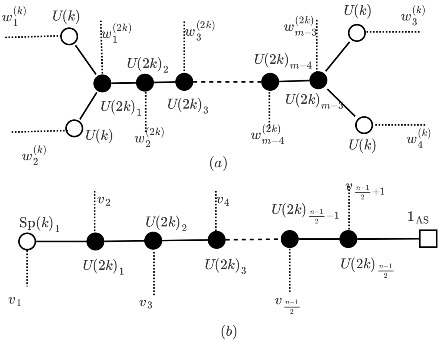

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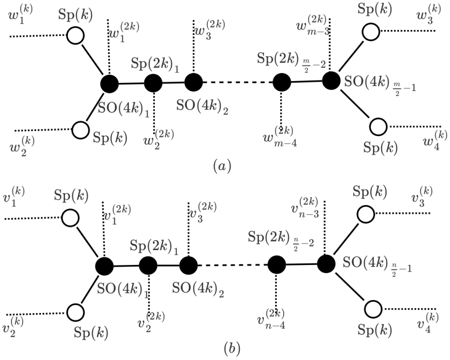

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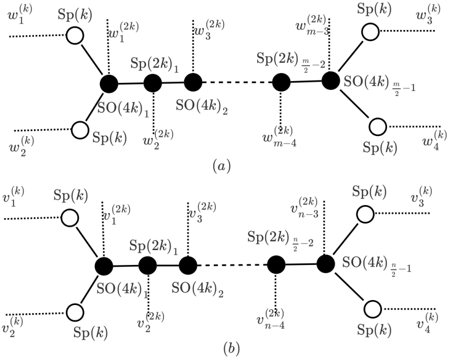

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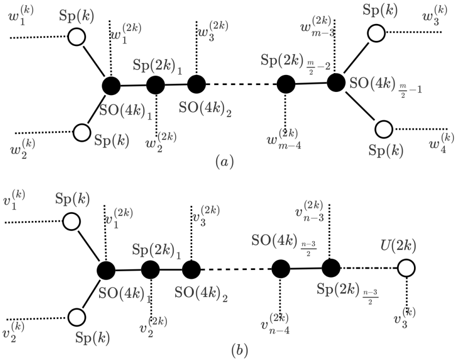

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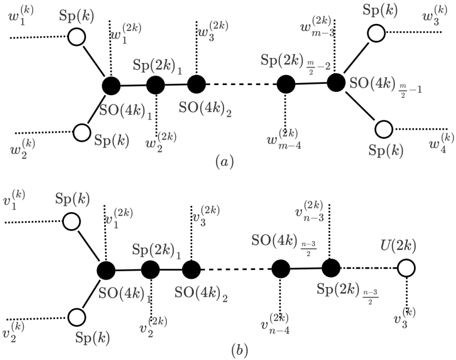

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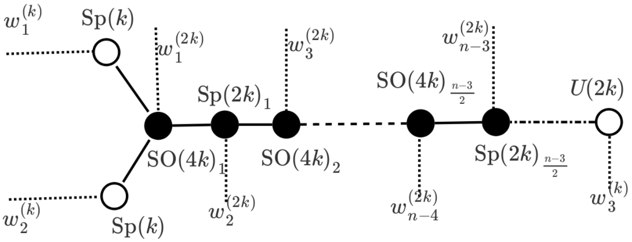

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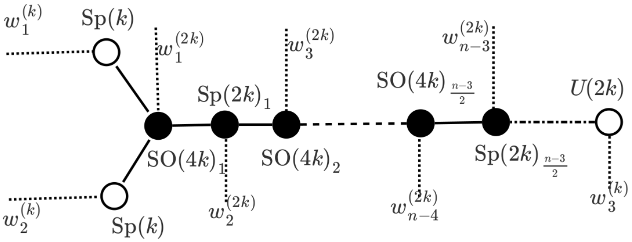

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- Comparing supersymmetric observables (like the partition function) on both sides as functions of FI parameters and masses and hence obtain the mirror map.
- Checking the duality via the latter route requires understanding:
  A recipe to write down the partition function of a given quiver gauge theory in 3 dimension.
  A prescription for implementing S-duality at the level of the partition function.

Checking the Duality (Continued)

- The recipe for writing down the partition function for a three-dimensional $\mathcal{N} = 4$ gauge theory with matter on S^3 was given by Kapustin and collaborators (later extended to $\mathcal{N} = 2$), using localization methods. Localization forces all bosonic fields to vanish except for a real adjoint scalar σ

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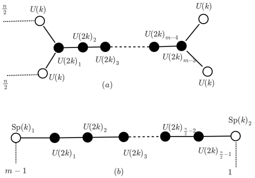
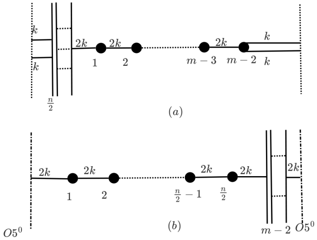
- For more complicated boundary conditions, the action of S-duality is not obvious. Our goal is to understand this action for the $\Gamma_1 = \mathbb{Z}_n, \Gamma_2 = D_m(neven)$ duals, where the boundary conditions involve orbifold/orientifold 5-planes.

Example $\Gamma_1 = \mathbb{Z}_n, \Gamma_2 = D_m$ Mirror Duals (n even)





Introducing Orbifold/Orientifold: $\Gamma_1 = \mathbb{Z}_n, \Gamma_2 = D_m$

- Z_A can be recast in the form:

$$Z_A = \int (\sum_{\rho} (-1)^{\rho} \frac{\prod_i \sinh \pi \tau^i}{\prod_i \cosh \pi \tau^i} \exp 2\pi i \tau^i (\sigma'^{i}_{\frac{n}{2}+1} - \sigma^{k+\rho(i)}_{\frac{n}{2}+1}))$$

$$\times (\prod_{a=1}^{\frac{n}{2}+1} \sum_{\rho_a} (-1)^{\rho_a} \prod_p \frac{\exp 2\pi i \tau'^{p}_a (\sigma'^{p}_a - \sigma'^{\rho_a(p)}_{a-1})}{I_a(\sigma', \tau')})$$

$$\times (\prod_{\beta=0,1,..,m-3} \sum_{\rho_\beta} (-1)^{\rho_\beta} \prod_p \frac{\exp 2\pi i \tilde{\tau}^p_\beta (\tilde{\sigma}^p_\beta - \tilde{\sigma}^{\rho_\beta(p)}_{\beta+1} + m_\beta)}{\cosh \pi \tilde{\tau}^p_\beta})$$

$$\times (\sum_{\rho'} (-1)^{\rho'} \frac{\prod_i \sinh \pi \tau'^{i}}{\prod_i \cosh \pi \tau'^{i}} \exp 2\pi i \tau'^{i} (\sigma'^{i}_{m-2} - \sigma^{k+\rho(i)}_{m-2}))$$

$$\times \prod_{\alpha} e^{2\pi i \eta_\alpha \sum_i \sigma^i_\alpha} \prod_{\beta} e^{2\pi i \tilde{\eta}_\beta \sum_p \tilde{\sigma}^p_\beta}$$

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- Correct S-duality in this picture is found to be a simple generalization of Kapustin's prescription:
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- $\tilde{Z}_A = Z_B$, provided the masses and FI parameters of the A-model satisfy:
  $\eta_1 = \eta_2; \eta_3 = \eta_4$ and $m^f_{1,a} = m^f_{2,a}$ (along with bifundamental masses)
  $\rightarrow$ A discrete gauge symmetry in the A-model.

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- The number of independent FI and mass parameters in the A-model are $(m-1)$ and $(n/2-1)$, while those for the B-model are $(n/2-1)$ and $(m-1)$ -check for the duality.

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The **Mirror Map** can now be read off from the equation $\tilde{Z}_A = Z_B$:

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- $$M^f_a = -(\eta + \eta_3 - \sum_{m-3}^{a} \eta_\beta) = -(\sum_{1}^{a-1} \eta_\beta + \eta_3); a = 1, 2, ..., m-3$$

  $$M^f_{m-2} = -(\eta + \eta_3), M^f_{m-1} = 0, M^f_m = 0$$

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- $$m_{bif} = -(\eta + \eta_1 + \eta_3)$$

- $$M^f_a = -(\eta + \eta_3 - \sum_{m-3}^{a} \eta_\beta) = -(\sum_{1}^{a-1} \eta_\beta + \eta_3); a = 1, 2, ..., m-3$$
  $$M^f_{m-2} = -(\eta + \eta_3), M^f_{m-1} = 0, M^f_m = 0$$

- $$\tilde{\eta}_1 = m^f_2, \eta^B_\beta = m^f_{\beta+1} - m^f_\beta, \beta = 2, ..., \frac{n}{2} - 1$$

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- Agrees with the general expectations from the Type IIB brane constructions of these theories.

Conclusion

- We have catalogued a large class of 3D mirror duals from the M-theory description of mirror symmetry, obtaining new dual pairs in the process. We have checked the duality for a subset of new theories by comparing their partition functions.

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- The computation provides a way to specify the dual theories more accurately - for example, predicting discrete gauge symmetries.
- Future direction: Extending the calculation to include S-duals of generic boundary conditions.