New Aspects of 3D Mirror Symmetry

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Based on

“Rethinking mirror symmetry as a local duality on fields,” Phys.Rev.D 106 (2022) 10, 105014,

“The SL(2, $\mathbb{Z}$) dualization algorithm at work,” JHEP 06 (2023) 119,

“Probing bad theories with the dualization algorithm. Part I,” JHEP 04 (2024) 008,

“Probing bad theories with the dualization algorithm. Part II,” JHEP 07 (2024) 165,

“Algorithmic Dualization of Unitary Circular Quivers,” arXiv:2607.01327

with R. Comi, S. Giacomelli, F. Marino, S. Pasquetti, M. Sacchi.

Outline

- Why is 3d gauge theory interesting?
- Mirror dualization algorithm
- Application: N=8 SYM
- Generalization

Why Is 3D Gauge Theory Interesting?

A bridge between

Different areas in physics

Keywords: Chern-Simons theory, duality

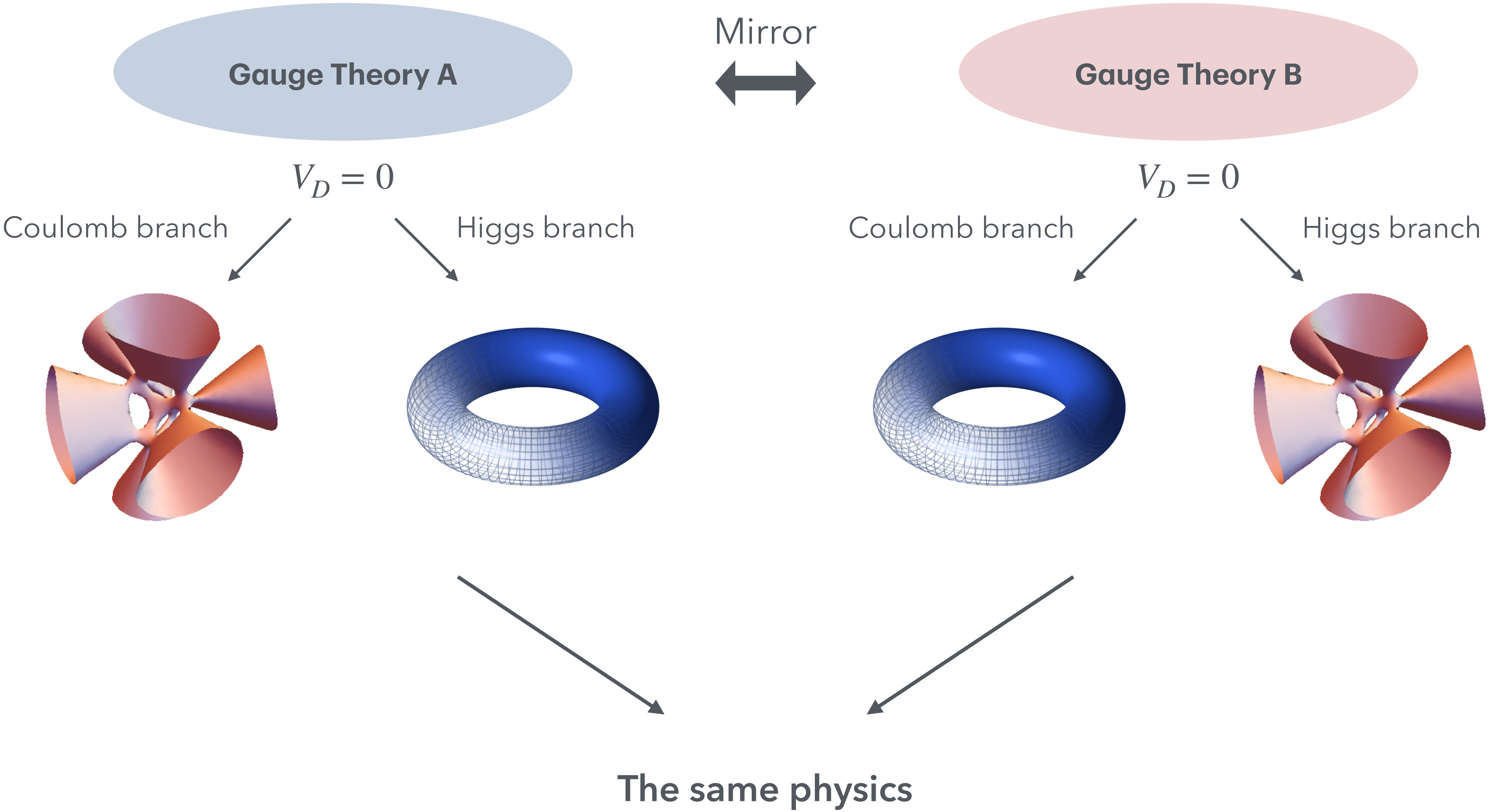
Physics and mathematics

Vacuum moduli space, hyperKahler

3d QFT and 4d quantum gravity

Holography

- Hard to solve because
  - Strongly coupled
  - Monopoles appear as nonperturbative local operators
- But also exhibits remarkably rich phenomena
- **3d mirror symmetry**
  Two 3-dimensional supersymmetric (N=4) gauge theories have the same low energy physics with the Coulomb and Higgs branches of the vacuum moduli space exchanged [Intriligator-Seiberg 96, …].


Gauge Theory A
Mirror
Gauge Theory B
$V_D = 0$
$V_D = 0$
Coulomb branch
Higgs branch
Coulomb branch
Higgs branch
The same physics

Advantages of mirror symmetry—turn a hard question into an easy one

- The **quantum corrected** Coulomb branch from the **classically exact** Higgs branch of a mirror dual

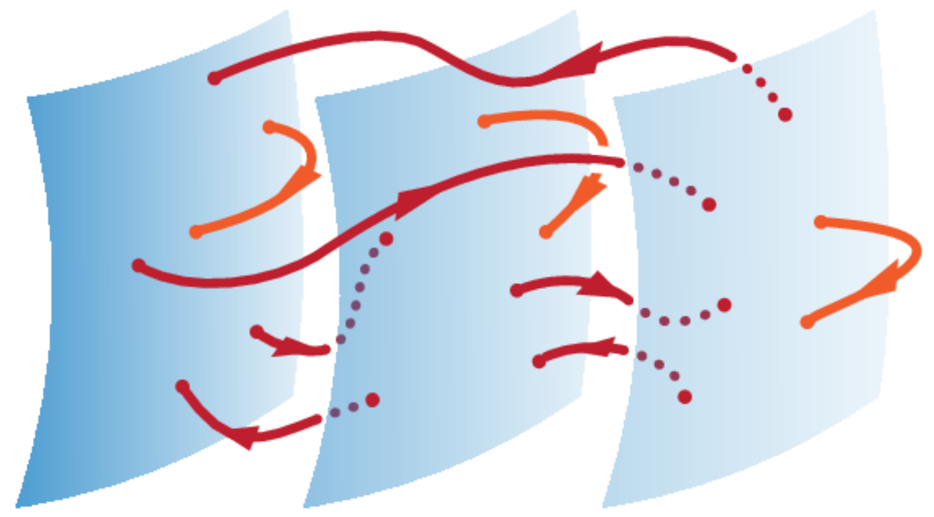
- **Nonperturbative** monopoles $\leftrightarrow$ **perturbative** mesons

- **Lagrangian** mirror duals of **non-Lagrangian** theories

Realization in String Theory

Hanany-Witten Setup

- 3d gauge theory can be realized as compact D3 branes intersecting with D5 and NS5 in type IIB string theory.

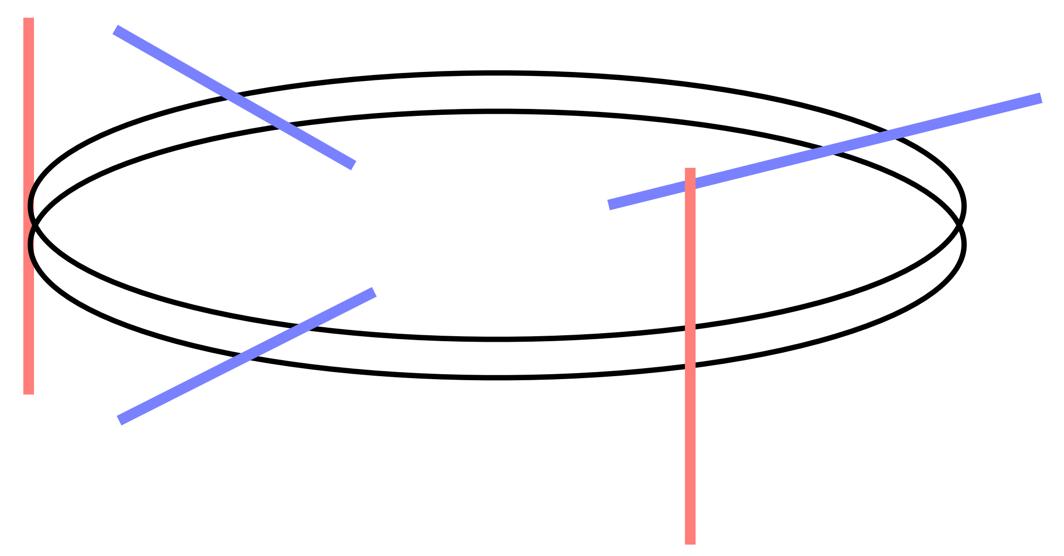


  - A stack of N D3 brane segments $\rightarrow U(N)$ gauge group
  - D5 brane $\rightarrow$ fundamental matter
  - NS5 brane $\rightarrow$ bifundamental matter

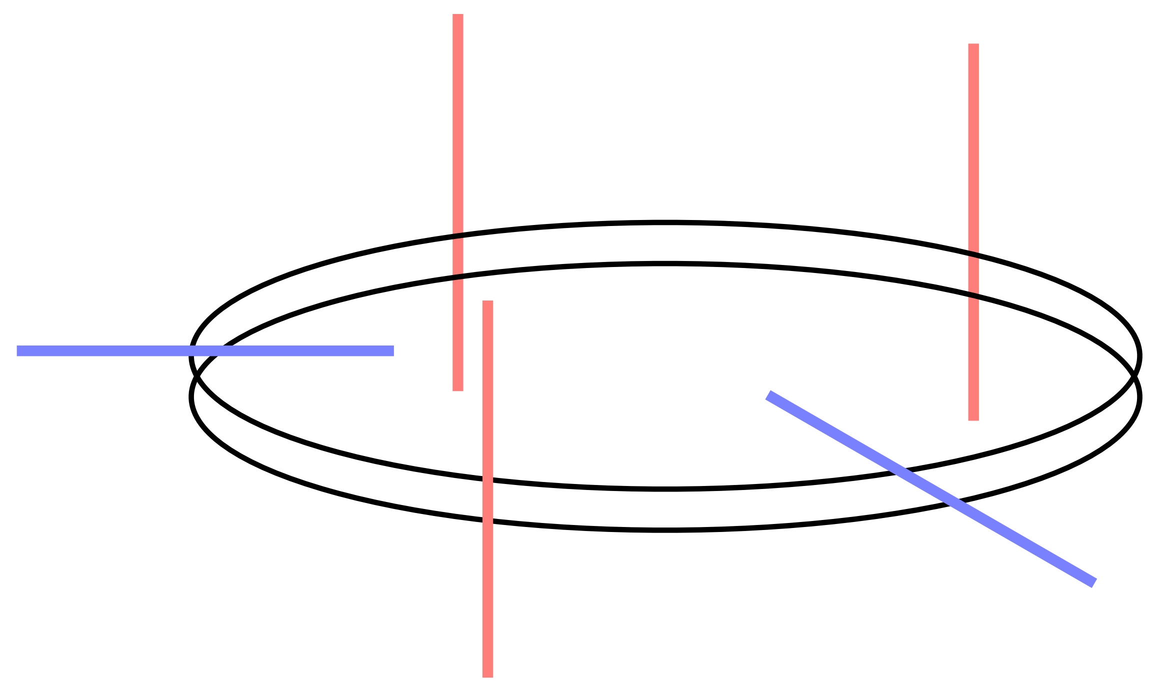
- 3d mirror symmetry corresponds to S-duality in type IIB string theory, which exchanges D5 and NS5.

Realization in String Theory

Example



S-dual



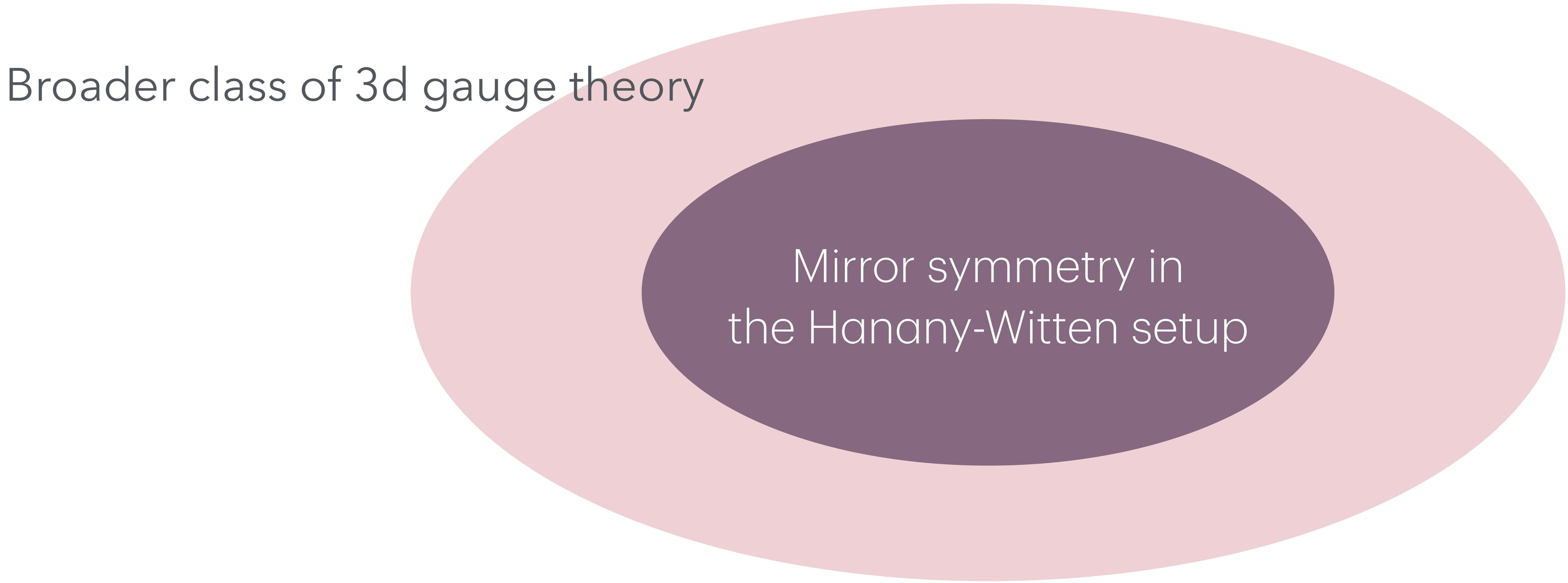
- $U(2) \times U(2)$
- One and two fundamental matters, respectively
- Bifundamental matters between the gauge groups

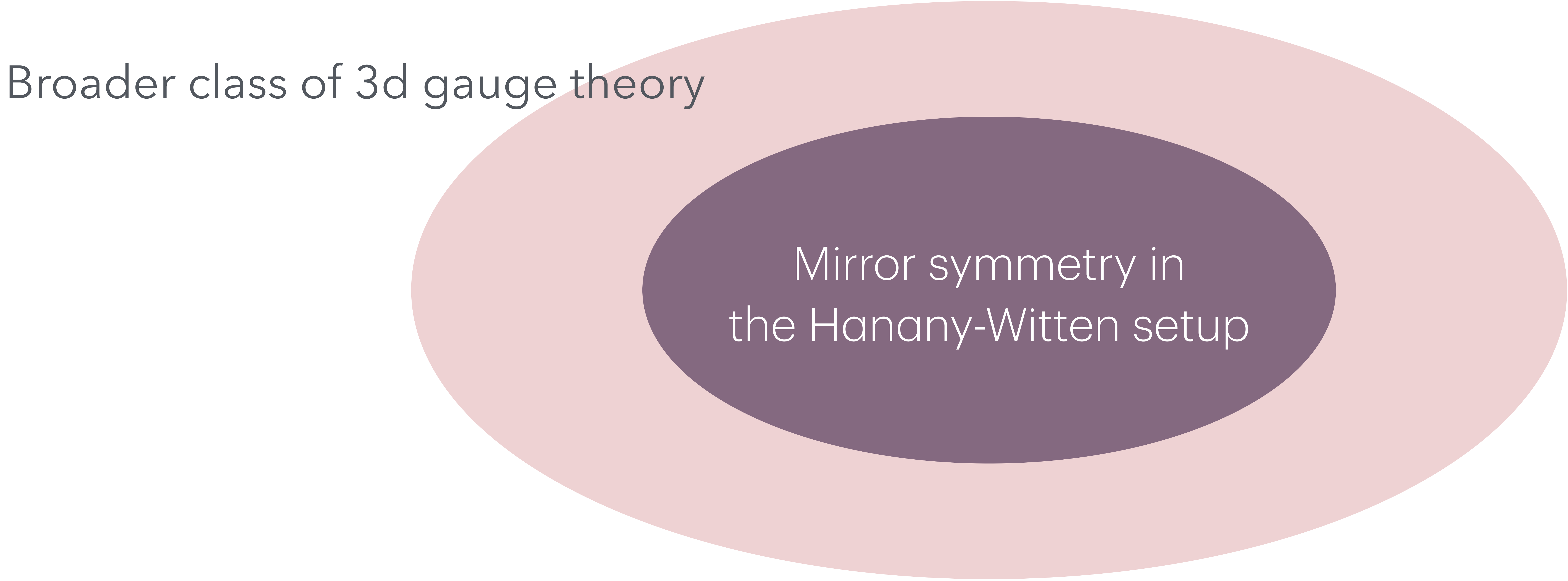
Mirror

- $U(2) \times U(2) \times U(2)$
- One, one, and no fundamental matters, respectively
- Bifundamental matters between the gauge groups

S-duality in type IIB string theory

Mirror symmetry in
the Hanany-Witten setup


Broader class of 3d gauge theory
Mirror symmetry in
the Hanany-Witten setup



Direct understanding from field-theoretic perspective?

Mirror Dualization Algorithm

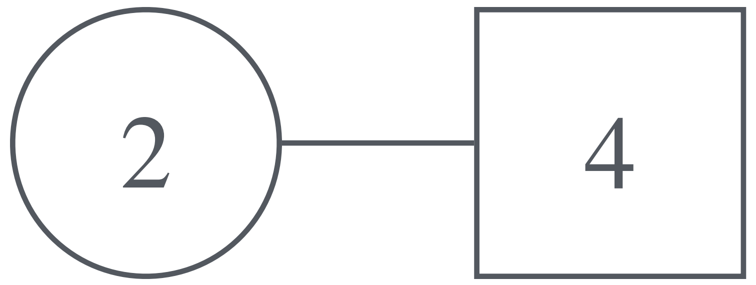
Quiver Representation of Gauge Theories

- Necessary data for 3d $\mathcal{N} = 4$ gauge theories: the symmetry group and representations
- The quiver representation is useful if the matters are restricted to the (bi-)fundamental representation.

Gauge group

Flavor group

Bifundamental matter



$U(2)$ gauge theory with 4 flavors

$SU(4) \times U(1)$

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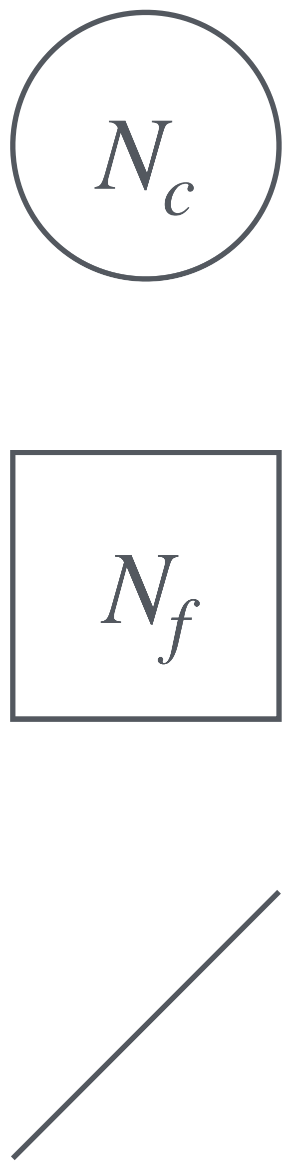
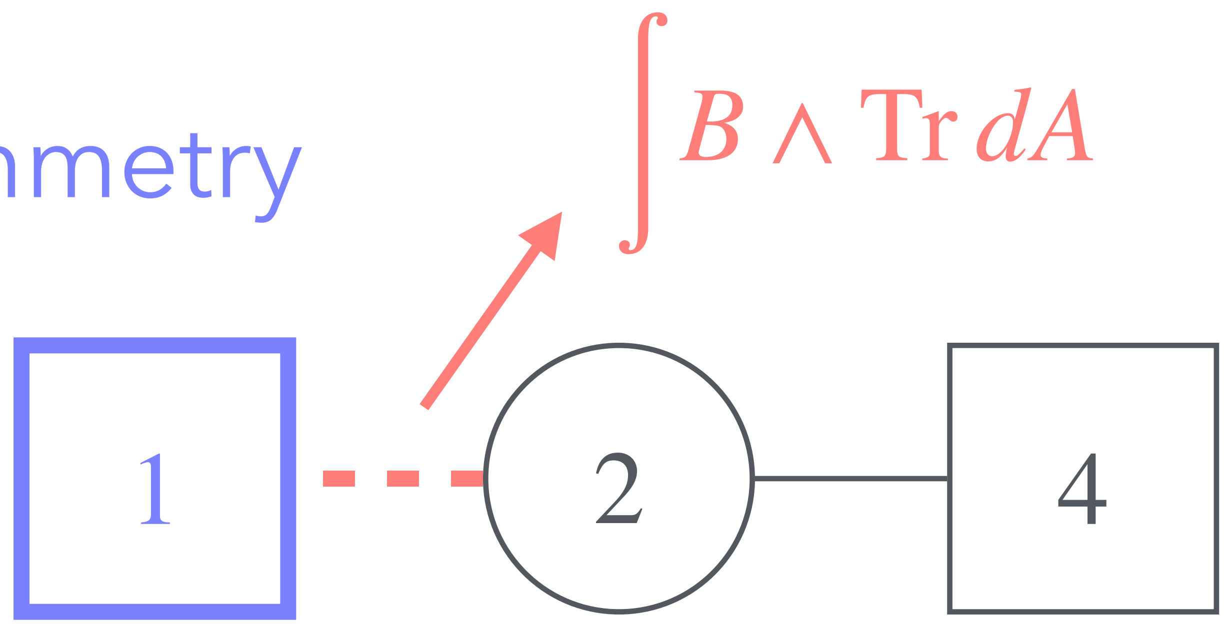


Gauge group

Flavor group

Bifundamental matter

Monopole symmetry



$U(2)$ gauge theory with 4 flavors

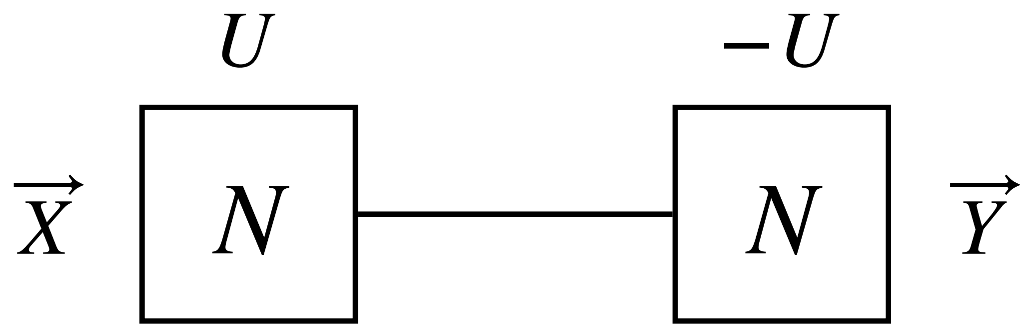
$SU(4) \times U(1)$

Mirror dualization algorithm

A field-theoretic construction of 3d mirror symmetry from ***two fundamental building blocks***

[**CH**-Pasquetti-Sacchi 21]

Bifundamental Field:



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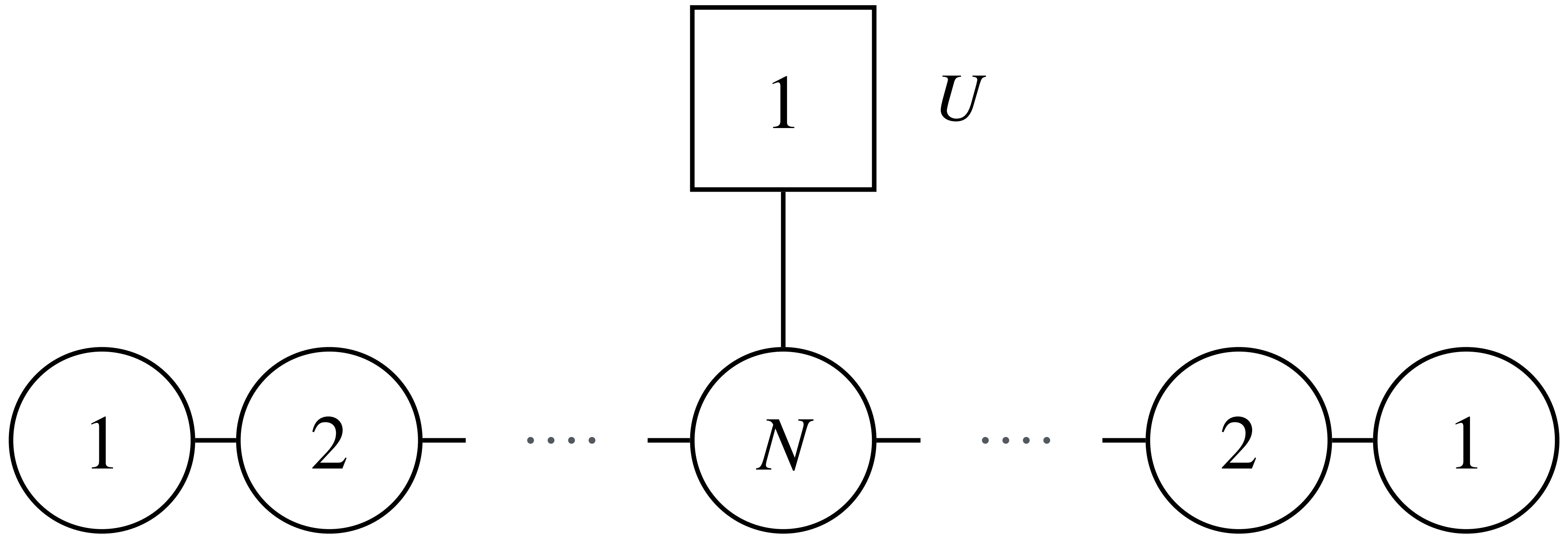
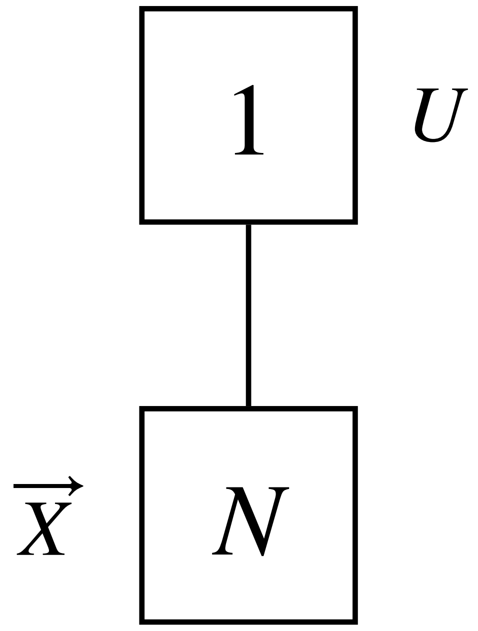
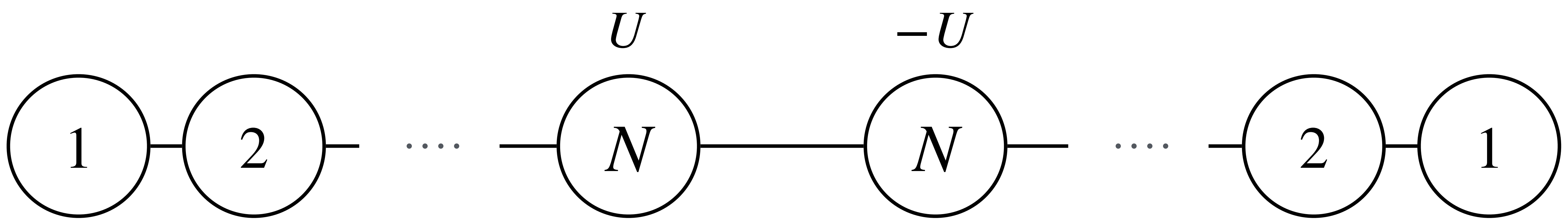
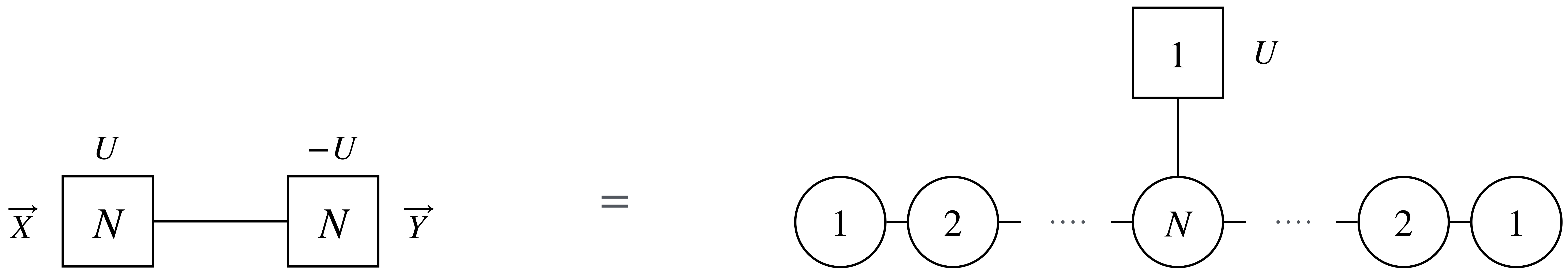


Fundamental Field:



$\times \; \hat{\delta}(\vec{X}, \vec{Y})$ $=$





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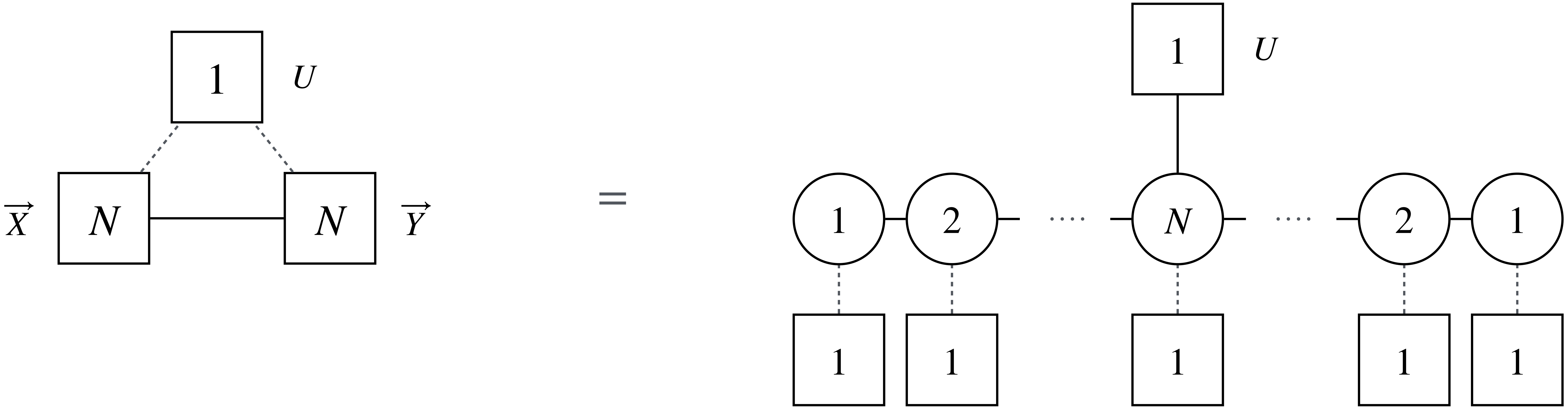

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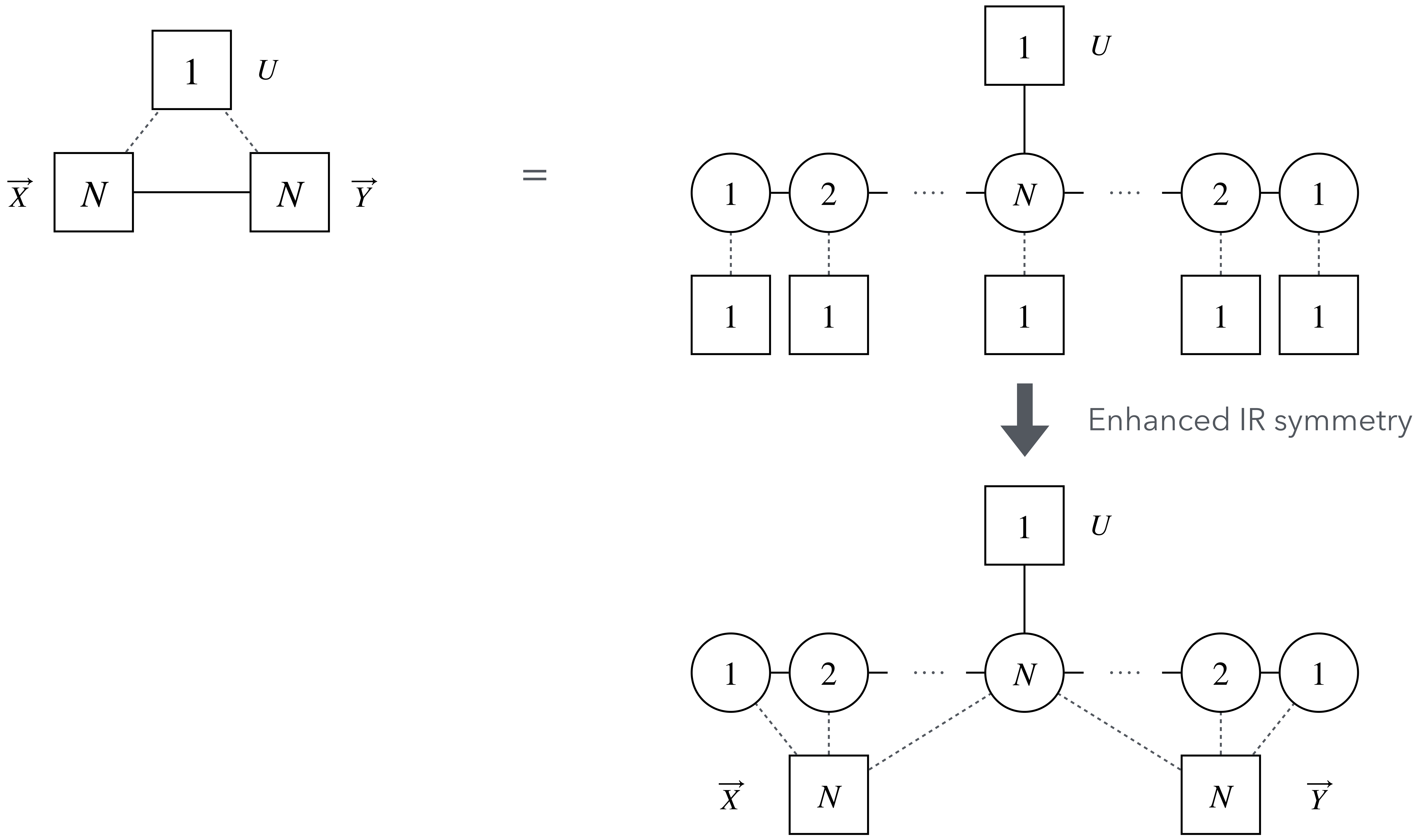
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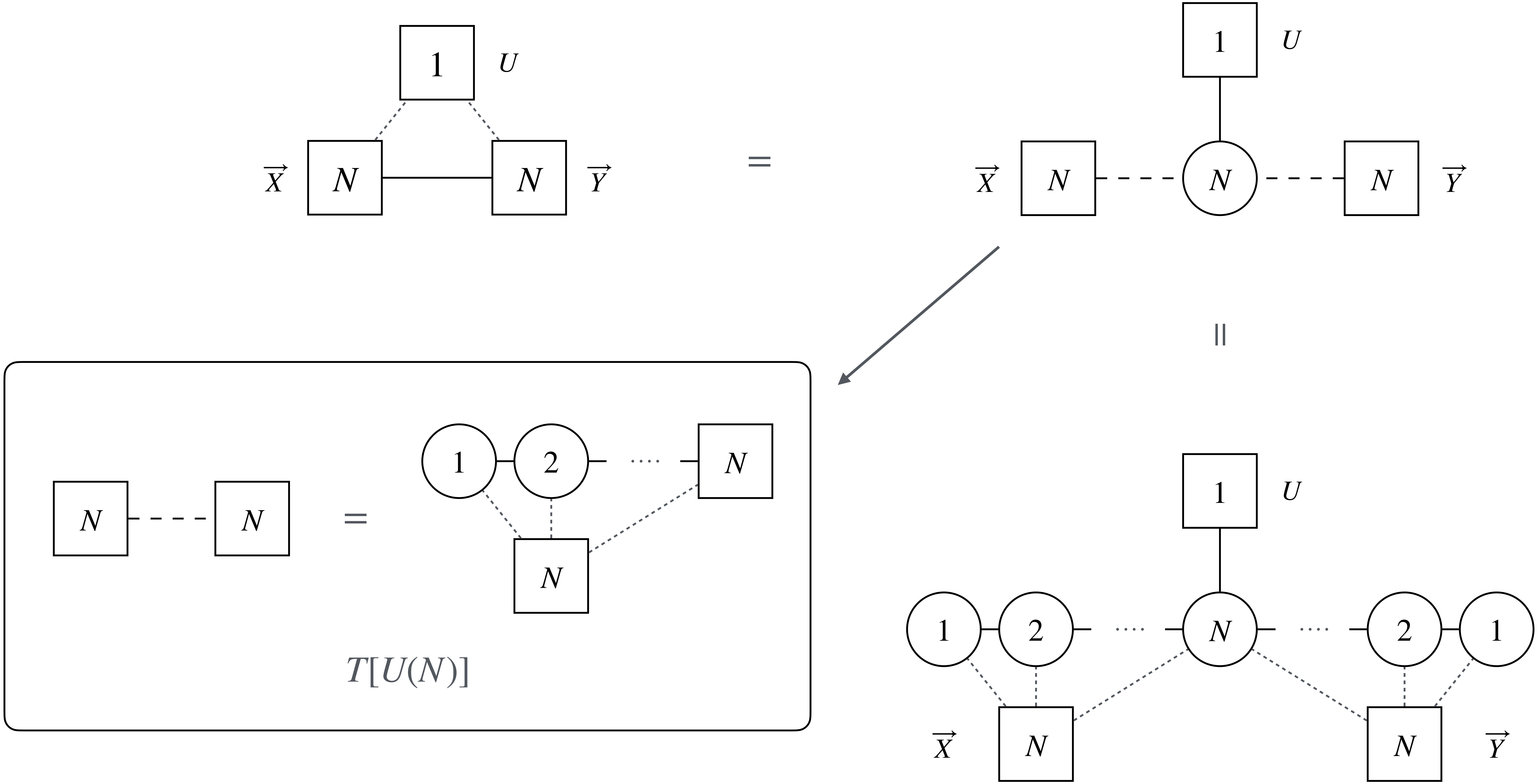
Enhanced IR symmetry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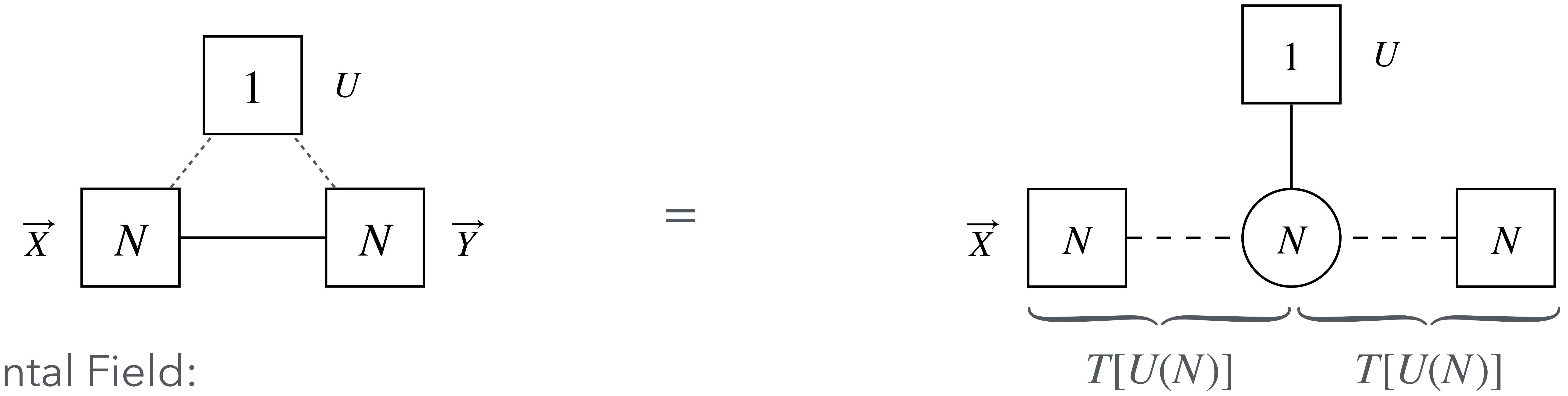
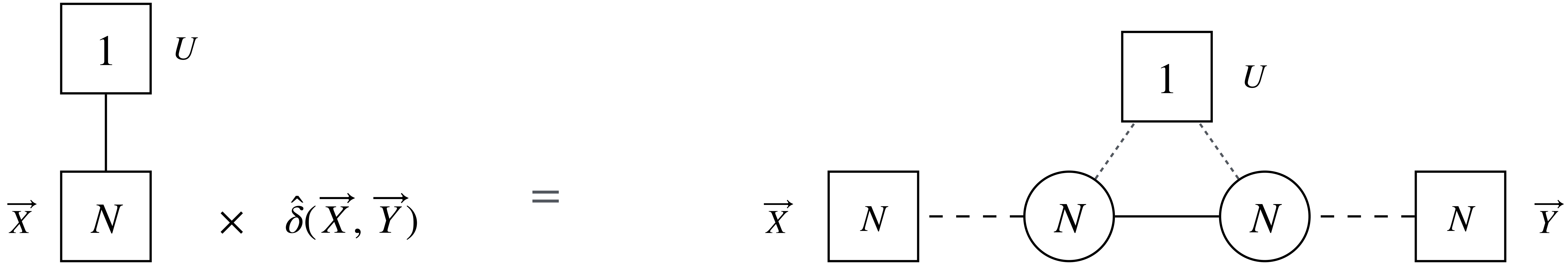
Mirror dualization algorithm

A field-theoretic construction of 3d mirror symmetry from ***two fundamental building blocks***
[**CH**-Pasquetti-Sacchi 21]

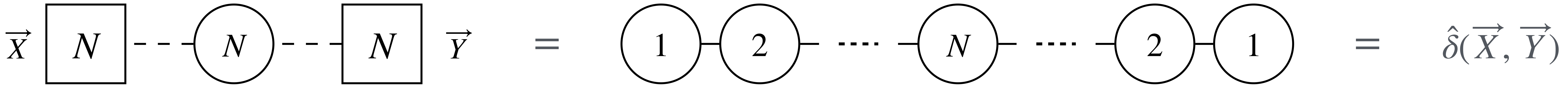
Bifundamental Field:



Fundamental Field:



Gluing T[U(N)] & Symmetry Breaking



- The moduli space is parametrized by the VEVs of monopole operators, charged under enhanced topological $U(N)_X \times U(N)_Y$ symmetry.
- The partition function is proportional to the sum of δ distributions identifying $\vec{X}$ & $\vec{Y}$ up to permutations.
  → Smooth moduli space where $U(N)_X \times U(N)_Y$ is spontaneously broken to diagonal $U(N)$
- It triggers **Higgs mechanism** if a symmetry group is gauged.

- One can dualize each field instead of the entire theory.
  → *A field-theoretic algorithm for constructing 3d mirror pairs*

  1. Decompose the theory into fundamental and bifundamental building blocks

  2. Dualize them

  3. Glue back the dualized blocks together

  4. Implement Higgs mechanism

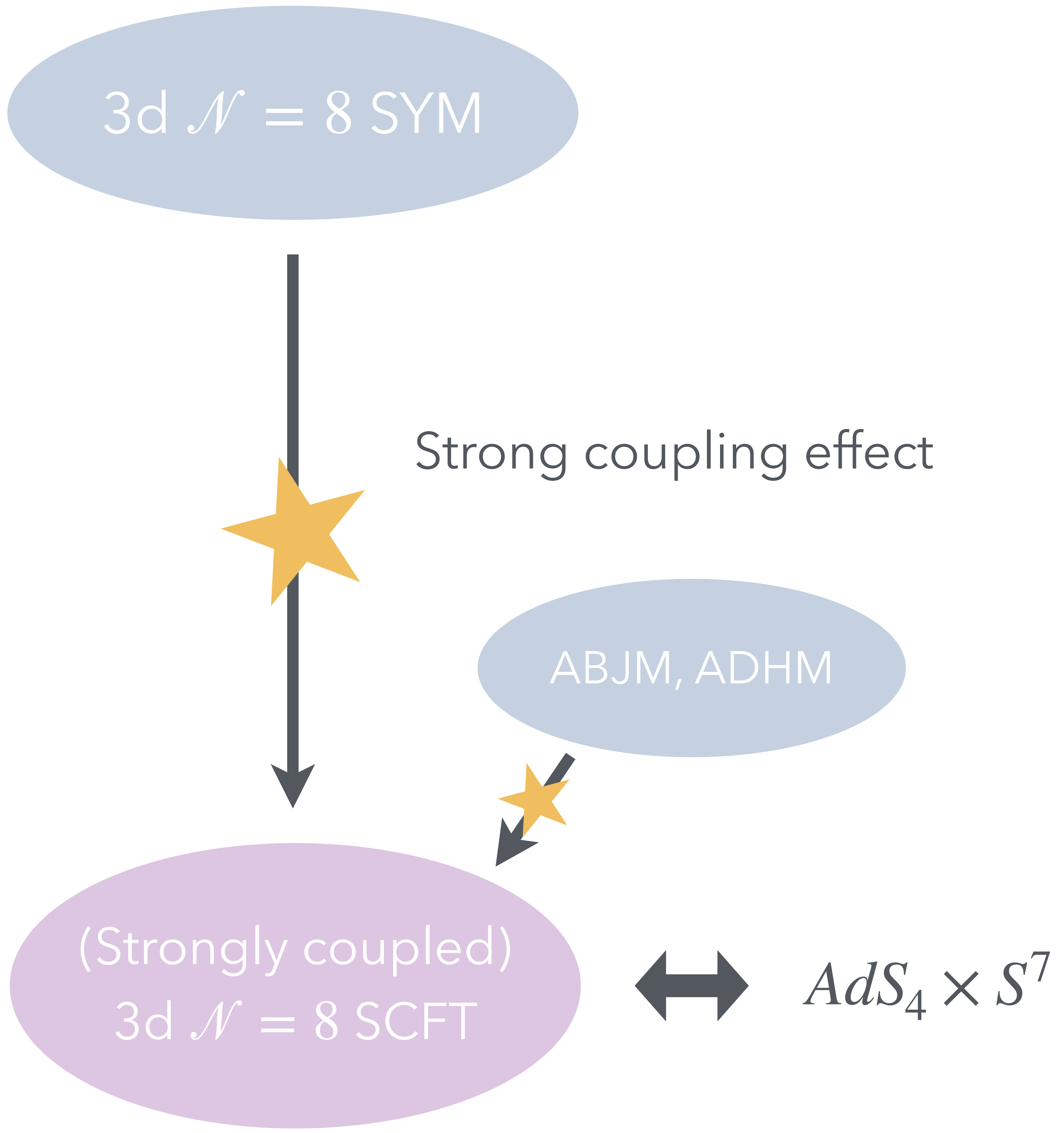
- Reproduce known mirror pairs derived from the Hanany-Witten setup

- **Extends beyond the Hanany-Witten setup**

Application

Example: 3D N=8 SYM

- SYM with three adjoint chirals (= 4d N=4 SYM)
- World-volume theory of D2-branes
- Strongly coupled in the IR
- Protected observables? Not useful since IR (R-)symmetry $\neq$ UV (R-)symmetry
- More controllable dual descriptions
  - ABJM
  - $\mathcal{N}=4$ SQCD with one adjoint hyper & one fundamental hyper (the ADHM quiver)



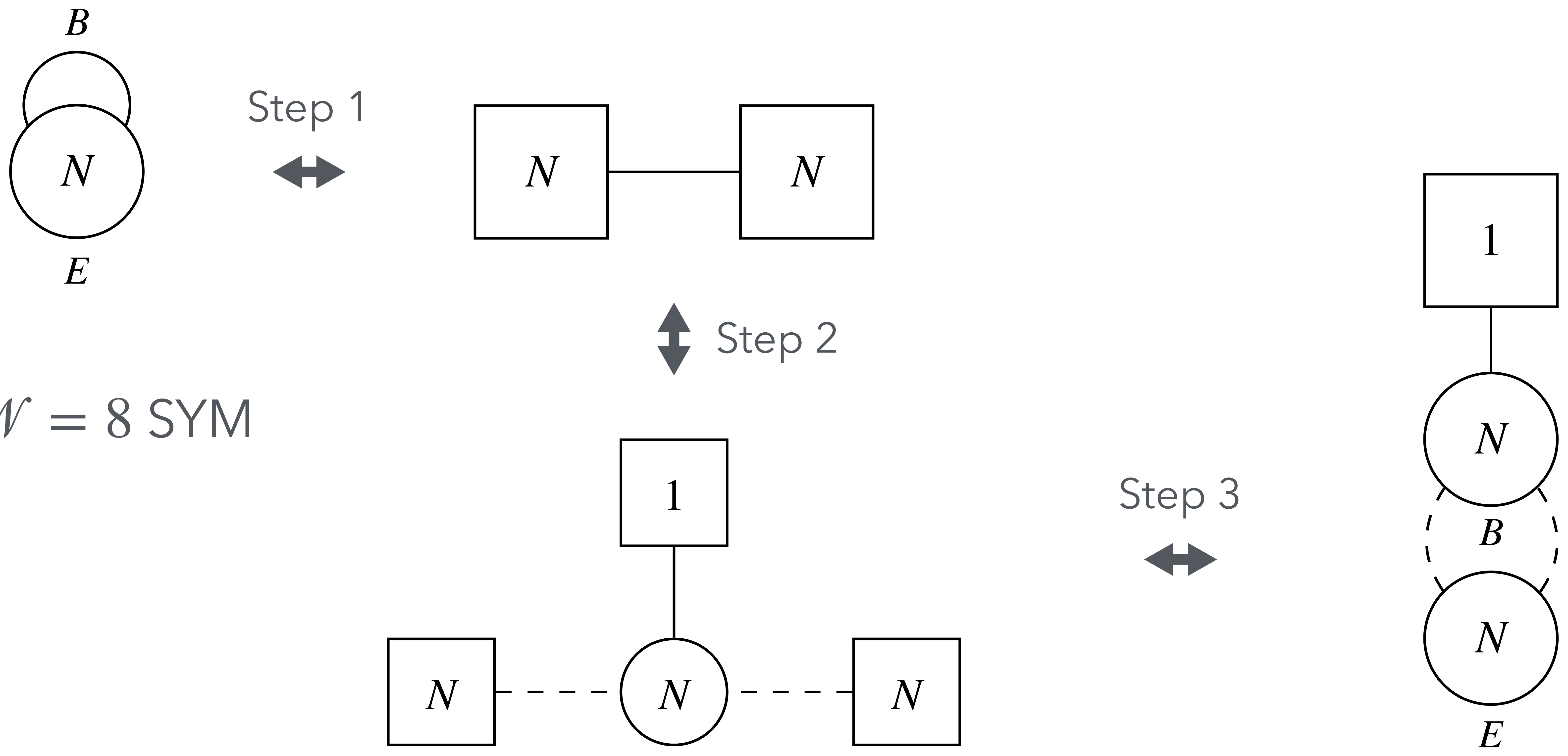
More generally…

- Belongs to a class of 3d gauge theories called **bad** [Gaiotto-Witten 08].
- Bad theories include **monopole operators decoupling in the IR,** whose naive conformal dimensions are less than 1/2, typically ≤ 0 and violate the unitarity bound.
- **Emergent symmetries** arise in the IR and affect R-symmetry; i.e.,

  the superconformal IR R-symmetry $\neq$ the manifest UV R-symmetry.

- Partition functions are **divergent** ($\sim e^{-R[\mathfrak{m}^{\pm}]x}$ [Willett-Yaakov 11]). → No quantitative study
- Any meaningful information? Yes–from the ***mirror dualization algorithm.***

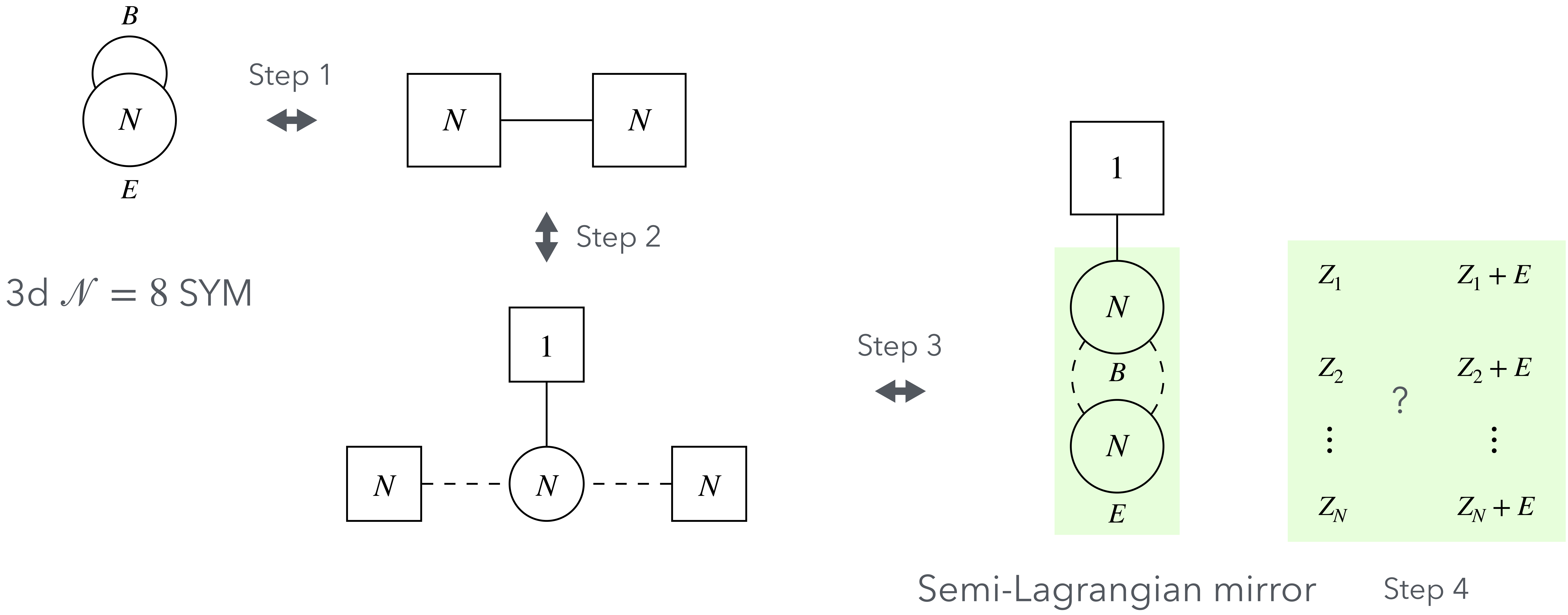
Mirror Algorithm on N=8 SYM



3d $\mathcal{N} = 8$ SYM

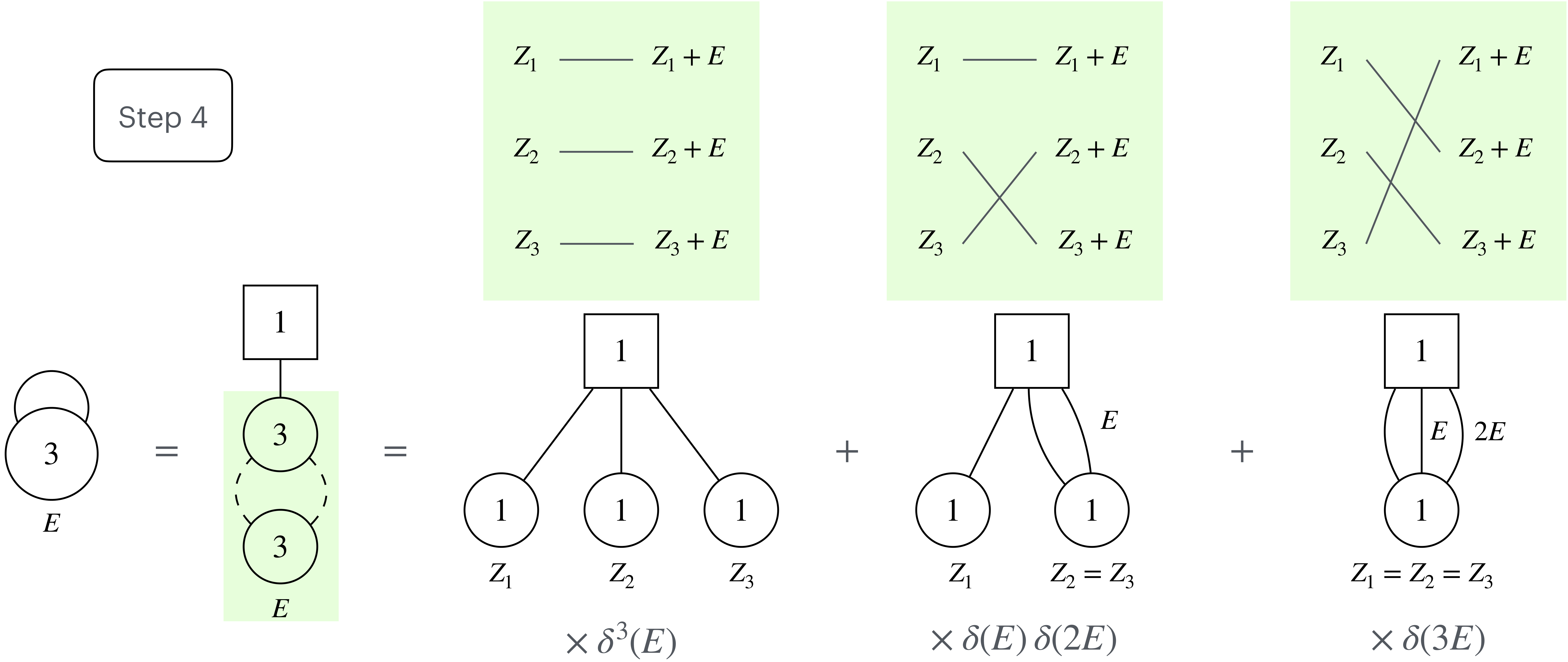
Semi-Lagrangian mirror

Mirror Algorithm on N=8 SYM



Mirror Algorithm on N=8 SYM

Step 4

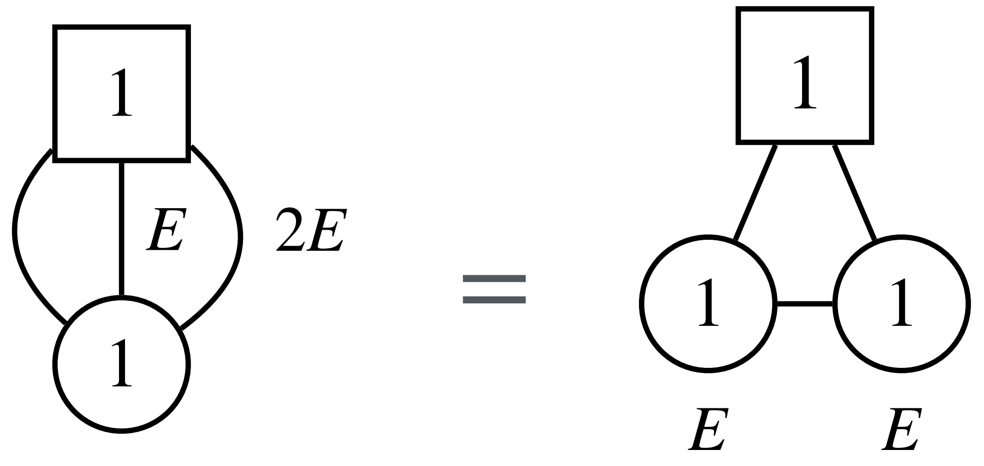


Abelianized!

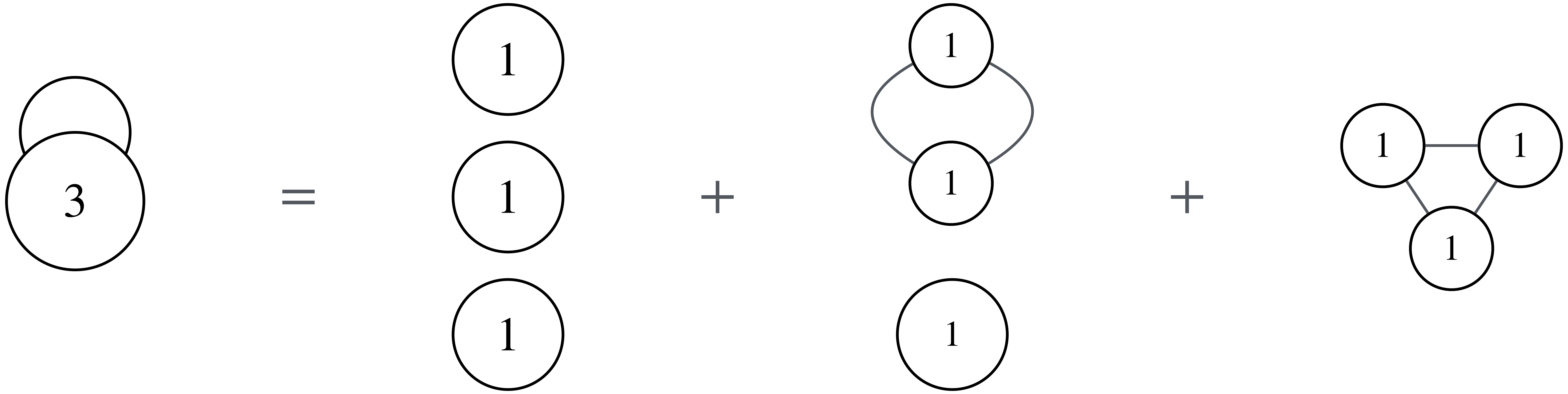
- *Semi*-Lagrangian mirror description with the emergent IR symmetries gauged
- The resulting Higgs mechanism leads to multiple **Abelian** IR phases.
- $\neq$ the Coulomb phases
- *Let's go back to the electric side.*

Electric Dualization of N=8 SYM

- One can mirror-dualize each magnetic frame to obtain the corresponding electric frame.
- Each magnetic frame is SQED, whose mirror-dual is a linear quiver.

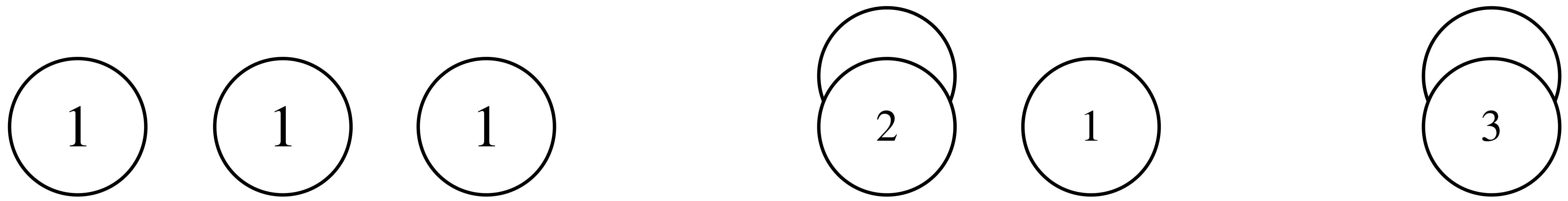


- Together with δ, which is equivalent to the diagonal $U(1)$, the electric duals are as follows:

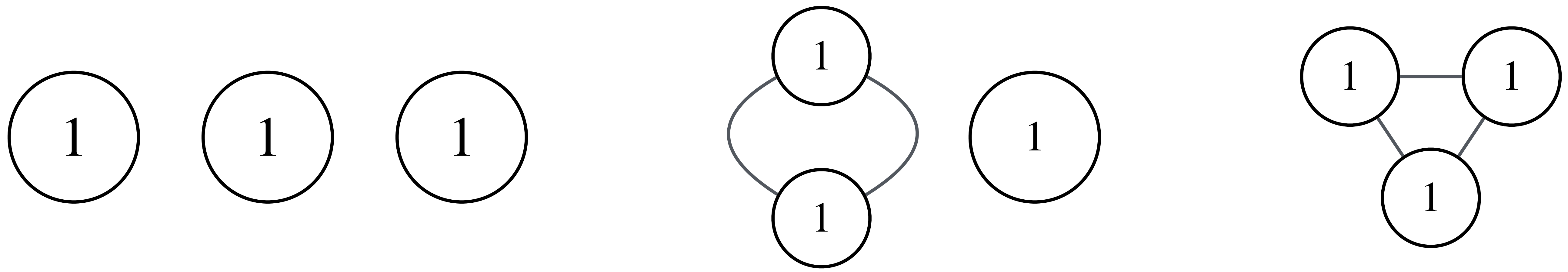


Novel Monopole Higgsing

- Recall that the vector multiplet includes adjoint scalar σ_{ij}.
- Semi-classically, generic Cartans $\sigma_{ii} \neq \sigma_{jj}$ $(i \neq j)$ break the gauge group into $U(1)^N$, i.e., the Coulomb phase, whereas a non-Abelian subgroup is restored if some of σ_{ii} coincide.



- However, the true chiral operators breaking the gauge group in the IR are **monopole operators of non-unit flux**, decomposing the theory into **Abelian circular quivers**.



Novel Monopole Higgsing

- The VEVs of monopoles with non-unit flux leads to a ***new type of Higgsing*** distinct from that of an adjoint field.

- For general N & L, the partition function of a circular quiver with constant ranks can be decomposed as

$$Z_{N,L} = \frac{1}{N!} \sum_{\substack{\sigma = \{N^{l_N}, \ldots, 2^{l_2}, 1^{l_1}\}, \\ |\sigma| = N}} \mathrm{dim}(\sigma) \times \left(Z_{1,L}\right)^{l_1} \times \left(Z_{1,2L}\right)^{l_2} \times \ldots \times \left(Z_{1,NL}\right)^{l_N}$$

where the IR phases are again described by Abelian theories.

Generalization

Generalization

The local-dualization philosophy goes beyond 3d N=4 mirror symmetry

- Generalization to $SL(2,\mathbb{Z})$ duality webs
  [Comi-**CH**-Marino-Pasquetti-Sacchi 22, Comi-**CH**-Marino 26]

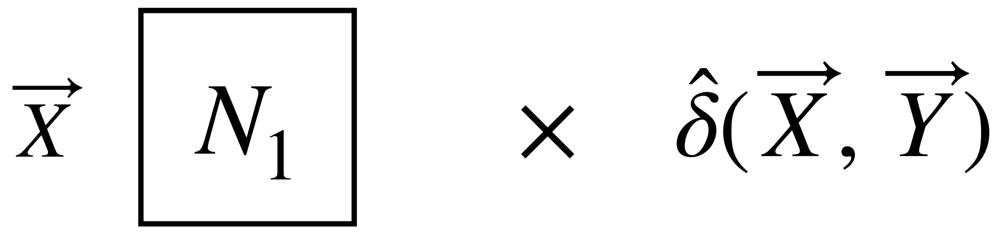
- Generalization to $\mathcal{N} < 4$
  [Benvenuti-Comi-Pasquetti 23, Benvenuti-Cagioni-Comi-Pasquetti-Ungureanu-Rota-Shiri 24-26]

- Generalization to 4d
  [**CH**-Pasquetti-Sacchi 20, 21, Comi-**CH**-Marino-Pasquetti-Sacchi 22]

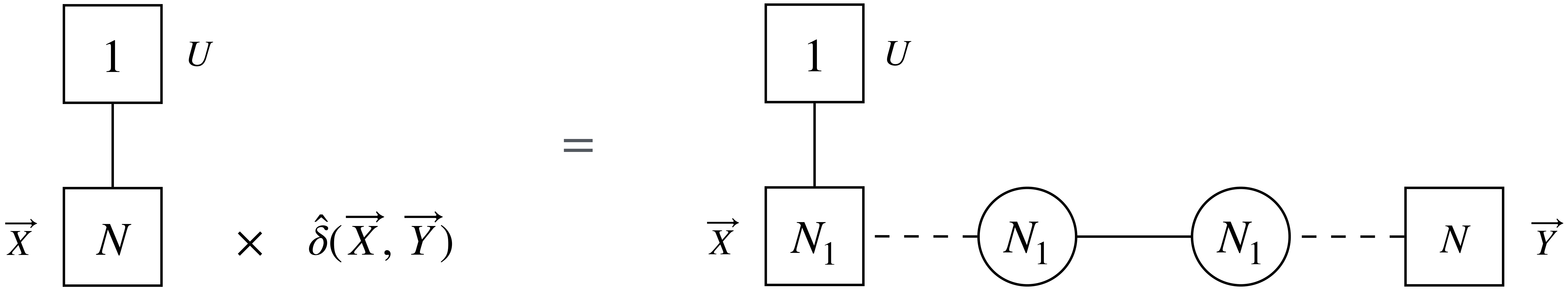
- Generalization to Class S [Comi-Garavaglia-Giacomelli-Pasquetti-Singh 25]

$SL(2,\mathbb{Z})$ Generalization [Comi-**CH**-Marino-Pasquetti-Sacchi 22]

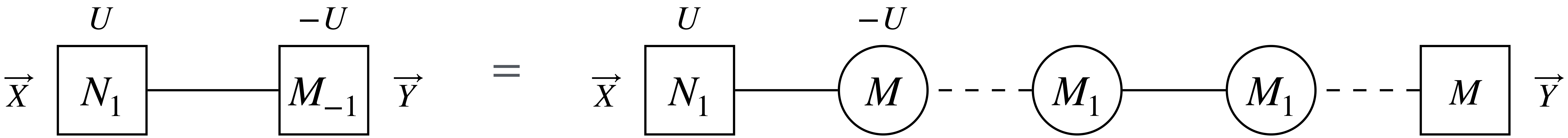
T-duality wall



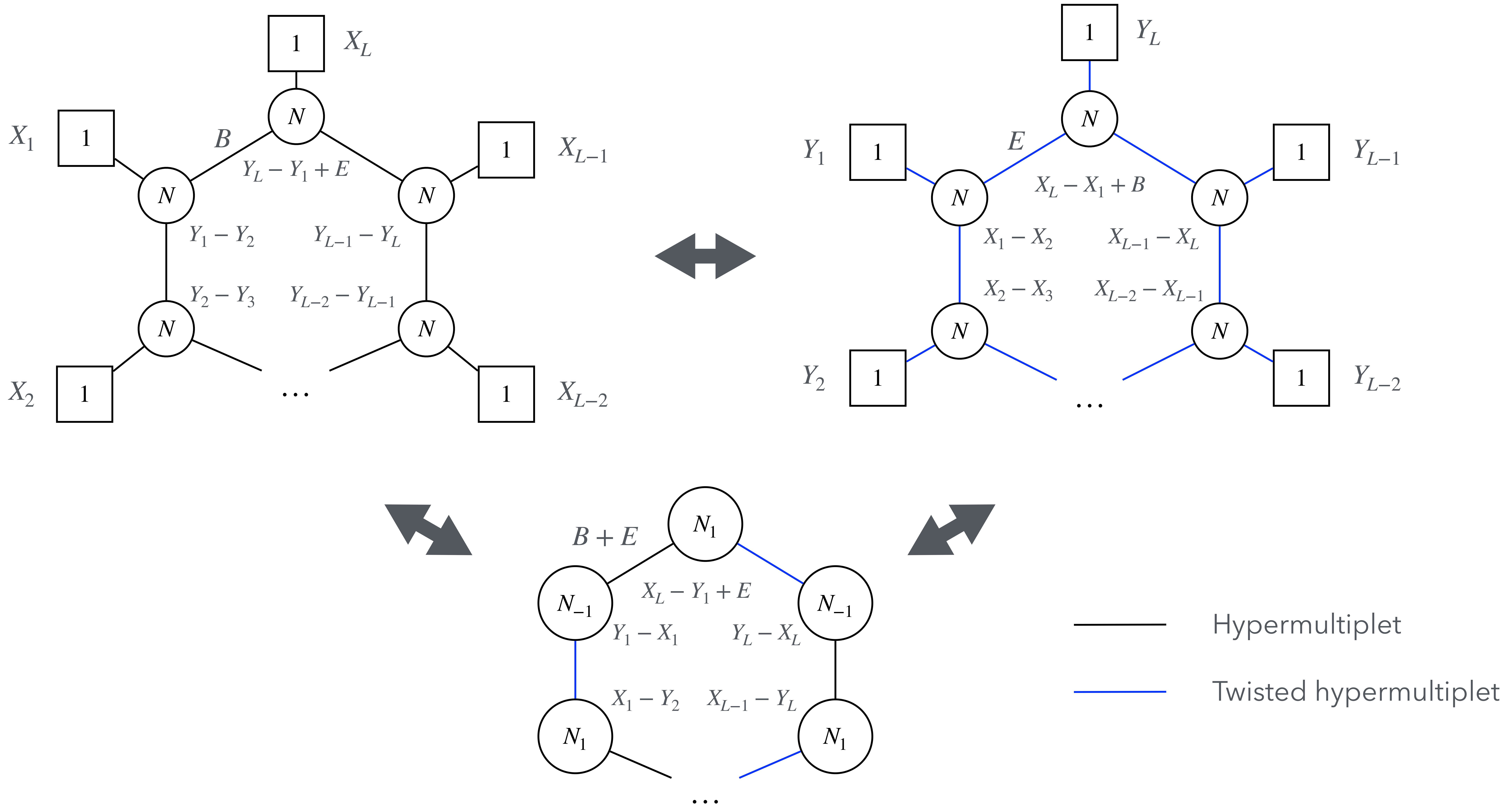
$TB_{01}T^{-1} = TB_{01}STSTS$



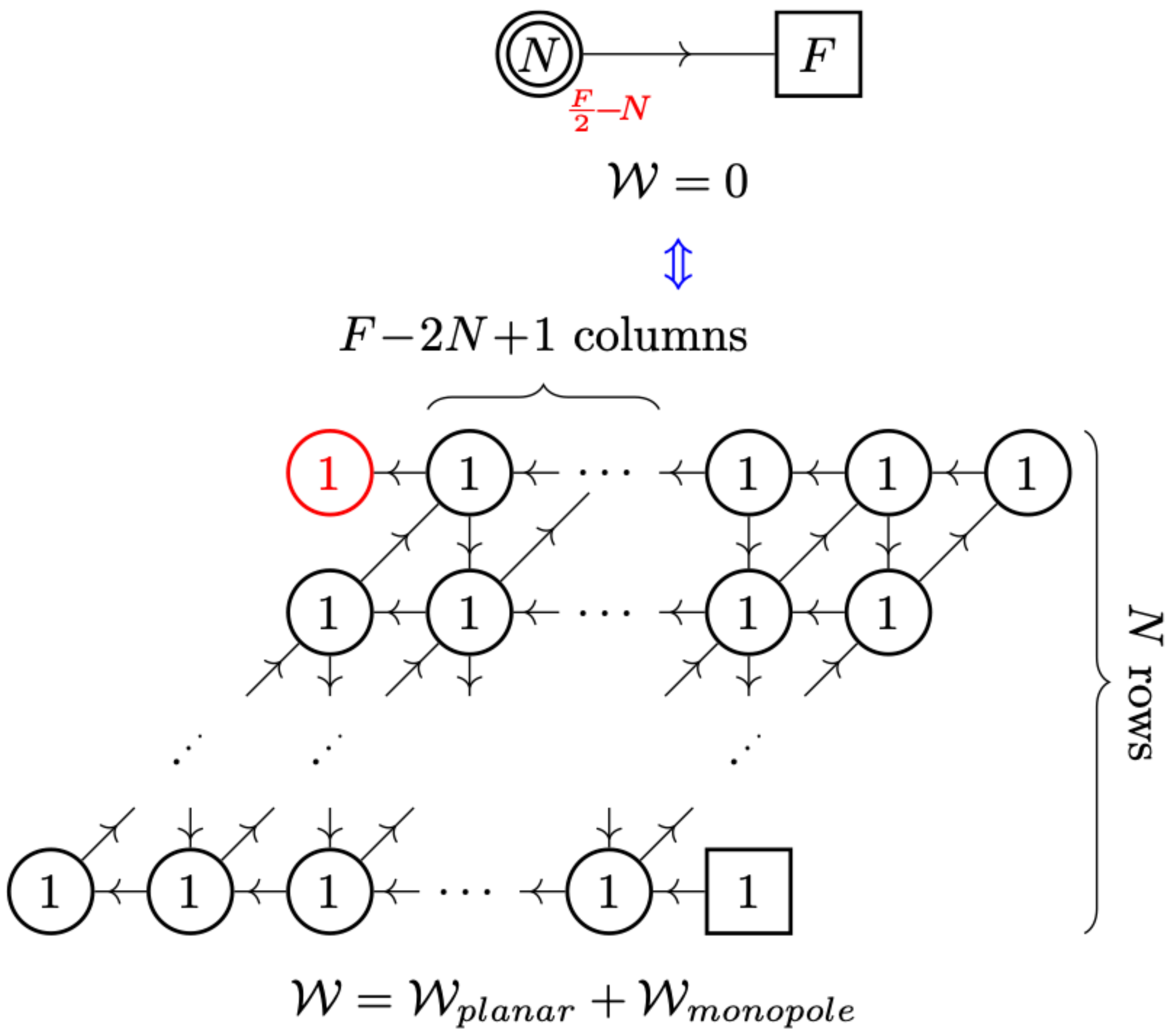
$TB_{11}T^{-1} = TB_{10}STSTS$



Example: $SL(2,\mathbb{Z})$ triality of an ABJM-like theory



$\mathcal{N} = 2$ Planar Mirror [Benvenuti-Cagioni-Comi-Pasquetti-Ungureanu-Rota-Shiri 24-26]



- Deformation of $\mathcal{N} = 4$ mirror leads to an **Abelian planar** mirror dual
- Another type of Abelianization of 3d SQCD
- Any connection to the Abelianzation of $\mathcal{N} = 8$ SYM?
- Generalization to adjoint SQCD (WIP)

Conclusion

- Mirror dualization algorithm provides a systematic way of deriving 3d mirror pairs, even beyond those in the Hanany-Witten setup.
- Using the algorithm, a new pattern of monopole Higgsing is observed for $\mathcal{N} = 8$ SYM, or more generally, for bad circular quivers.
- Abelianization of 3d gauge theories–*coincidence or a generic phenomenon*?
- A new approach to strongly coupled gauge dynamics–and much more to explore

Mirror dualization algorithm

A new window into dynamics of 3d gauge theories and mirror symmetry

Thank you!