Topological Defects and Symmetry

Nordic Network Meeting on Branes, Fields, and Strings

University of Stavanger — December 5, 2023

Michele Del Zotto

UPPSALA UNIVERSITET

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SCGCS

Based on joint projects with

- Christian **Copetti**, Kantaro **Ohmori**, Yifan **Wang**
- Kantaro **Ohmori**
- Robert **Moscrop** and Shani Nadir **Meynet**
- Vladimir **Bashmakov**, Azeem **Hasan**, and Justin **Kaidi**
- Matteo **Dell'Acqua**, Shani Nadir **Meynet**, and Elias **Riedel Gårding**

annonse

- **GCS24:** workshop and school on symmetry categories (June 2024)
- **KITP Program on Symmetries** (in spring 2025 - deadline now: 15/12/2023)

scgcs.berkeley.edu

for details and links!

Executive Summary

Symmetries are a topological subsector of the spectrum of operators of a given QFT.

Today I will explain some features and some first applications of symmetries that arise from this perspective.

Generalized Symmetries: Lightning Review

Well-known **fact**: quantum fields can have **extended operators.**

Wilson 1974
’t Hooft 1975
Polyakov 1975

in this talk, by “quantum fields” we mean Poincaré invariant unitary quantum fields

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Generalized global symmetries ≡ **Framework** to express corresponding conserved **quantum numbers**

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$\bullet\, \mathcal{O}(p)$

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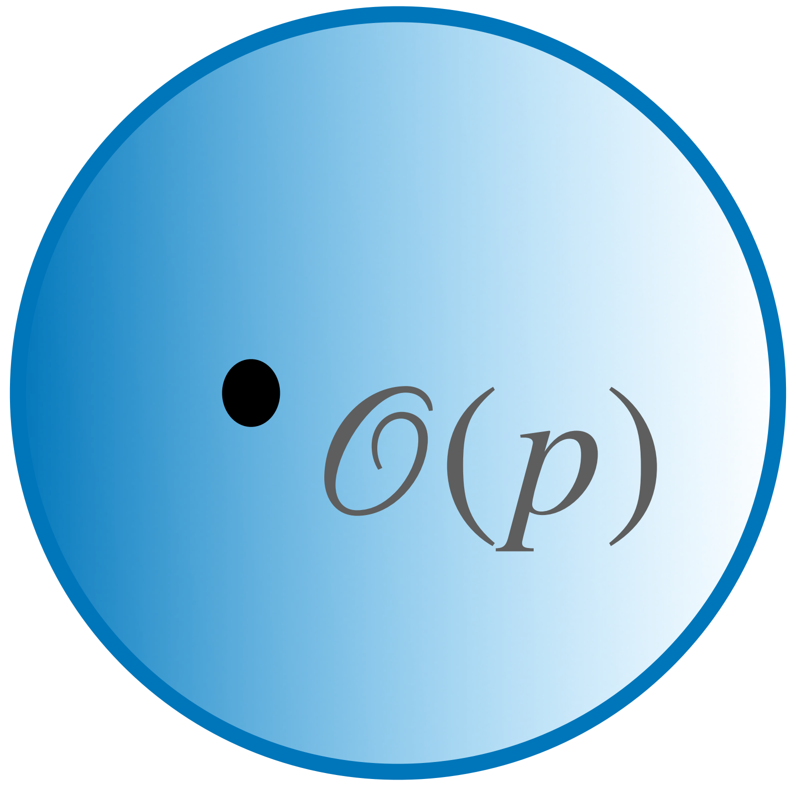

$$\langle\, \mathcal{U}_g(\mathbb{S}^D)\, \mathcal{O}(p) \;\cdots \rangle$$

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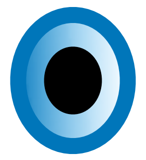 $\mathcal{O}(p)$

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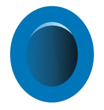

$R_g\,\mathcal{O}(p)$

$$\langle\, \mathcal{U}_g(\mathbb{S}^D)\, \mathcal{O}(p) \;\; \cdots \rangle \;=\; \langle\, R_g\, \mathcal{O}(p) \;\; \cdots \rangle$$

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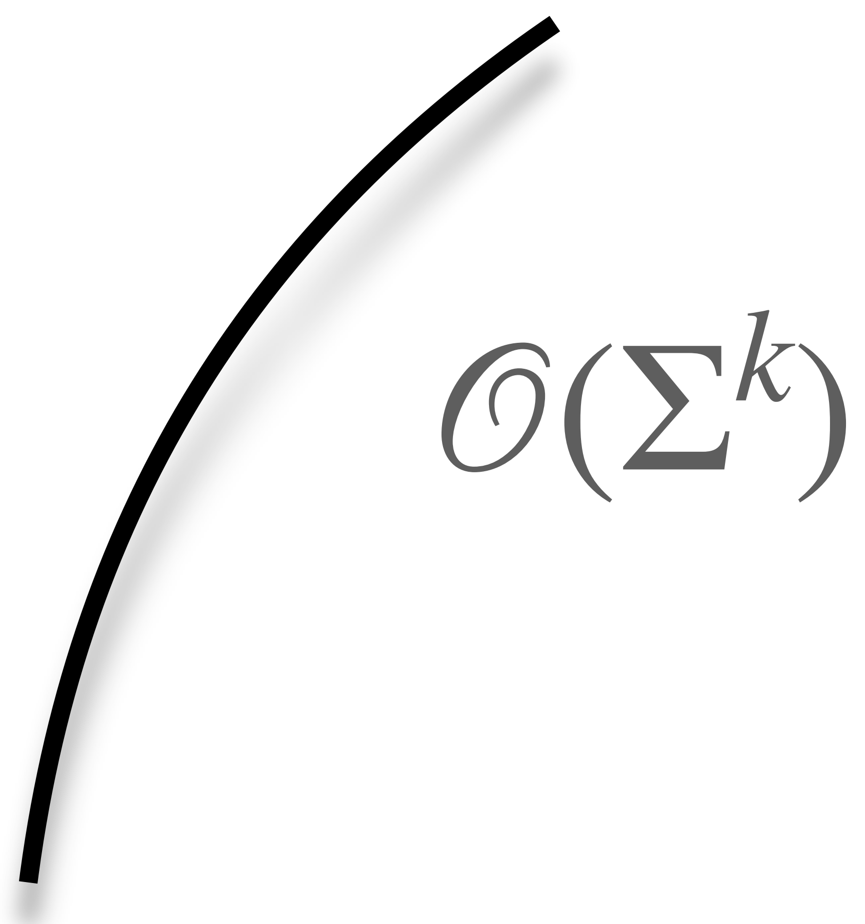

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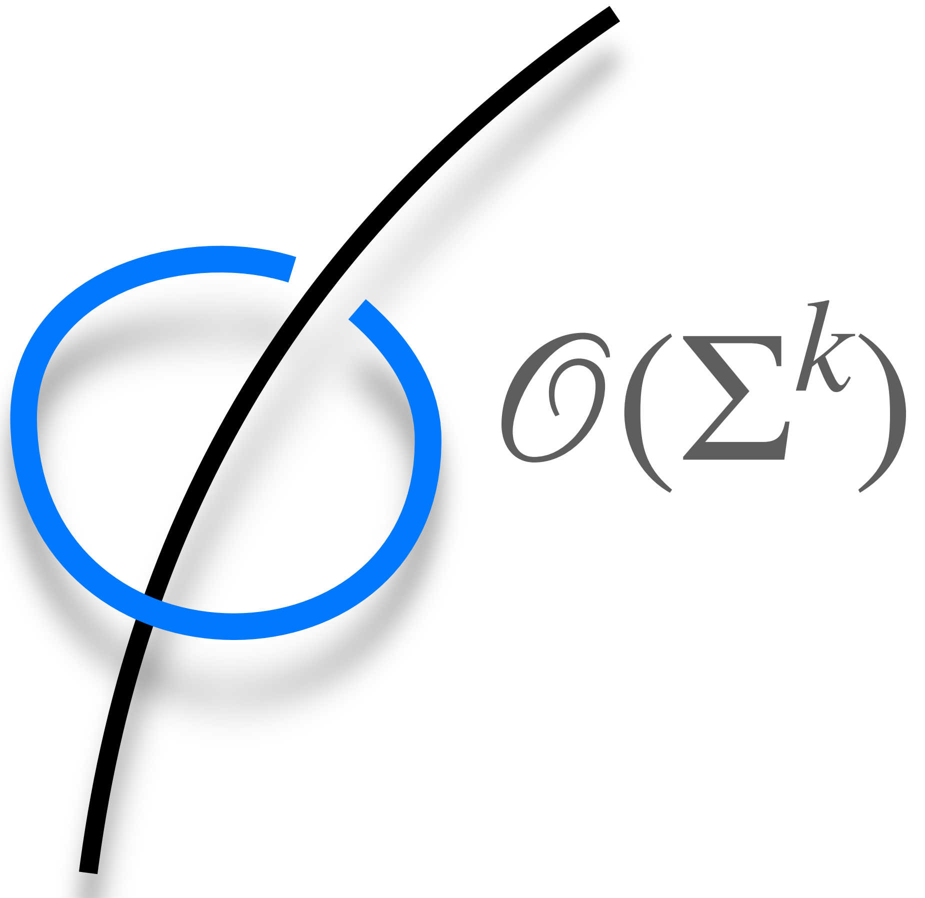

$$\langle\, \mathcal{U}_g(\mathbb{S}^{D-k})\ \mathcal{O}(\Sigma^k) \cdots \rangle$$

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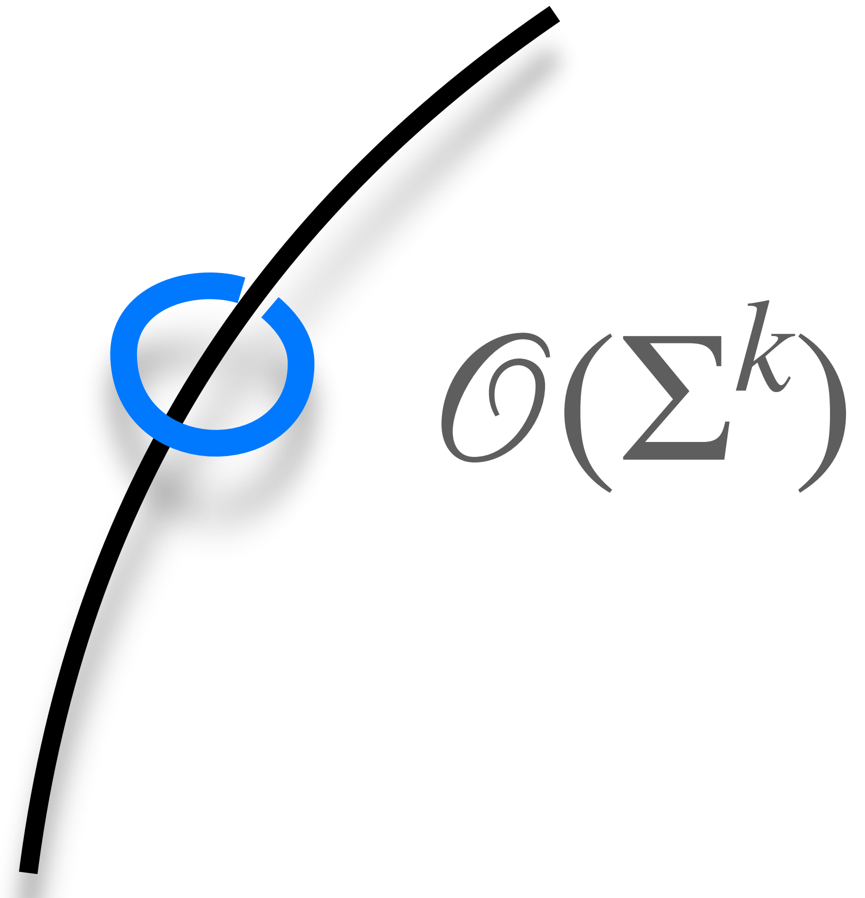

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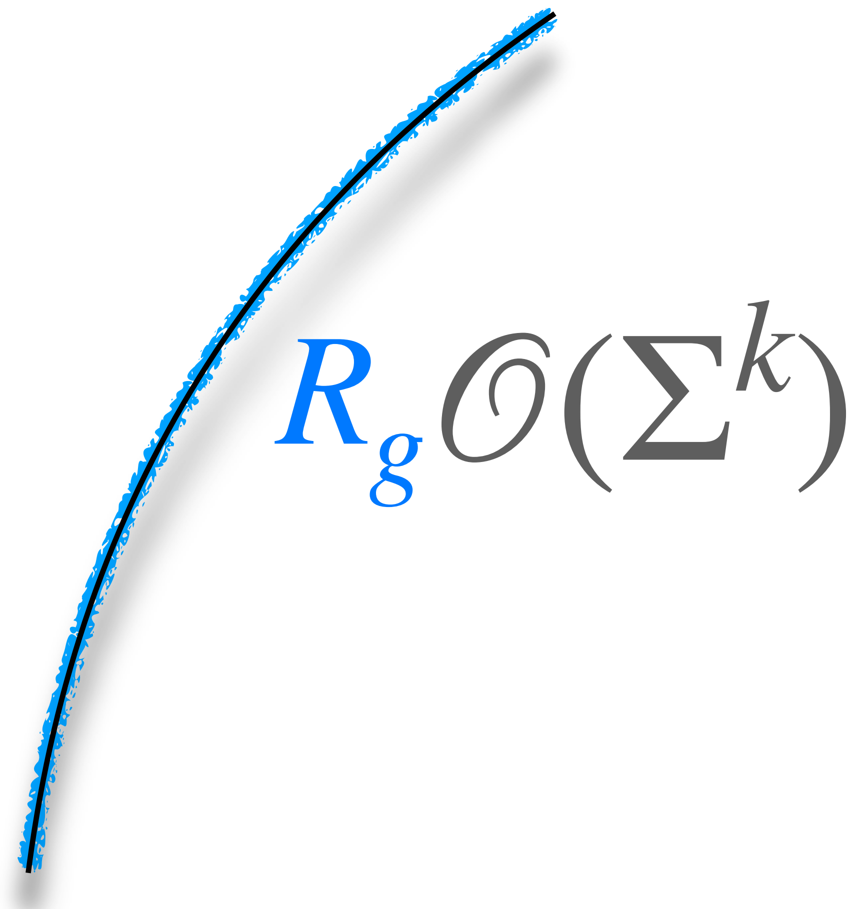

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Example: Maxwell theory

Electric and magnetic 1-form symmetries

$$\mathcal{U}_\theta^{(e)}(\mathbb{S}^2) = e^{i\theta \int_{\mathbb{S}^2} * J_e^{(2)}}$$

$$J_e^{(2)} = \frac{f}{e^2}$$

$$\mathcal{O}_{q_e}(\Sigma^1) = e^{i q_e \int_{\Sigma^1} a^{(1)}}$$

Wilson lines

$$\mathcal{U}_\theta^{(m)}(\mathbb{S}^2) = e^{i\theta \int_{\mathbb{S}^2} * J_m^{(2)}}$$

$$J_m^{(2)} = * \frac{f}{2\pi}$$

$$\mathcal{O}_{q_m}(\Sigma^1) = e^{i q_m \int_{\Sigma^1} a_D^{(1)}}$$

't Hooft lines

$$\mathcal{U}_\theta^{(\bullet)}(\mathbb{S}^2)\ \mathcal{O}_{q_\bullet}(\Sigma^1) = e^{i\theta q_\bullet}\ \mathcal{O}_{q_\bullet}(\Sigma^1) \qquad \bullet = e, m$$

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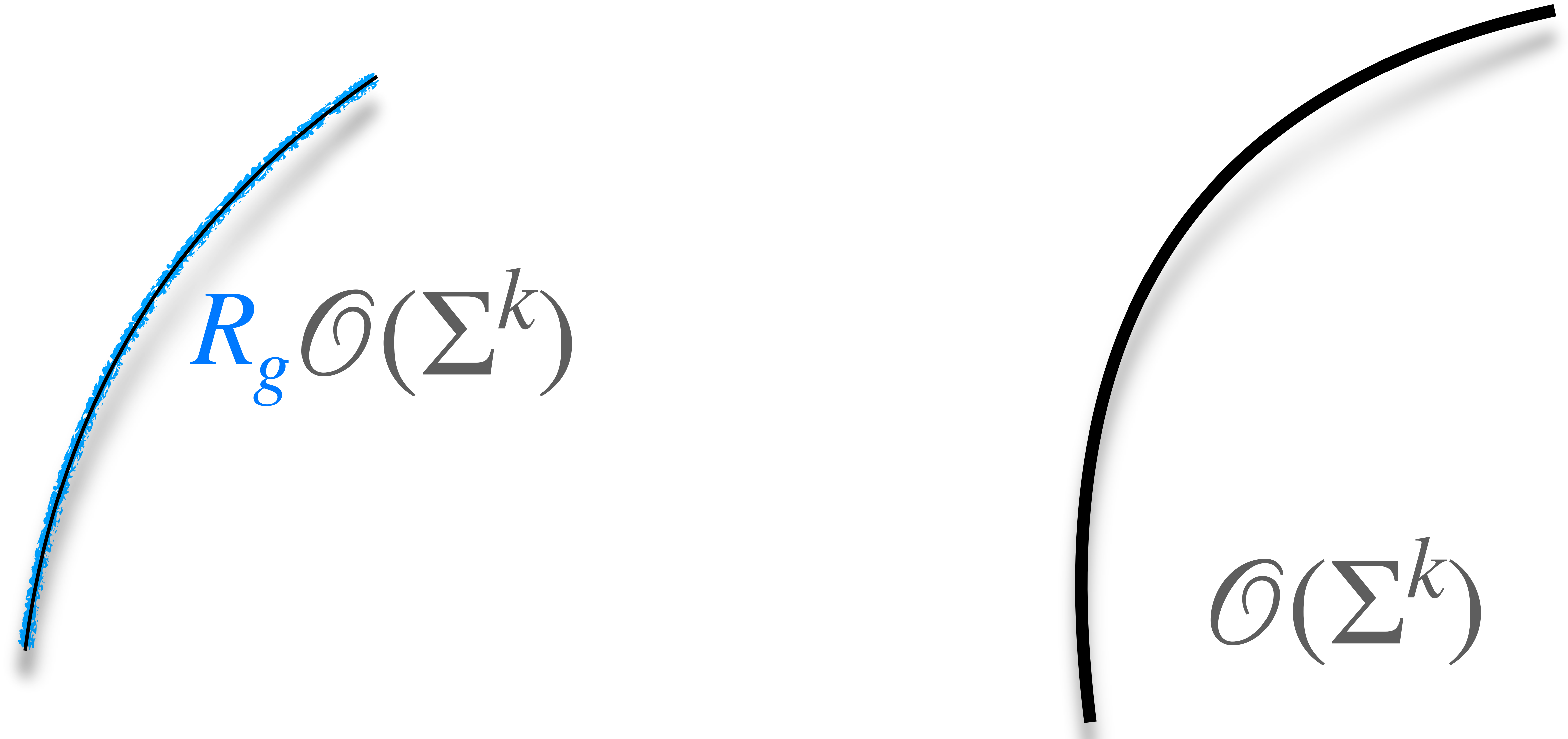

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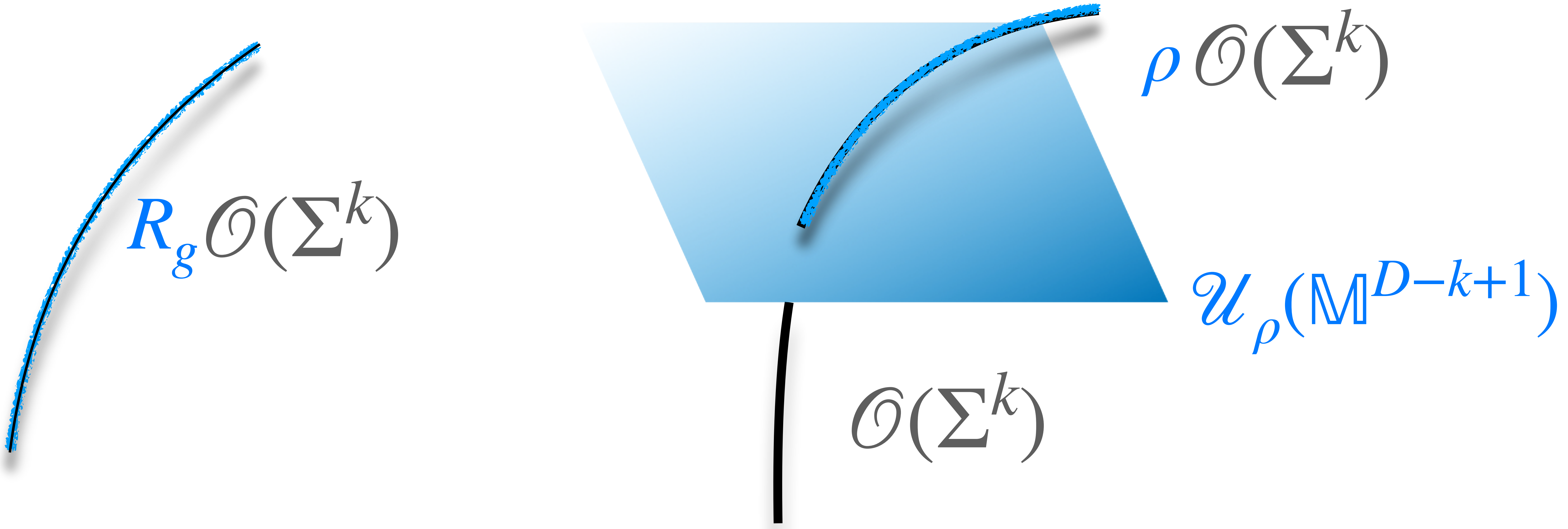

More charges

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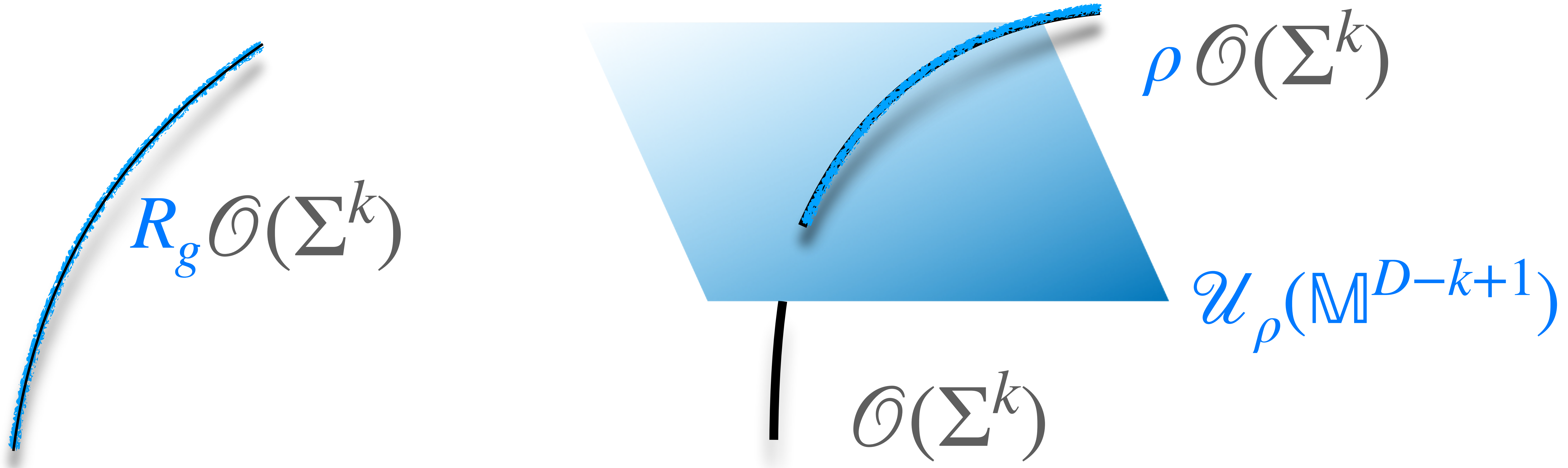

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"Topological" is in quotes because the dependence of symmetry operators on their support is topological up to contact terms with charged operators

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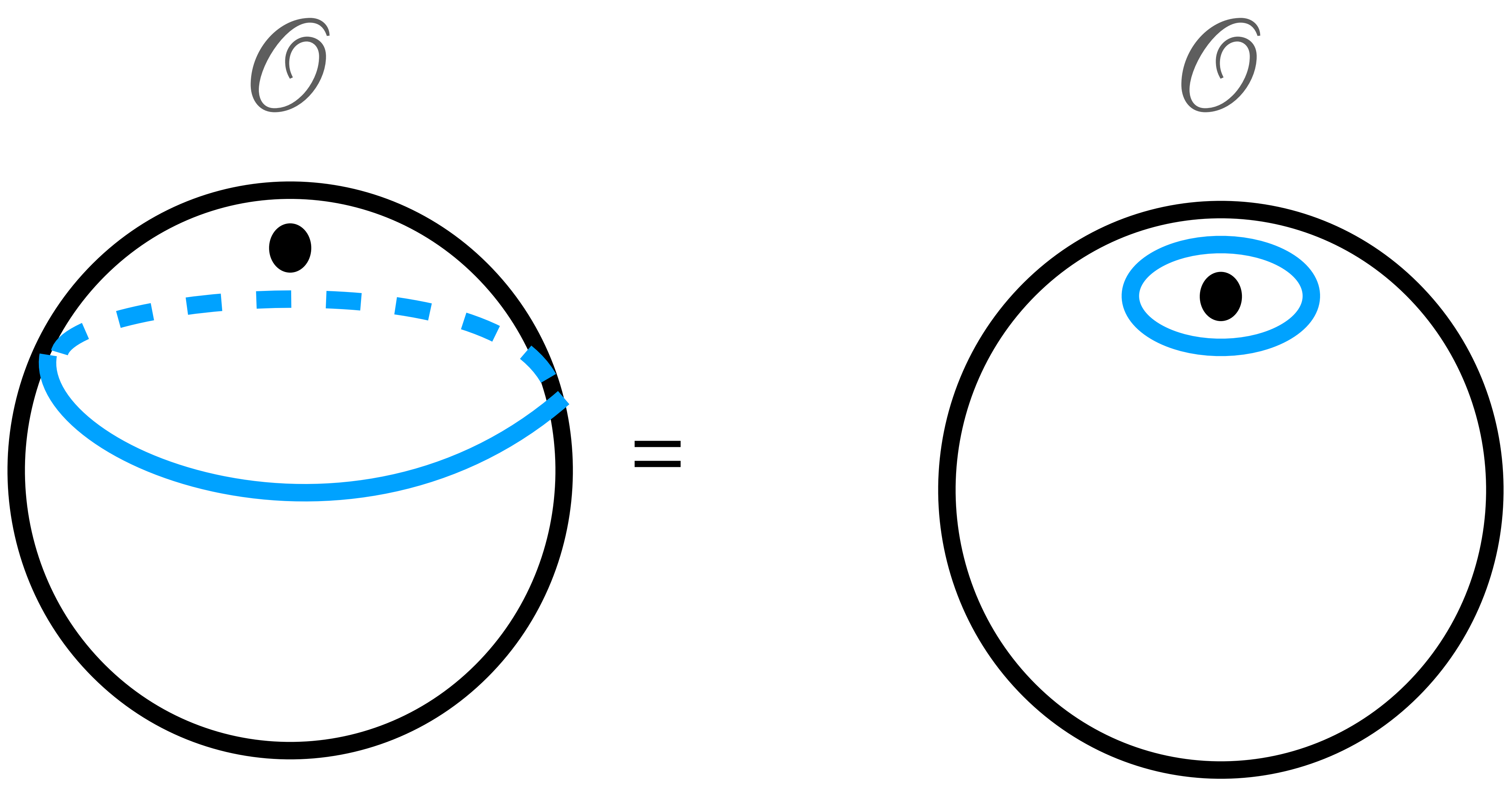

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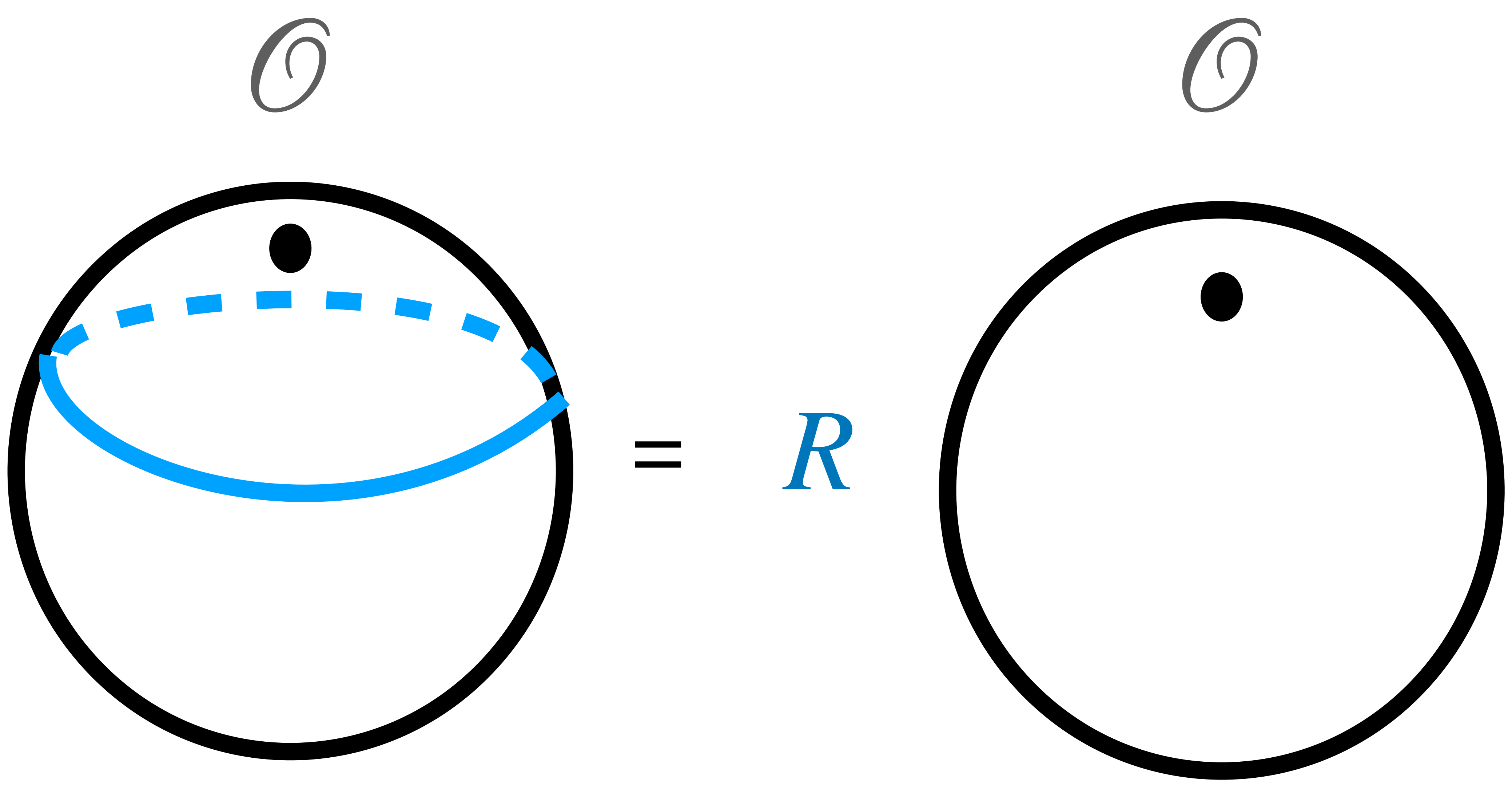

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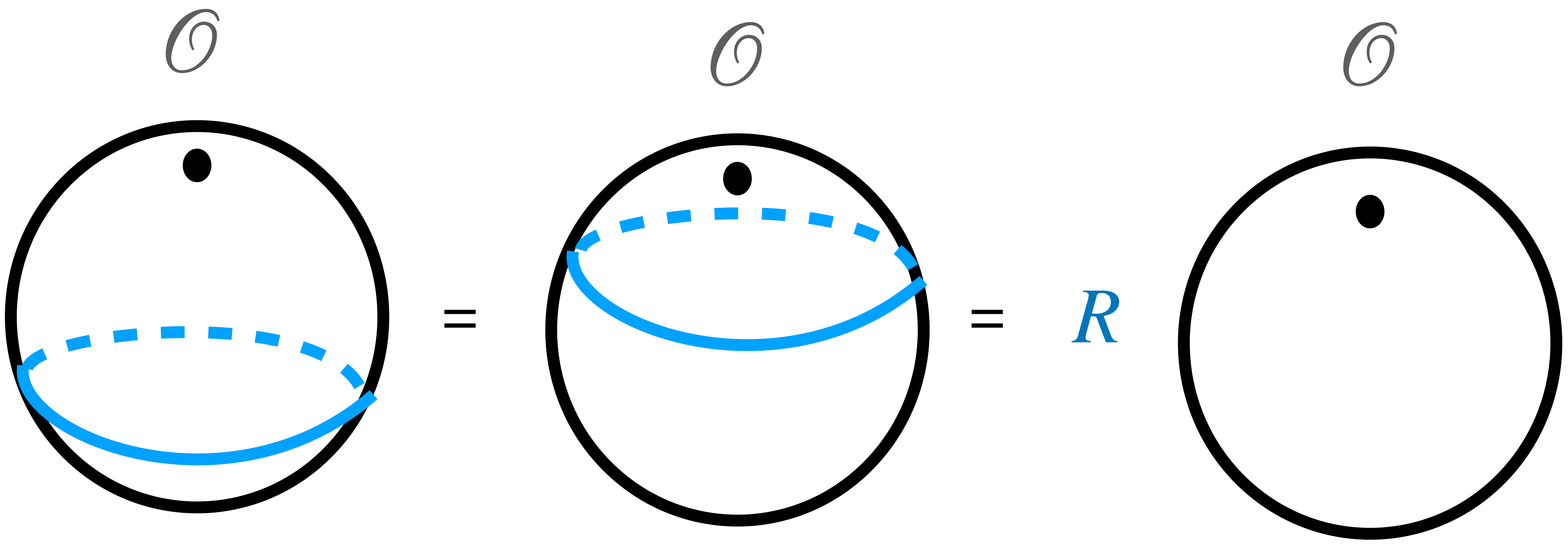

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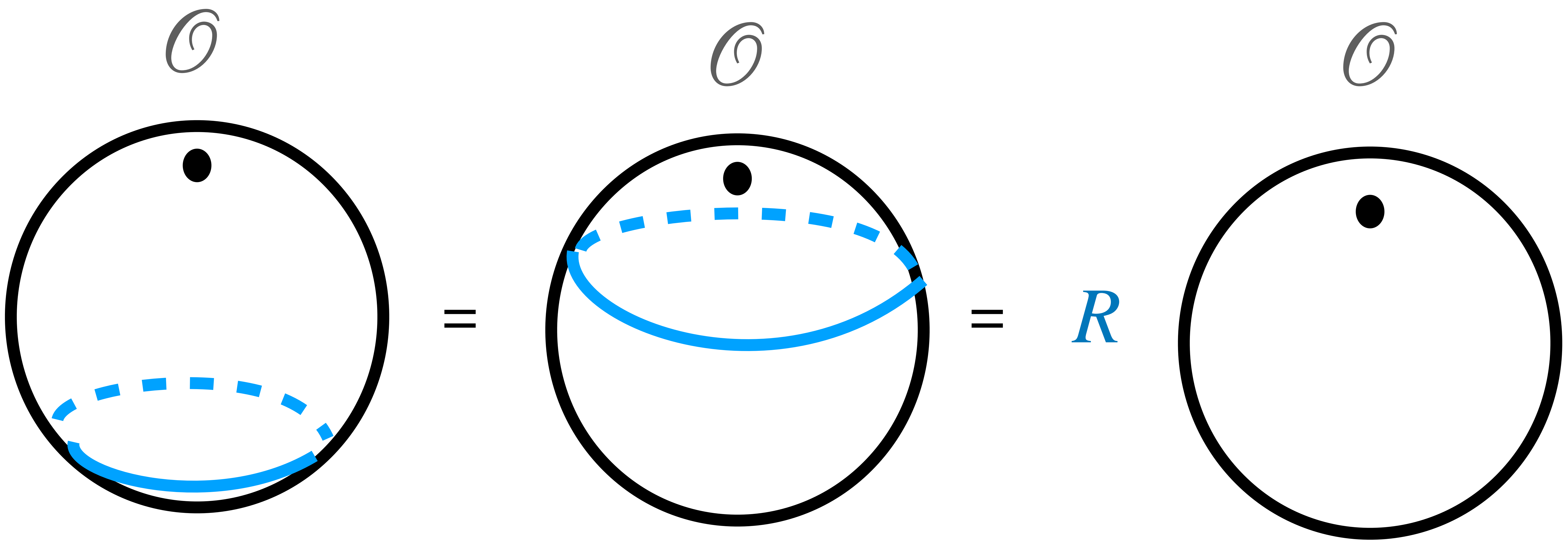

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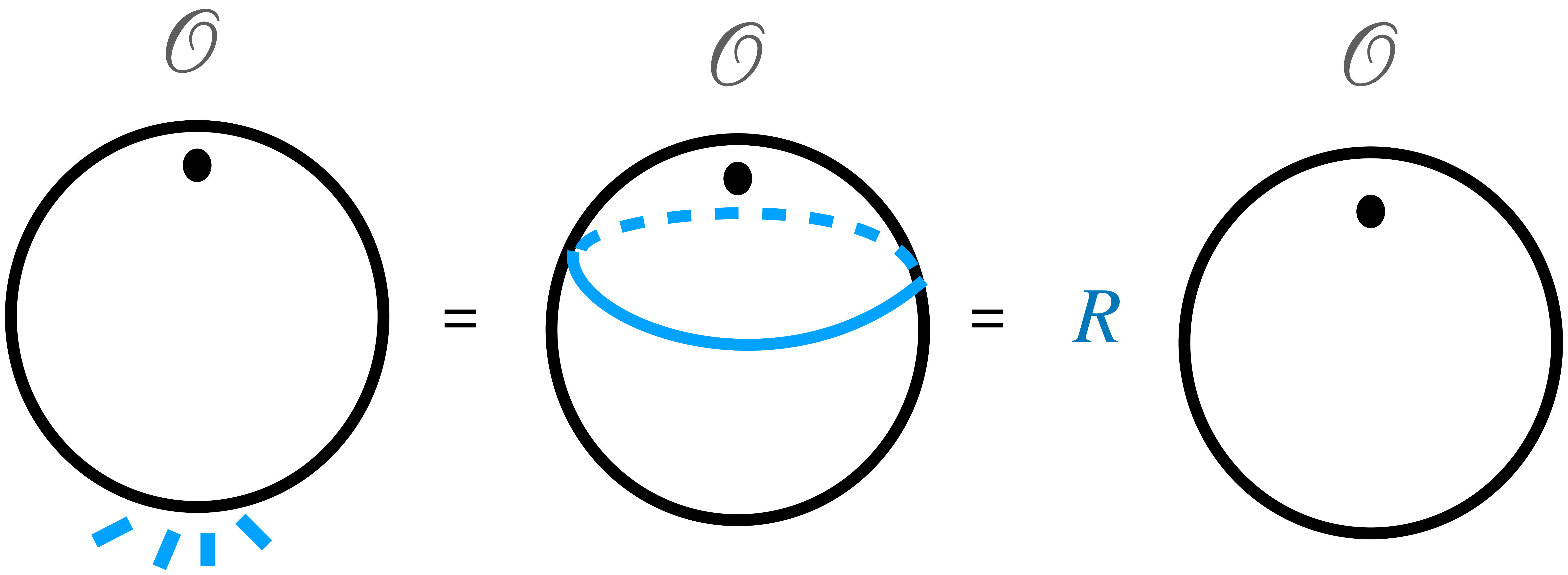

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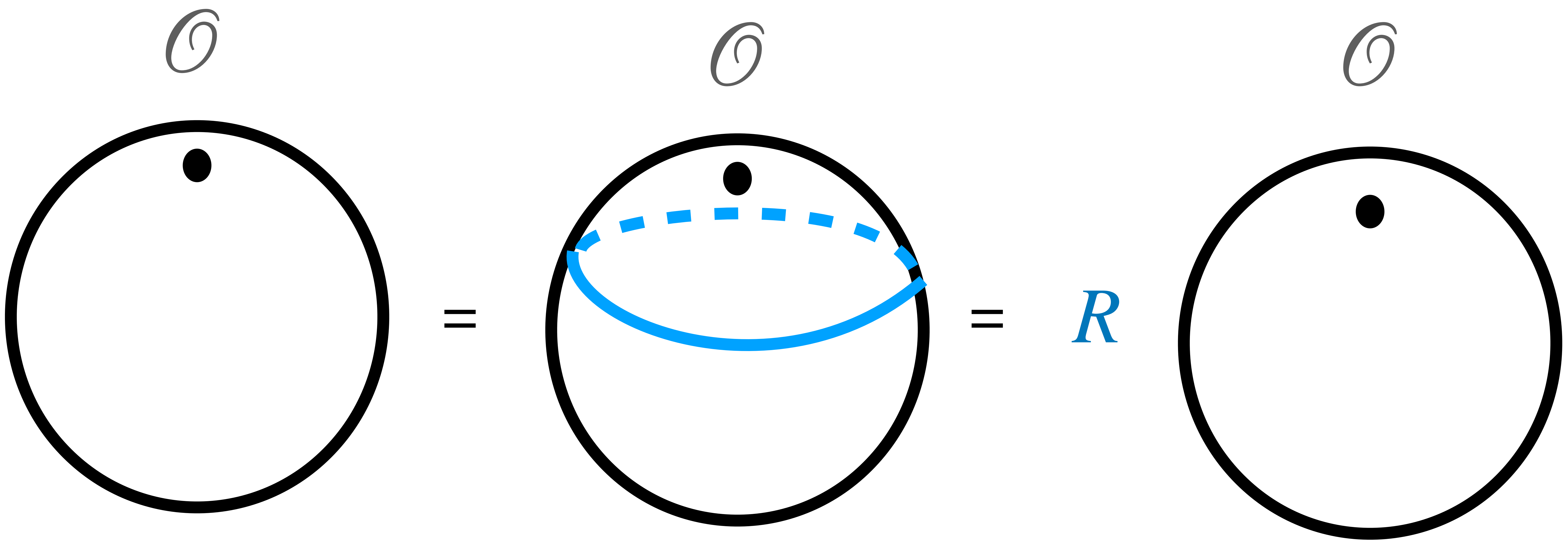

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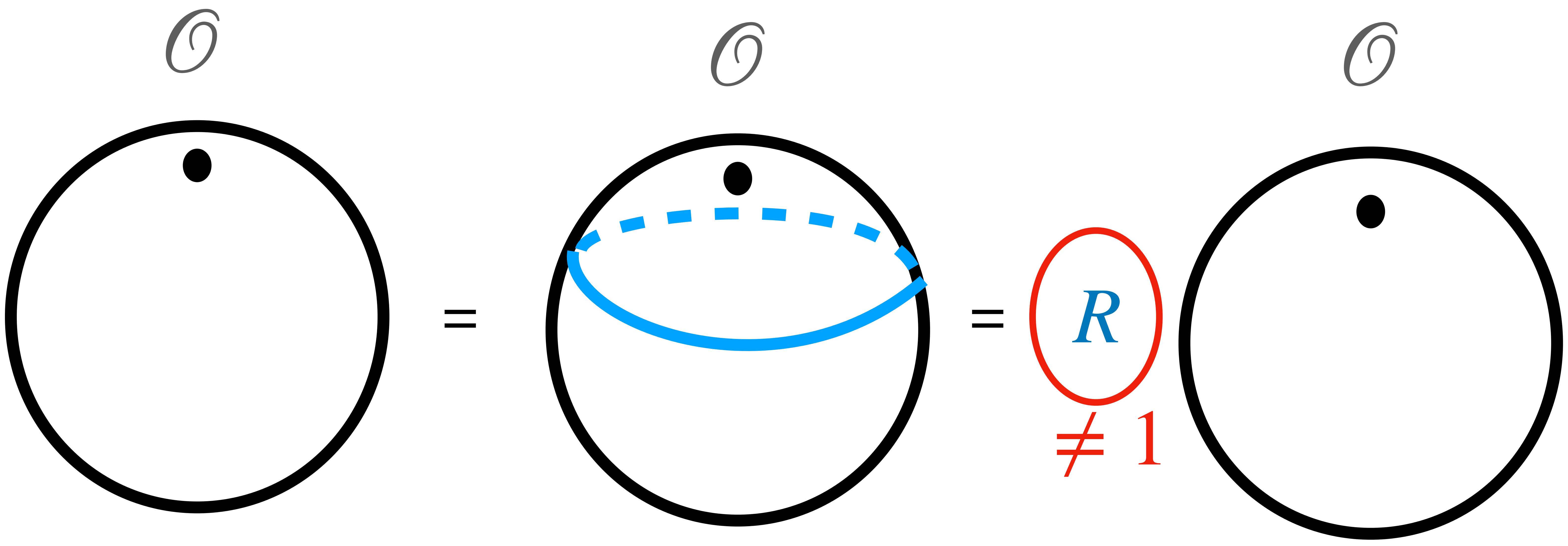

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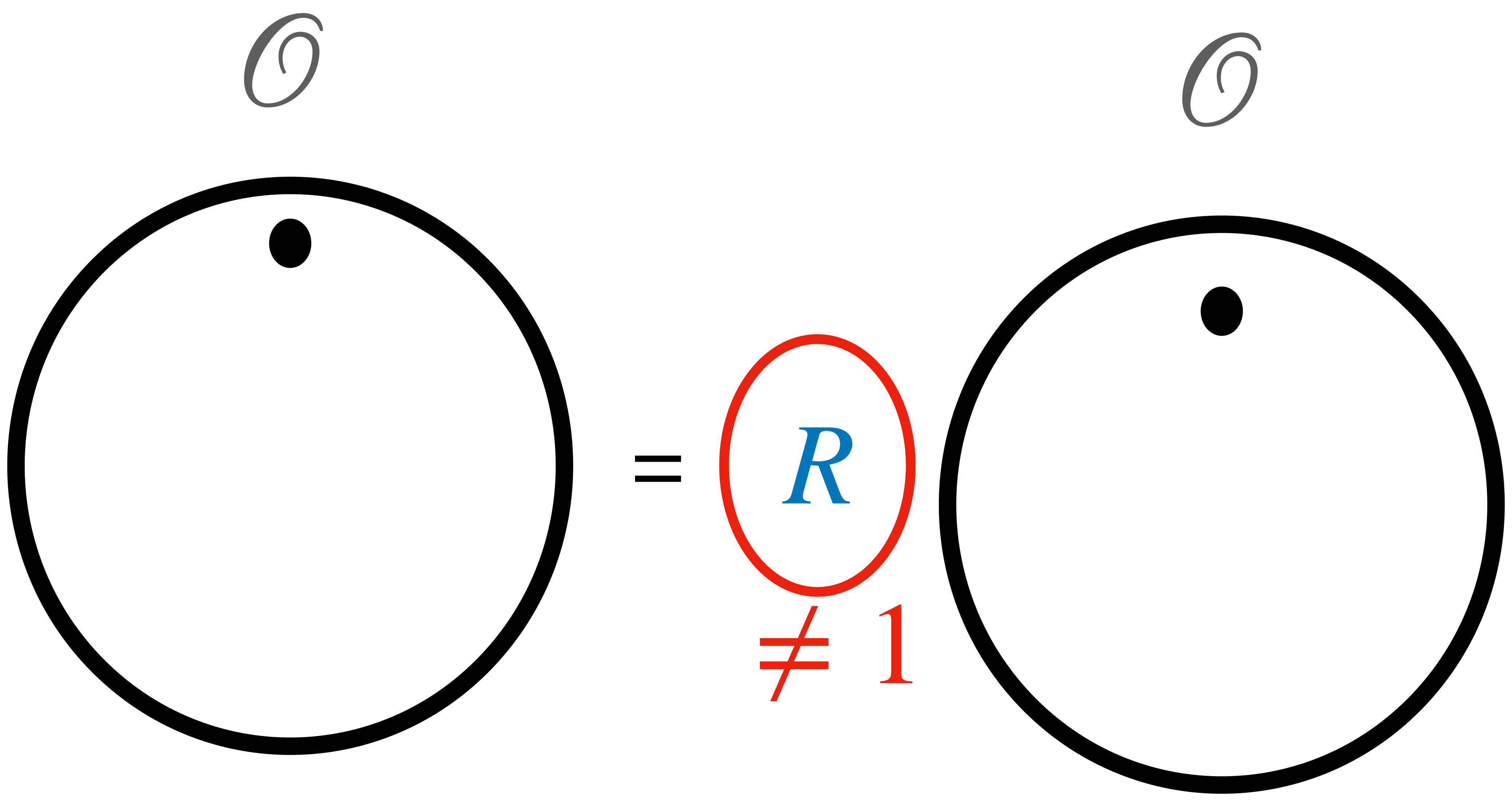

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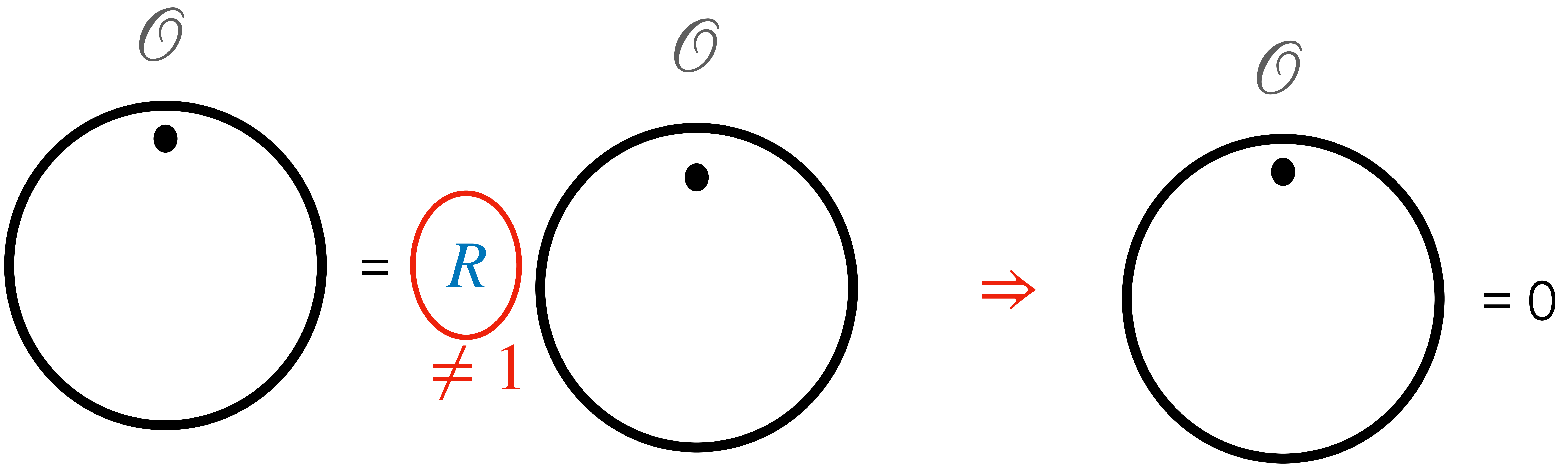

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$$D_1 \otimes D_2 = D_3$$

Group Multiplication

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Group Multiplication $\rightarrow$ Fusion Product

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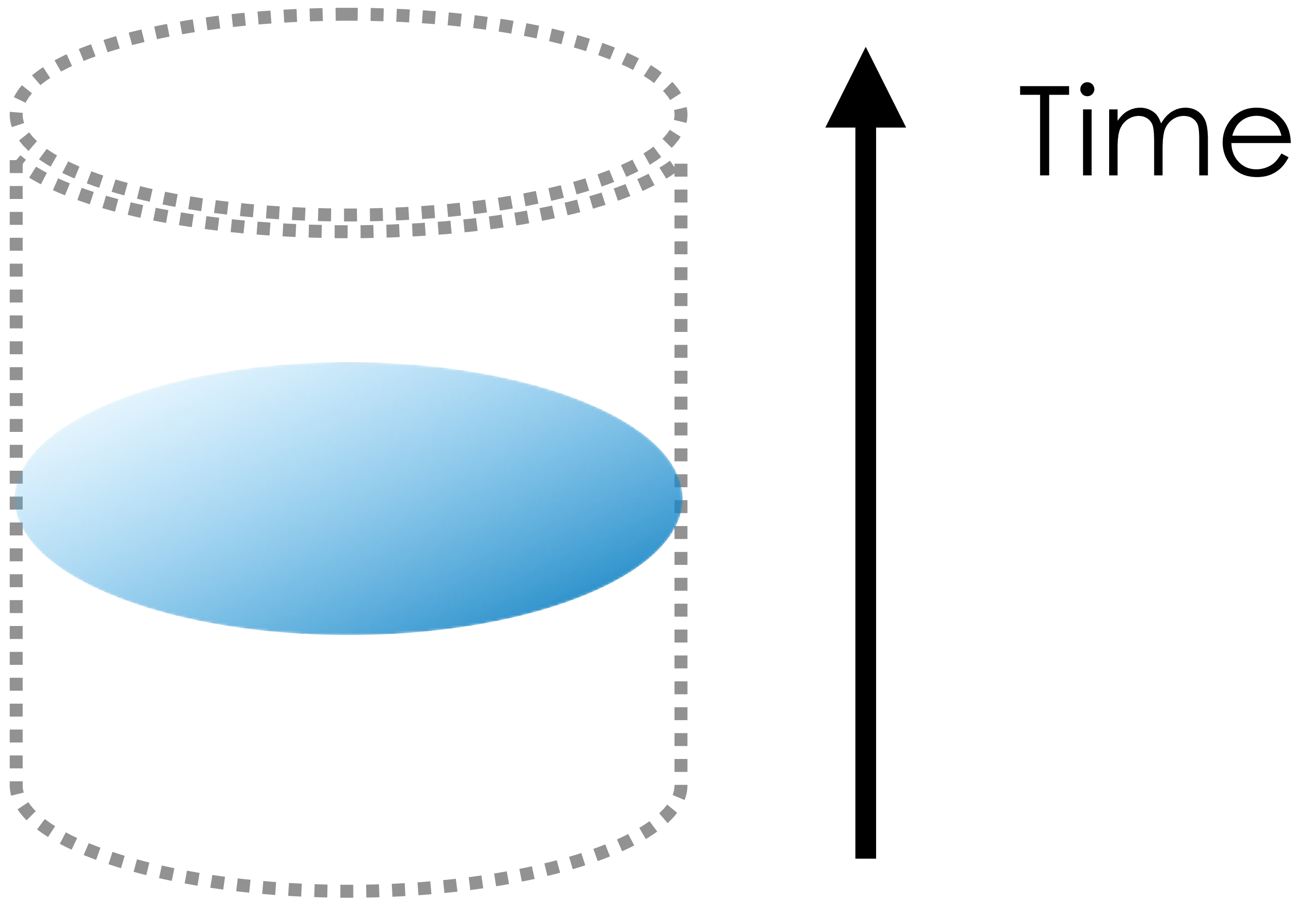
only positive integers on the RHS

Locality principle

So far we have not made a distinction among defects and operators (spacetime is Euclidean), but for RQFT there is:

- **Operators** : inserted along space



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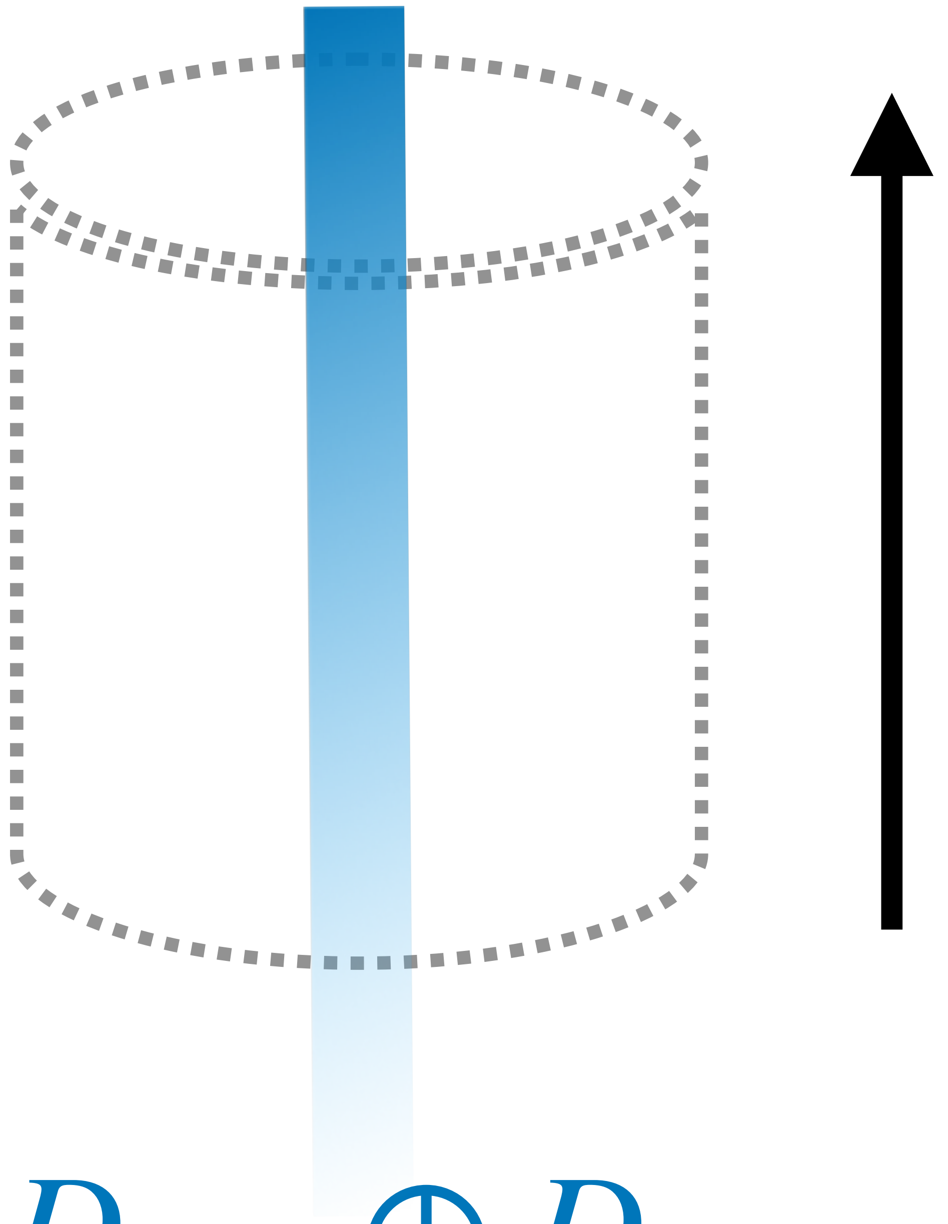

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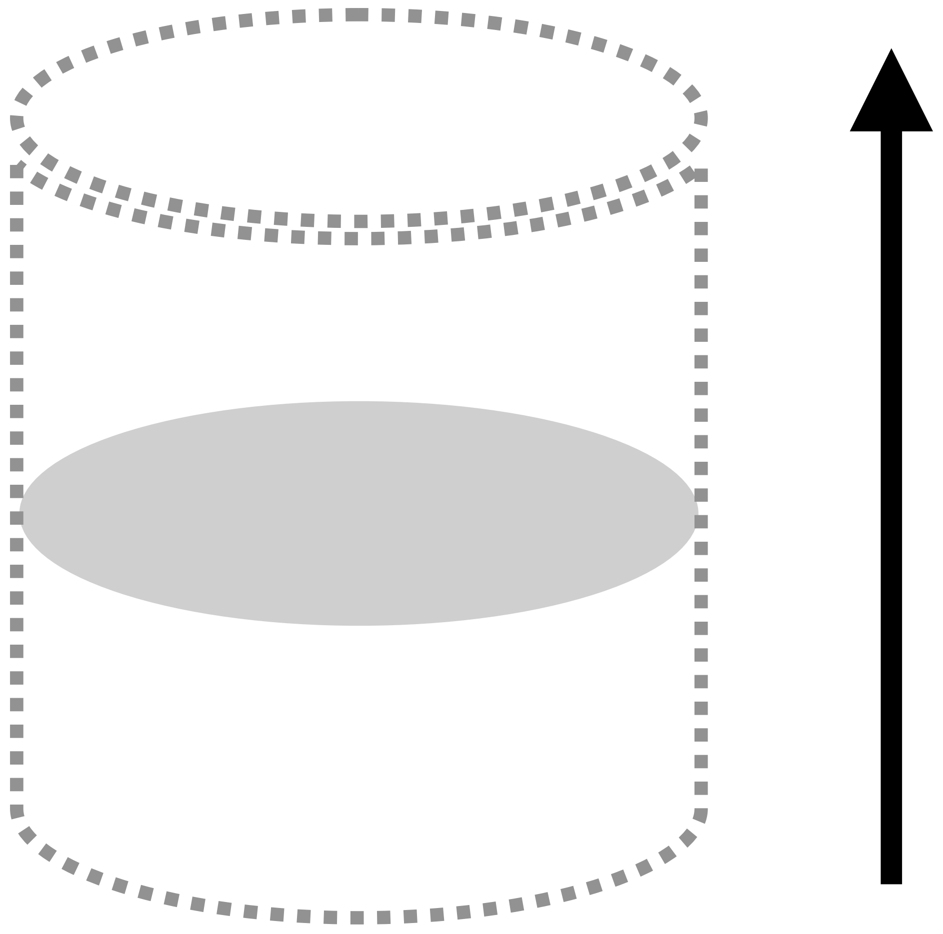

Time

eg. Free scalar in 2d

$$\phi(x + 2\pi) = \phi(x)$$

$\mathbb{S}^1$ Hilbert space

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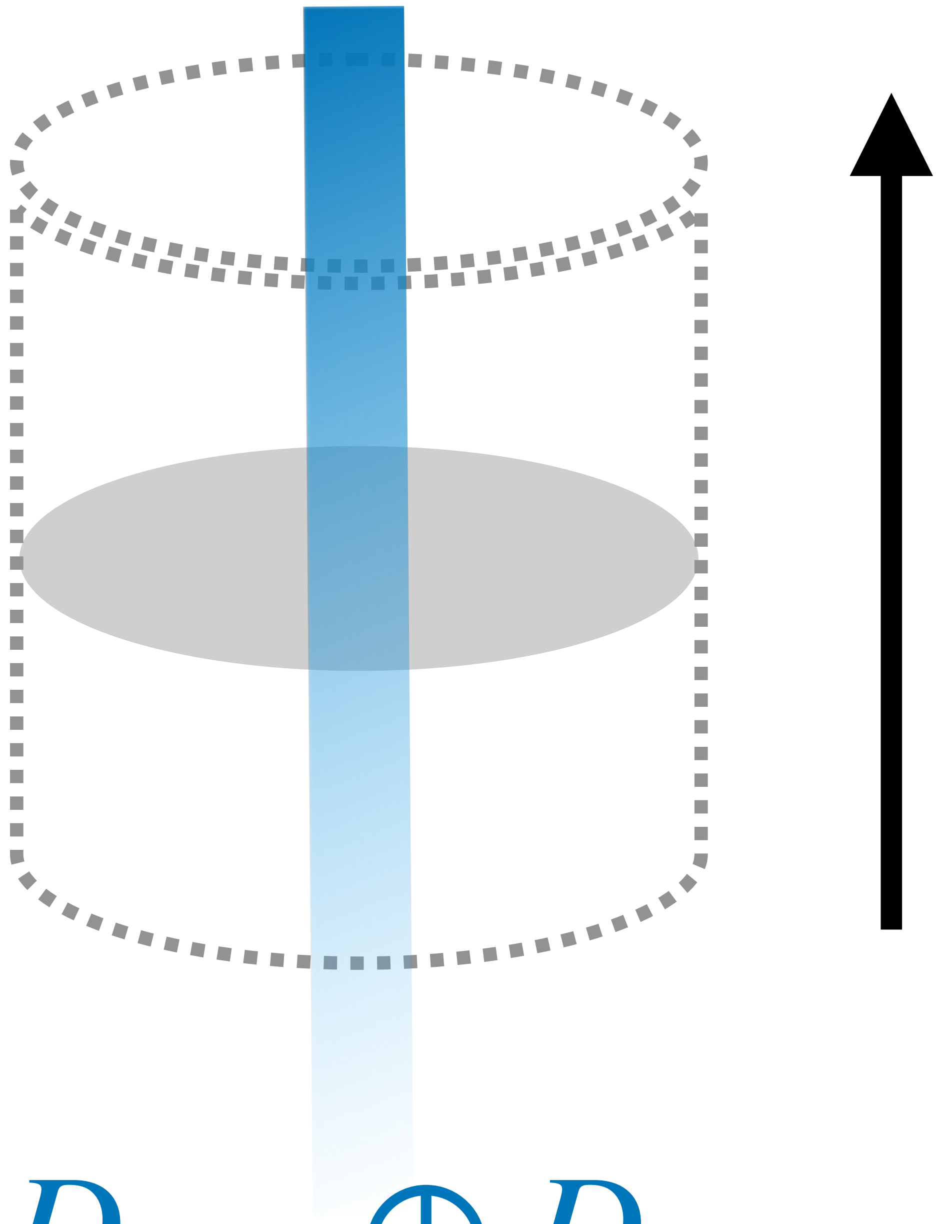

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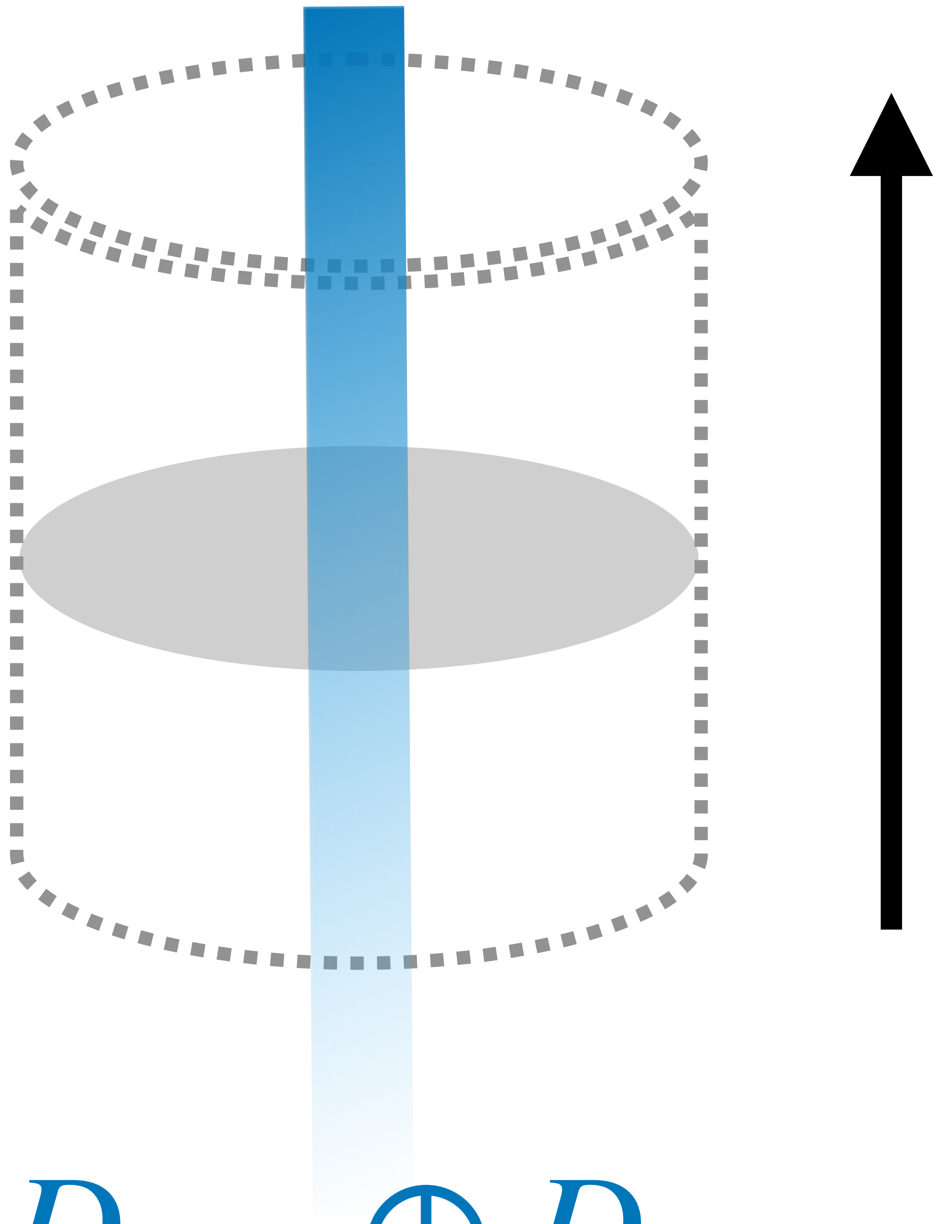
$\Rightarrow$ can only take direct sums



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- Selection Rules
- Anomalies
- Spontaneous breaking

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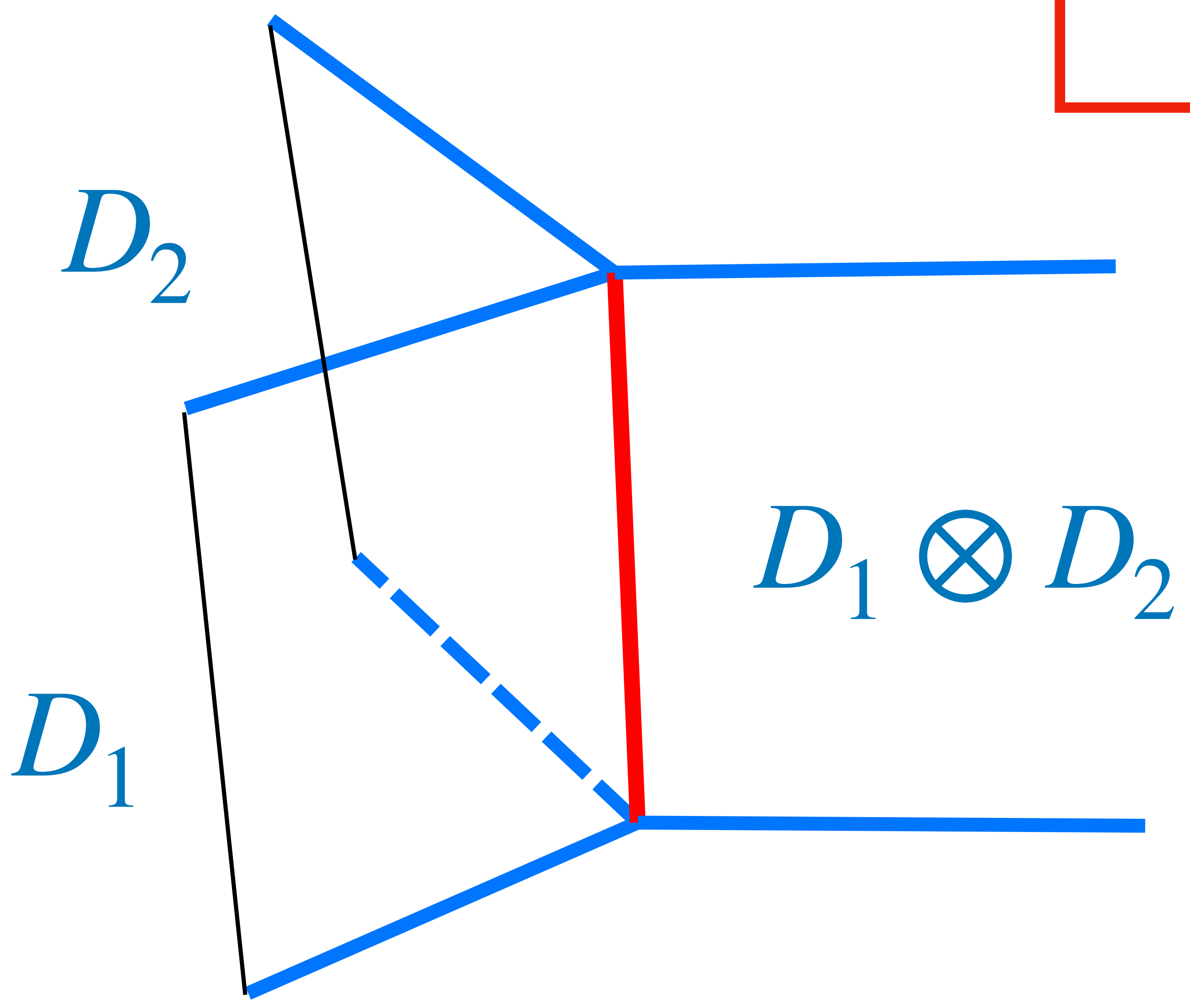

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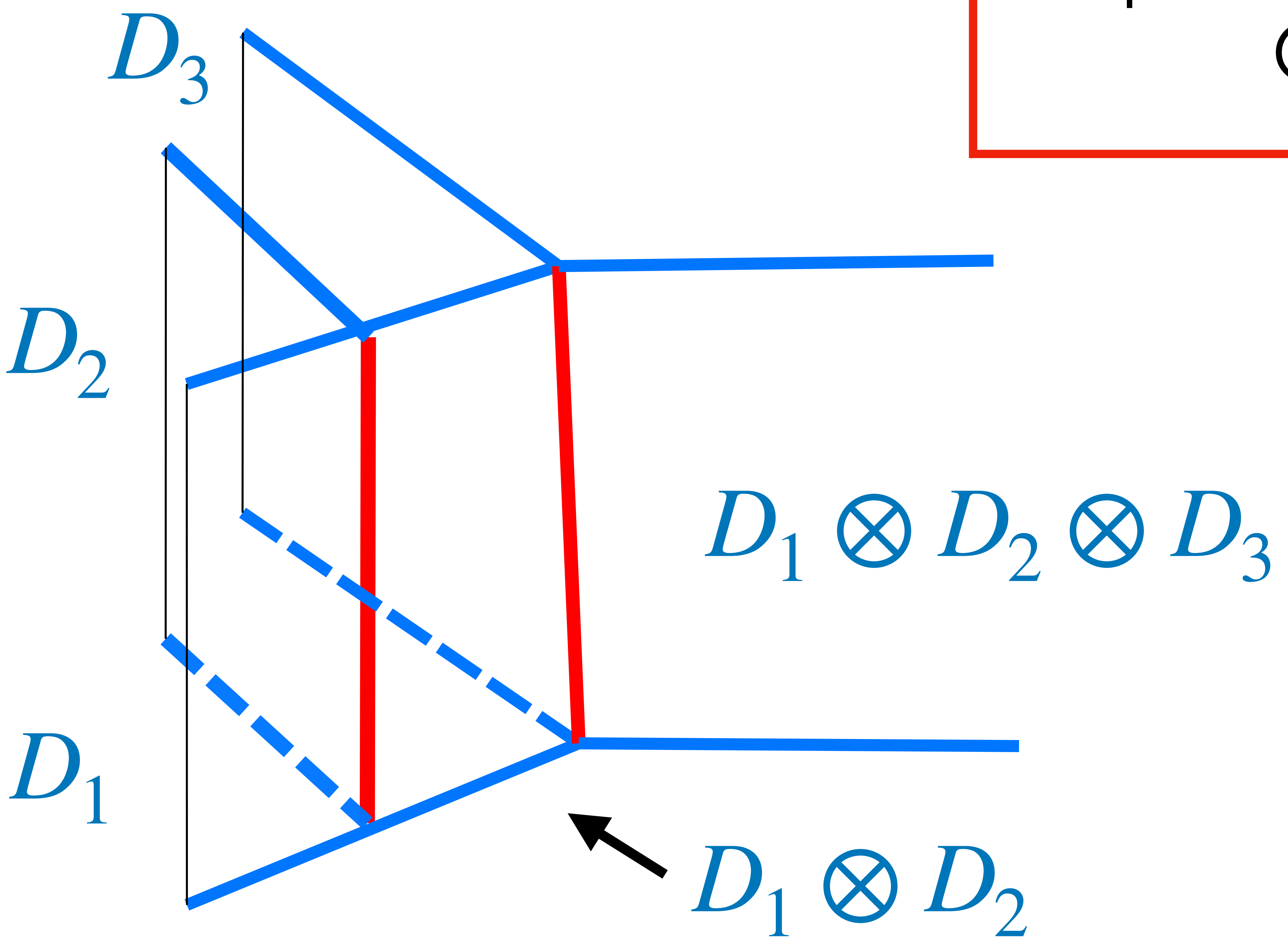

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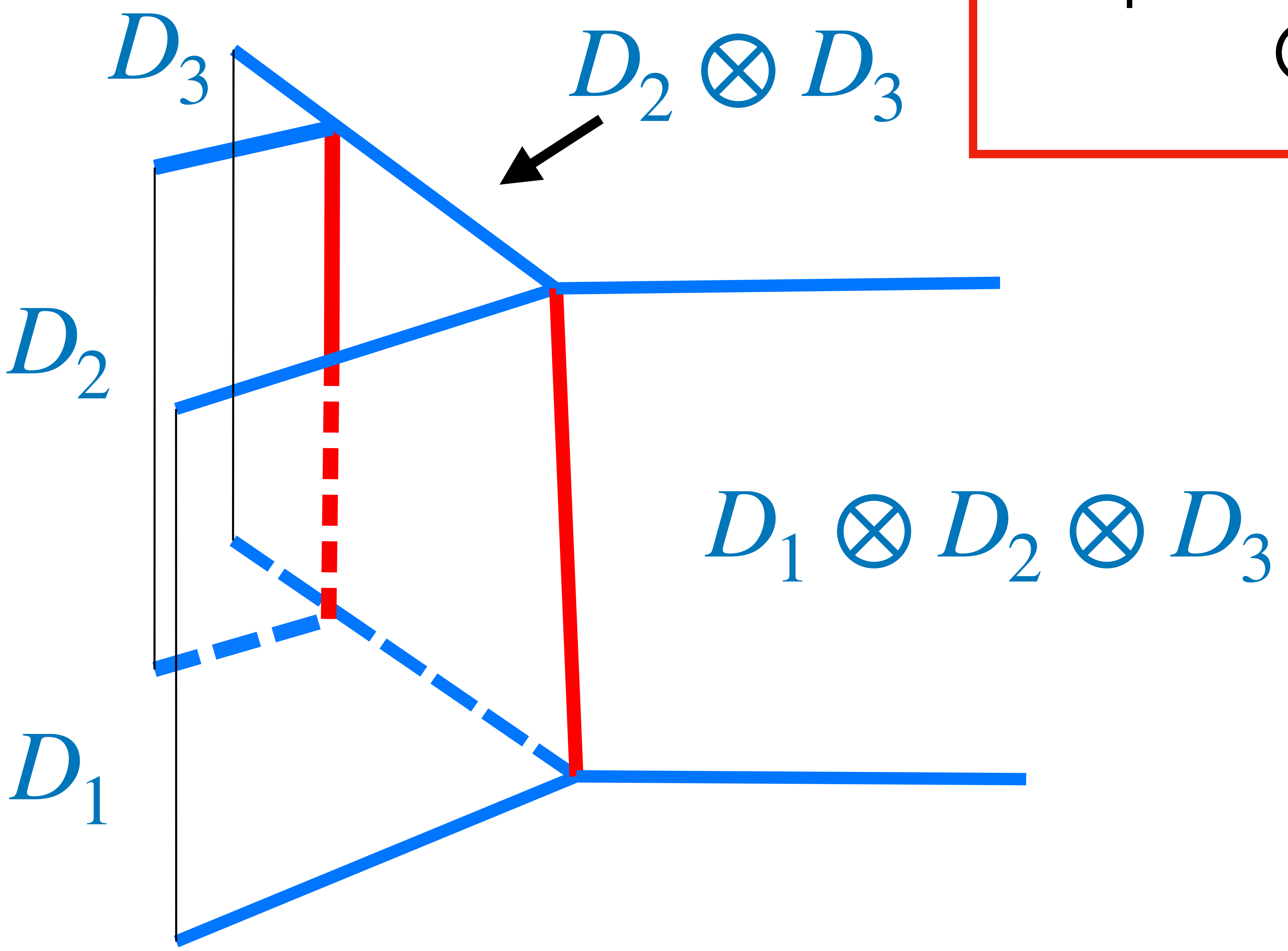

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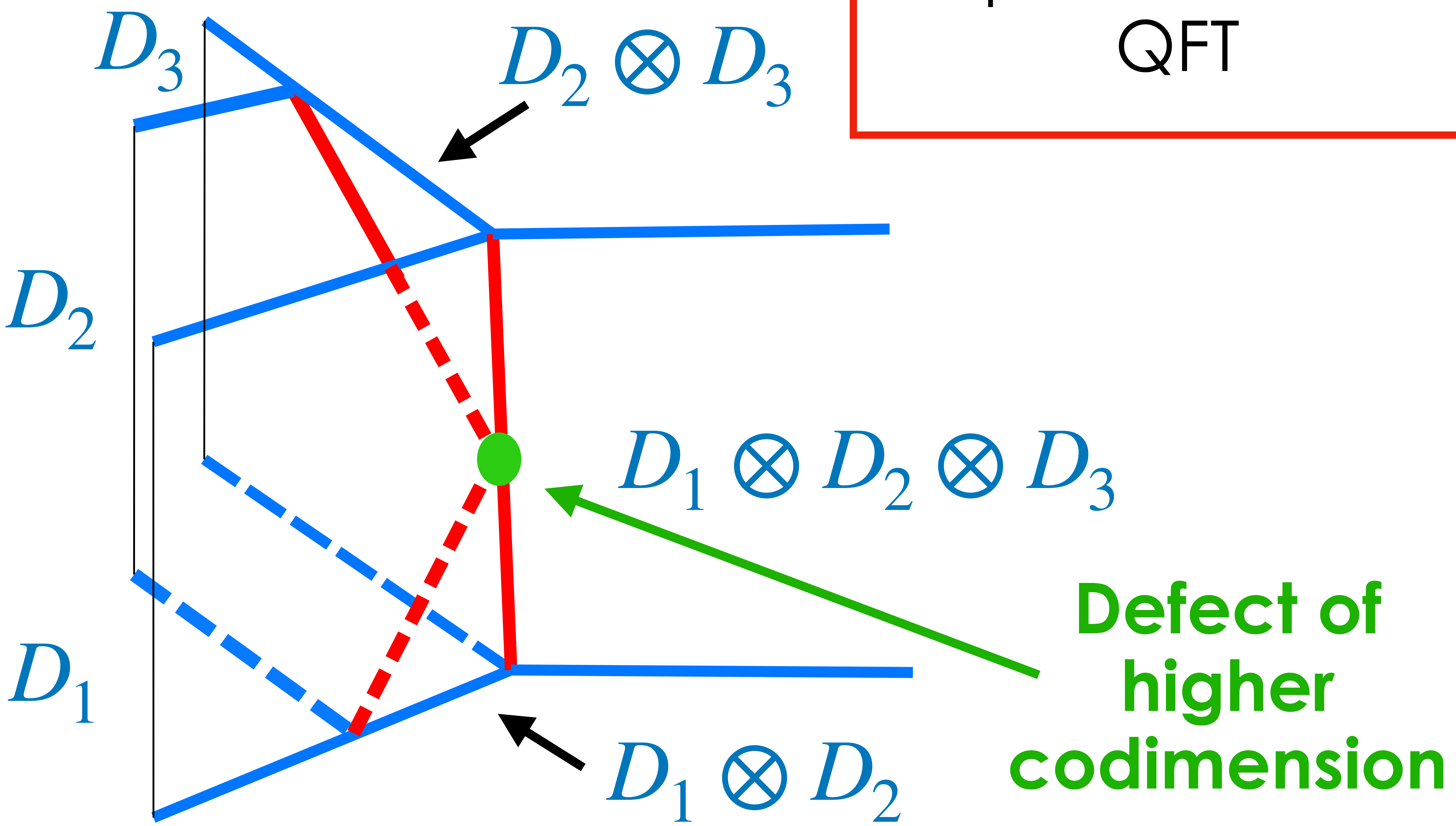

- Ward identities
- Selection Rules
- Anomalies
- Spontaneous breaking

… but also **other features**!

- **Fusion product**
- **Higher structure**

Extended defects can form **junctions**

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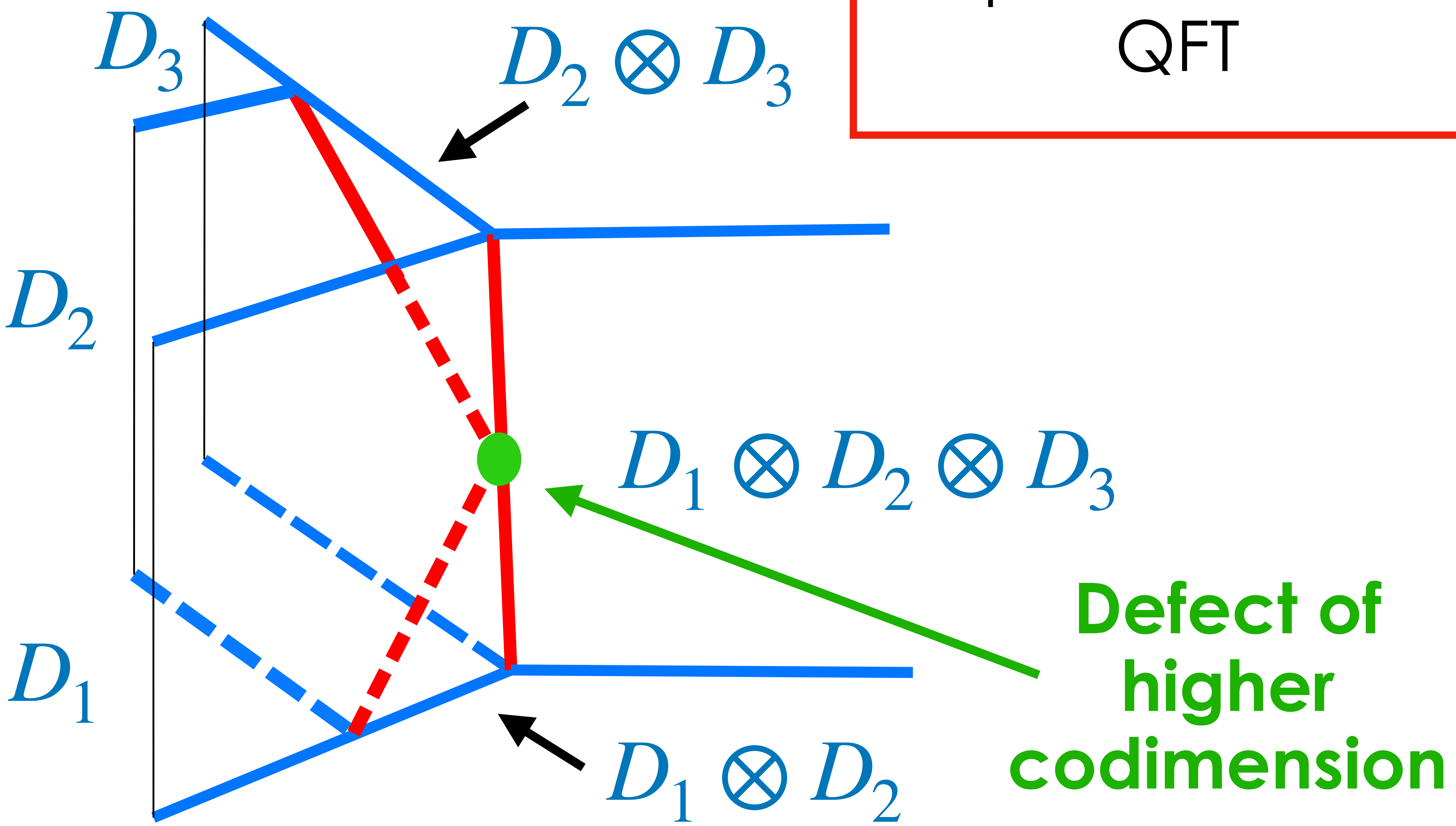
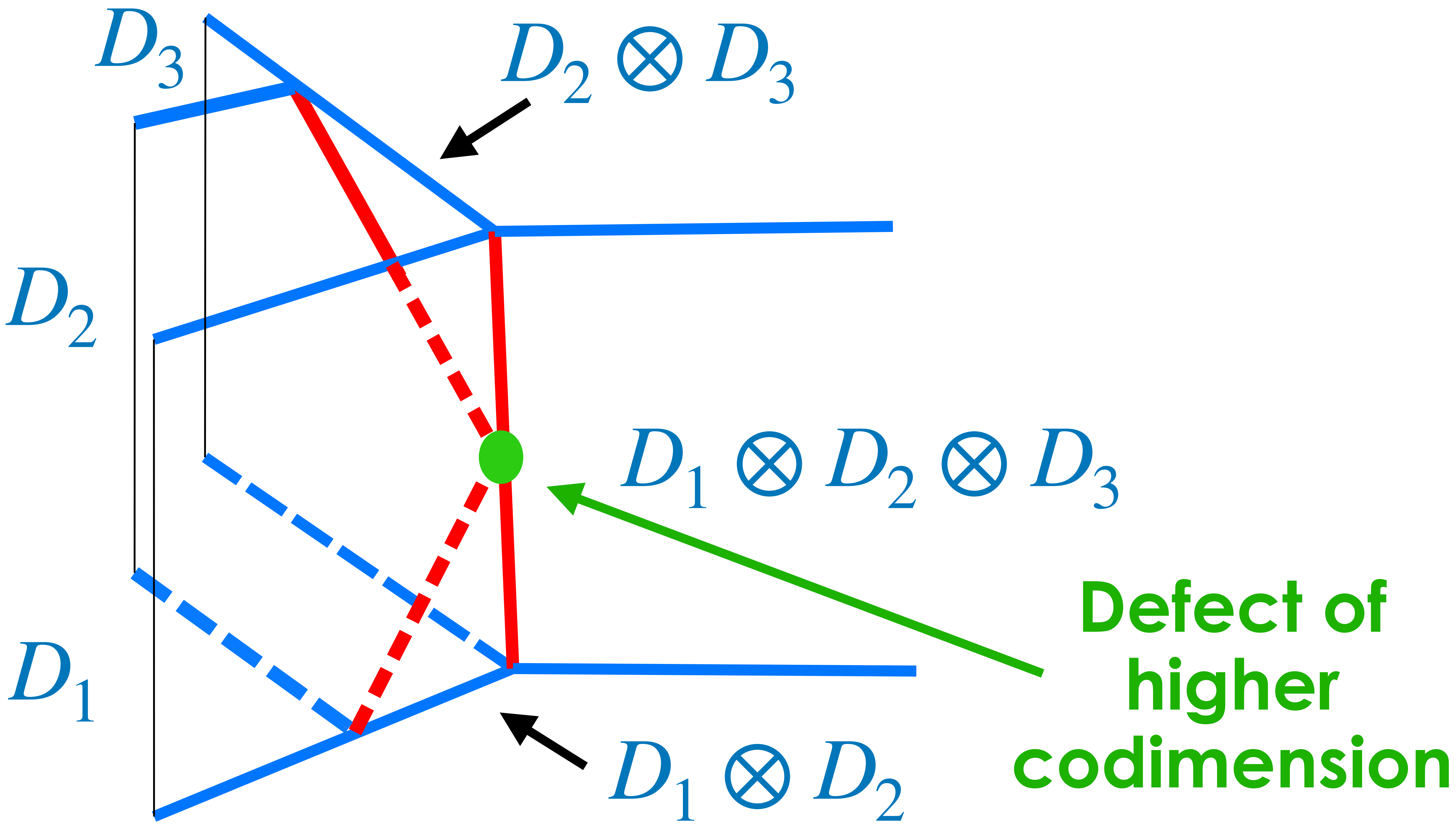


Extended defects can form **junctions**

e.g. higher group

Cordóva, Dumitrescu, Intriligator 16; Benini, Cordóva, Hsin 18; Bhardwaj, Shafer-Nameki 23; Bullimore, Barscht, Grigoletto 23

Example: 2-group symmetry



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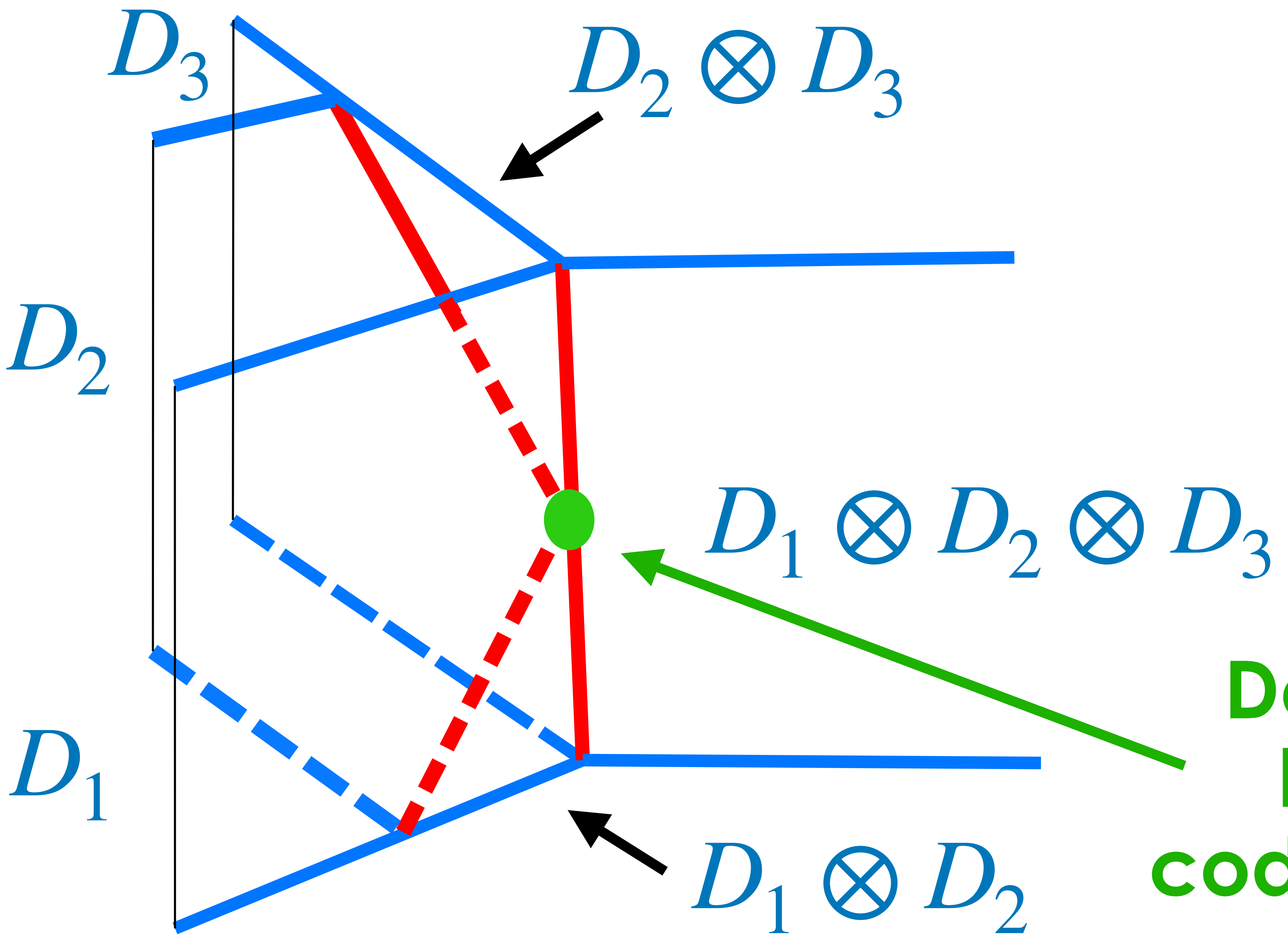

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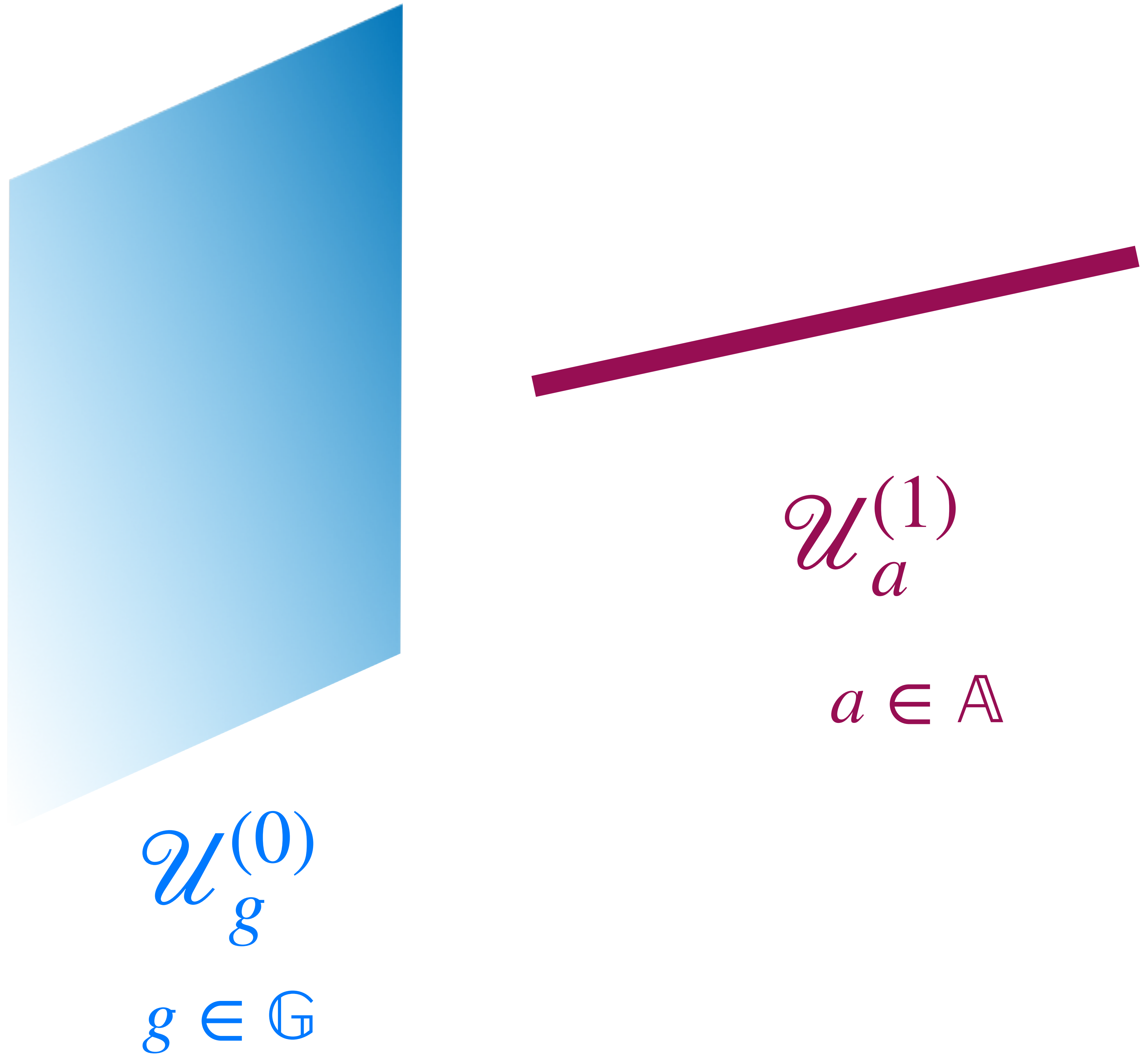

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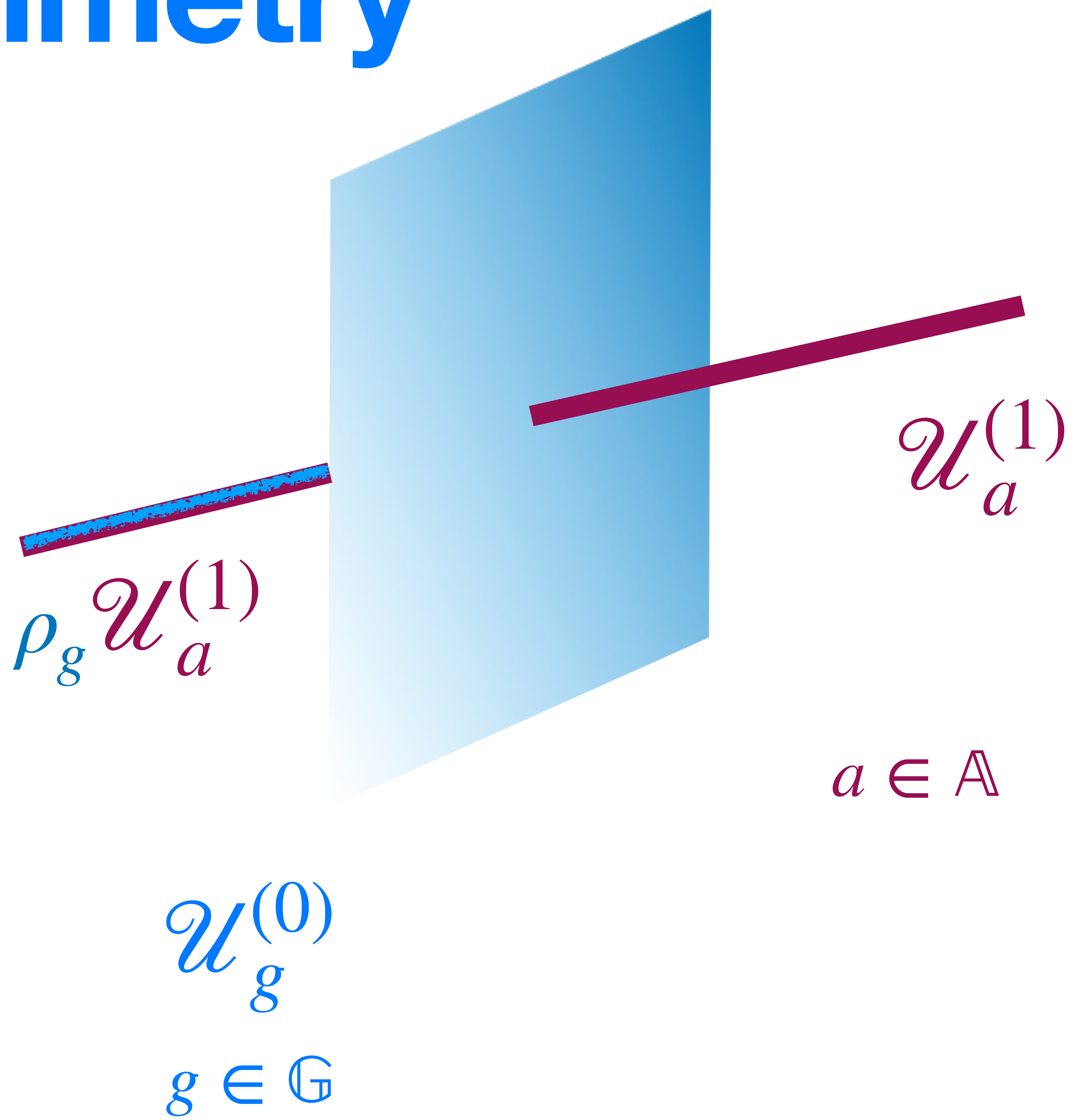

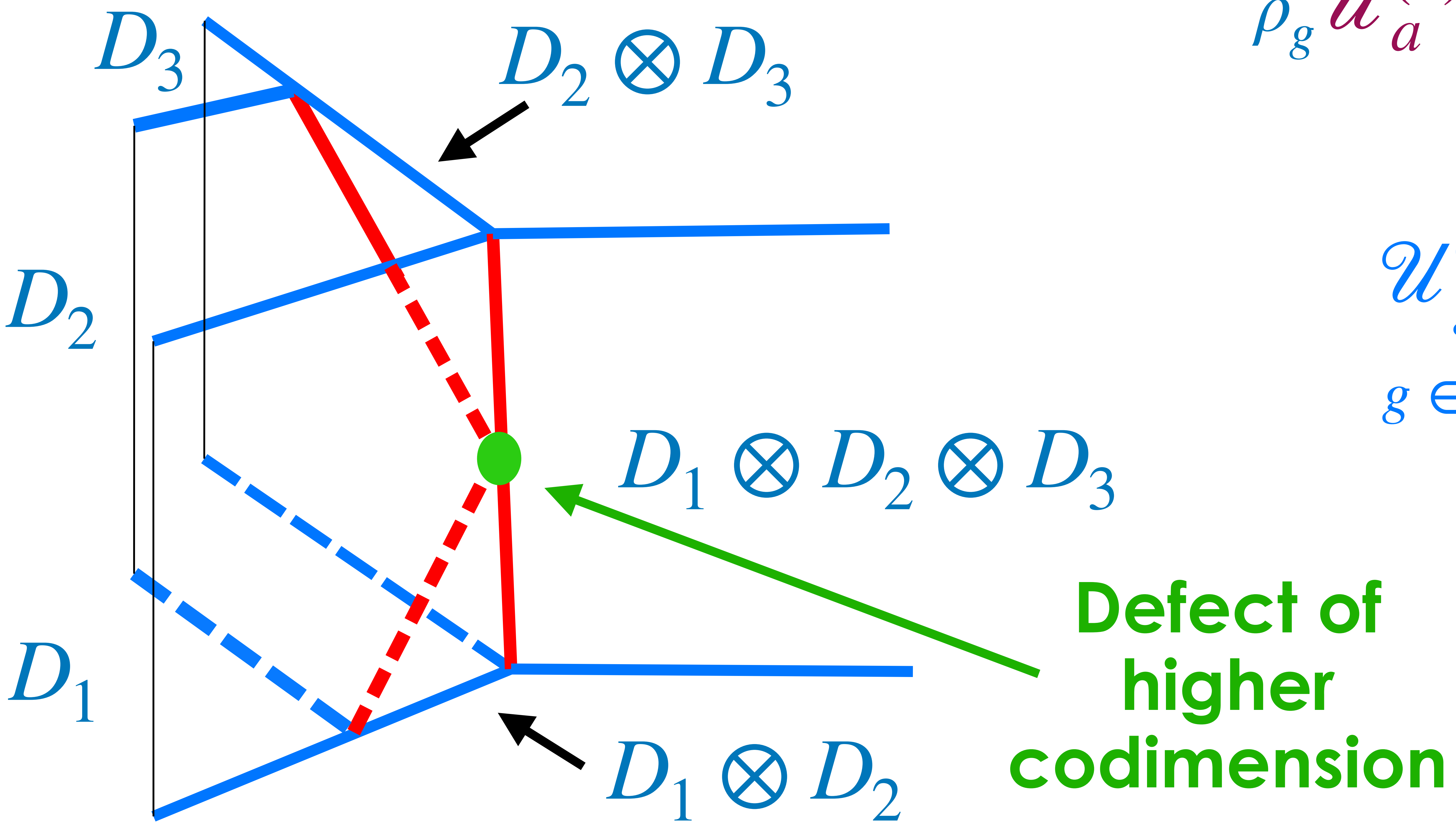

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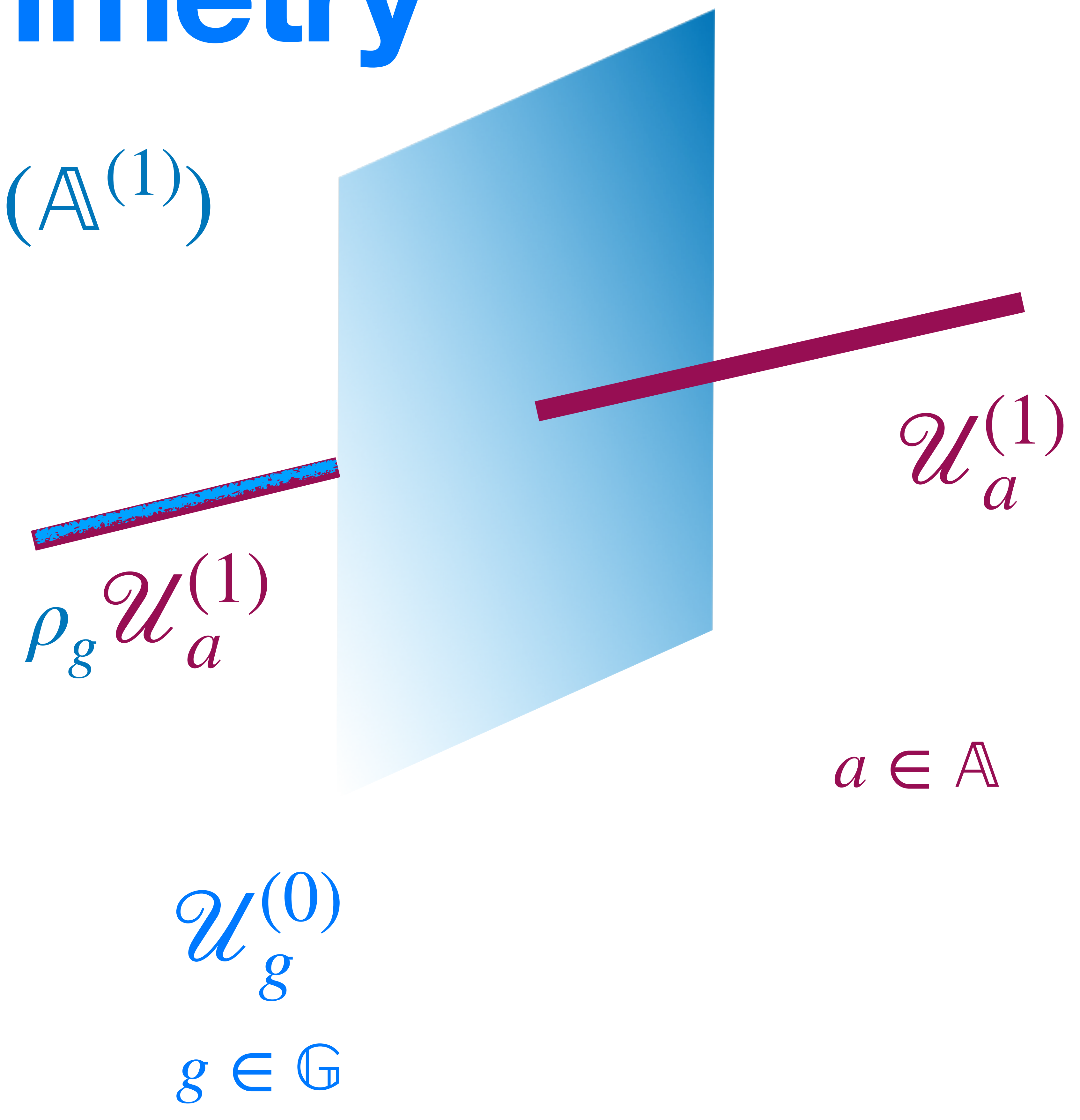

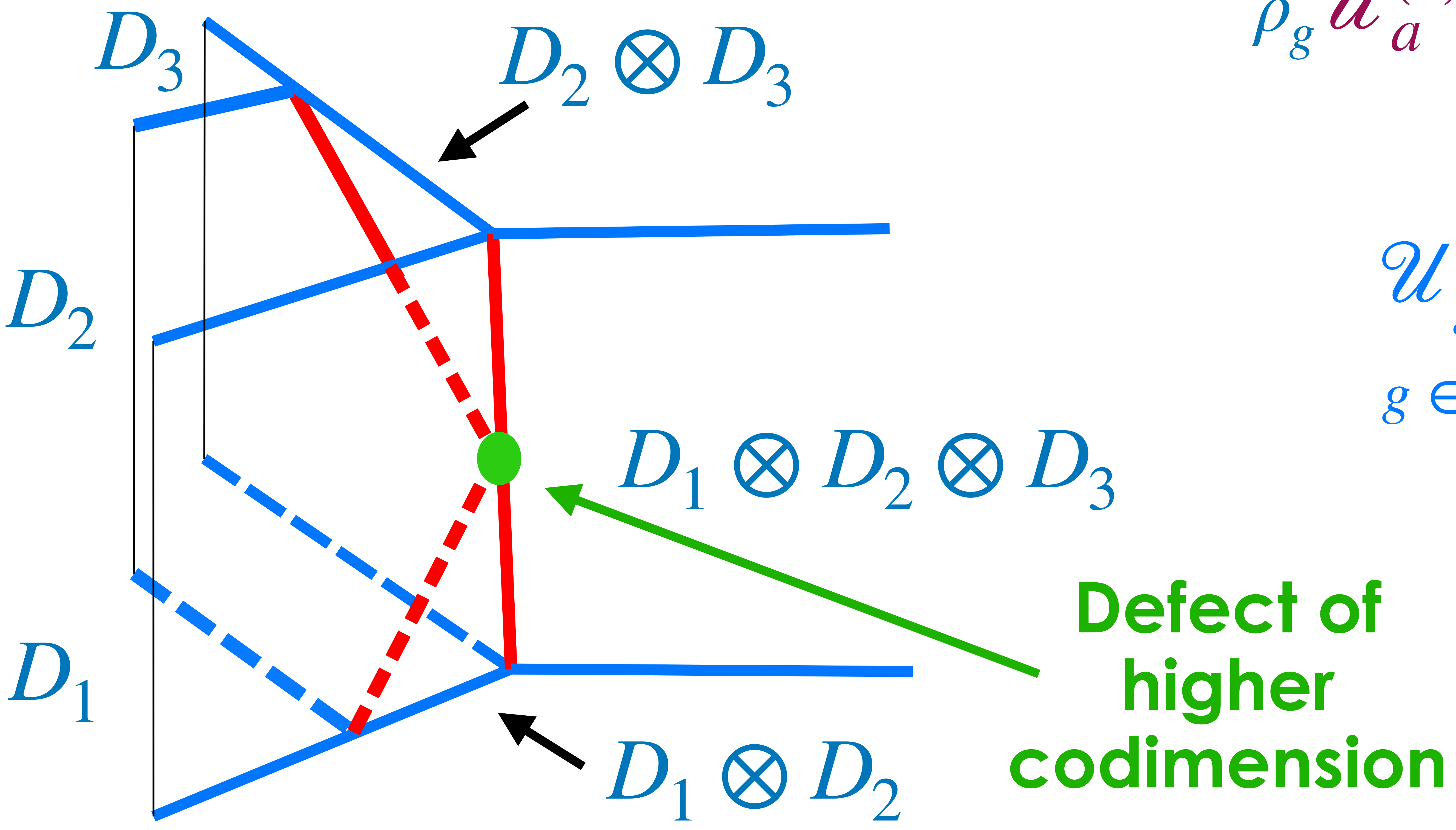

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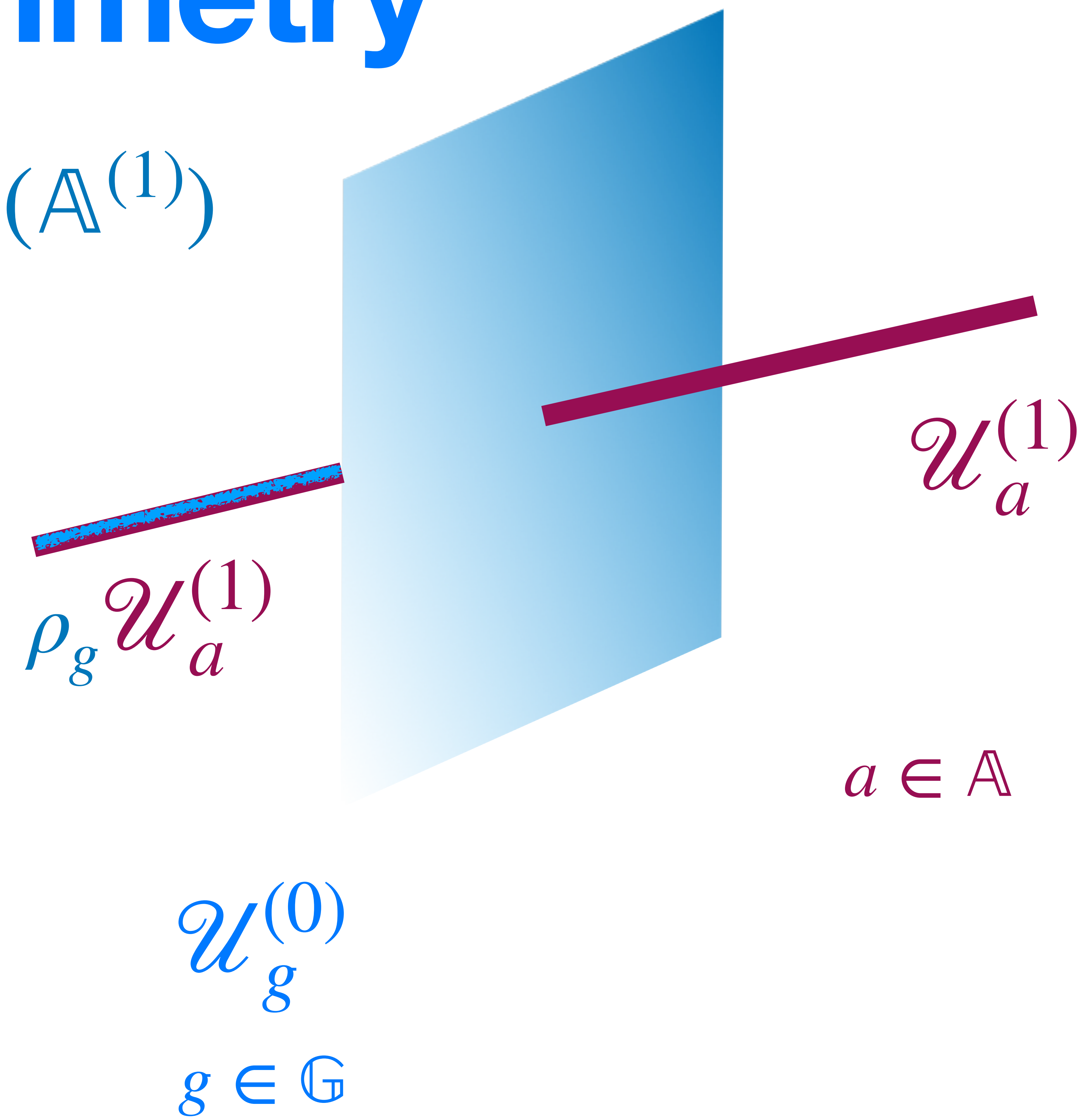

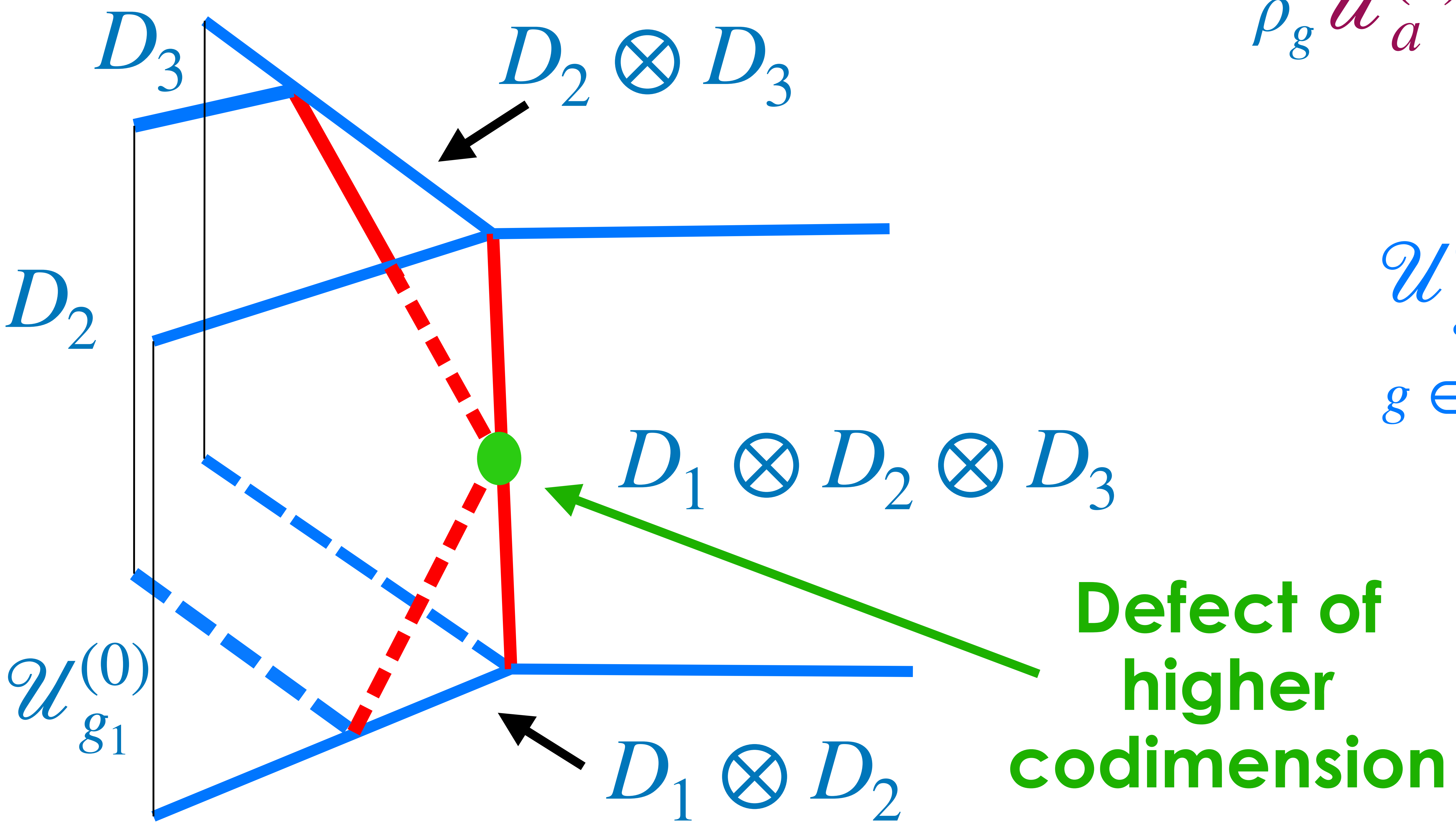

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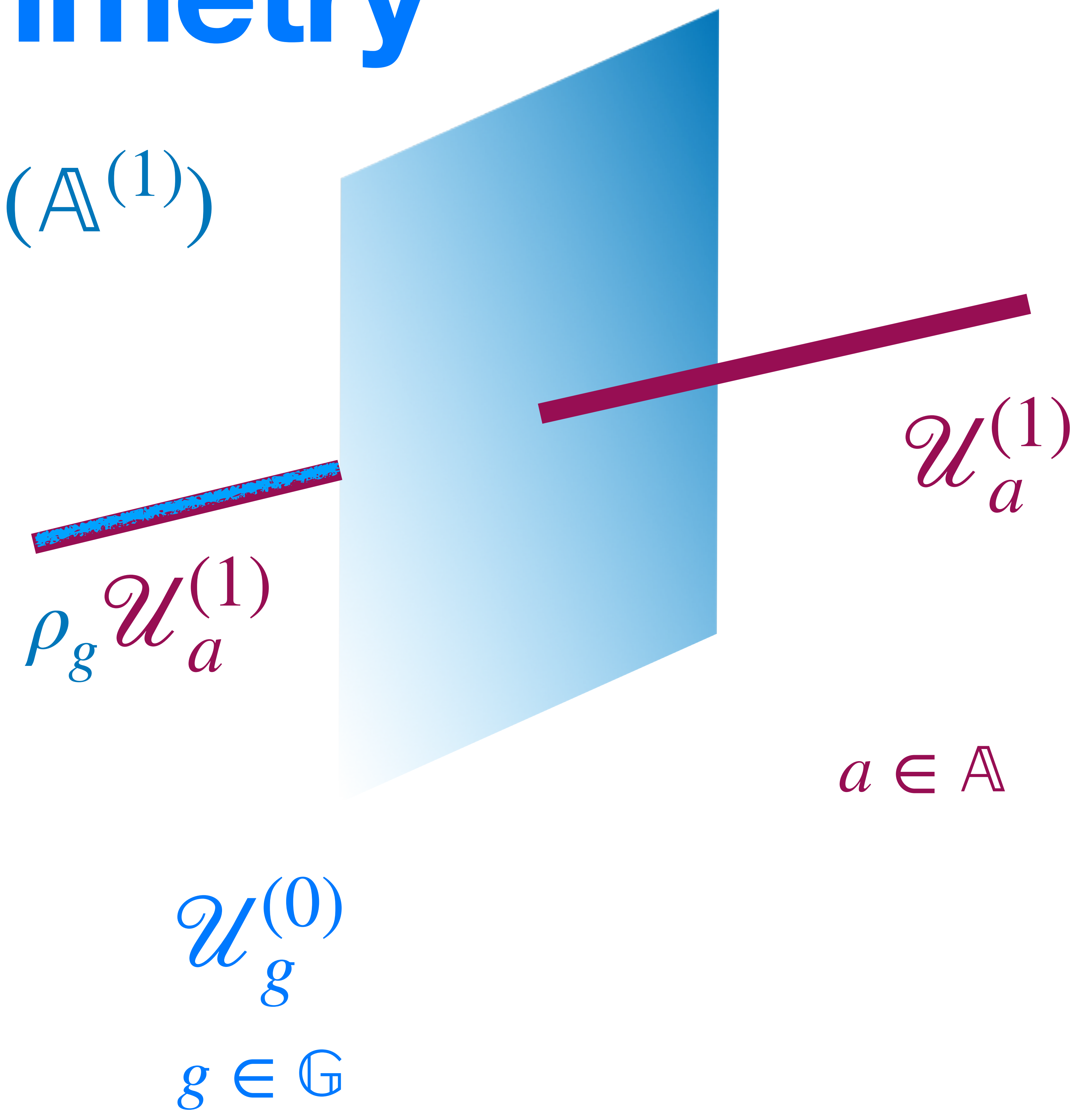

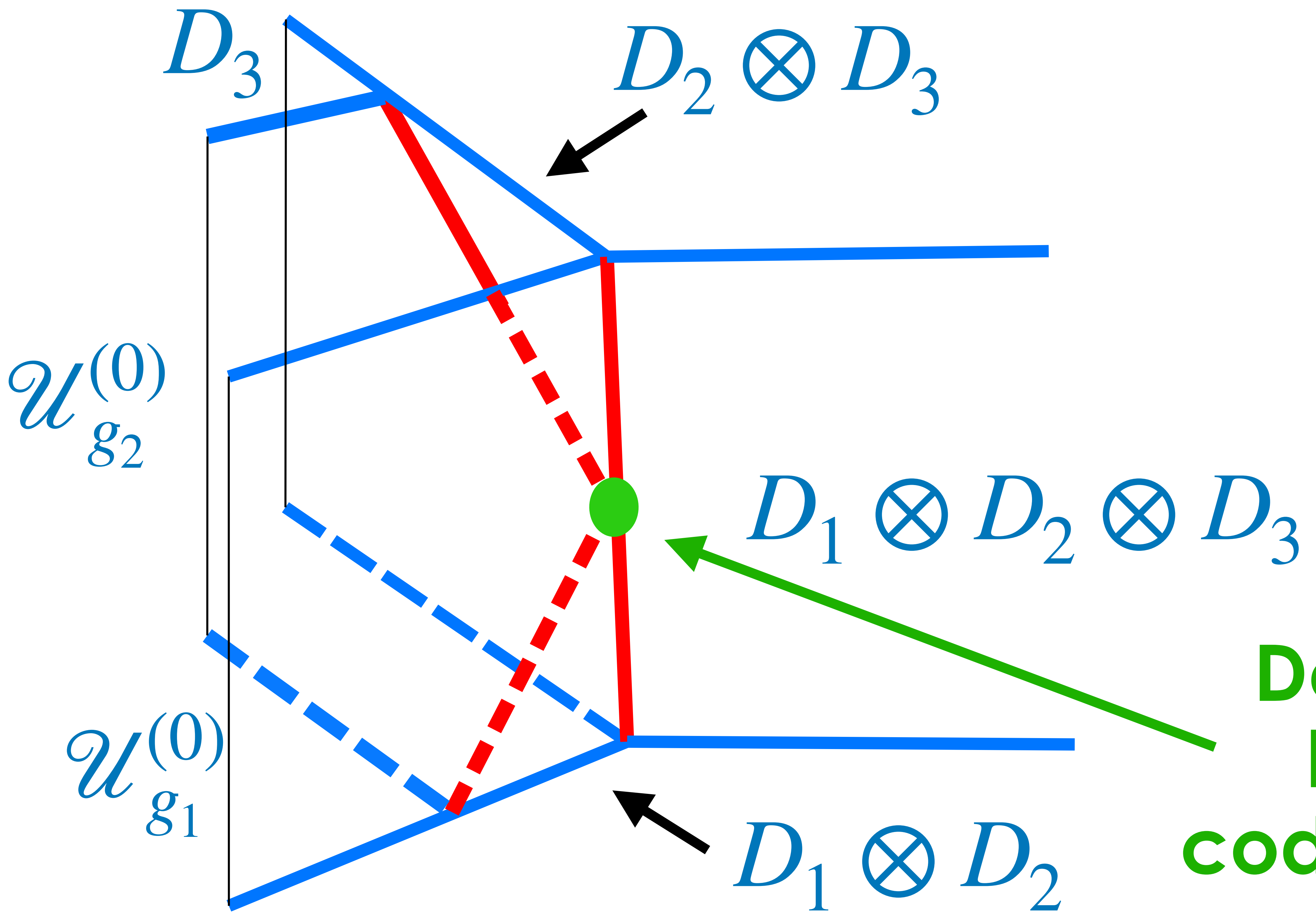

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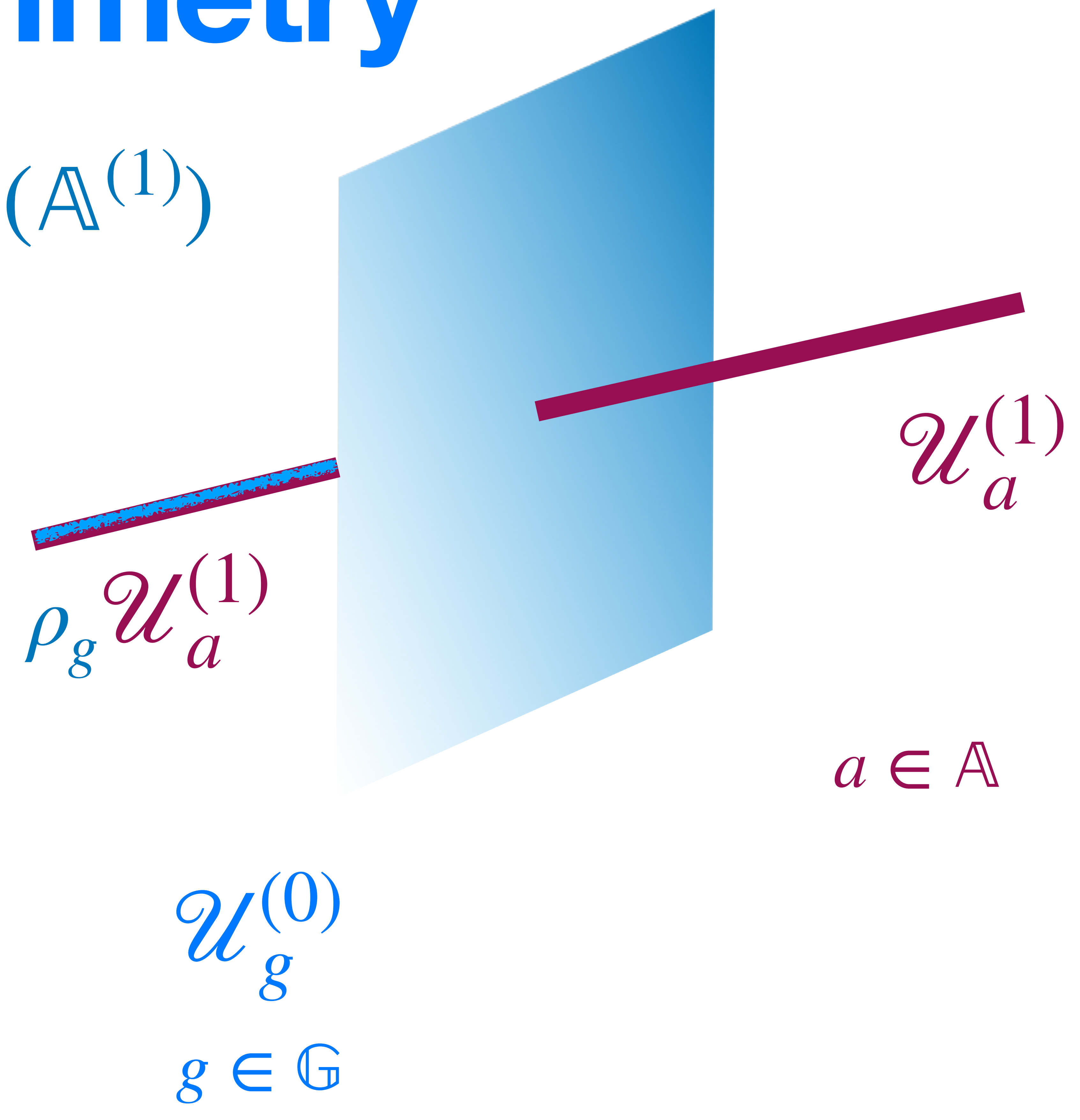

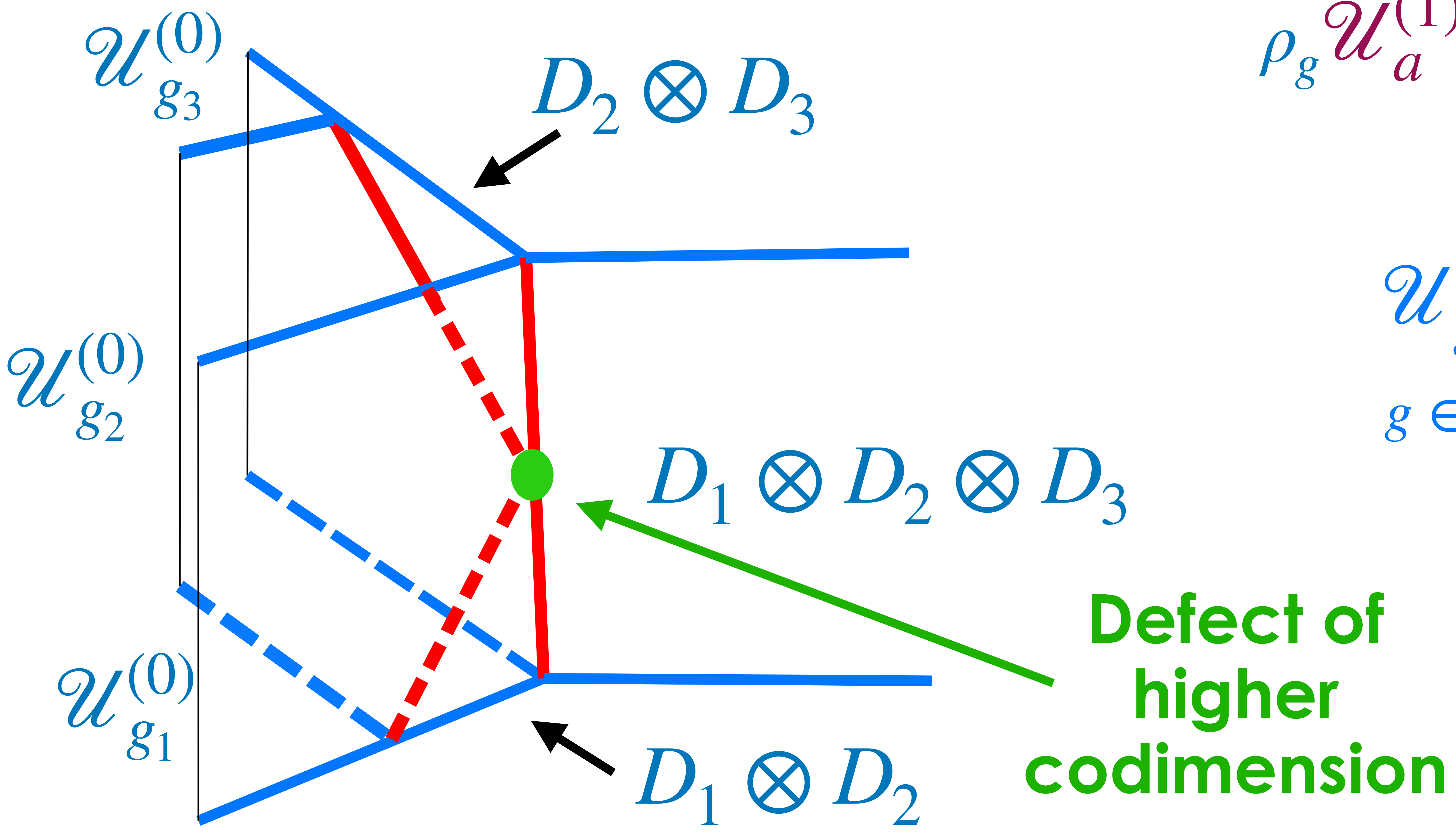

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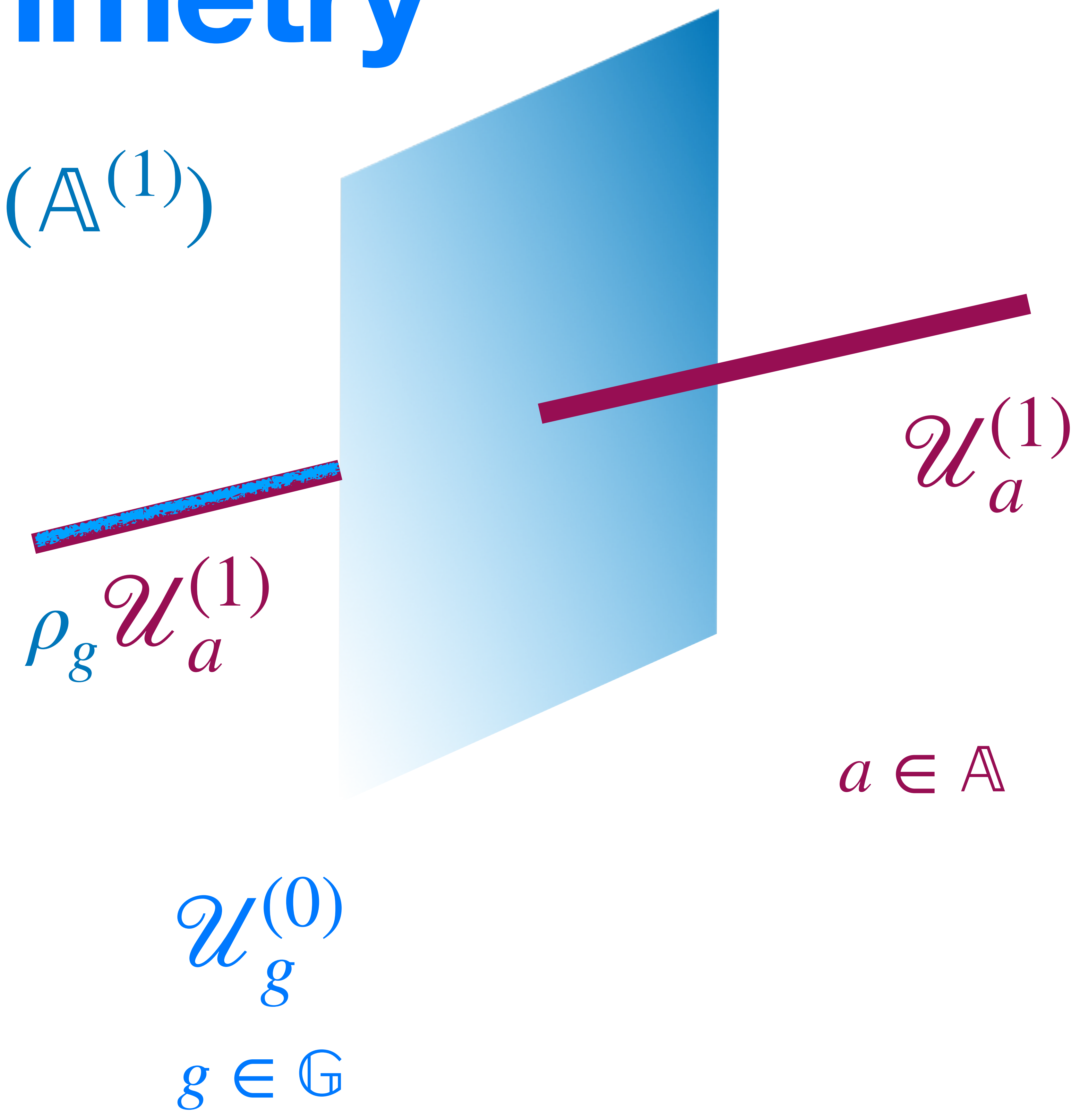

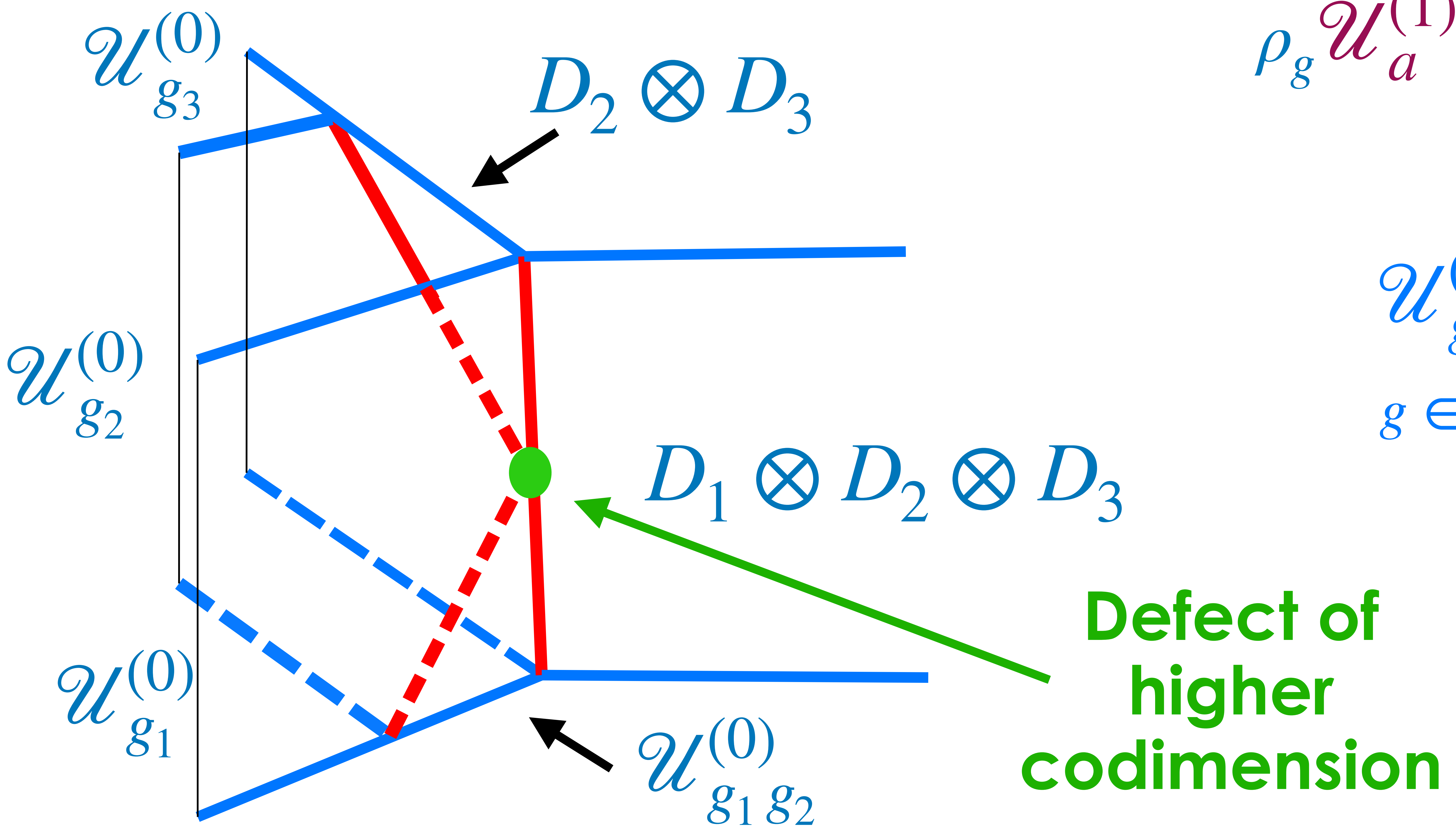

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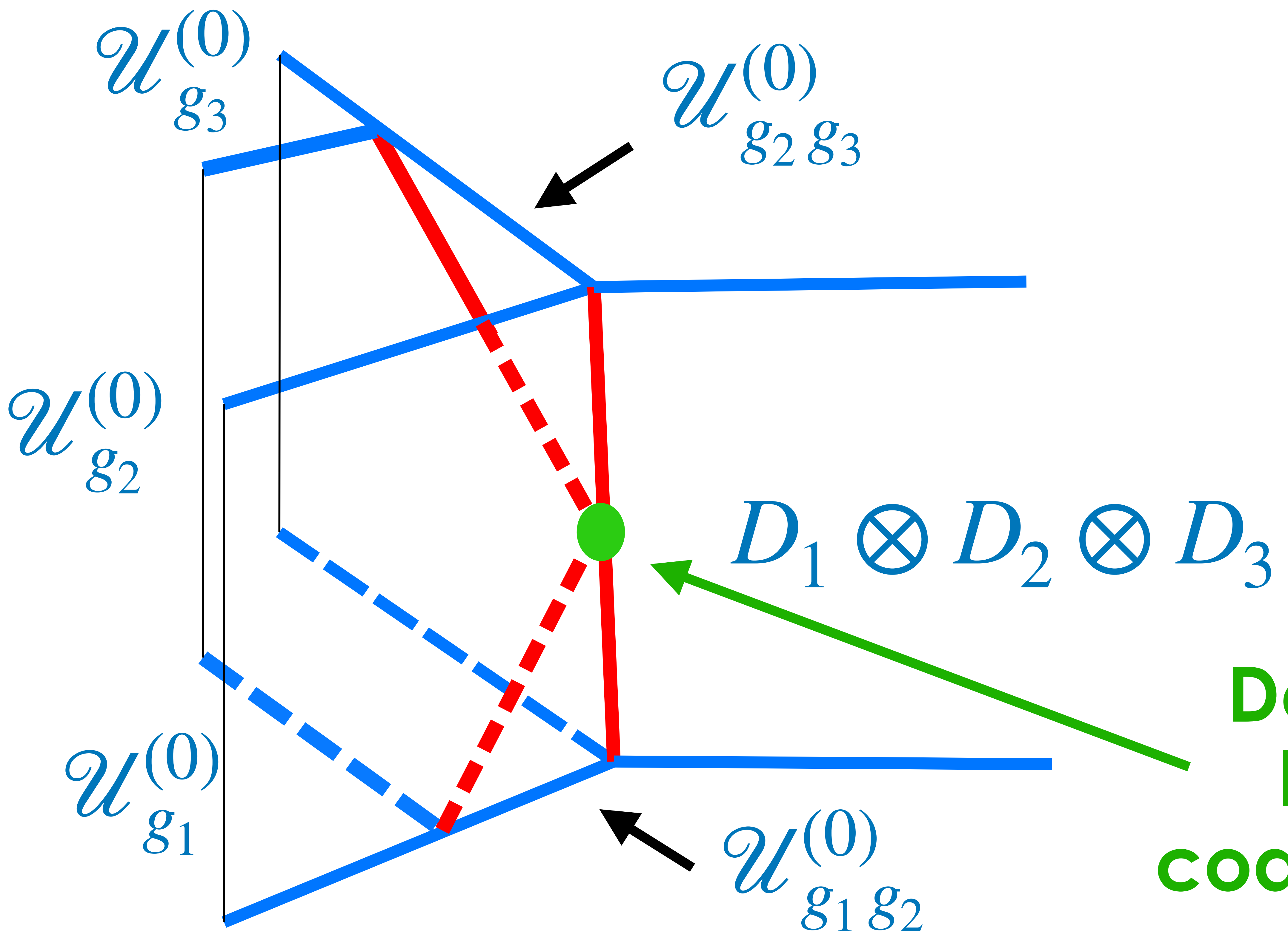

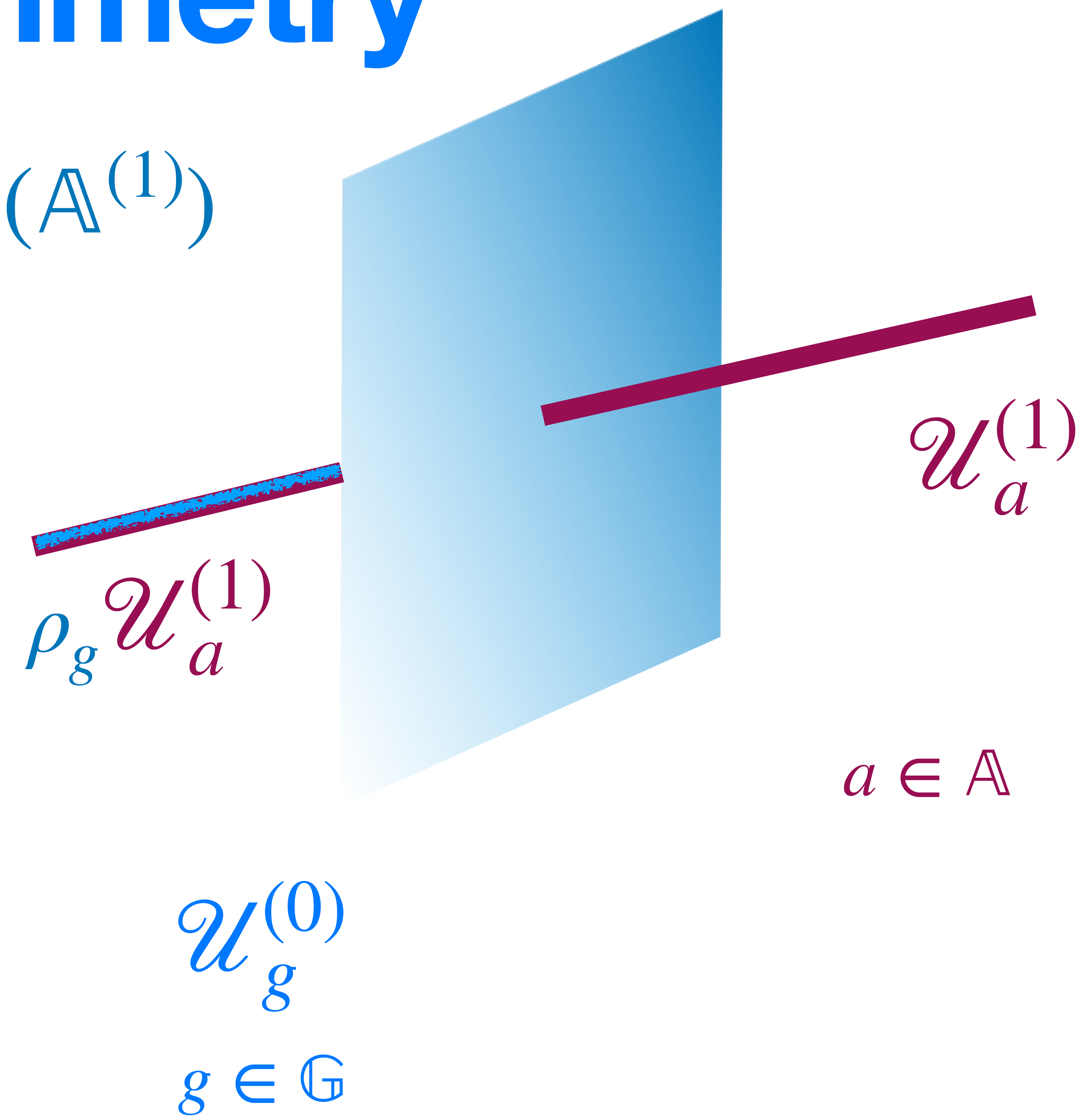

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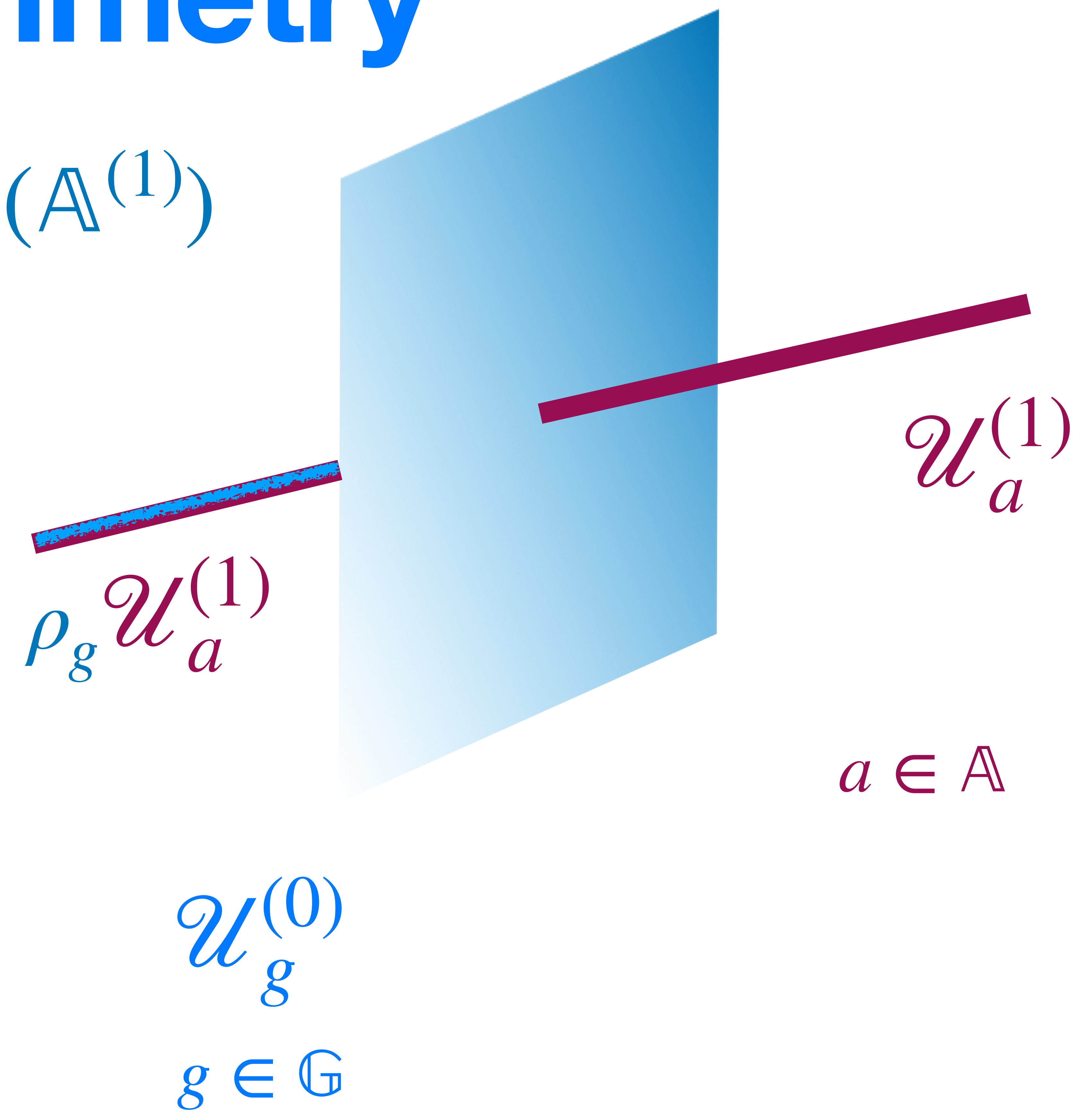

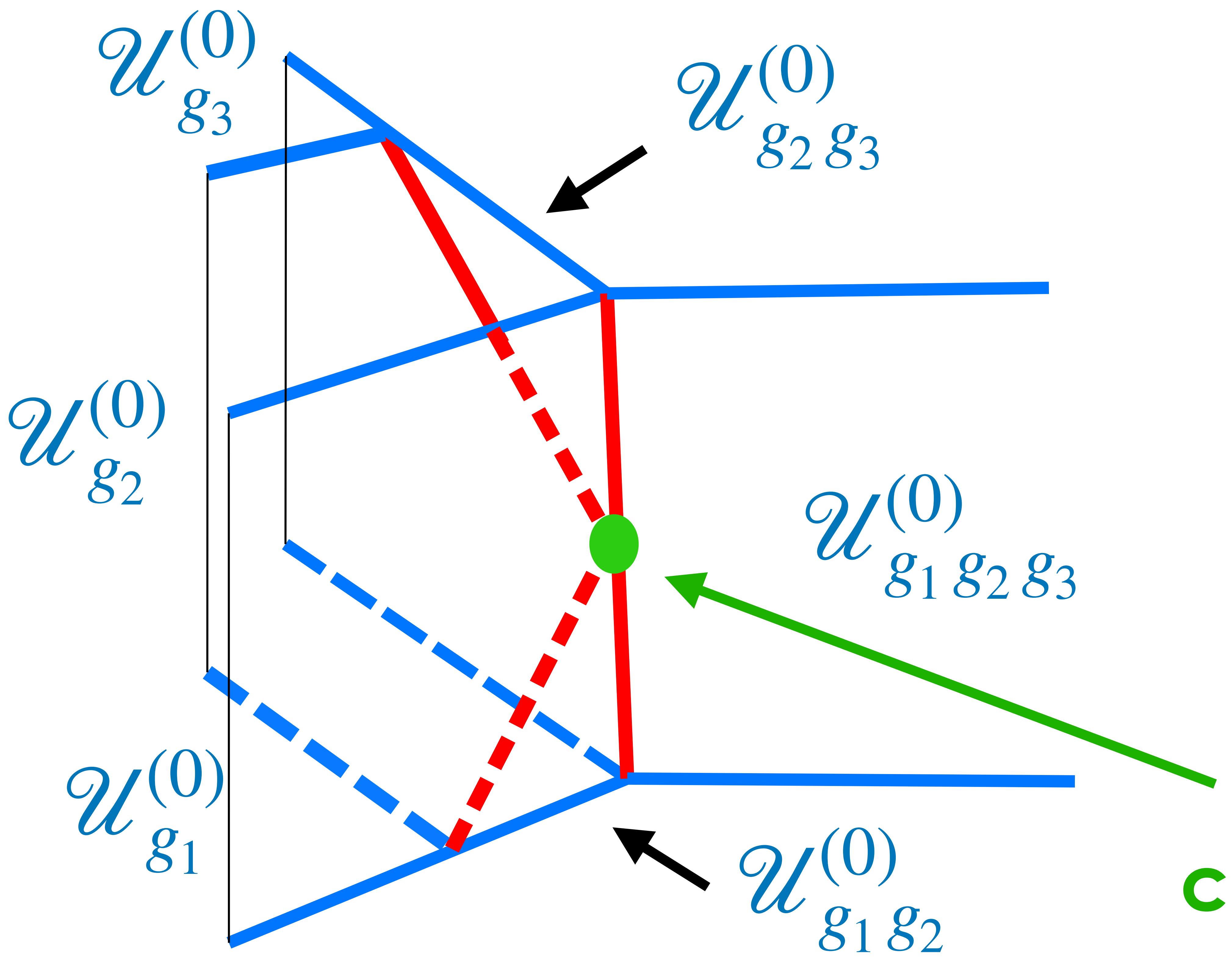

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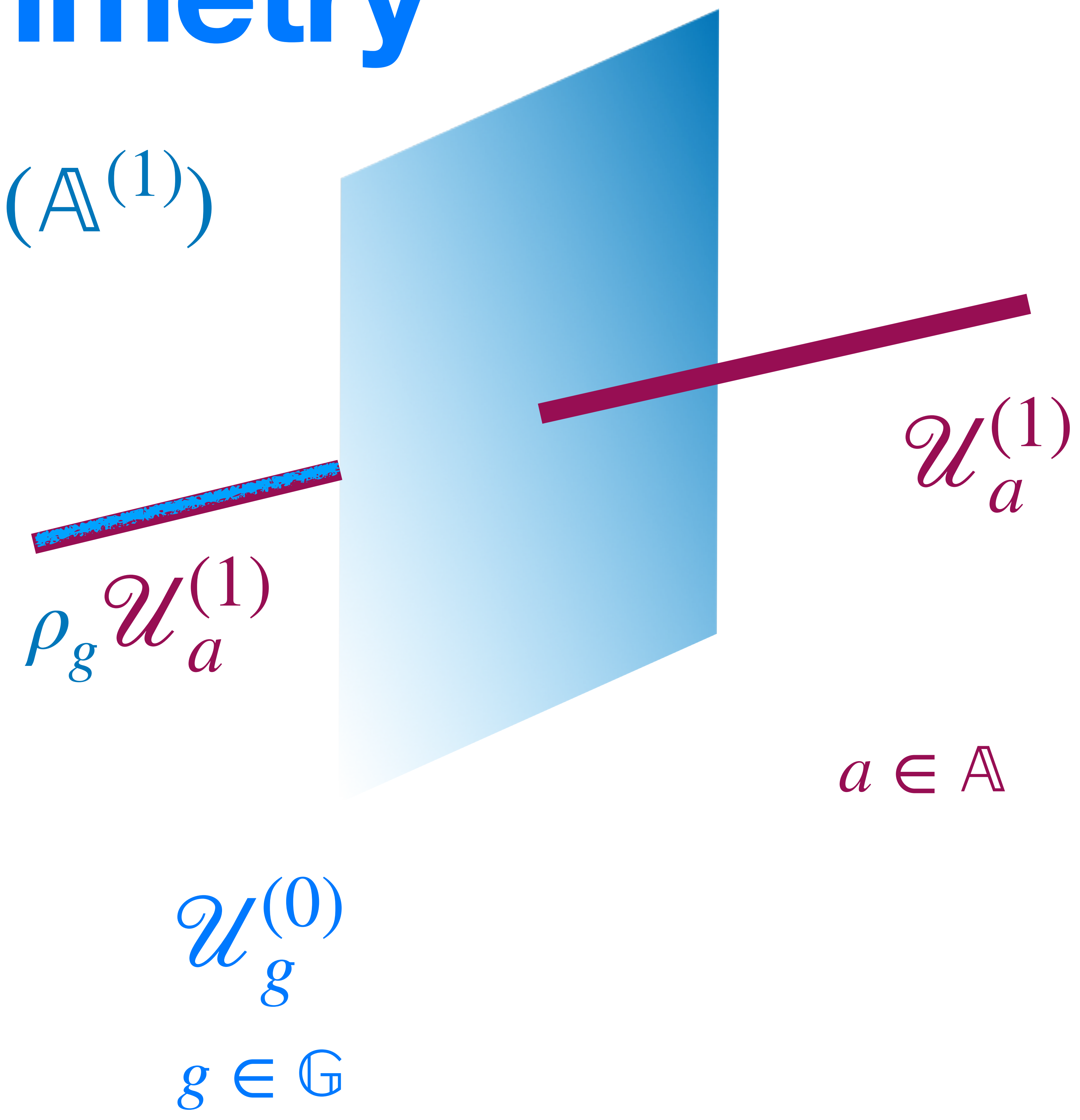

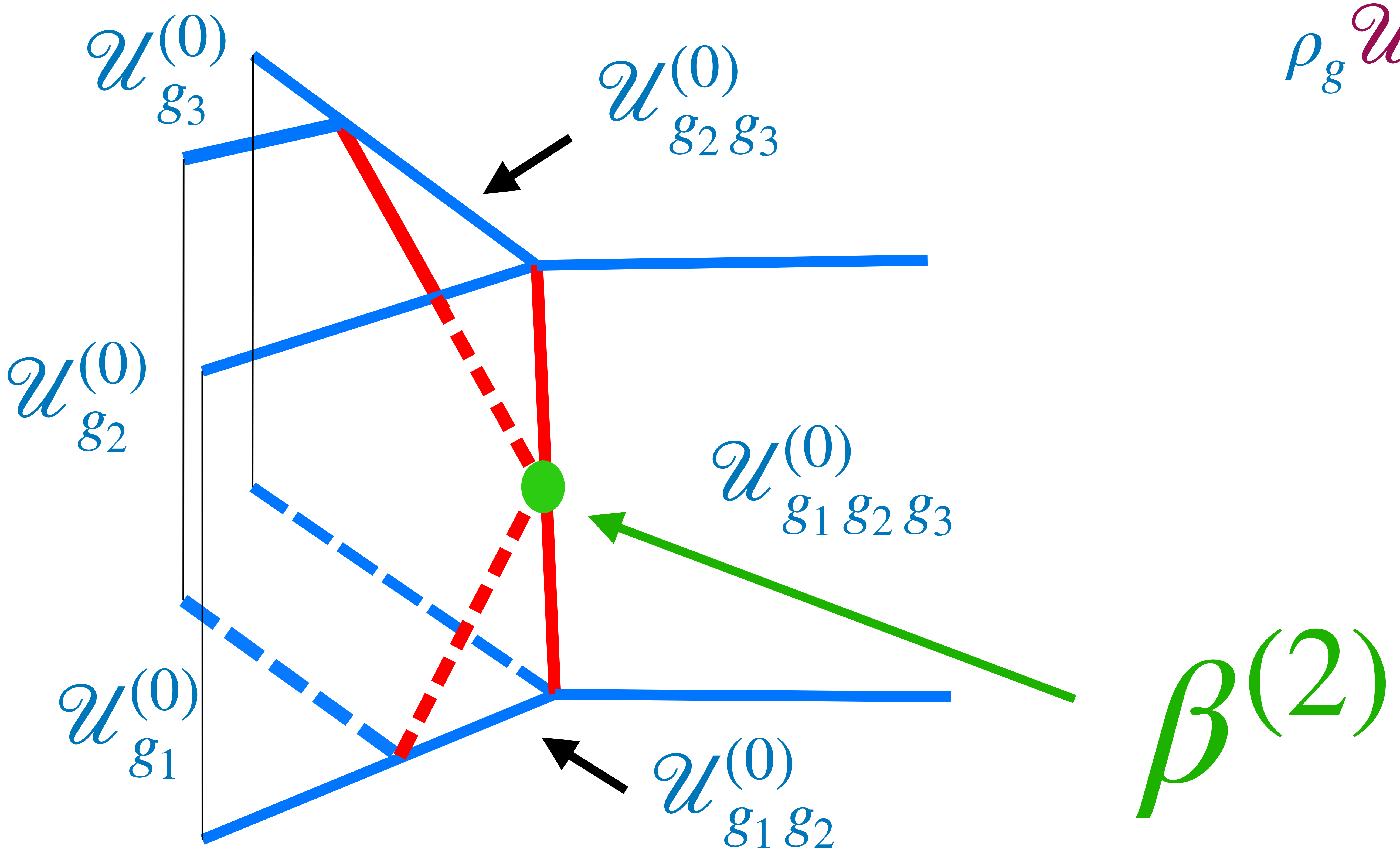

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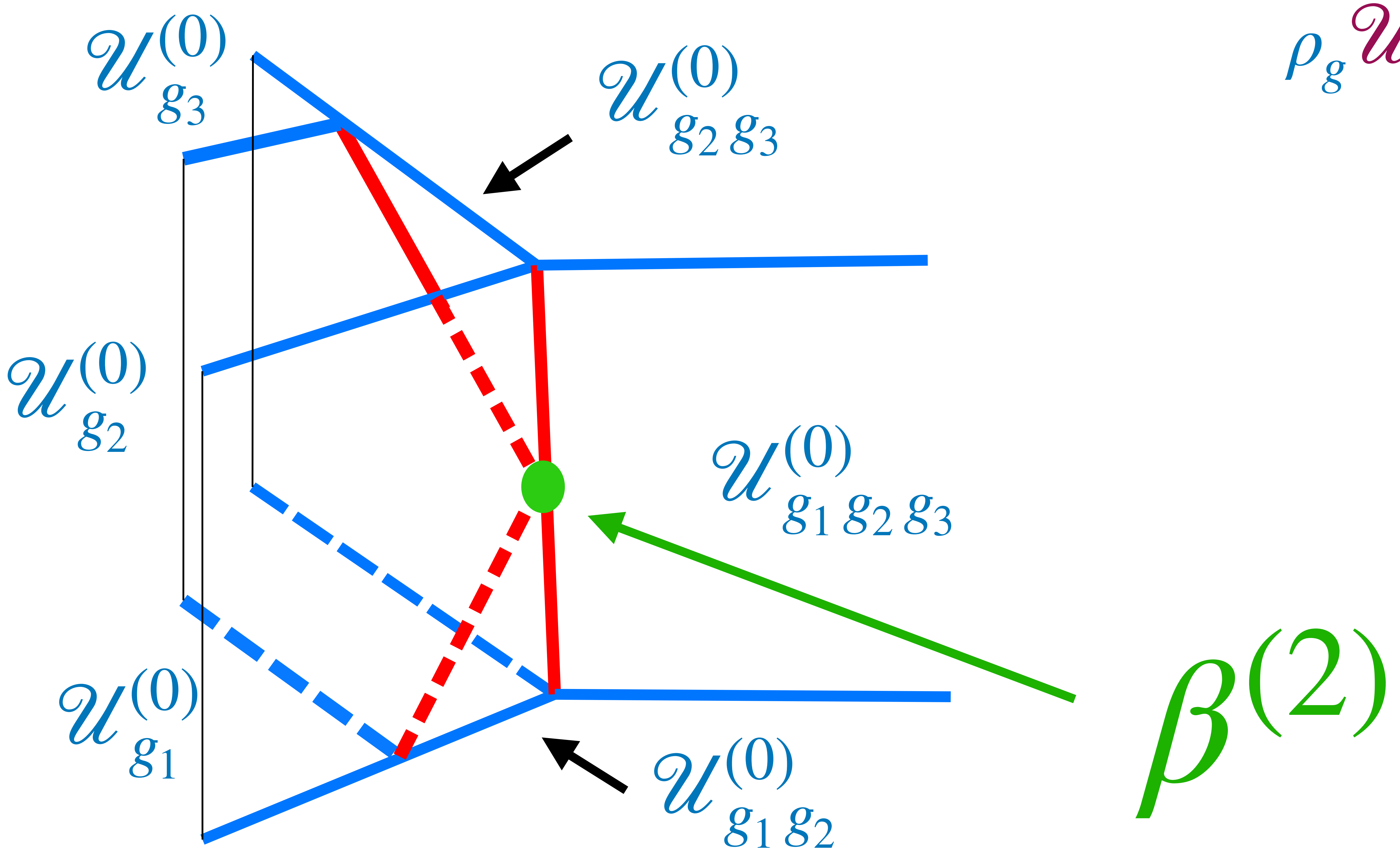

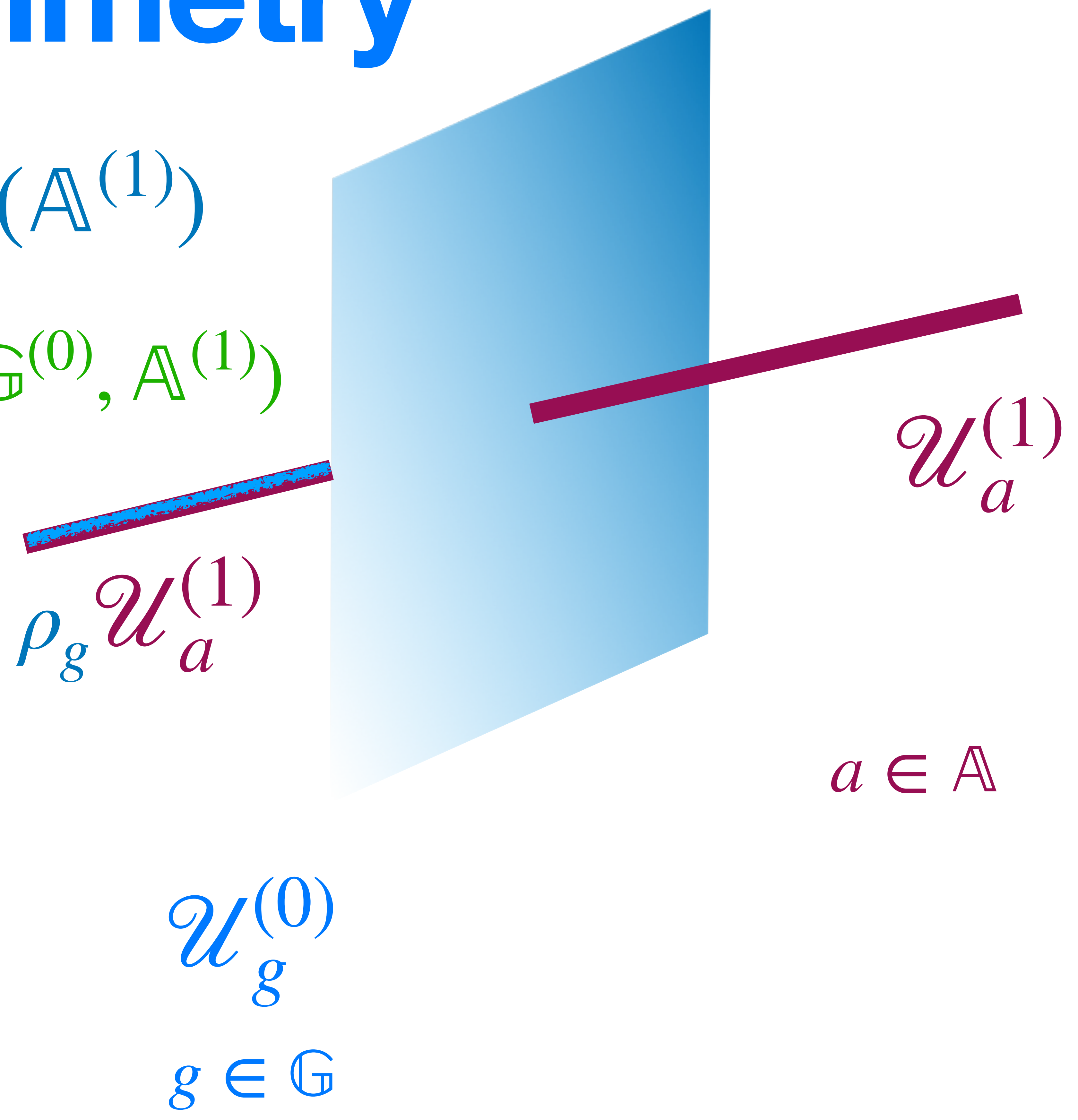

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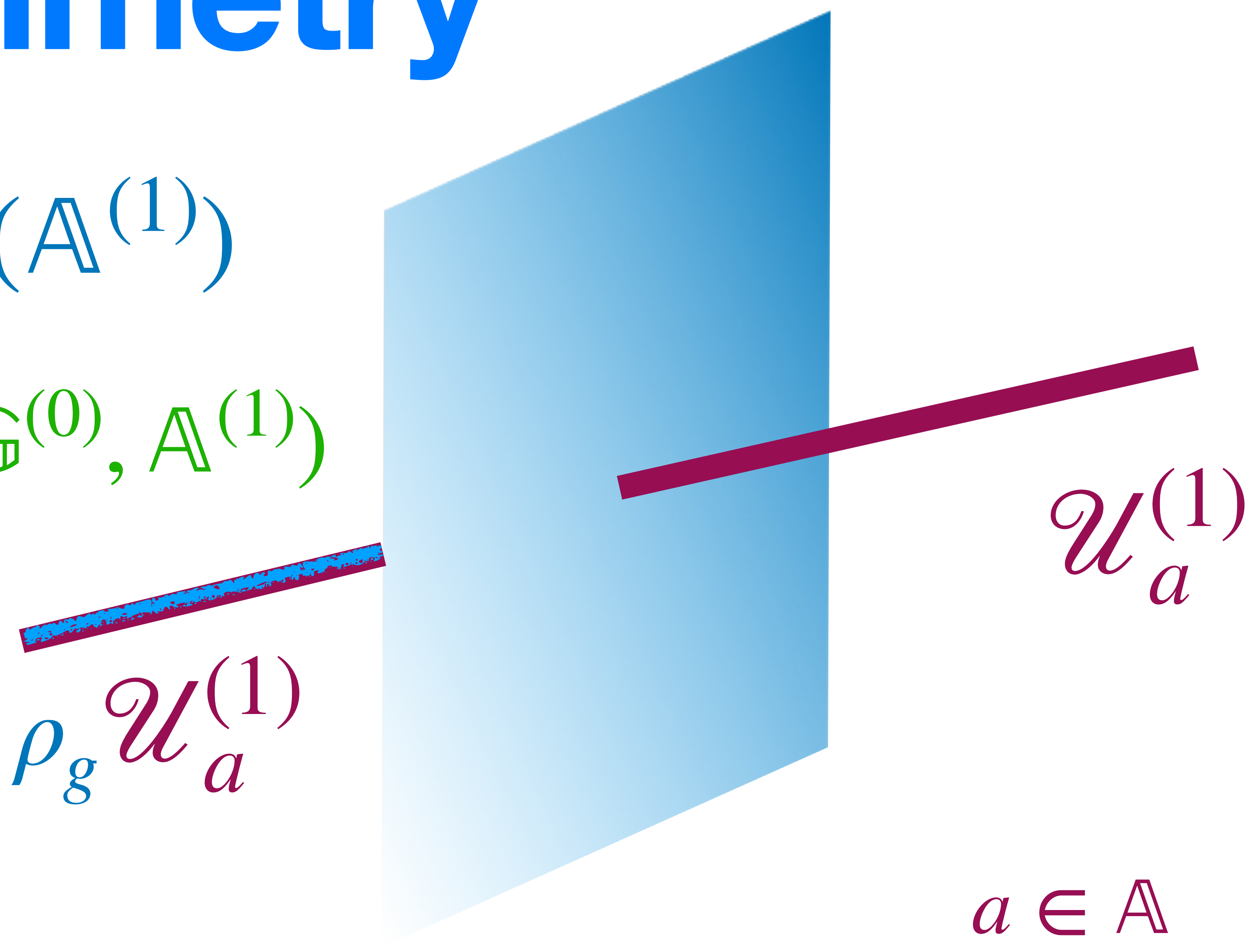

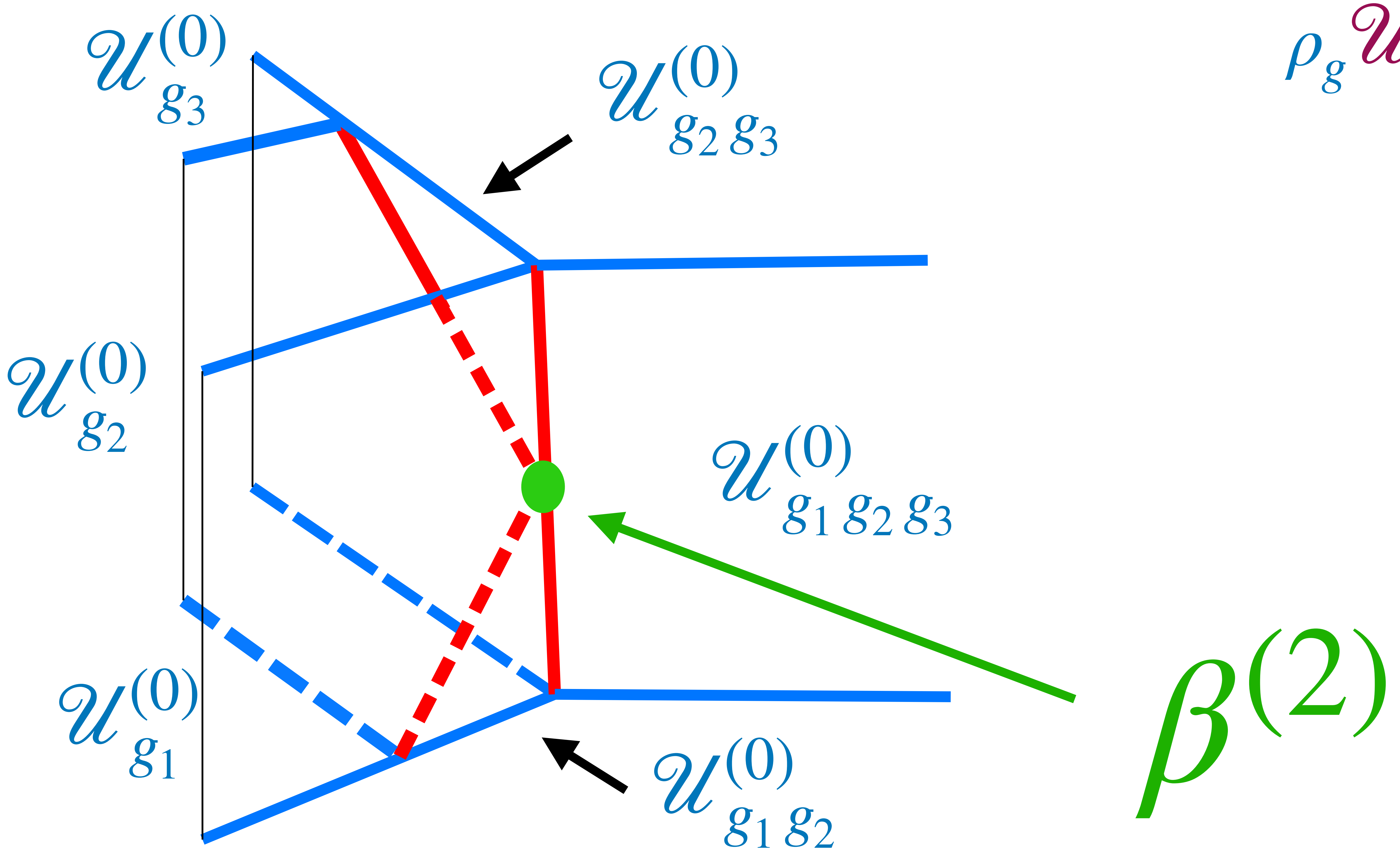

Useful: all these data *match* across dualites

Del Zotto, Ohmori 20
Lee, Ohmori, Tachikawa 21

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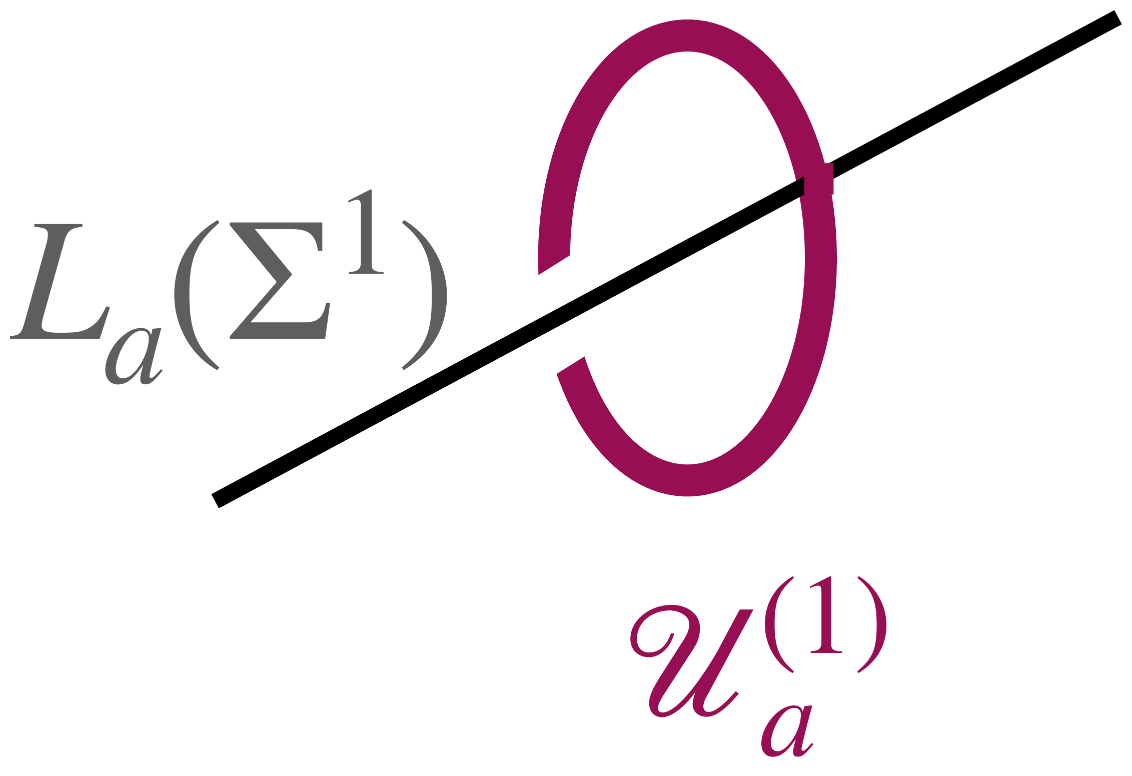

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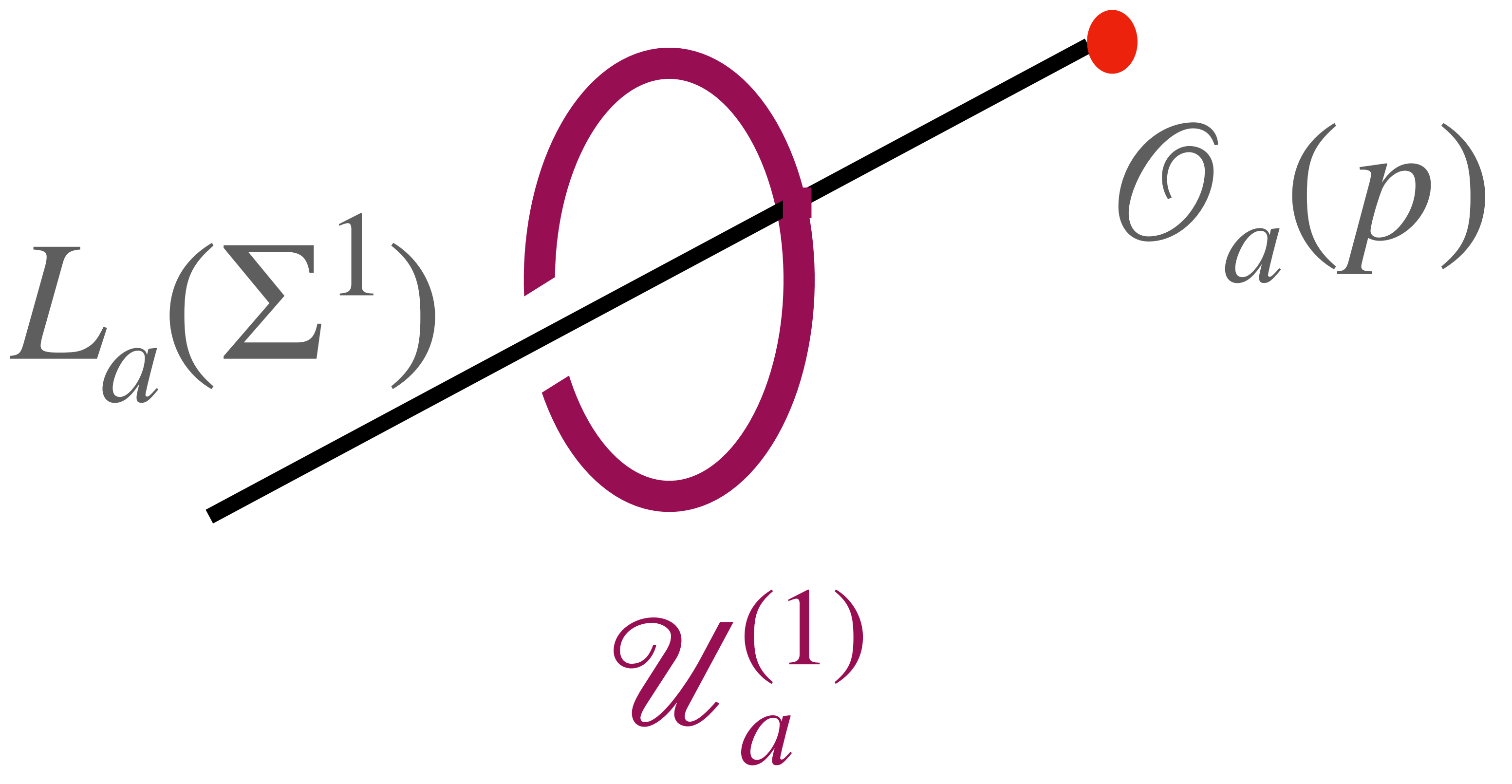

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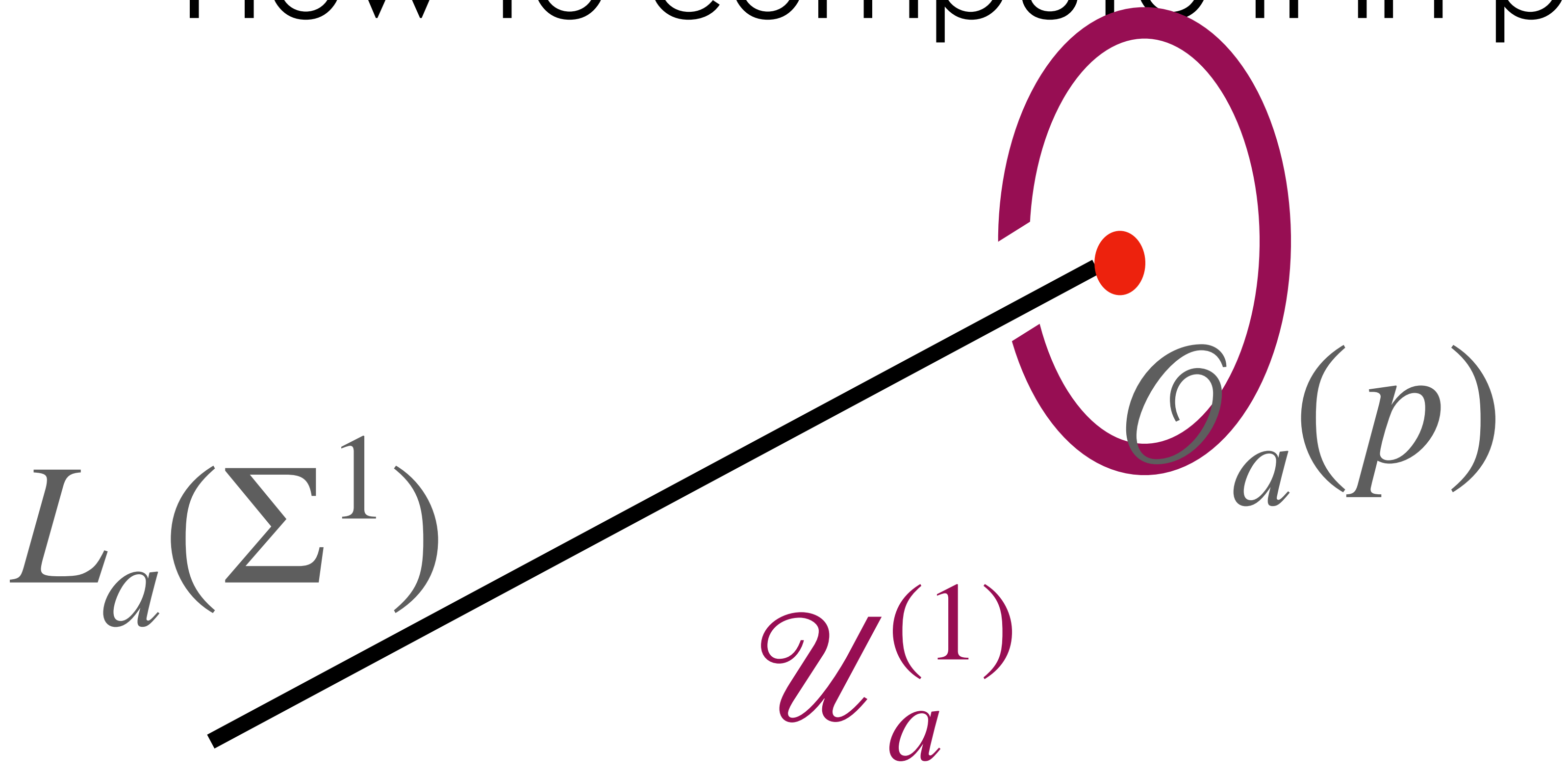

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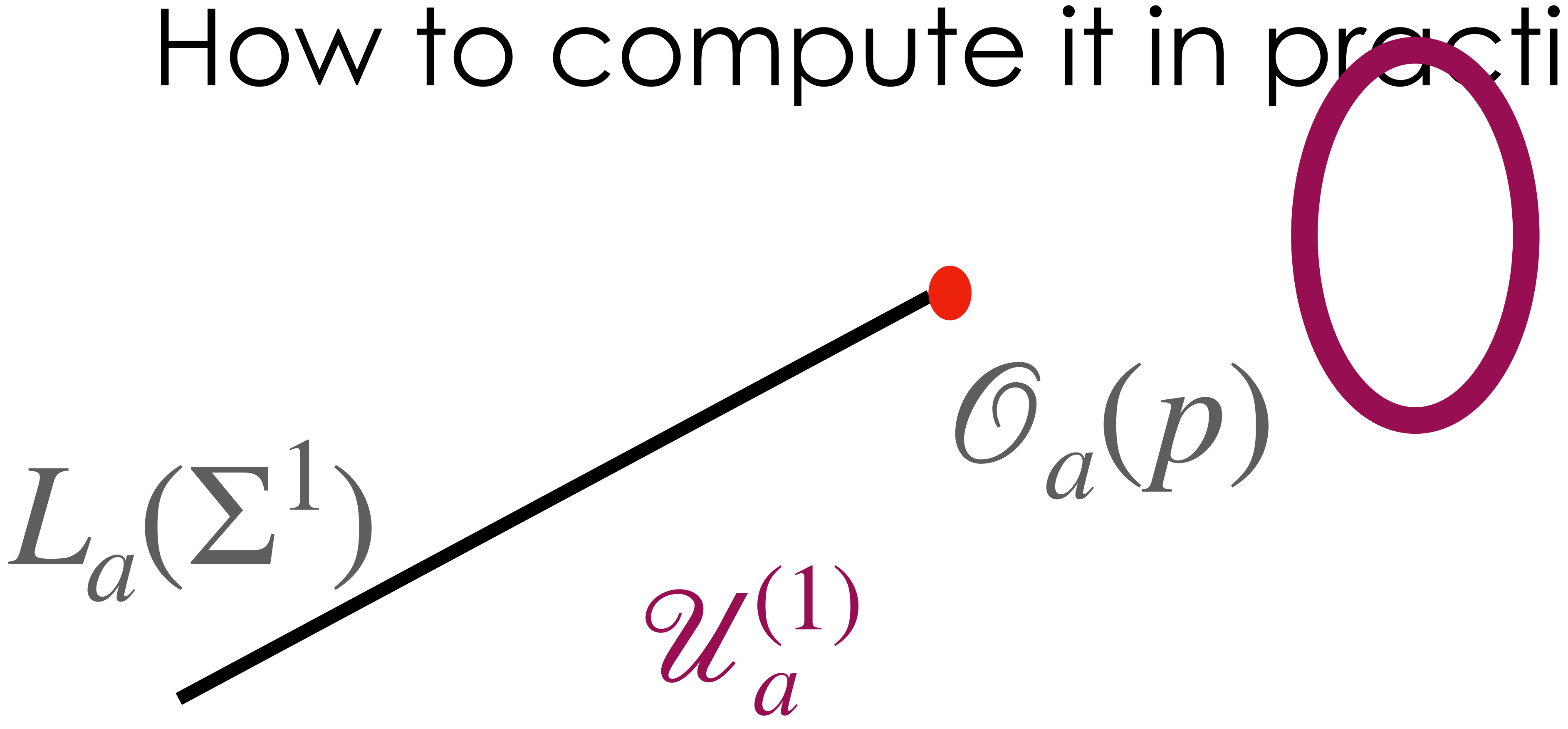

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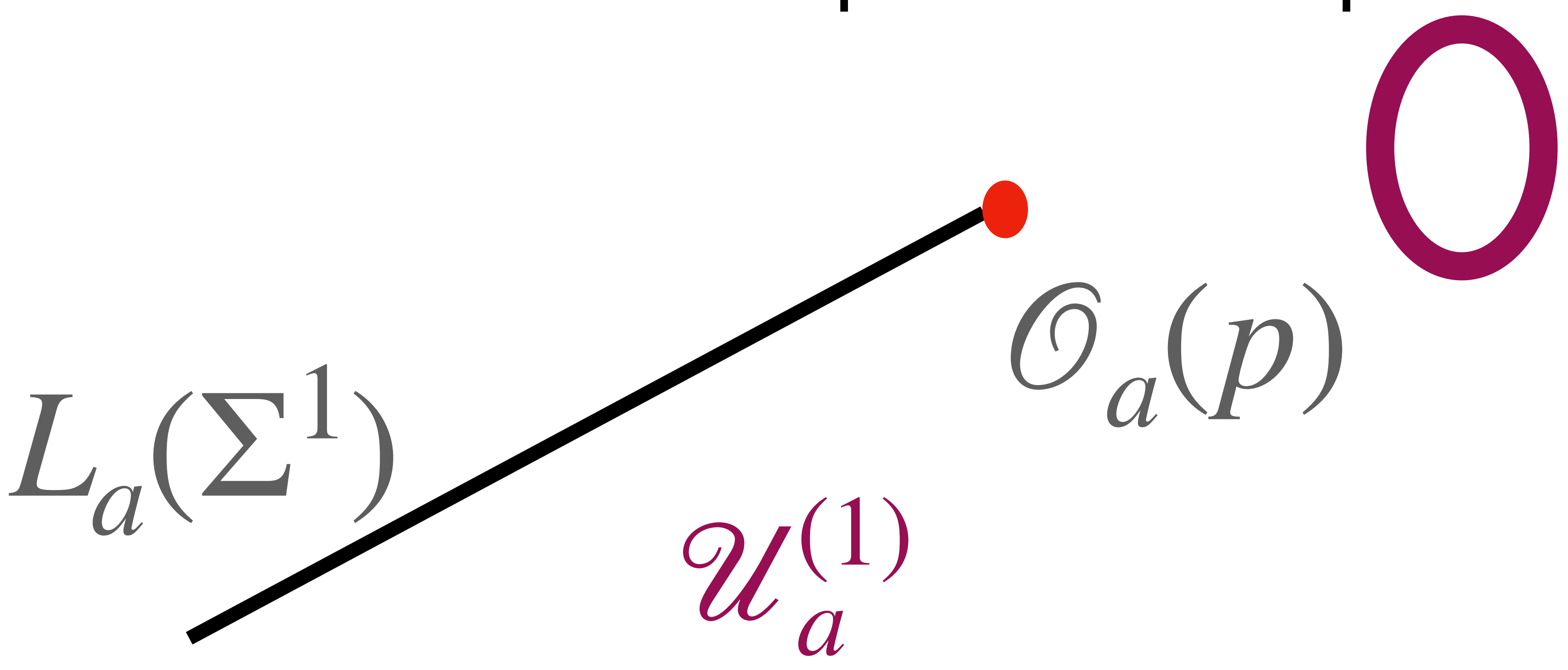

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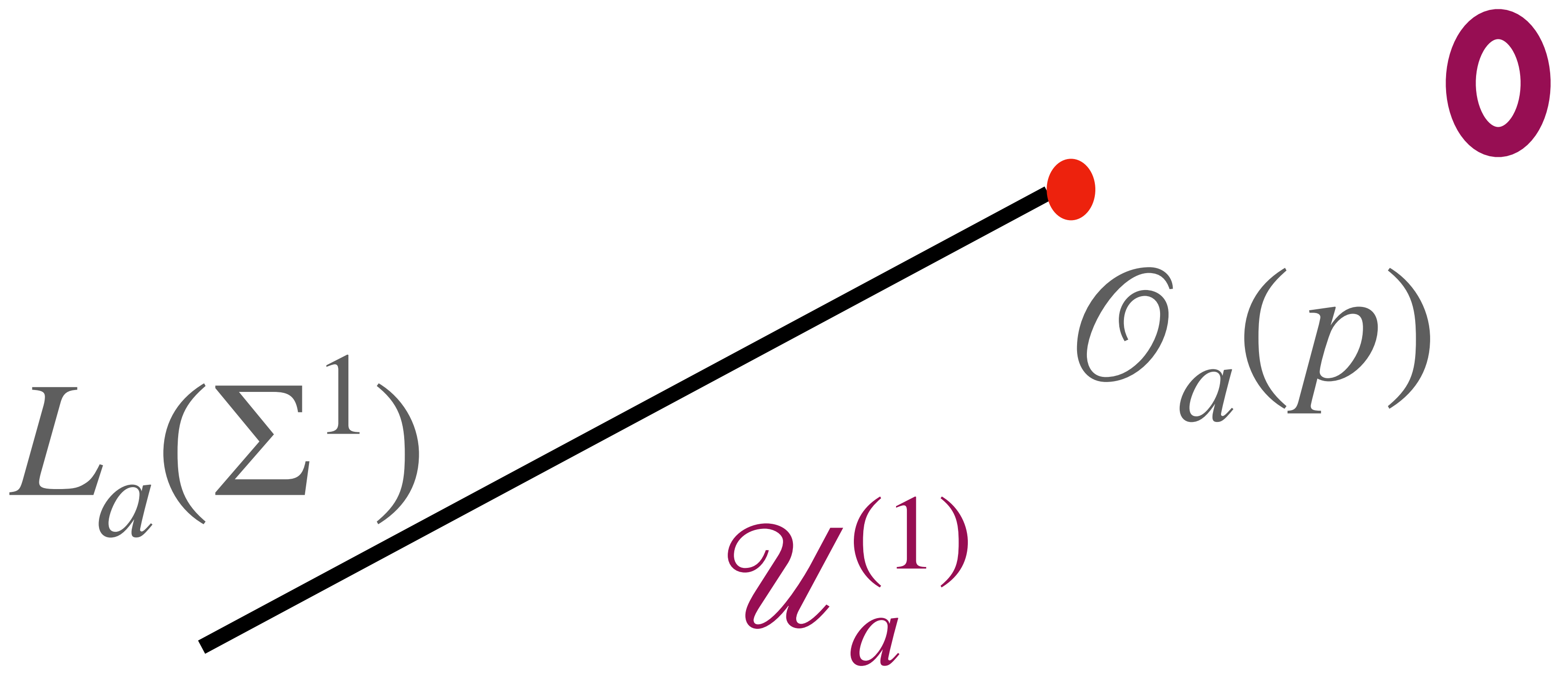

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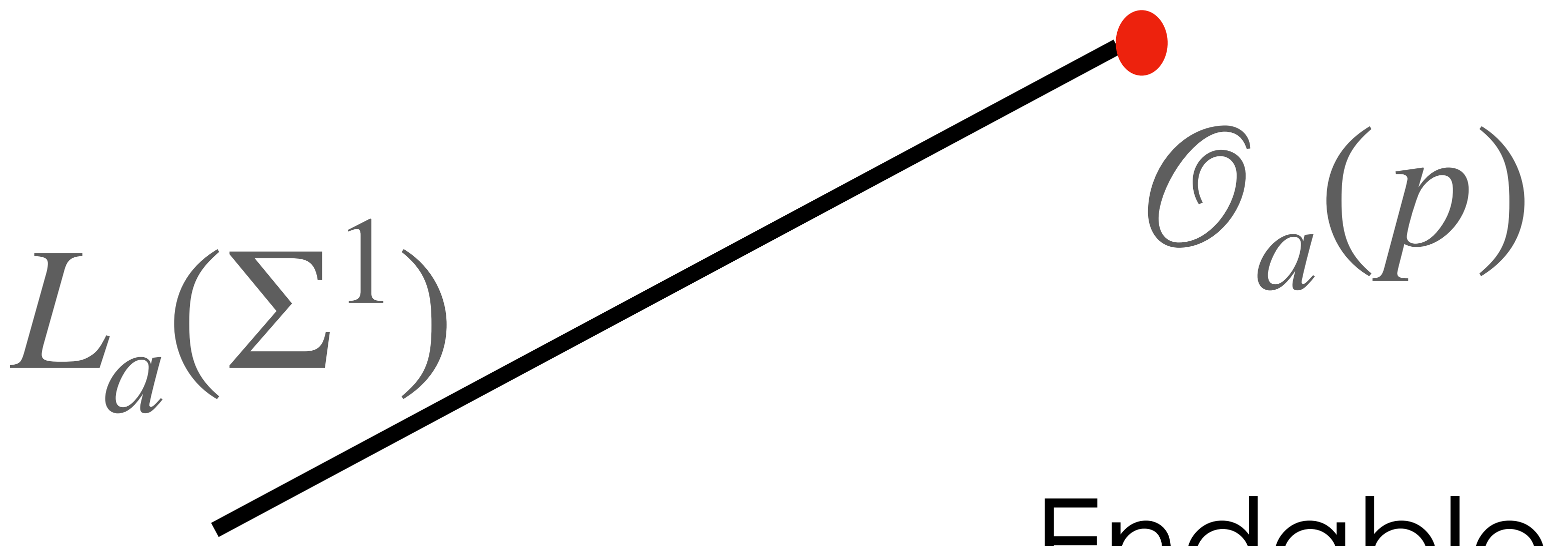

Endable lines are screened

$\mathbb{A}^{(1)}$ = charges of non-endable lines

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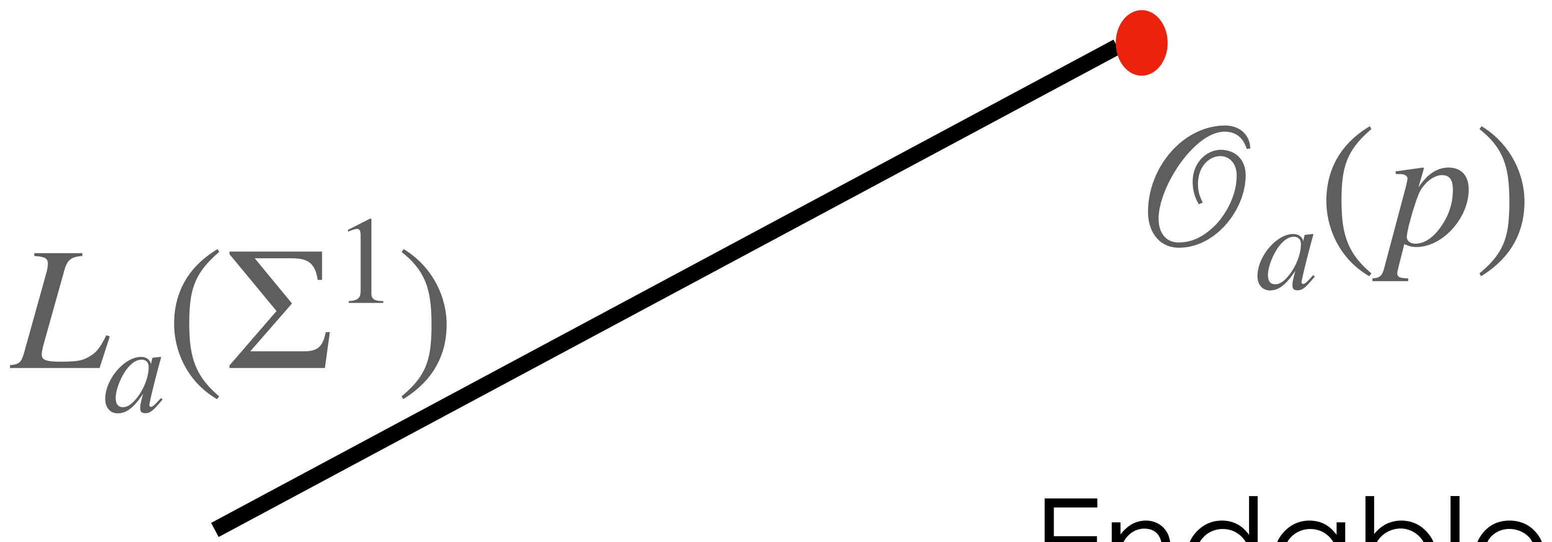

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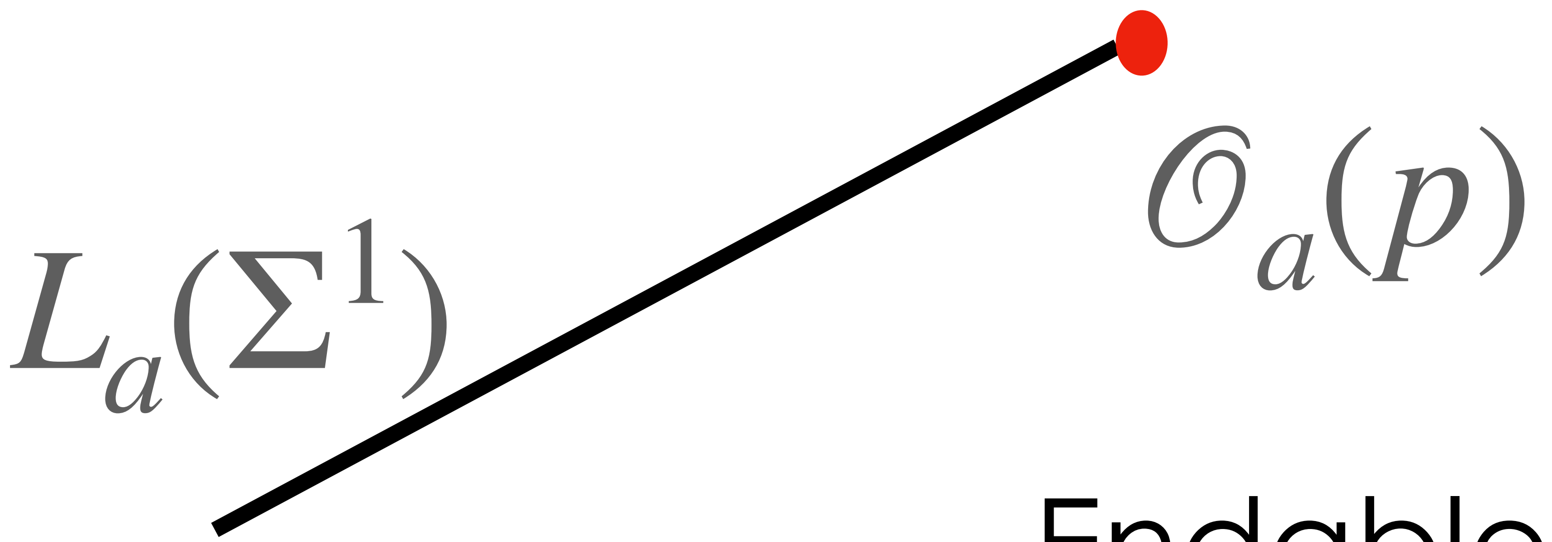

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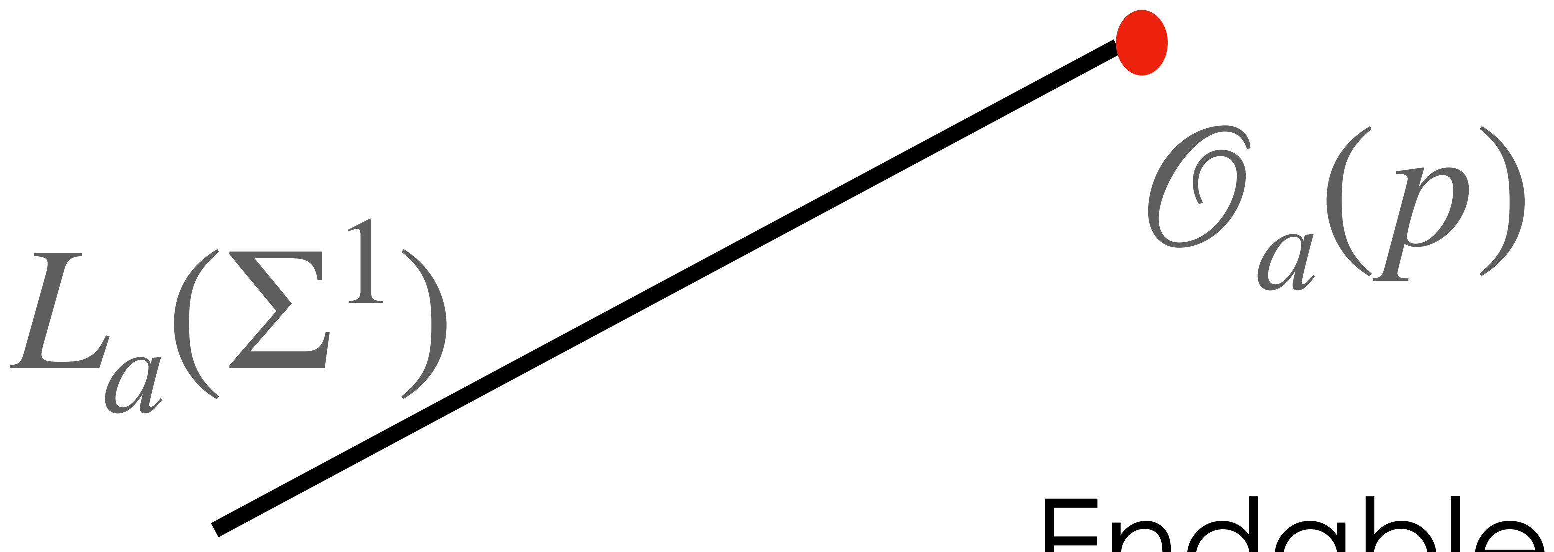
How to compute it in practice?

$$1 \to \mathbb{A}^{(1)} \to \Gamma^{(1)} \to \mathcal{C} \to 1$$



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mismatch given by projective reps of $\mathbb{G}^{(0)}$

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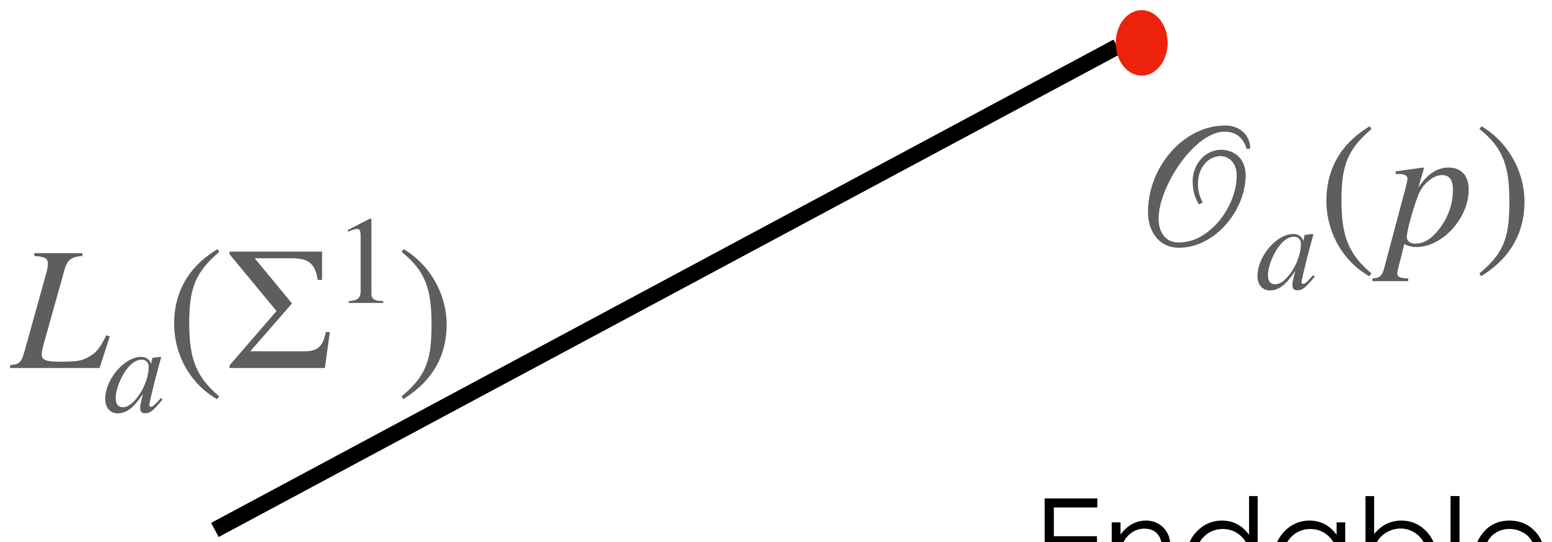

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mismatch given by projective reps of $\mathbb{G}^{(0)}$

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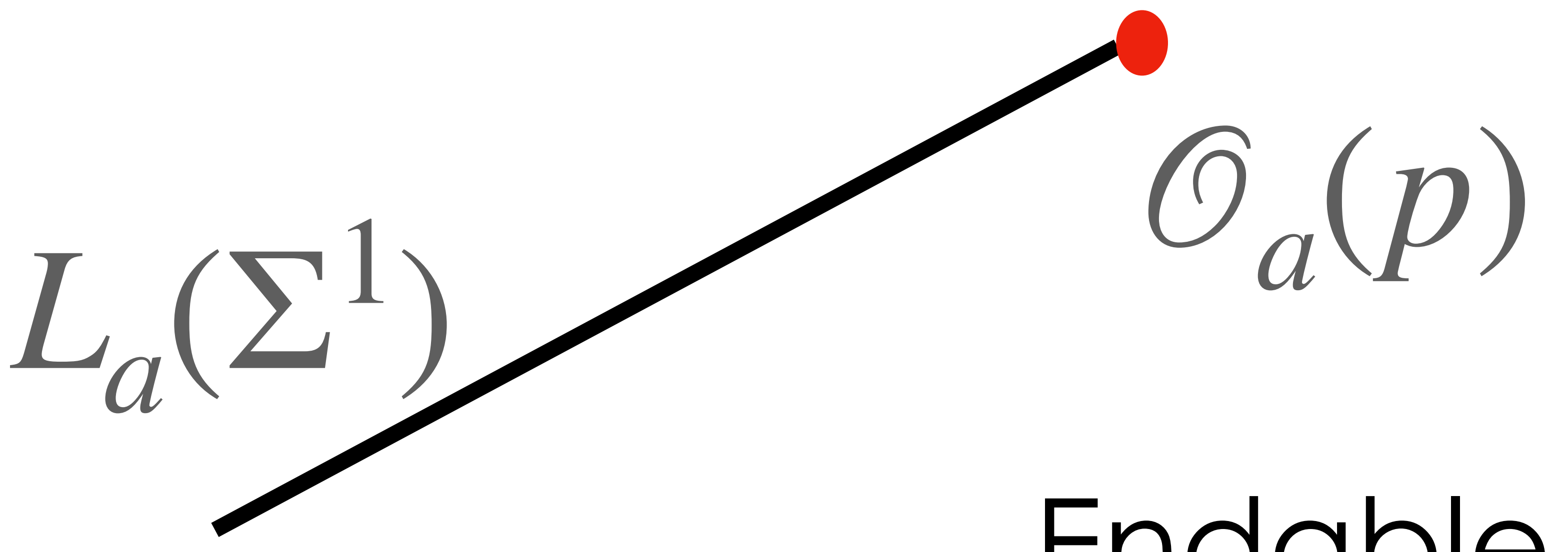
$$\beta^{(2)} = \delta_\rho w$$

How to compute it in practice?

$$1 \to \mathbb{A}^{(1)} \to \Gamma^{(1)} \to C \to 1$$



Endable lines are screened

Useful: all these data *match* across dualites

Del Zotto, Ohmori 20
Lee, Ohmori, Tachikawa 21

Consider screening only with operators in definite representations of $\mathbb{G}^{(0)}$: $\Gamma^{(1)}$

e.g. higher group

Cordóva, Dumitrescu, Intriligator 16; Benini, Cordóva, Hsin 18; Bhardwaj, Shafer-Nameki 23; Bullimore, Barscht, Grigoletto 23

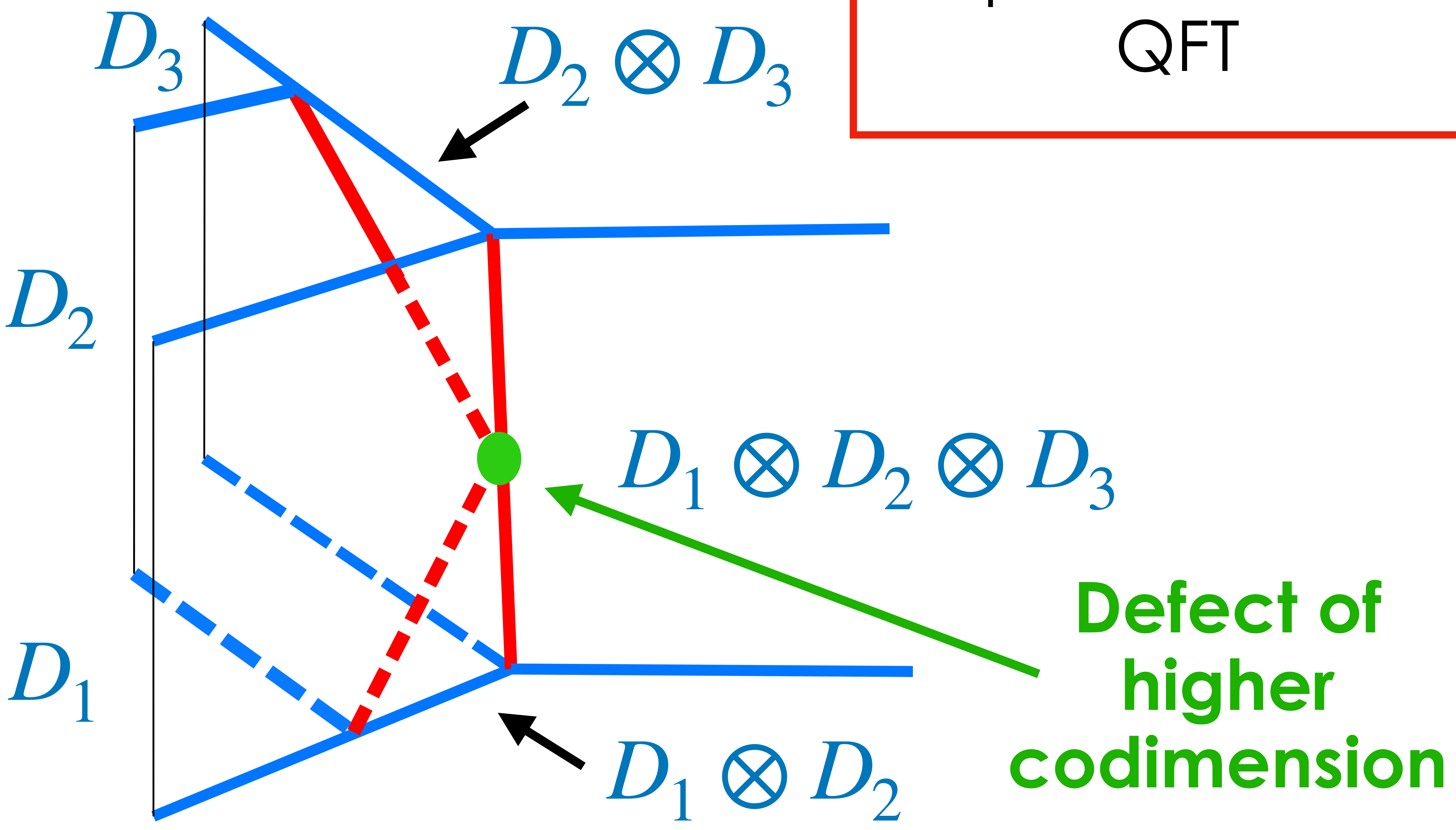
Generalized Symmetries: Lightning Review

Generalized global symmetries $\equiv$ "**Topological**" subsector of the spectrum of operators of a QFT

- Ward identities
- Selection Rules
- Anomalies
- Spontaneous breaking

… but also **other features**!

- **Fusion product**
- **Higher structure**



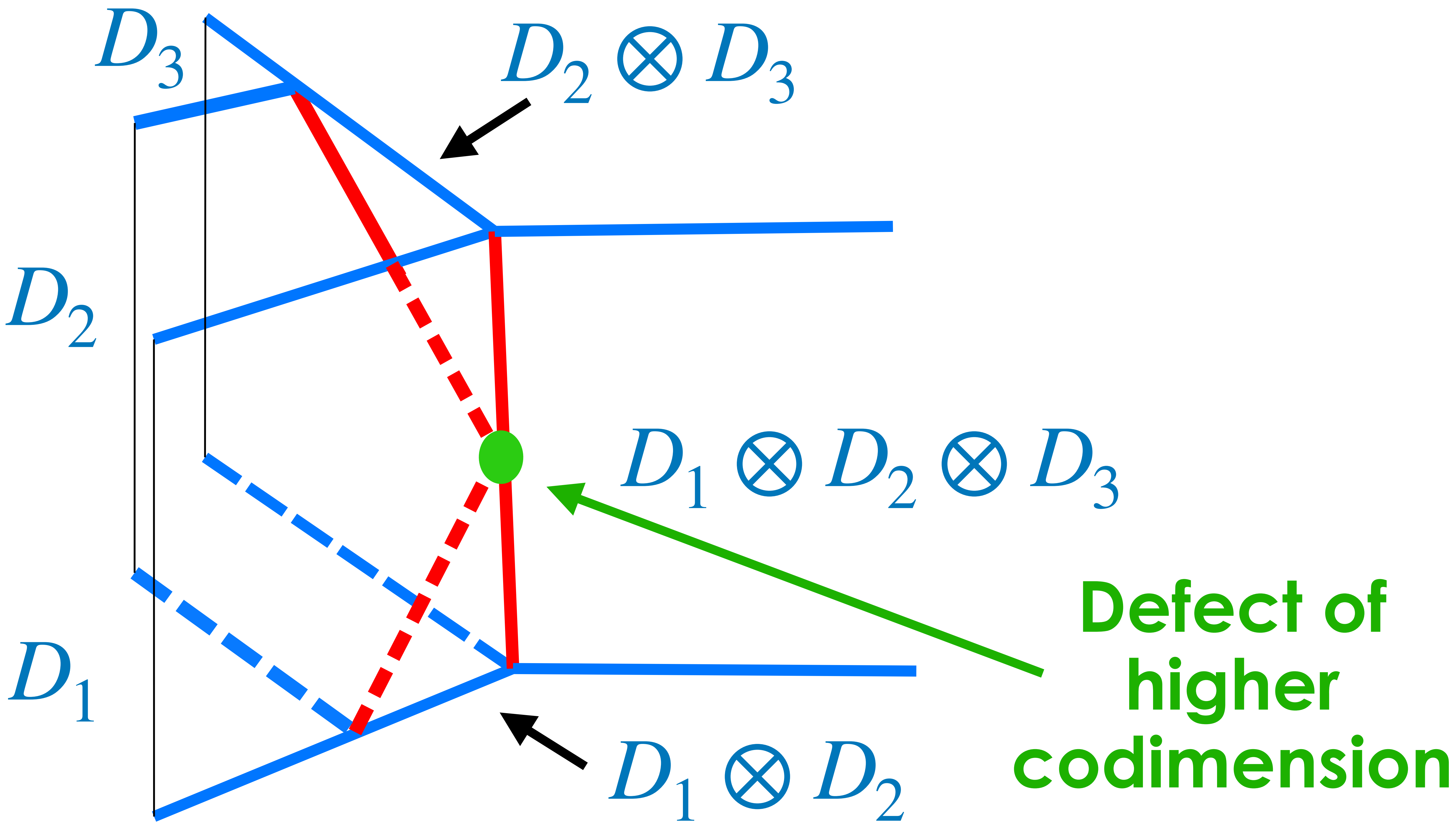
Extended defects can form junctions

e.g. higher group

Cordóva, Dumitrescu, Intriligator 16; Benini, Cordóva, Hsin 18; Bhardwaj, Shafer-Nameki 23; Bullimore, Barscht, Grigoletto 23

Symmetry Groups → Symmetry Categories

- Ward identities
- Selection Rules
- Anomalies
- Spontaneous breaking



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Symmetry Groups → Symmetry Categories

The structure of symmetries is better characterized exploiting **higher categories** than groups

Well-known in the TQFT community
Finds applications in cond-mat (topological order), eg. Johnson-Freyd, Gaiotto 17,19; Johnson-Freyd 20; Gaiotto, Kulp 20; Kong, Lan, Wen, Zhang, Zheng 20; now apply to QFT

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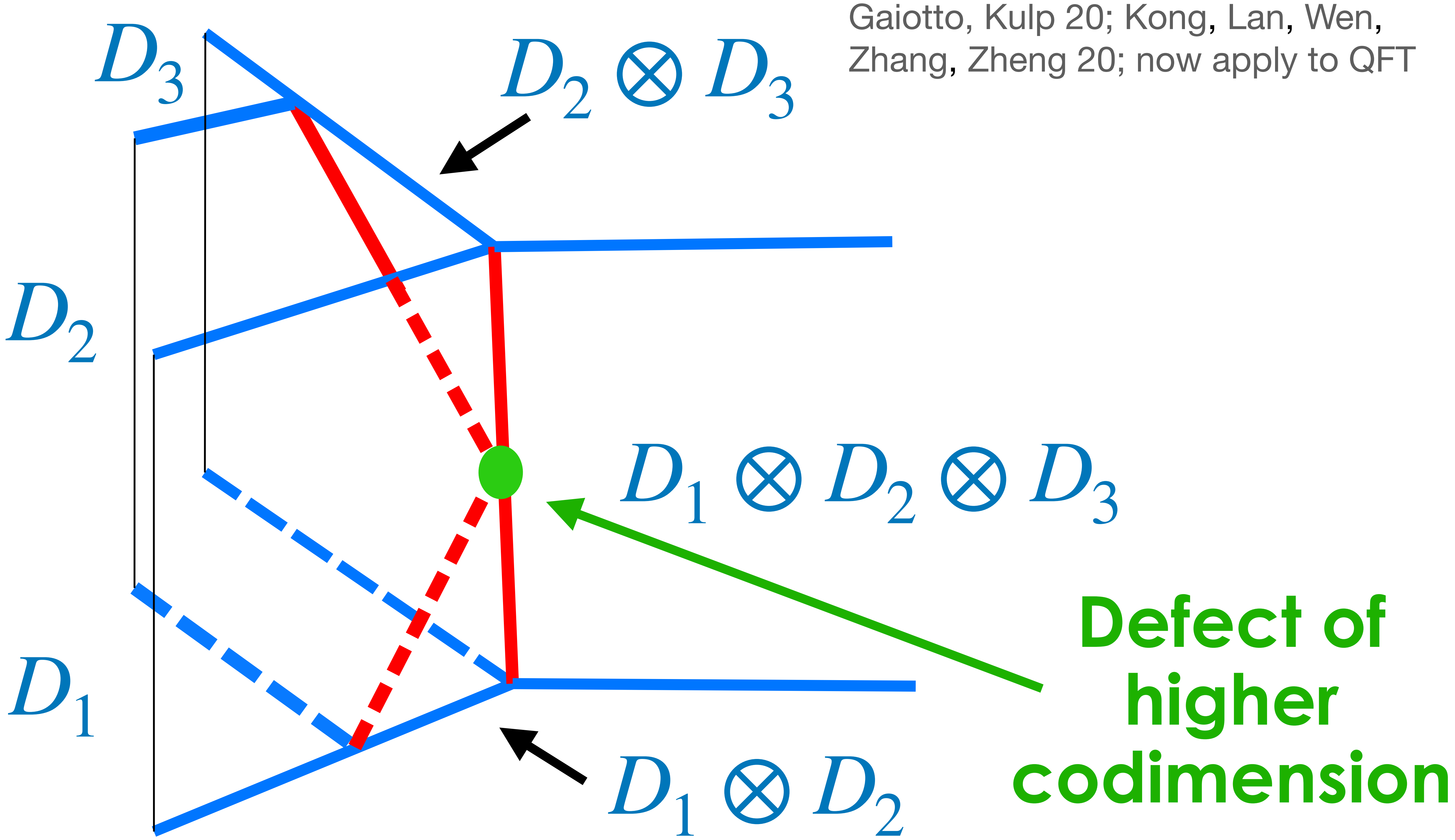

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TODAY

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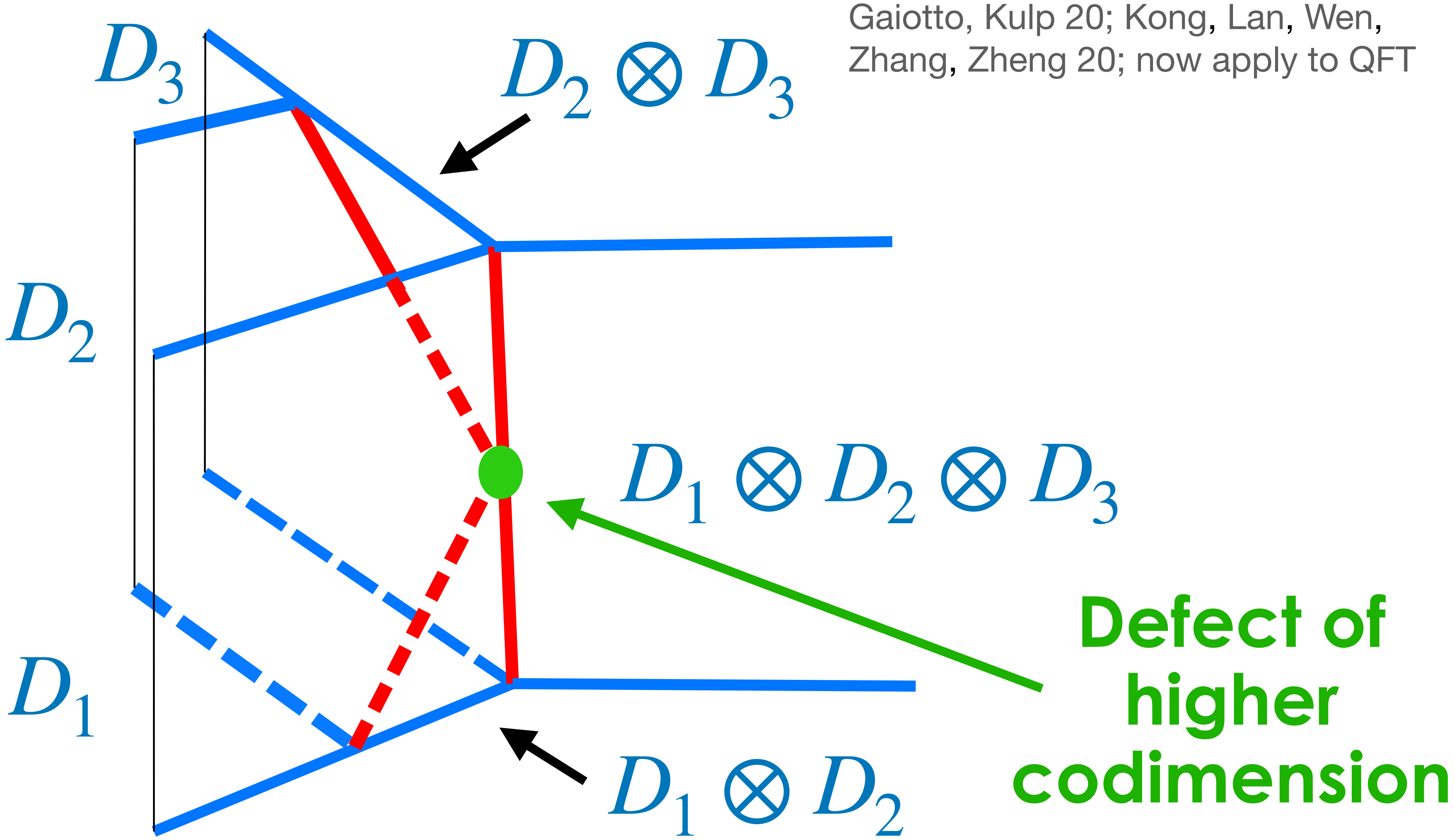

- **Fusion product**
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See also: Córdova, Ohmori 21; Choi, (Córdova), Lam, (Hsin), Shao 21,22; Roumpedakis, Seifnashri, Shao 22; Kaidi, Ohmori, Zheng 21,22; Kaidi, Nardoni, Zafrir, Zheng 23; Oxford group (Apruzzi, Bhardwaj, Bonetti, Bottini, …, Schäfer-Nameki); Durham group (Bartsch, Bullimore,… + García Etxebarria, Hosseini),…

Symmetry Categories oversimplified

Symmetry category graded by **charged operator** dimensions:

$\mathscr{C} = (\mathscr{C}^{(0)}, \mathscr{C}^{(1)}, \cdots, \mathscr{C}^{(D-1)})$ $\mathscr{C}^{(k)}$ = codim ***k+1*** top-ops

slogan: **everything is a morphism** and **every morphism is an interface**

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Remark: From this perspective it makes sense to consider a category of (D+1)-dimensional QFTs with morphisms topological interfaces

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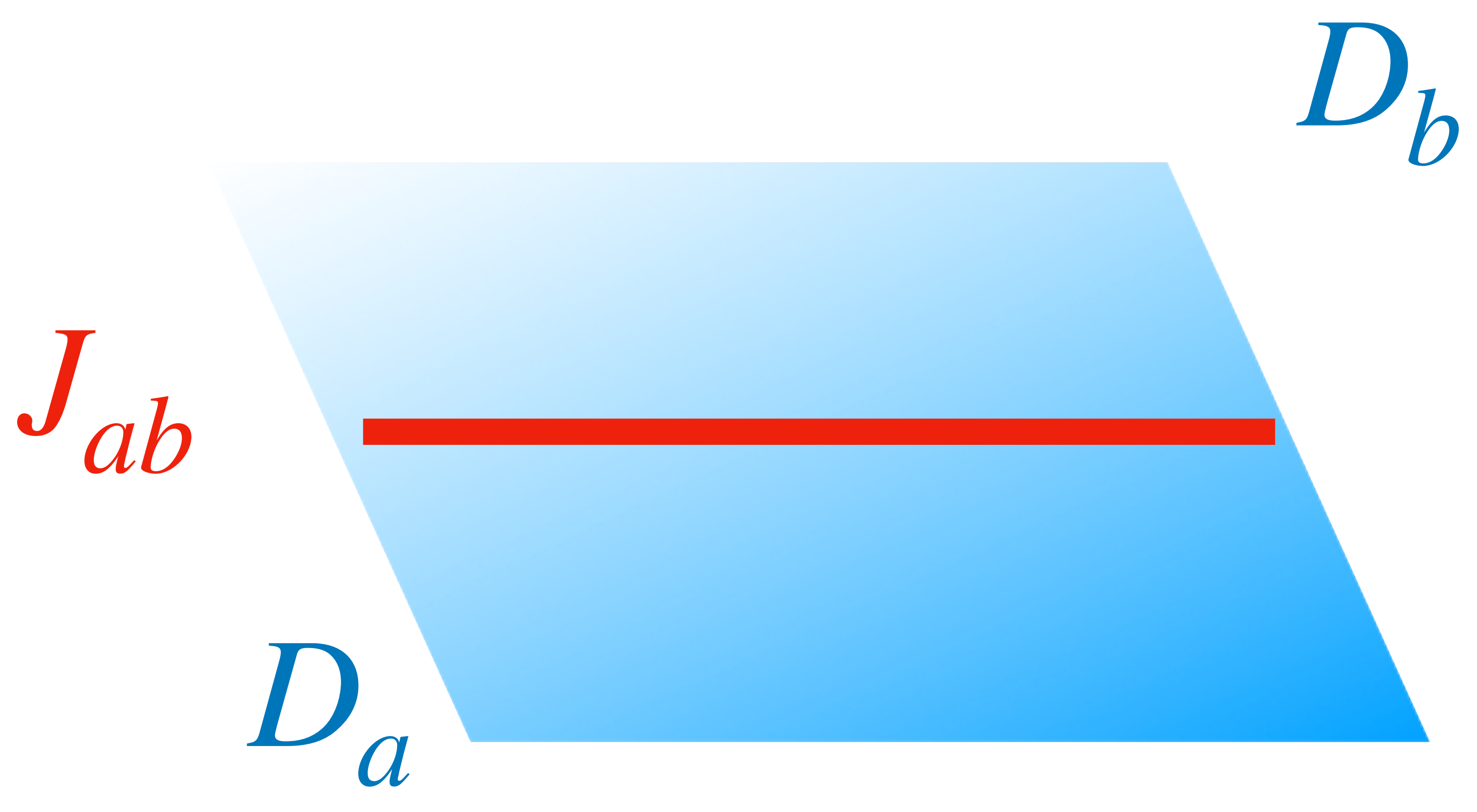

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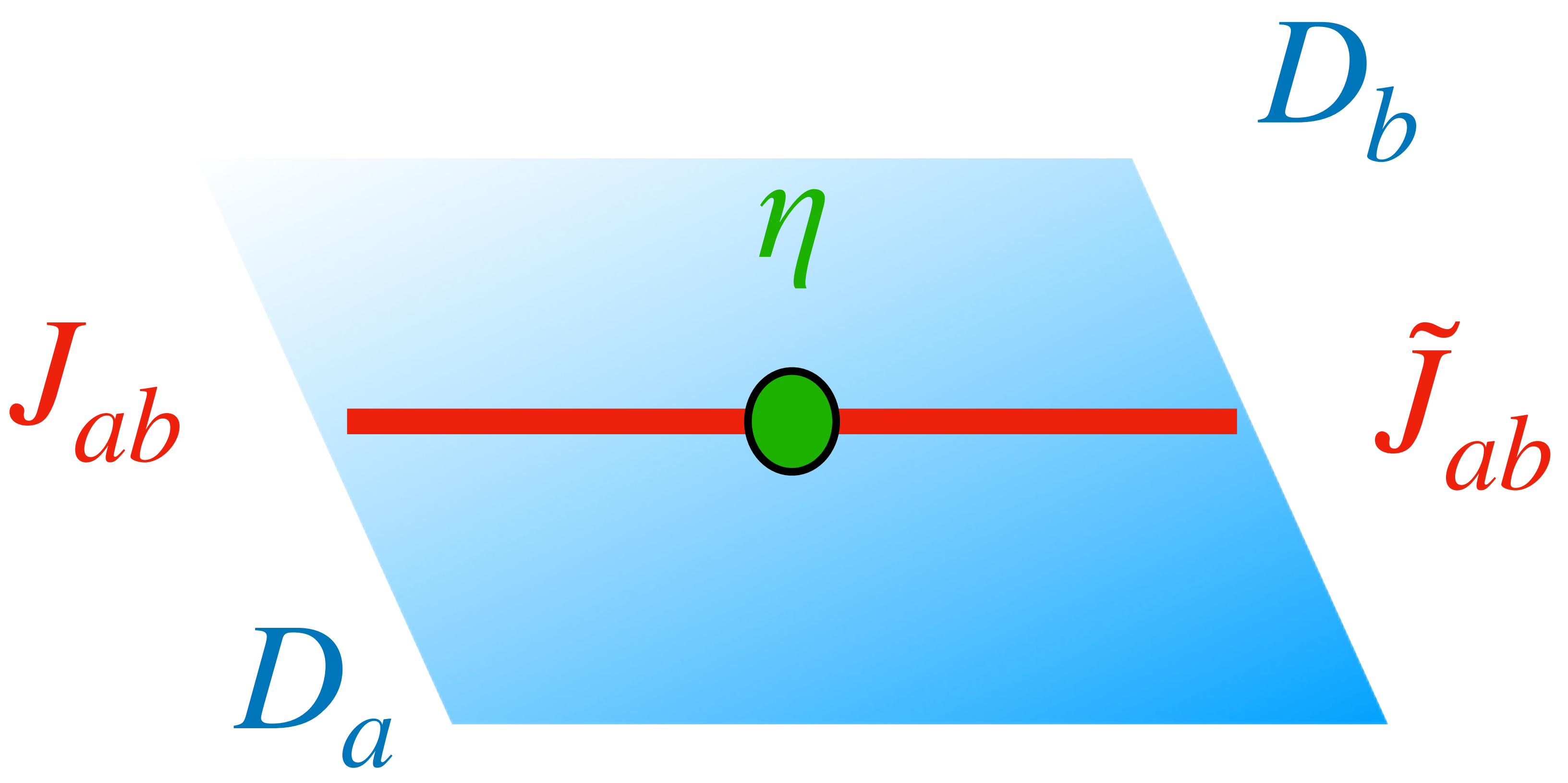

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Useful: instead of drawing, chase arrow diagrams

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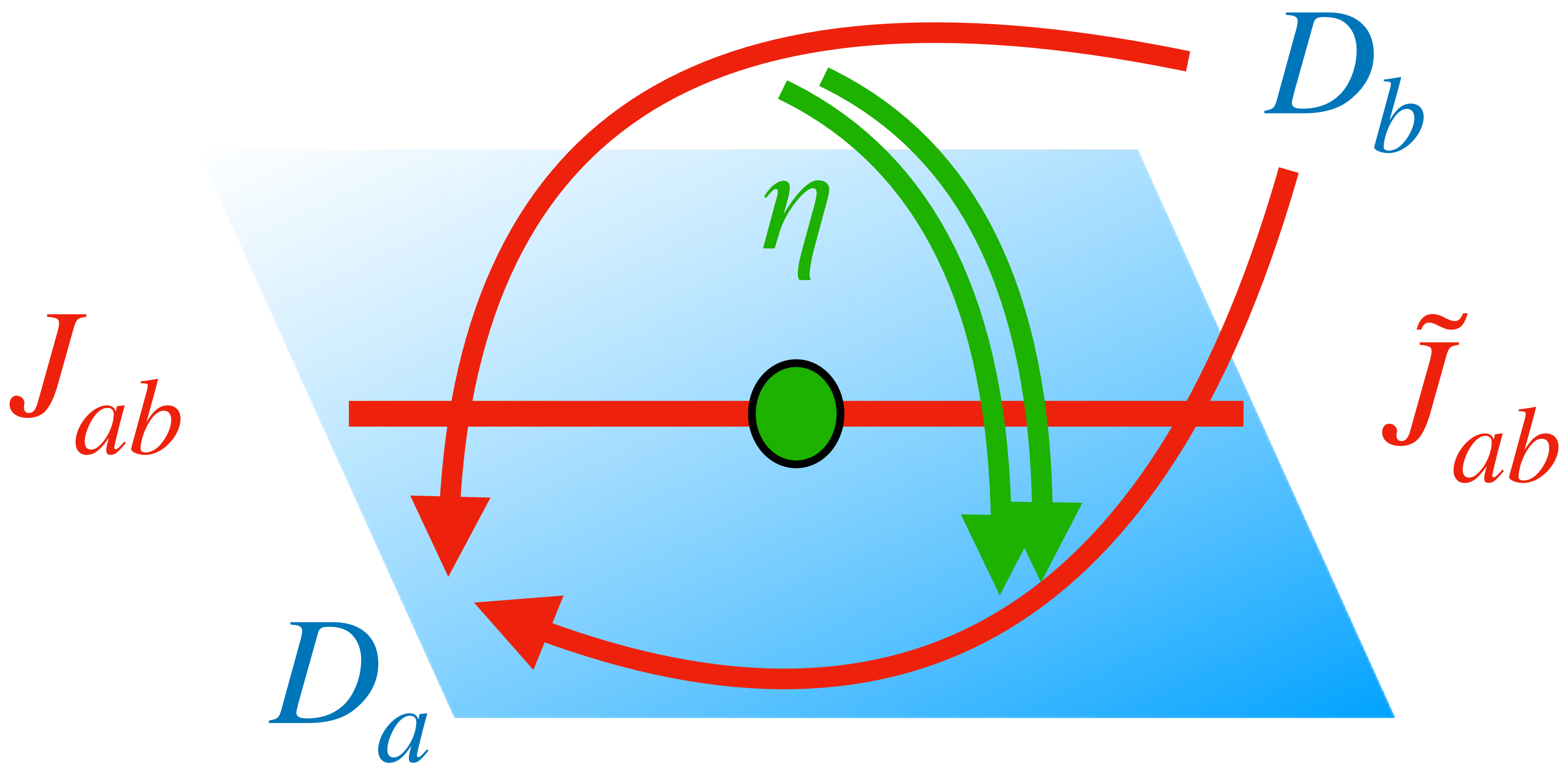

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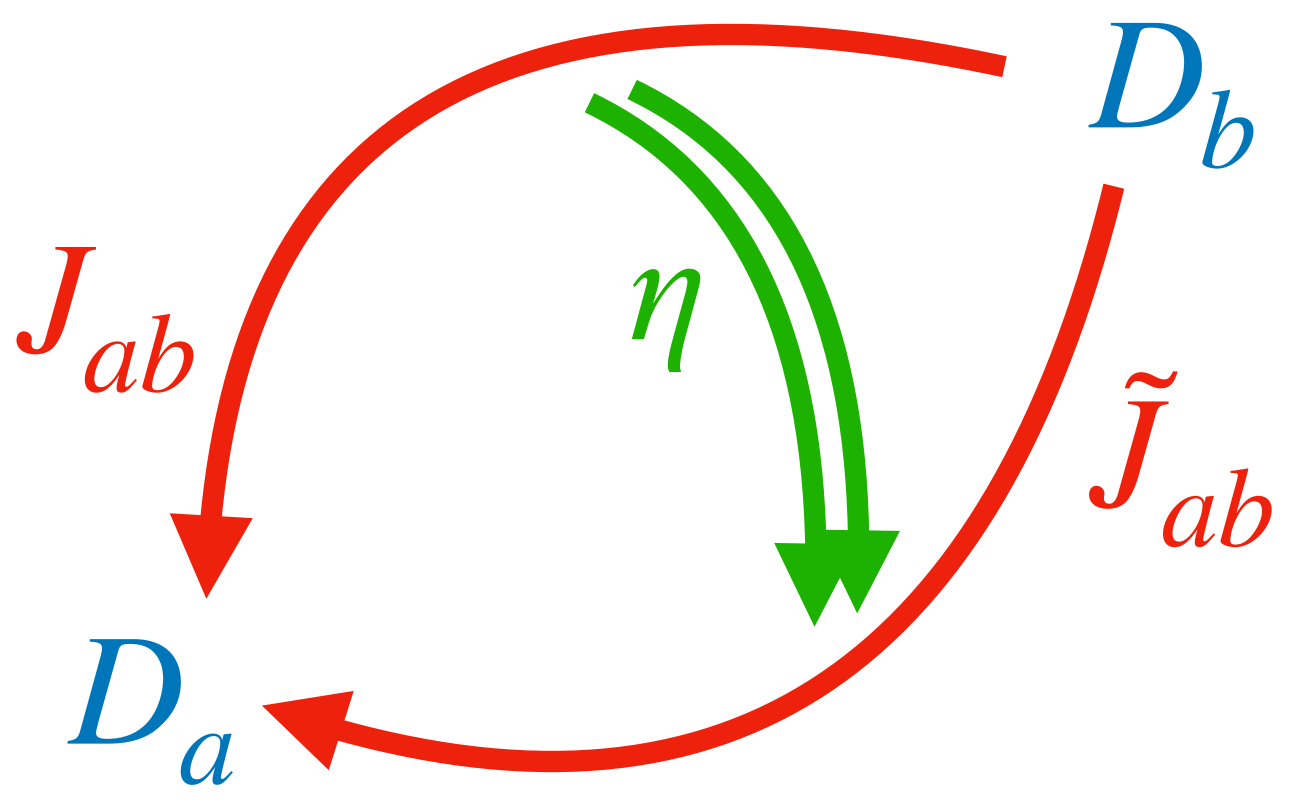

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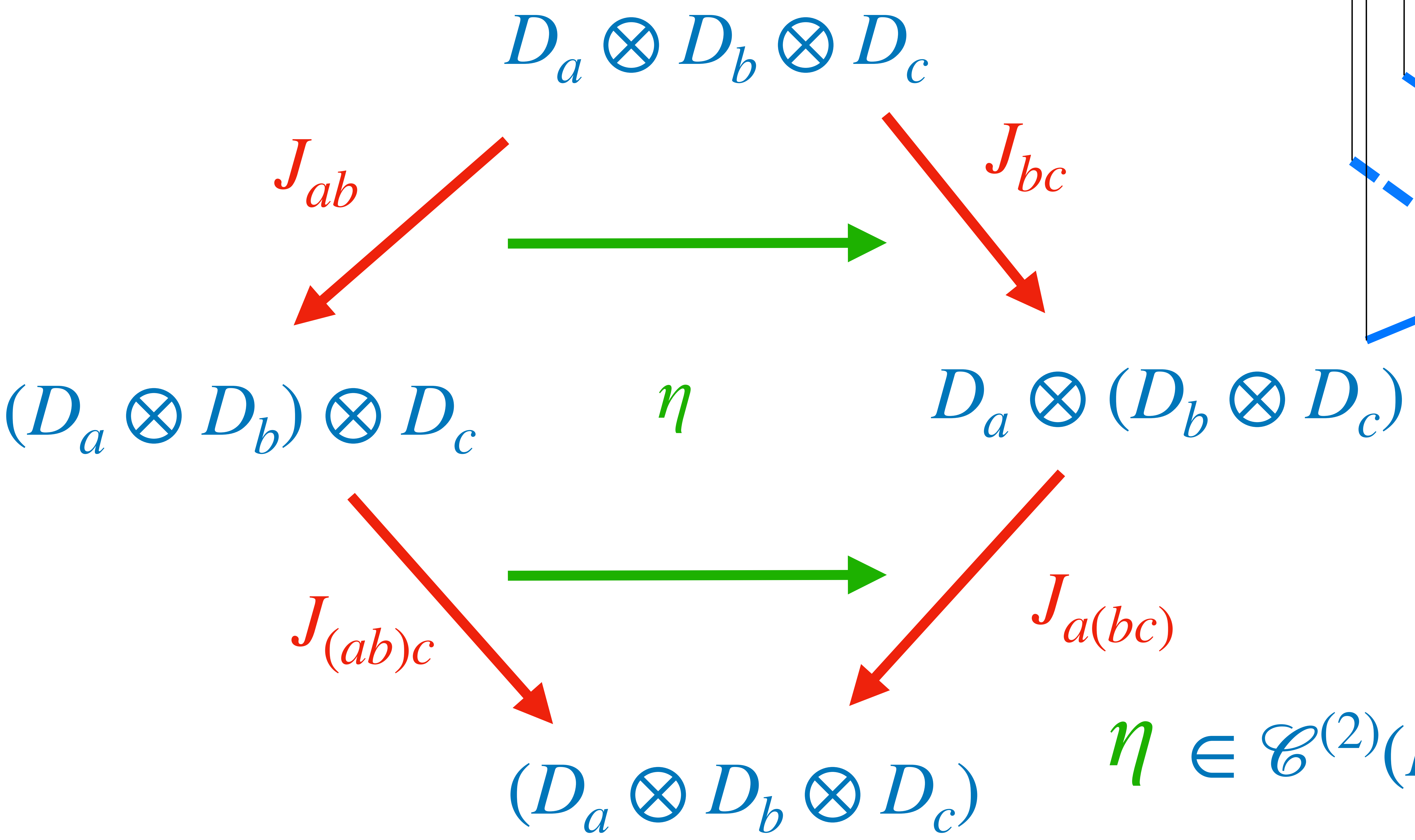
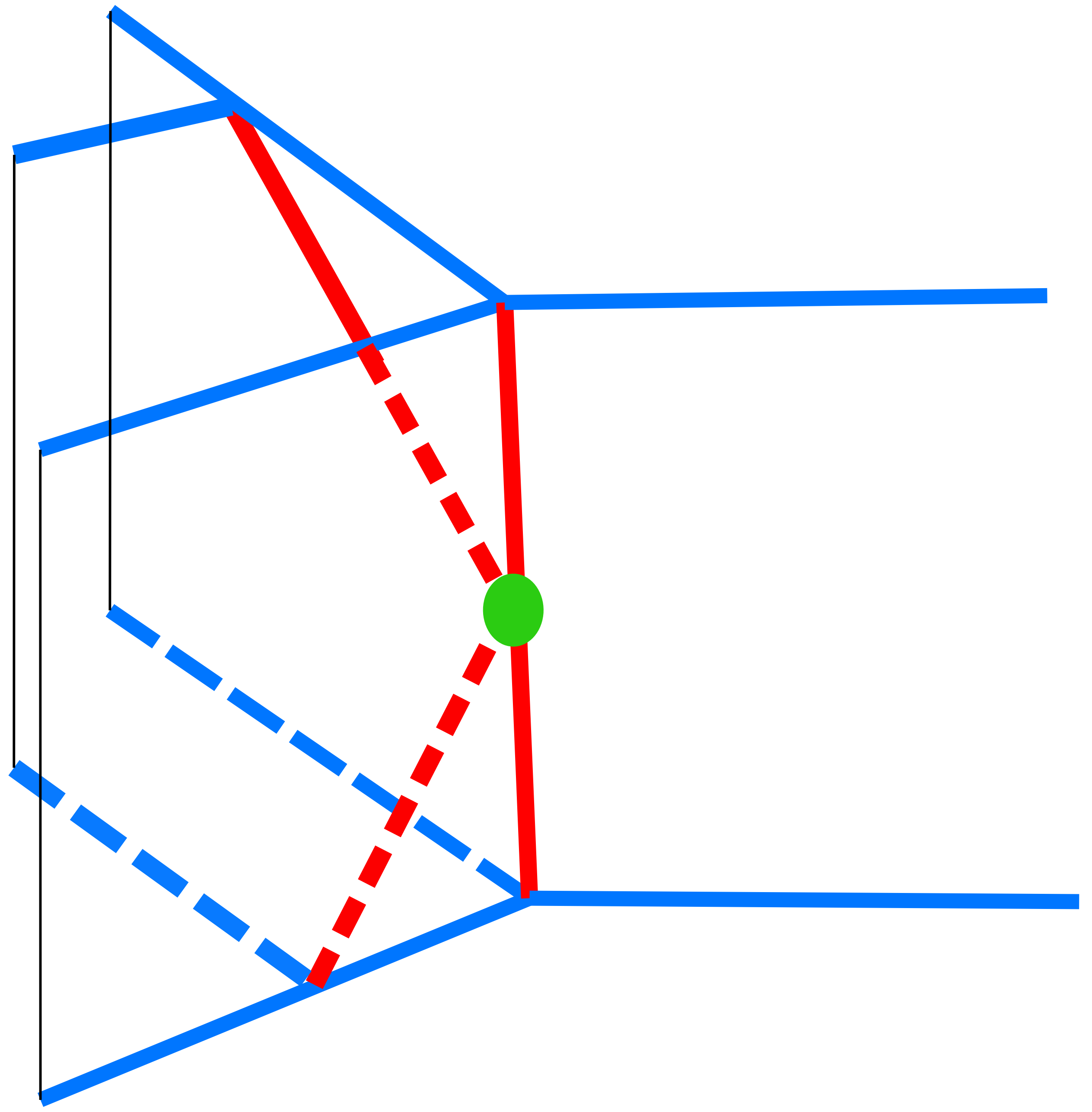
Example





$$\eta \in \mathscr{C}^{(2)}(D_{ab} \otimes D_c, D_a \otimes D_{bc})$$

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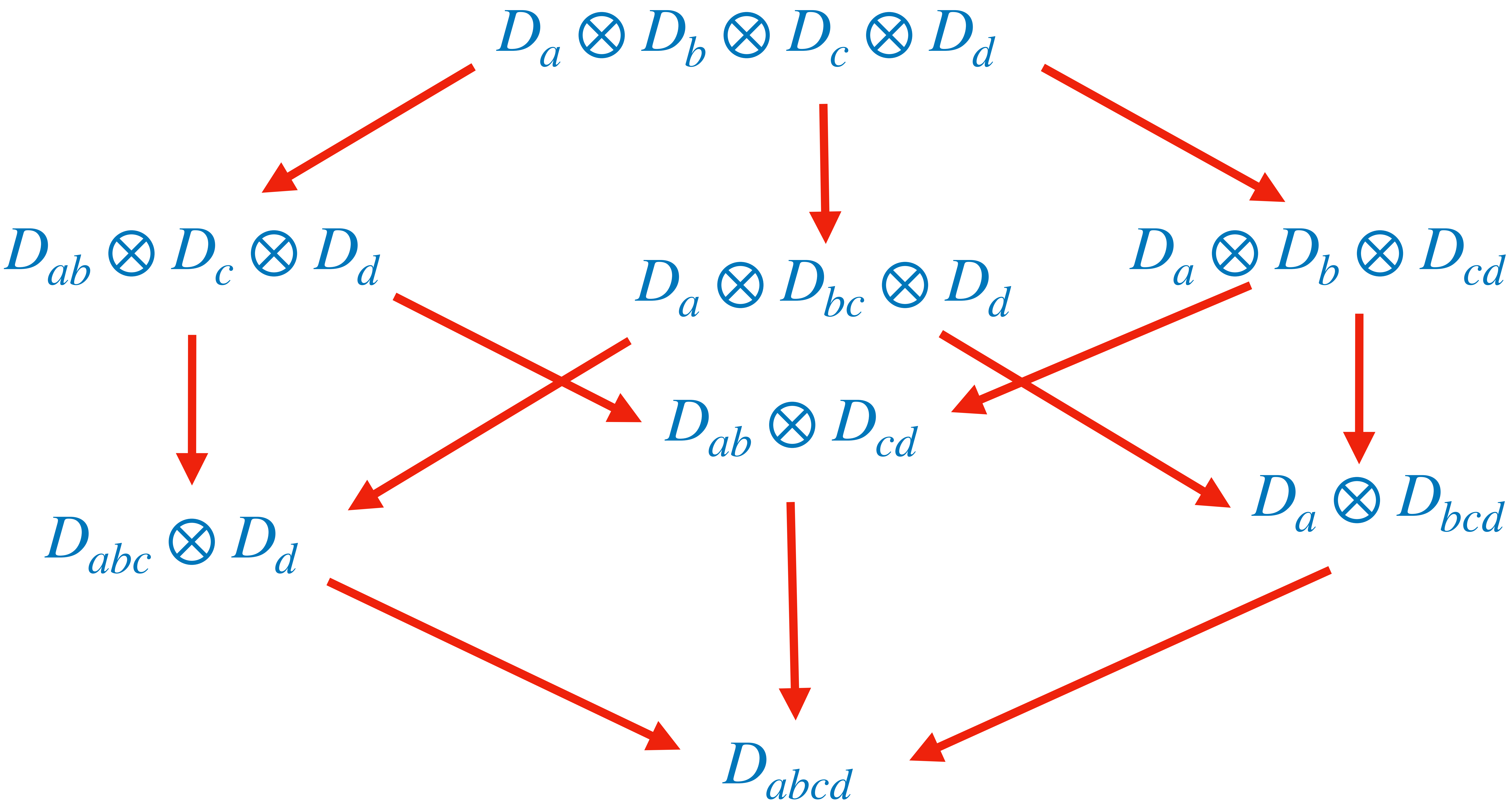
Higher associators

The associativity for (p + 1)-objects gives a p-morphism.



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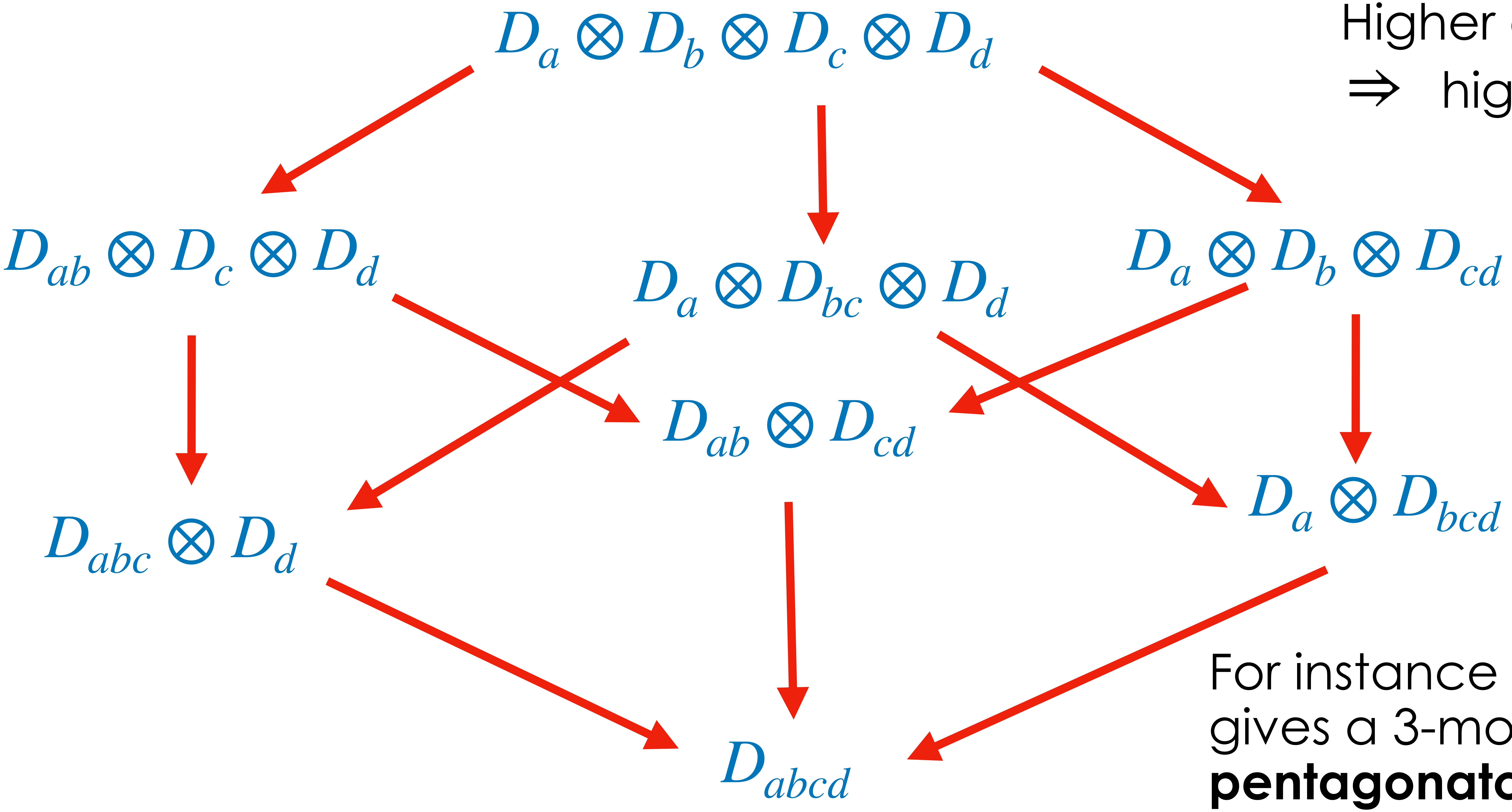

Higher associativity
$\Rightarrow$ higher codimension

For instance this diagram gives a 3-morphism (the **pentagonator**).

Gauging and Condensates

Feature of N-fusion categories for N>1: can form **condensates**

Gaiotto, Johnson-Freyd 19
Roumpedakis, Seifnashri, Shao 22

i.e. one can build lower codimension defects from higher condimension ones via the **higher gauging procedure**

For each **p-gaugeable** $\mathbb{A} \subseteq \mathscr{C}^{(k)}$ consistent higher structure requires

$$C_{\mathbb{A}}(\Sigma^{D+1-p}) \in \mathscr{C}^{(p)}$$

Σ^{D+1-p}

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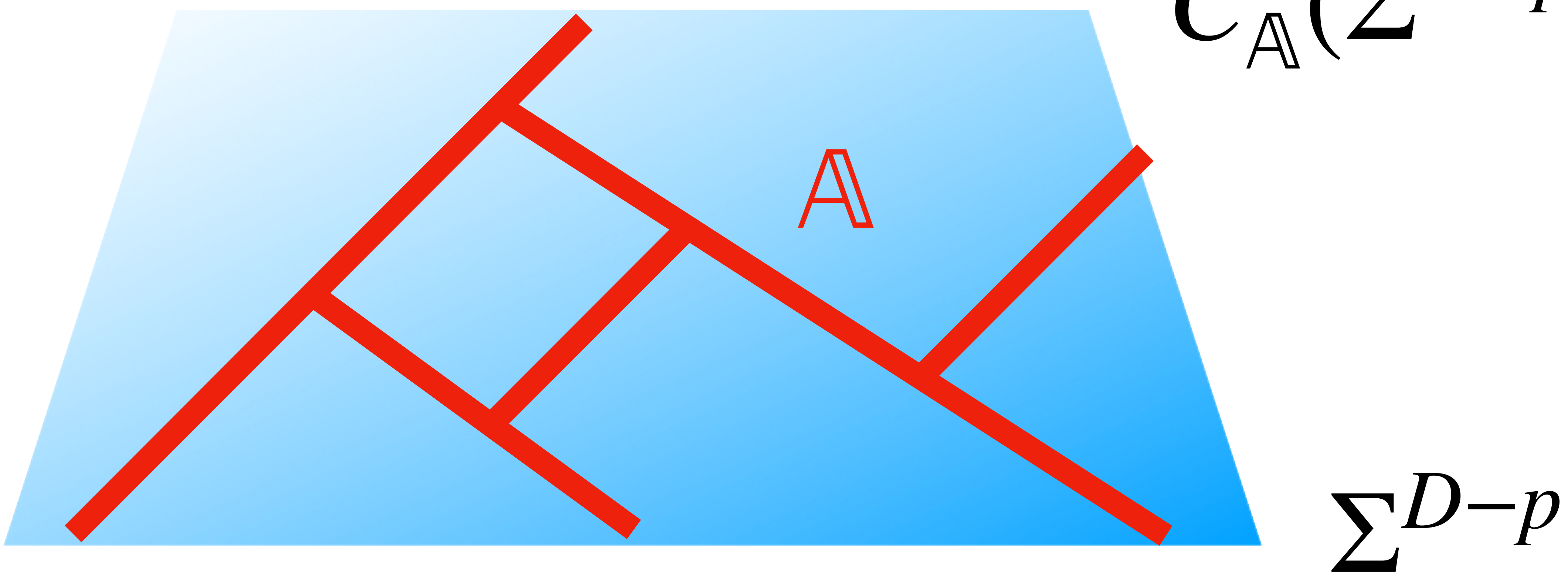

Obtained by inserting a mesh of $\mathbb{A}$ on a triangulation of Σ^{D-p}

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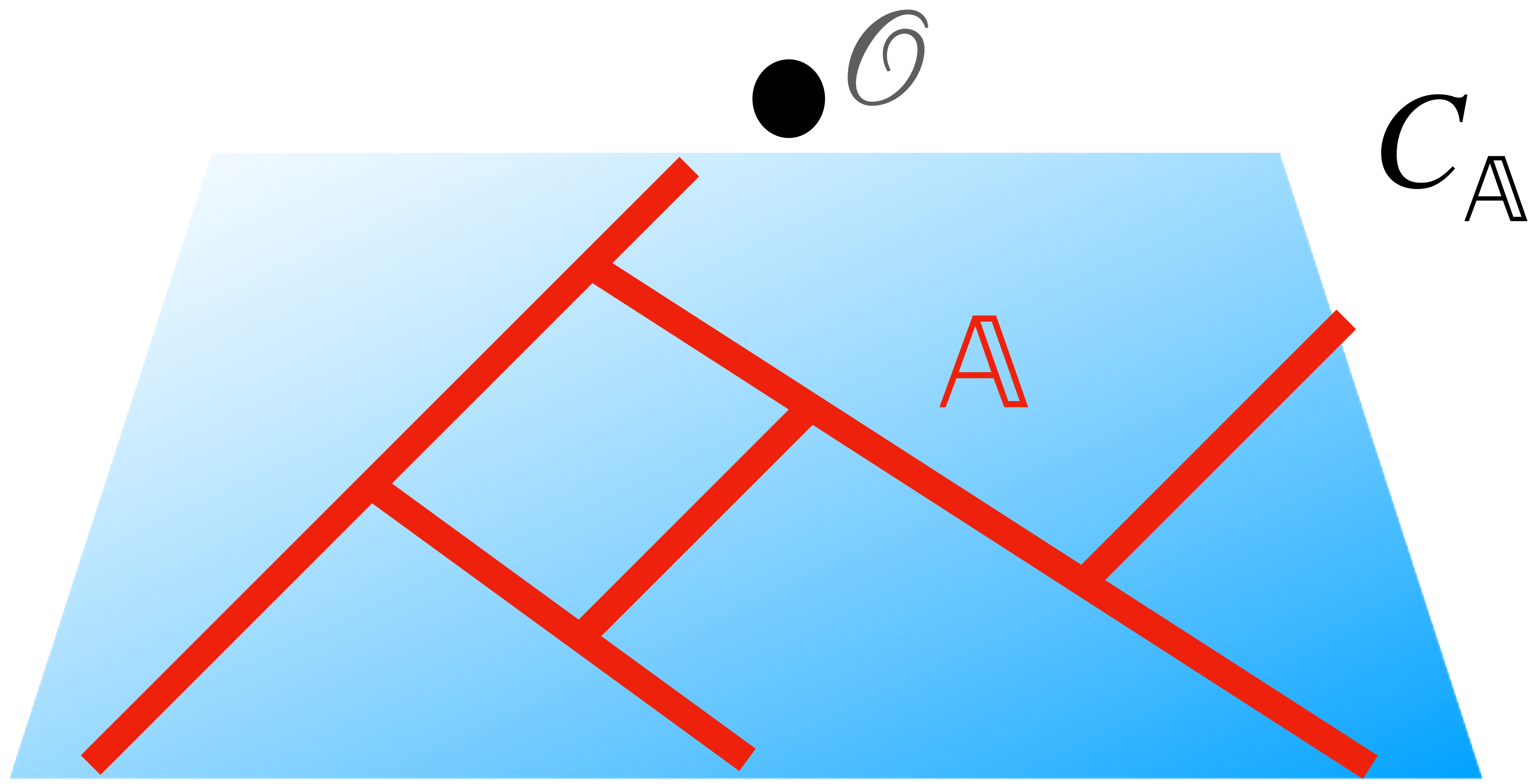

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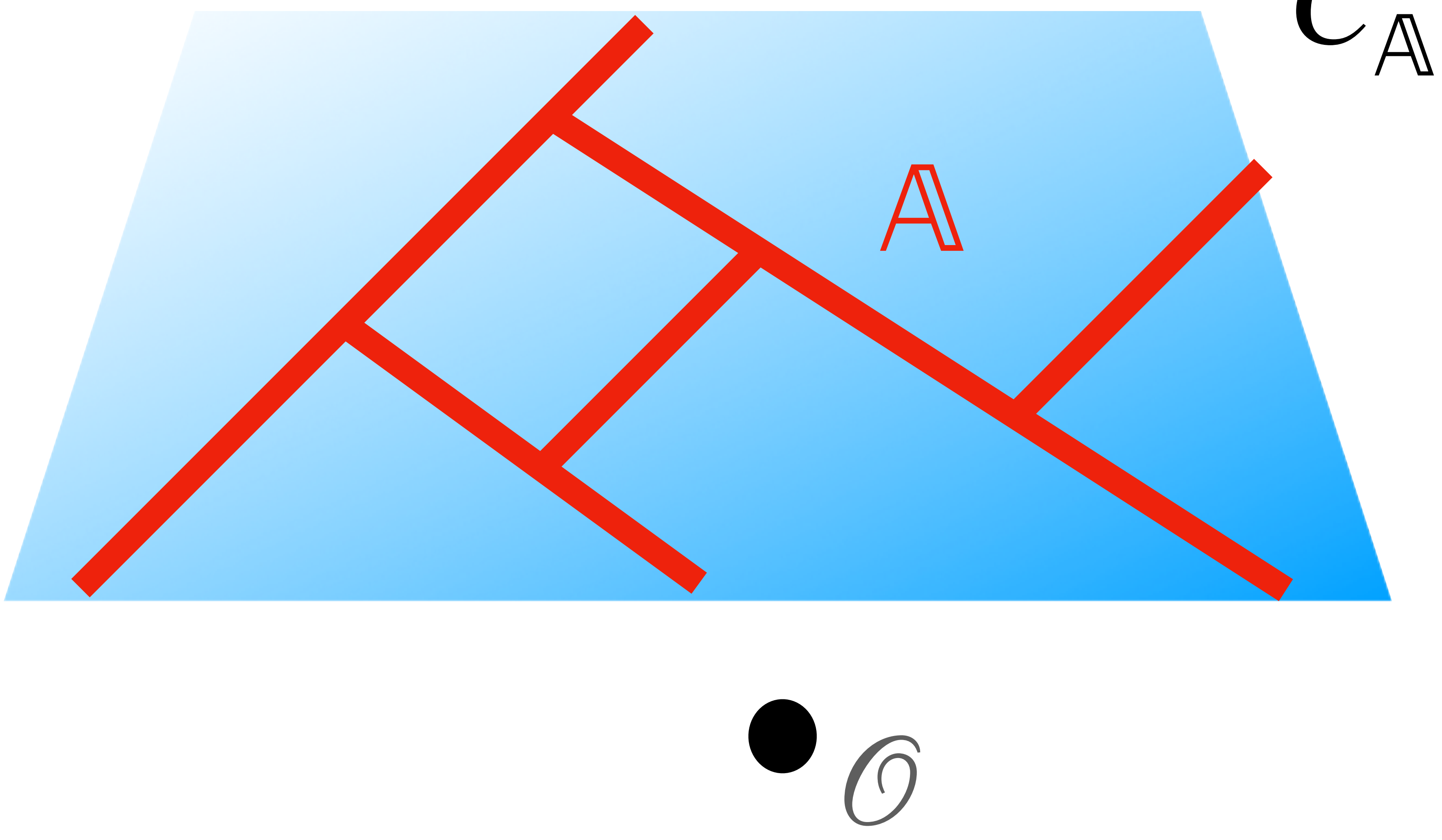

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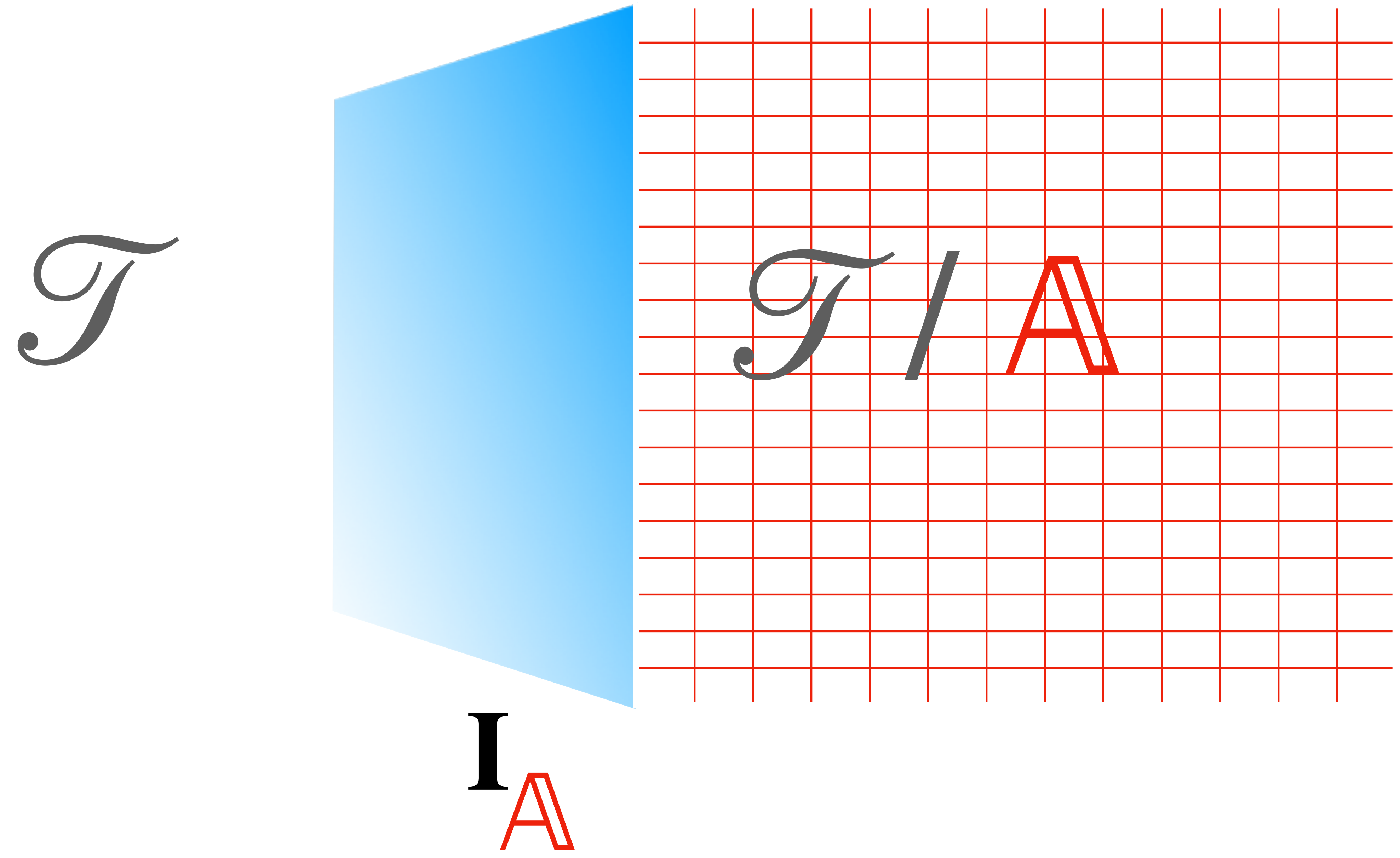
This gives useful way of building topological interfaces



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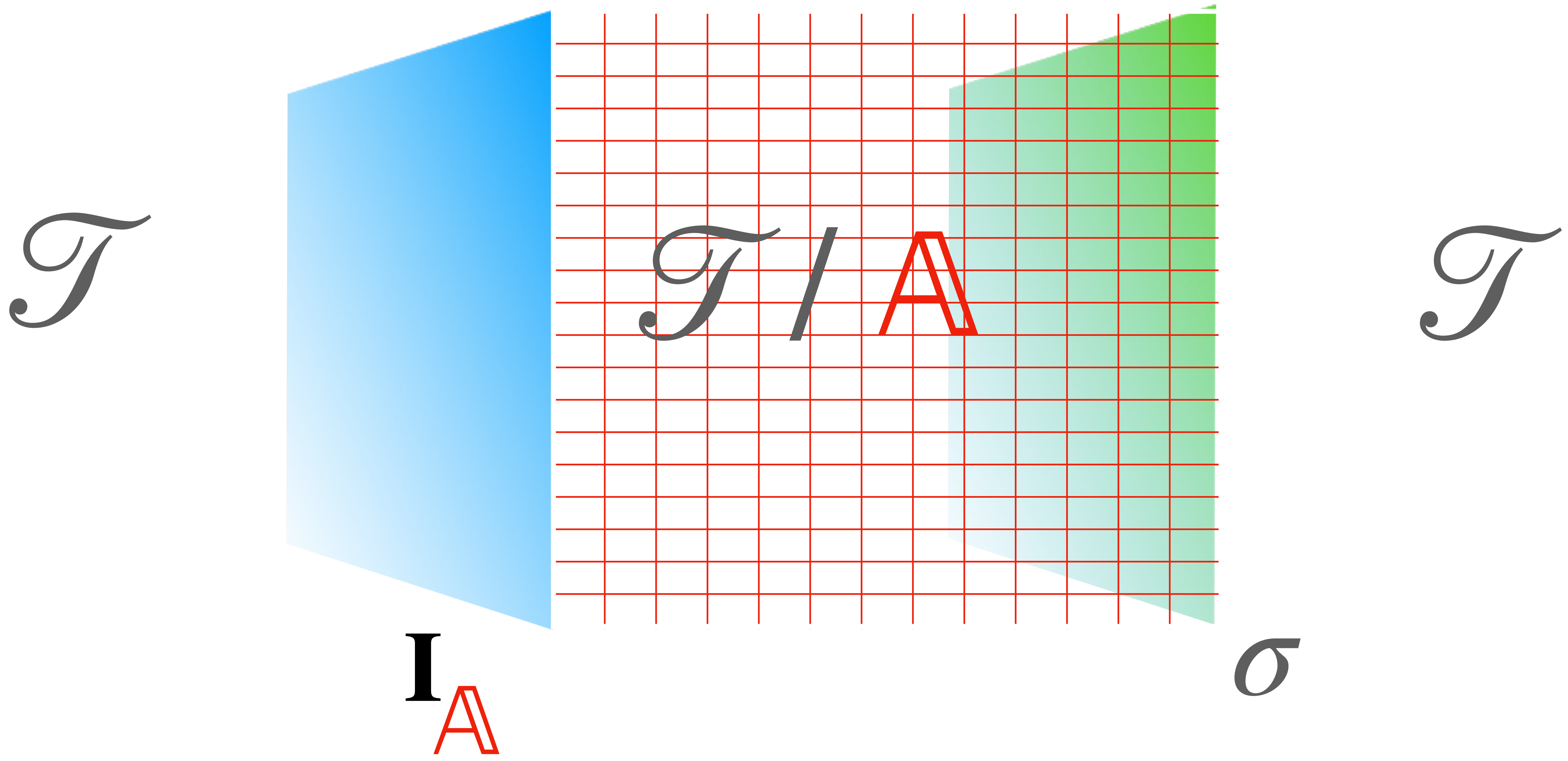

When the theory $\mathscr{T}$ is such that it has an equivalence $\sigma : \mathscr{T} \cong \mathscr{T}/\mathbb{A}$

One obtains a **duality defect** from composition

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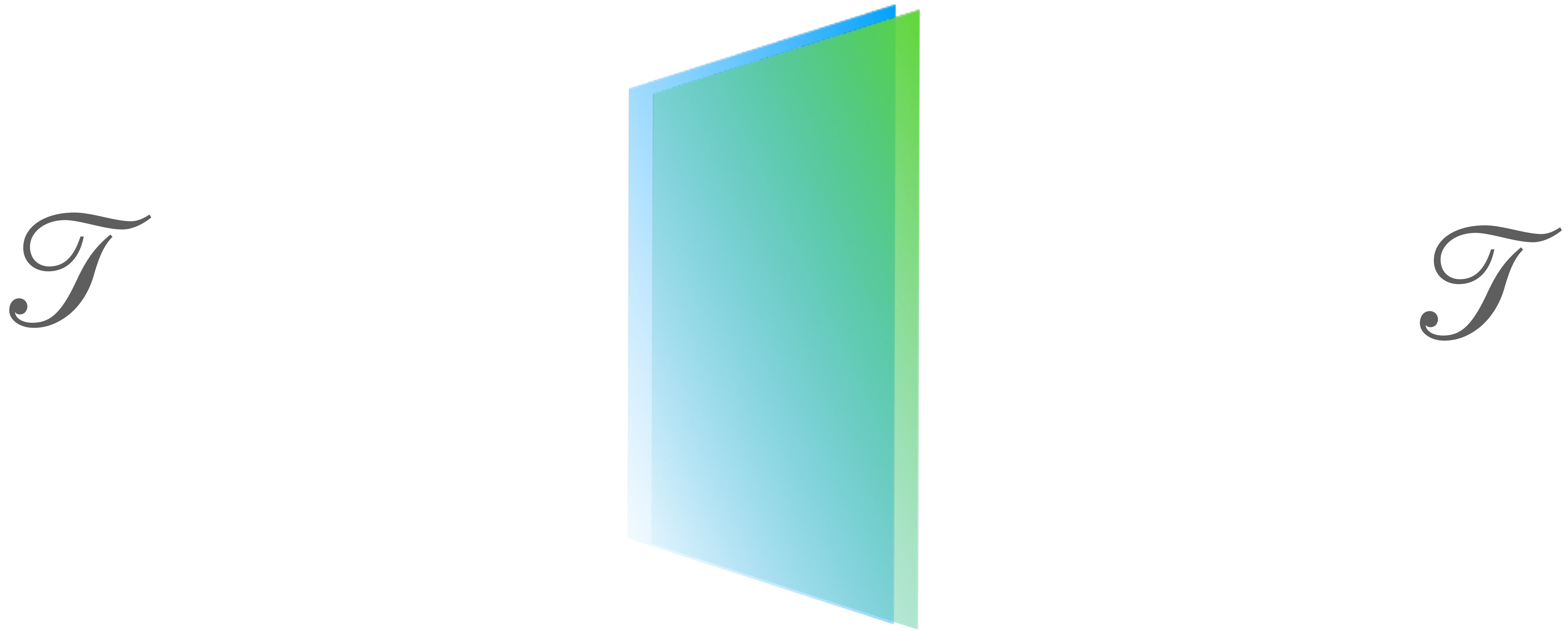

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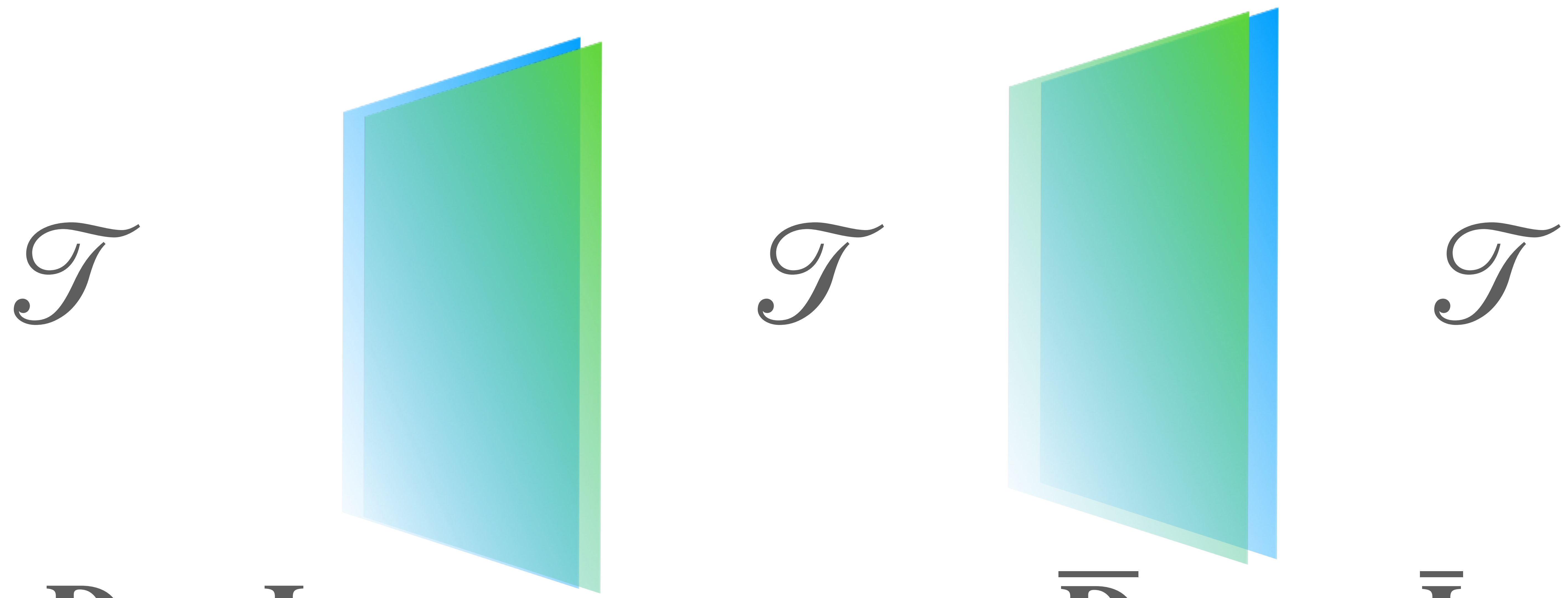

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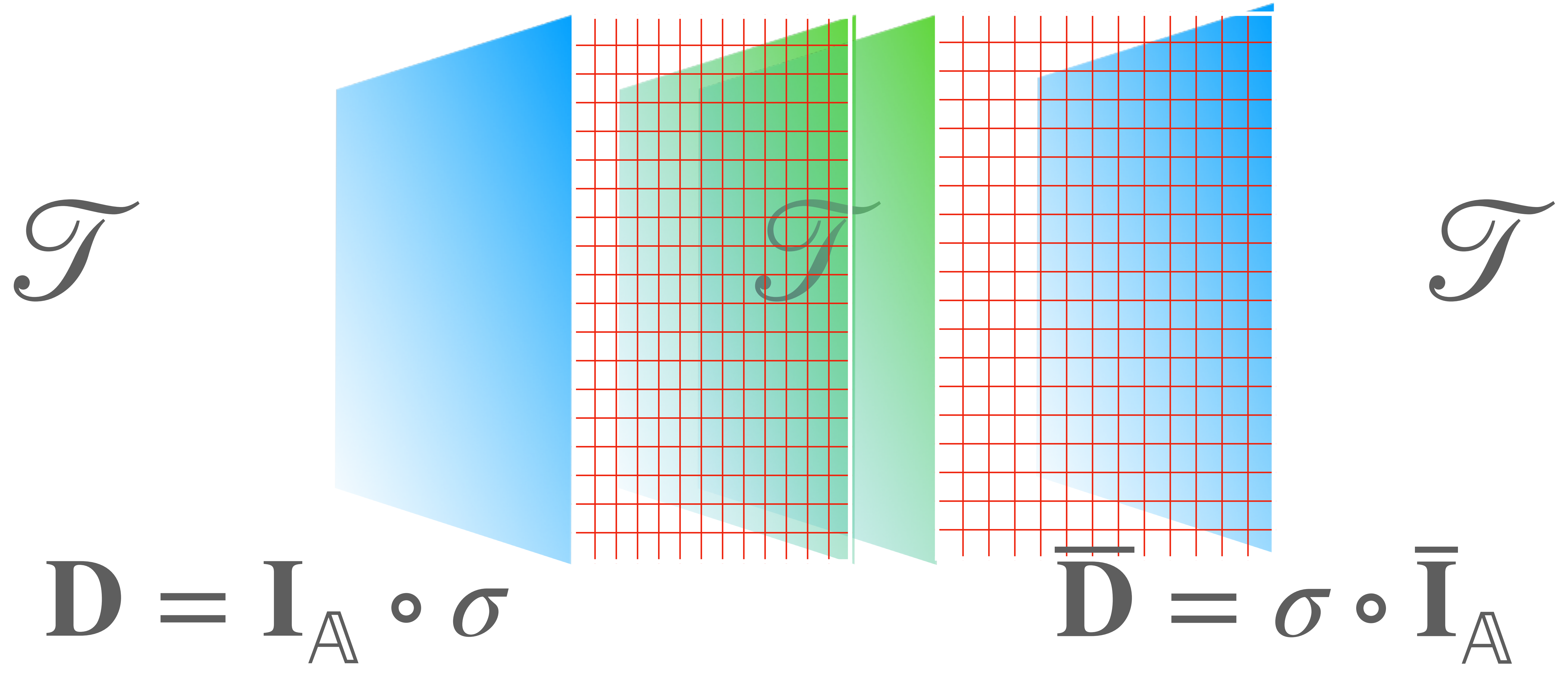

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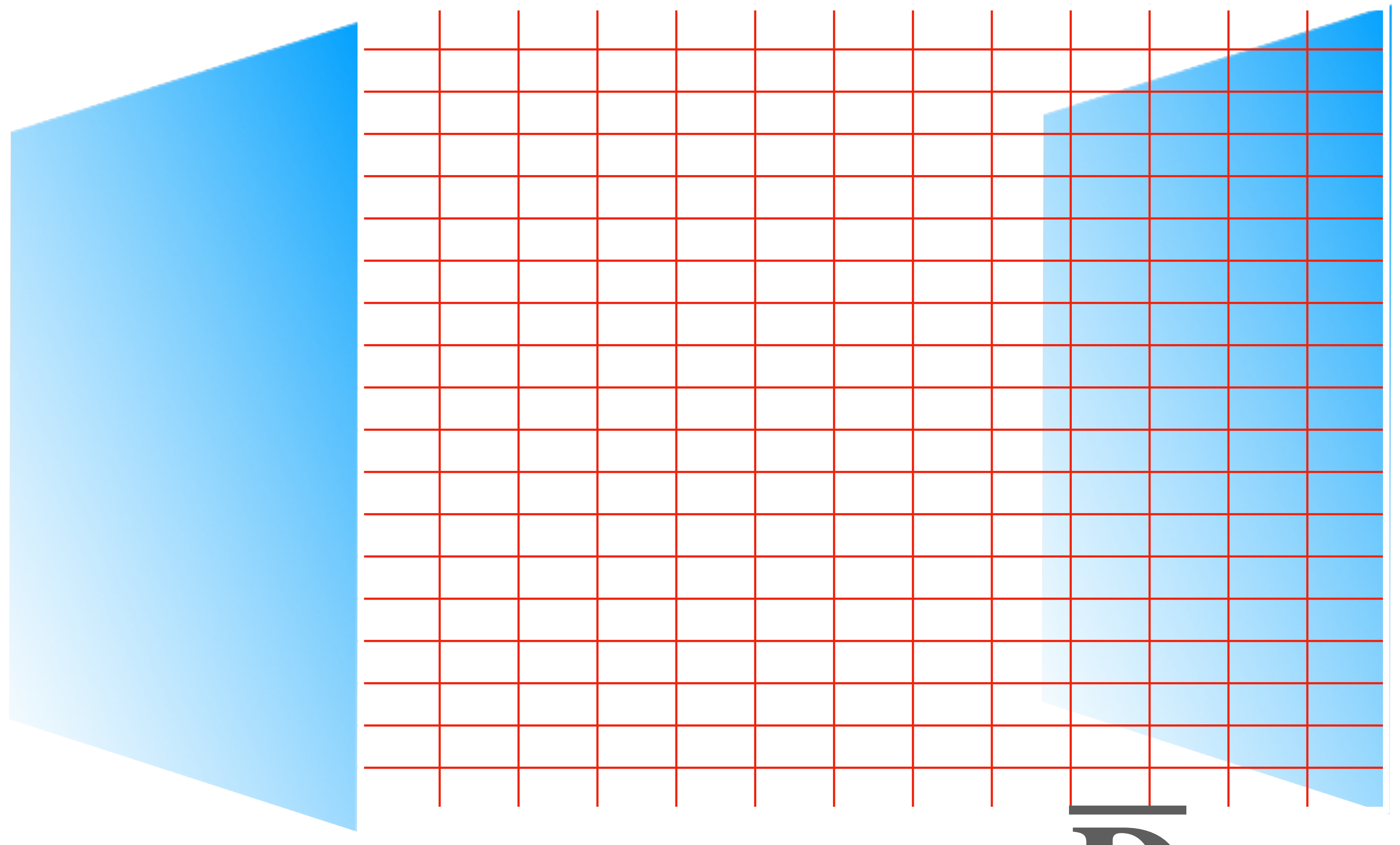

$\mathscr{T}$ $\qquad$ $\mathscr{T}$

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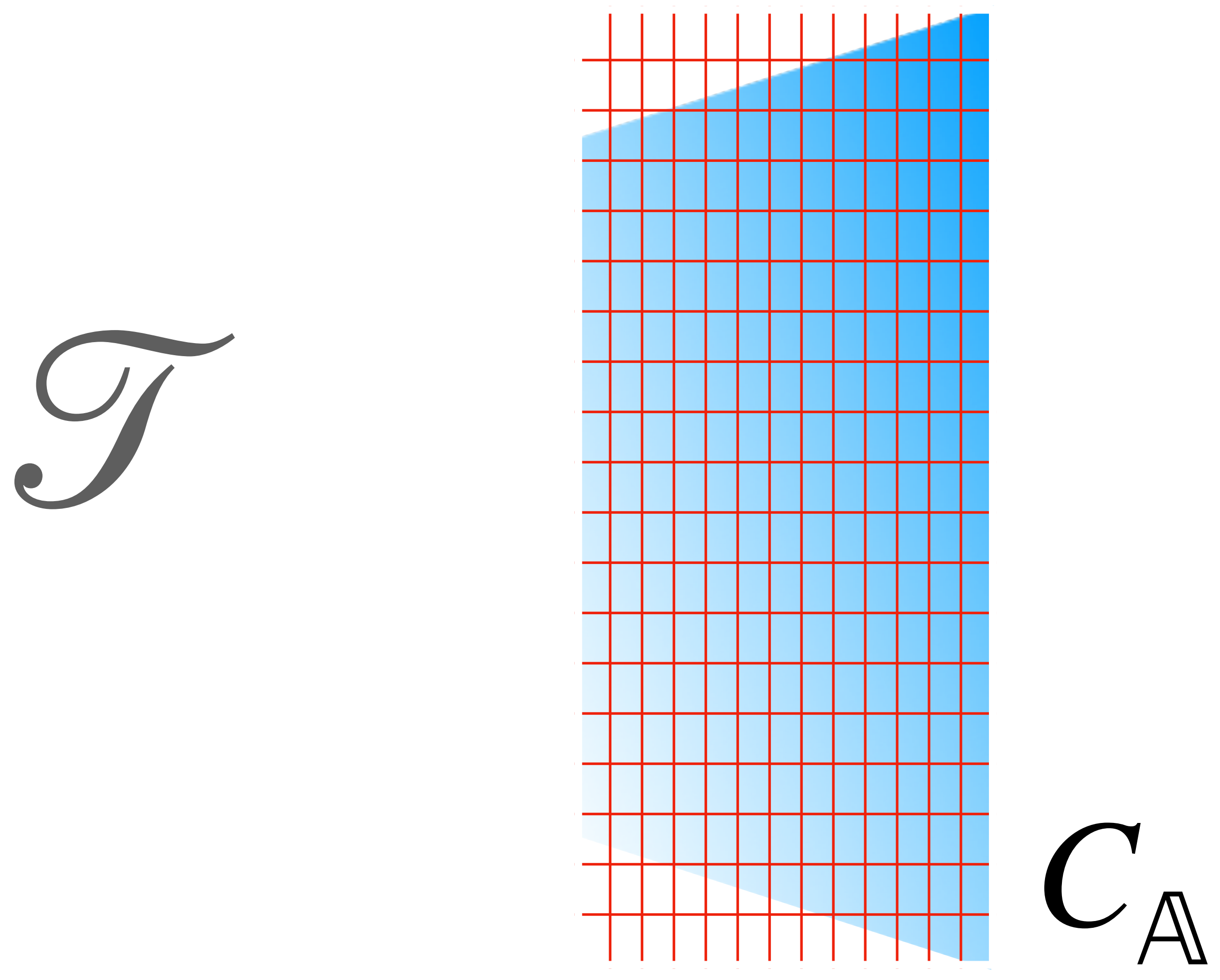


When the theory $\mathcal{T}$ is such that it has an equivalence $\boldsymbol{\sigma} : \mathcal{T} \cong \mathcal{T}/\mathbb{A}$

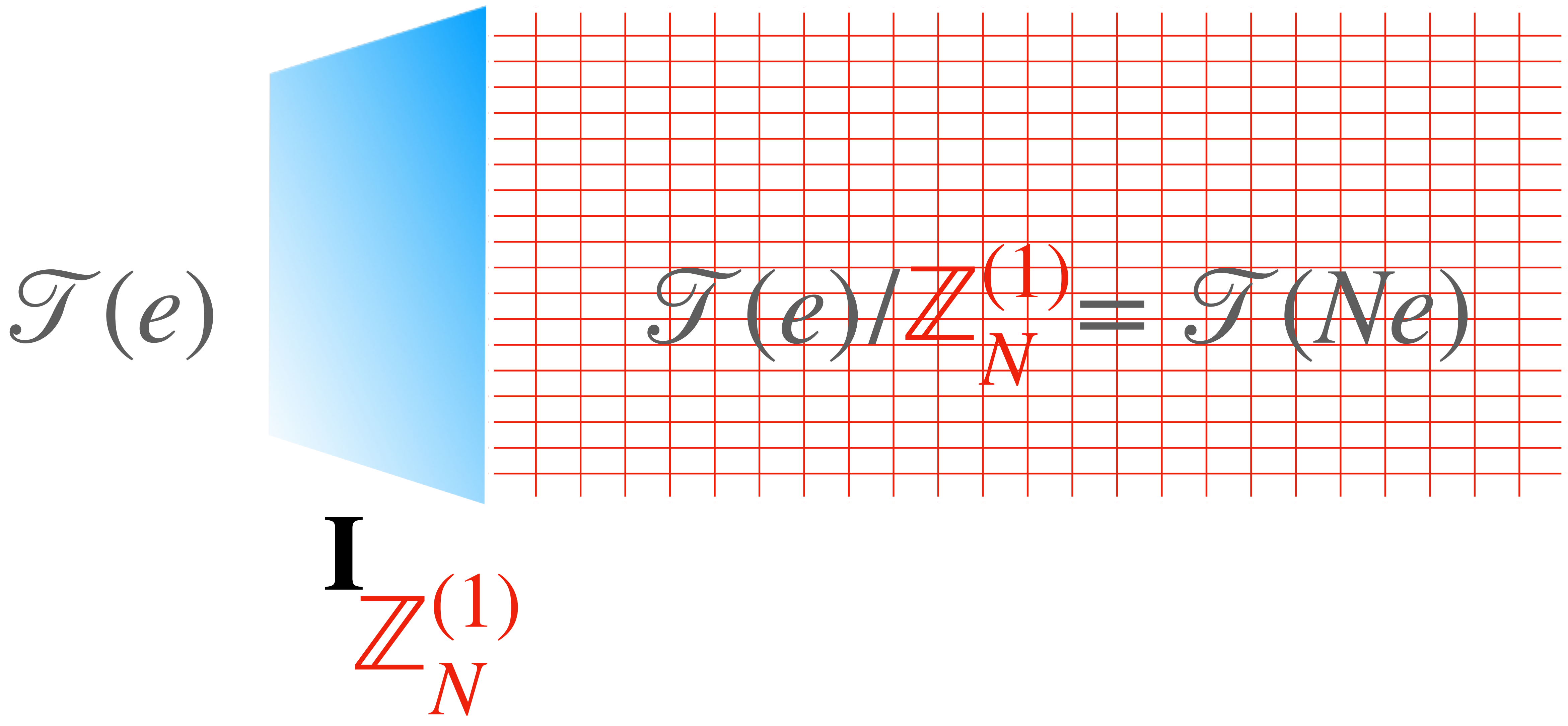
Iterating one obtains fusion rule $\mathbf{D} \otimes \overline{\mathbf{D}} = C_{\mathbb{A}}$

Example: Maxwell Theory

Consider gauging a $\mathbb{Z}_N^{(1)}$ subgroup of $U(1)_e^{(1)}$

This has the same effect as shifting the gauge potentials

$$a \to \frac{1}{N}a \qquad a_D \to N a_D \qquad e \to Ne$$



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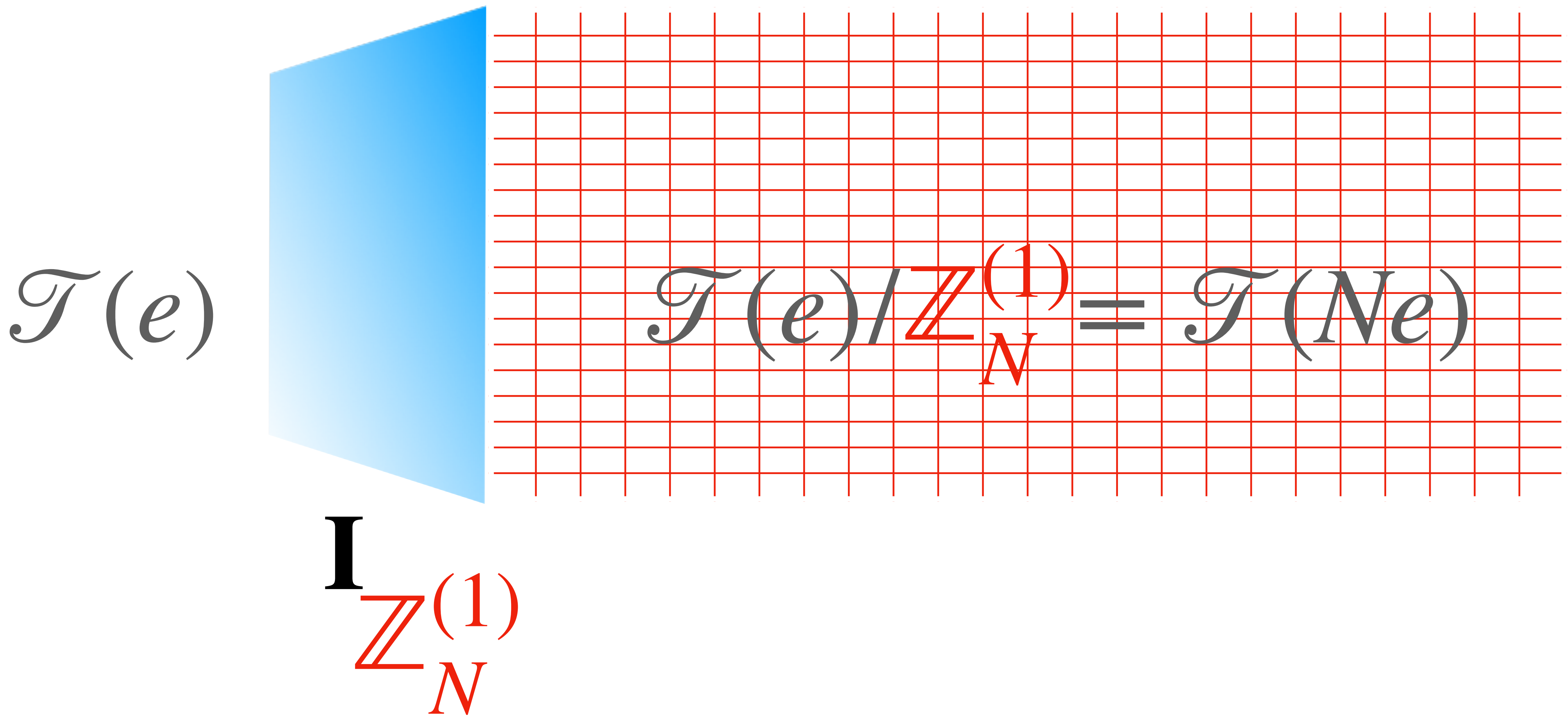
EM duality

$$\mathcal{T}(Ne) \cong \mathcal{T}(2\pi/Ne)$$

$$\Rightarrow \; e_* = \sqrt{2\pi/N}$$



Gives an equivalence

$\Rightarrow \; \mathcal{T}(e_*)$ has duality defects

Many more examples can be realized

- Using SYM at the self dual coupling $\tau = i$ one has the equivalence

$$SU(N) \cong PSU(N) = SU(N)/\mathbb{Z}_N$$

Cordova, Choi, Shao 21
Kaidi, Ohmori, Zheng 21

- Many more examples can be constructed exploiting class S theories at special points of their moduli spaces

$$\mathscr{X}^{6D}_{(2,0)}/\Sigma_{g,p}$$

Bashmakov, Del Zotto, Hasan 22

In particular one finds examples of n-ality defects, and generalized duality defects labeled by non-abelian finite groups in this way

Bashmakov, Del Zotto, Hasan, Kaidi 22
Antinucci, Copetti, Galati, Rizi 22

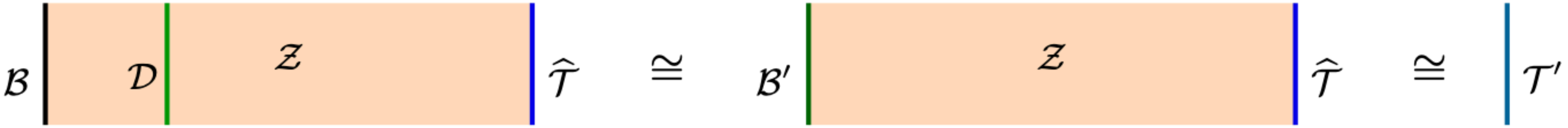
Symmetry theory

Idea: topological operators are encoded in a D+2 dimensional TFT

Kapustin Seiberg 14
Gaiotto, Kulp 20
Apruzzi, Bonetti, Garcia-Etxebarria, Schafer-Nameki, Hosseini 21
Freed, Moore, Teleman 22

Bhardwaj, Shafer-Nameki 23 (many)

- Separates the topological symmetry data from the theory
- Allows to import techniques from TFT (cobordism hypothesis)
- Gives generalization of 't Hooft anomaly matching
- Streamlines construction of duality defects:



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Associativity condition with codimension higher than the defect worldvolume itself ⟶ If non trivializable becomes **obstruction to gauging**

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Examples:

1. **Quantum mechanics:** by Wigner $\mathscr{H}$ can be in a projective representation: symmetry operators are inserted at points and associativity itself measures the anomaly

2. **QFT in 1+1:** symmetries are lines, associativity is encoded by F-symbol, consistency of F-symbol is encoded by pentagonator. When symmetry is a group, pentagonators are parametrized by class in $H^3(\mathbb{G}, U(1))$ which is the standard anomaly

Higher associators - continued

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Other notion: theory cannot have **trivial gapped symmetric phase**.

For non-invertible symmetries the two notions don't coincide and the second is more restrictive

Choi, Rayhuan, Sanghavi, Shao 23
Cordova, Hsin, Zheng 23
Antinucci, Benini, Copetti, Rizi 23

Chiral Symmetry

Choi, Lam, Shao 22
Córdova, Ohmori 22

Consider 3+1 dimensional QFT with $U(1)^{(1)}$ symmetry and a 1-form that satisfies an anomalous conservation equation of the ABJ type

$$d \star j_\chi^{(1)} = \star j^{(2)} \wedge \star j^{(2)}$$

Then **there is** a symmetry for wannabe $U(1)_\chi^{(0)}$ quantum numbers

Generators:

$$D_{p/N}^{(0)}(\Sigma^3) = \mathcal{U}^\chi_{p/N} \otimes \mathcal{A}^{N,p}[b] \qquad b = \frac{2\pi}{N} \star j^{(2)}$$

chiral rotation generator

Hsin-Lan-Seiberg minimal 3d $\mathbb{Z}_N$ TFT

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Choi, Lam, Shao 22
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$D^{(0)}_{p/N}(\Sigma^3)$ = [p,N]

$U^{(1)}_\alpha(\Sigma^2)$ 1-form symmetry

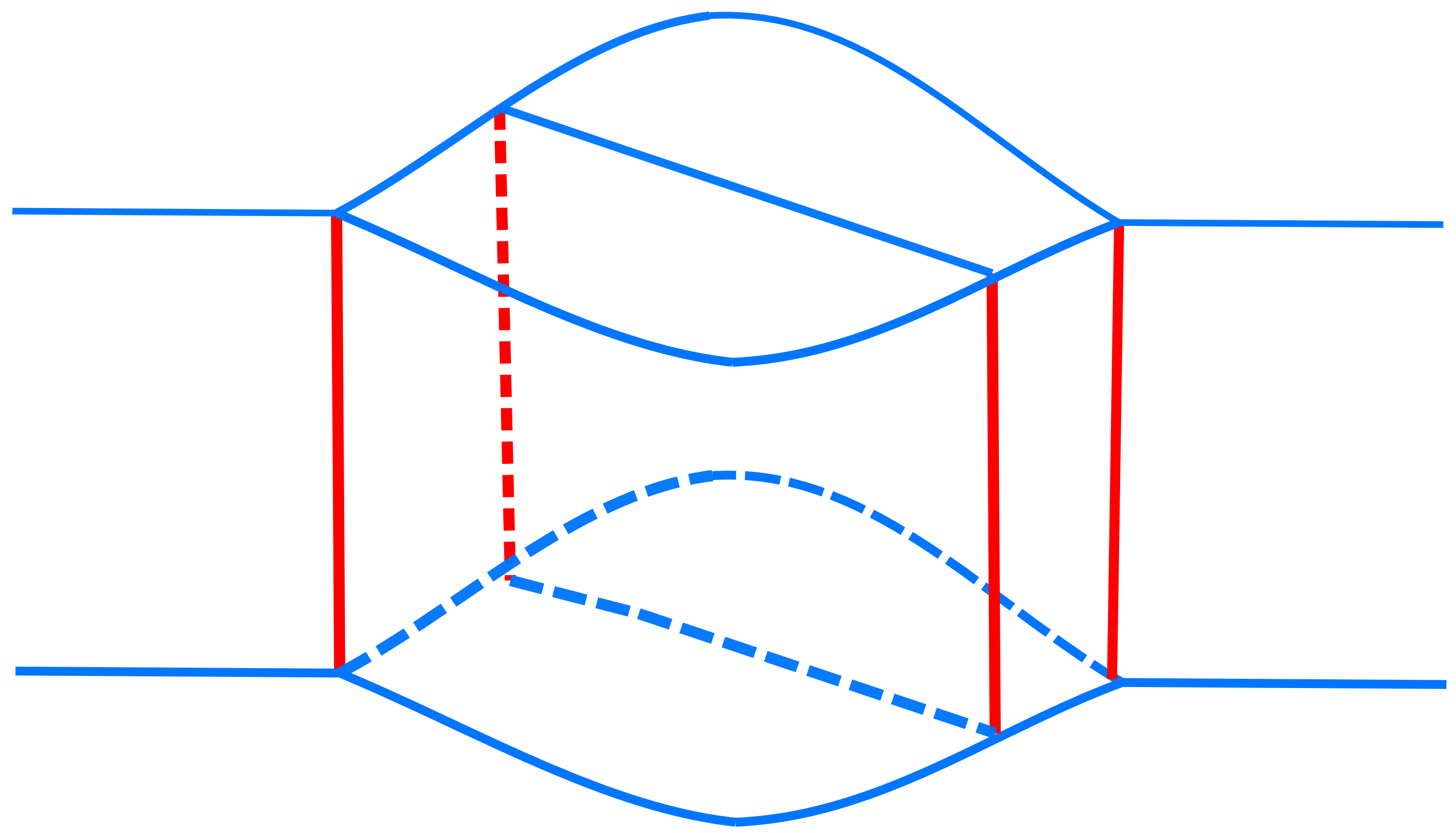
$C^{(1)}_L(\Sigma^2)$ $\mathbb{Z}^{(1)}_L$ subgroup condensates

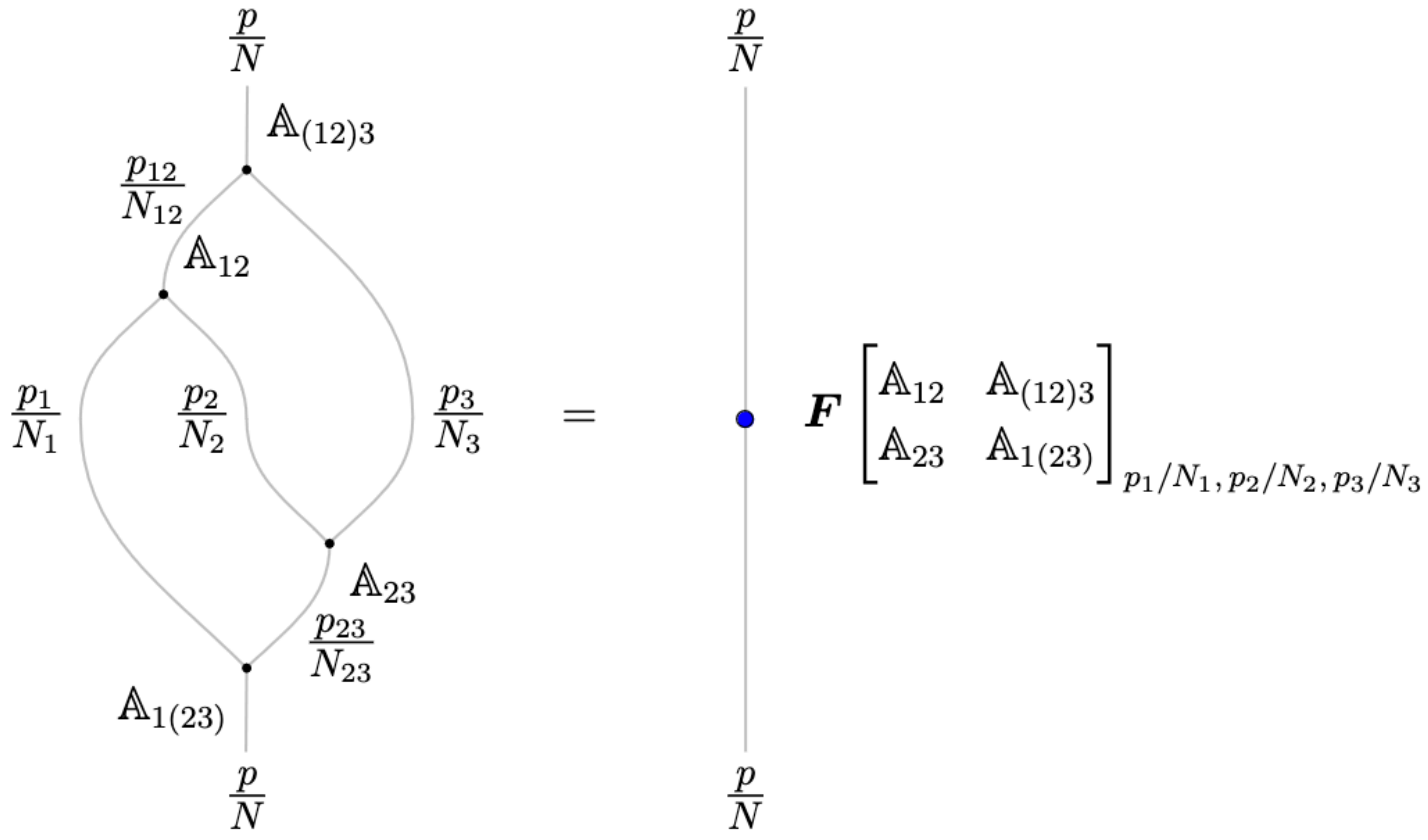
$C^{(0)}_{L,\alpha}(\Sigma^3)$

Discrete torsion

$\alpha \in H^3(B\mathbb{Z}_L, U(1))$

Chiral Symmetry Associator





Generators (light notation)

$D^{(0)}_{p/N}(\Sigma^3)$ = [p,N]

$U^{(1)}_{\alpha}(\Sigma^2)$ 1-form symmetry

$C^{(1)}_{L}(\Sigma^2)$ $\mathbb{Z}^{(1)}_{L}$ subgroup condensates

$C^{(0)}_{L,\alpha}(\Sigma^3)$

Discrete torsion

$\alpha \in H^3(B\mathbb{Z}_L, U(1))$

2d case: Bhardwaj, Tachikawa 17

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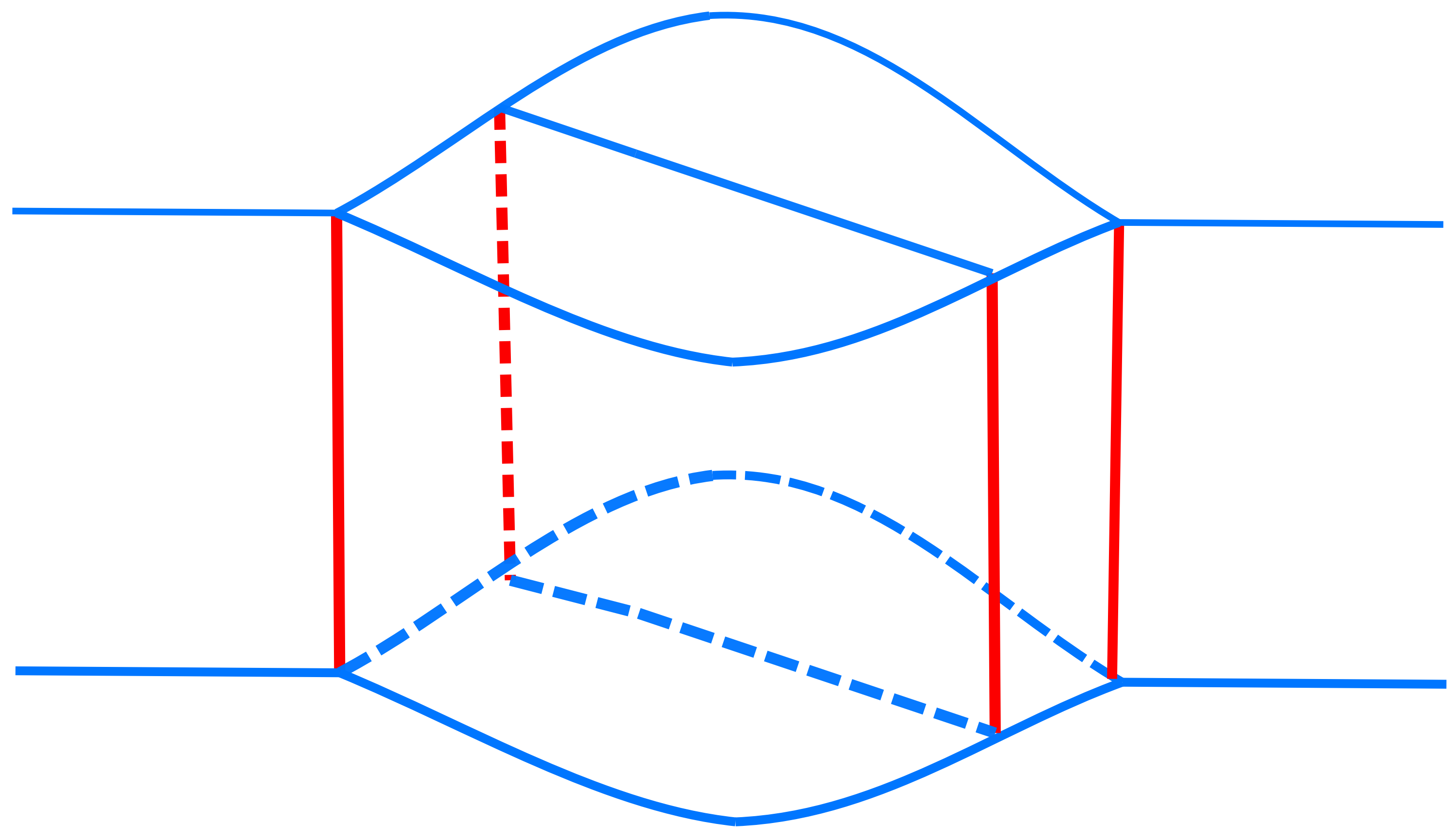
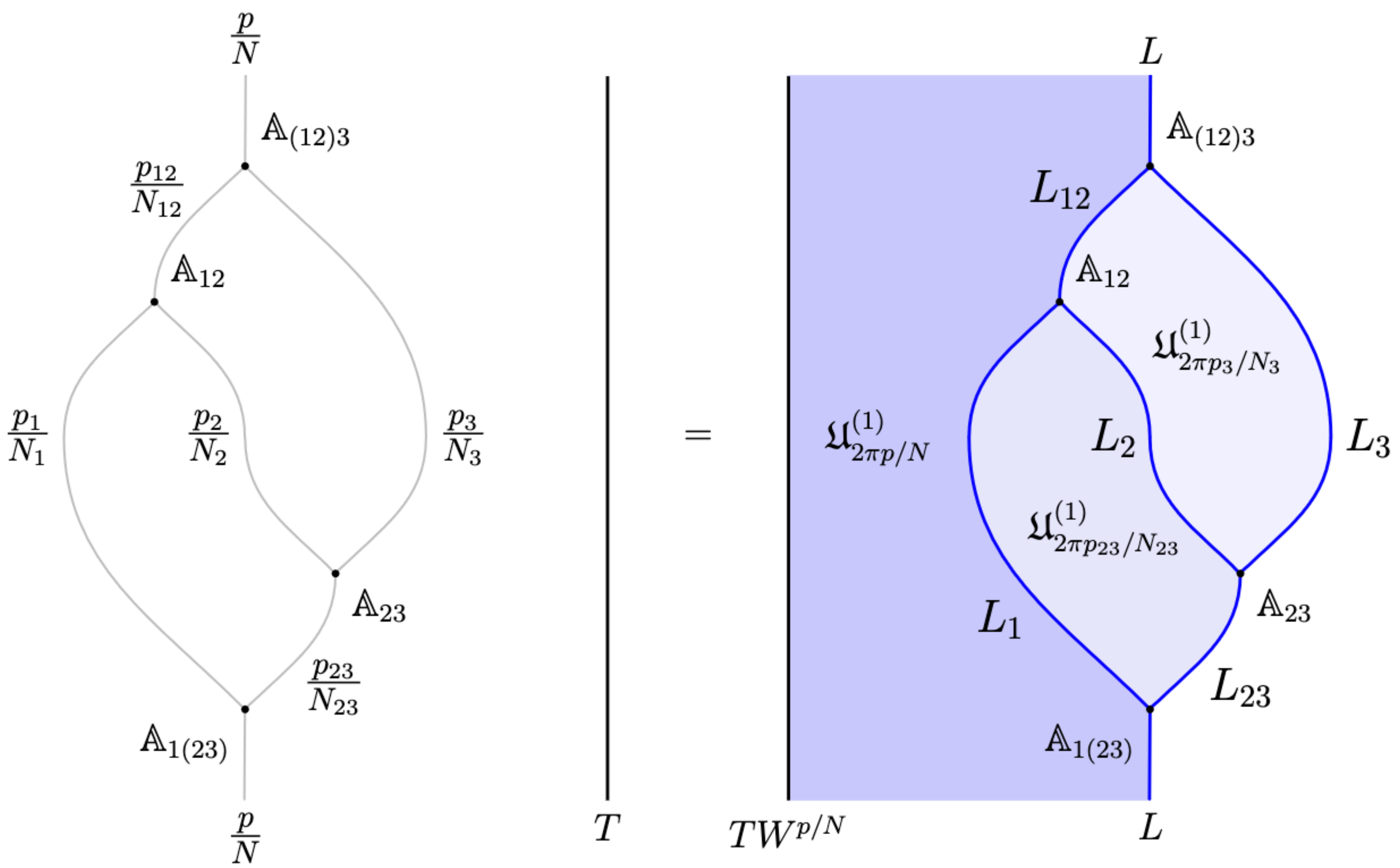


To **detect** the associator: we throw it against a 't Hooft line, which gets dressed by Wilson lines because of the Witten effect



Chiral Symmetry Ward Identity

Consider correlators on $\mathbb{S}^2 \times \mathbb{S}^2$

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A bit hard to visualize 4-manifolds. **IDEA:** draw fourth direction as time.

- **Solid black** we draw $\mathbb{R}^3$
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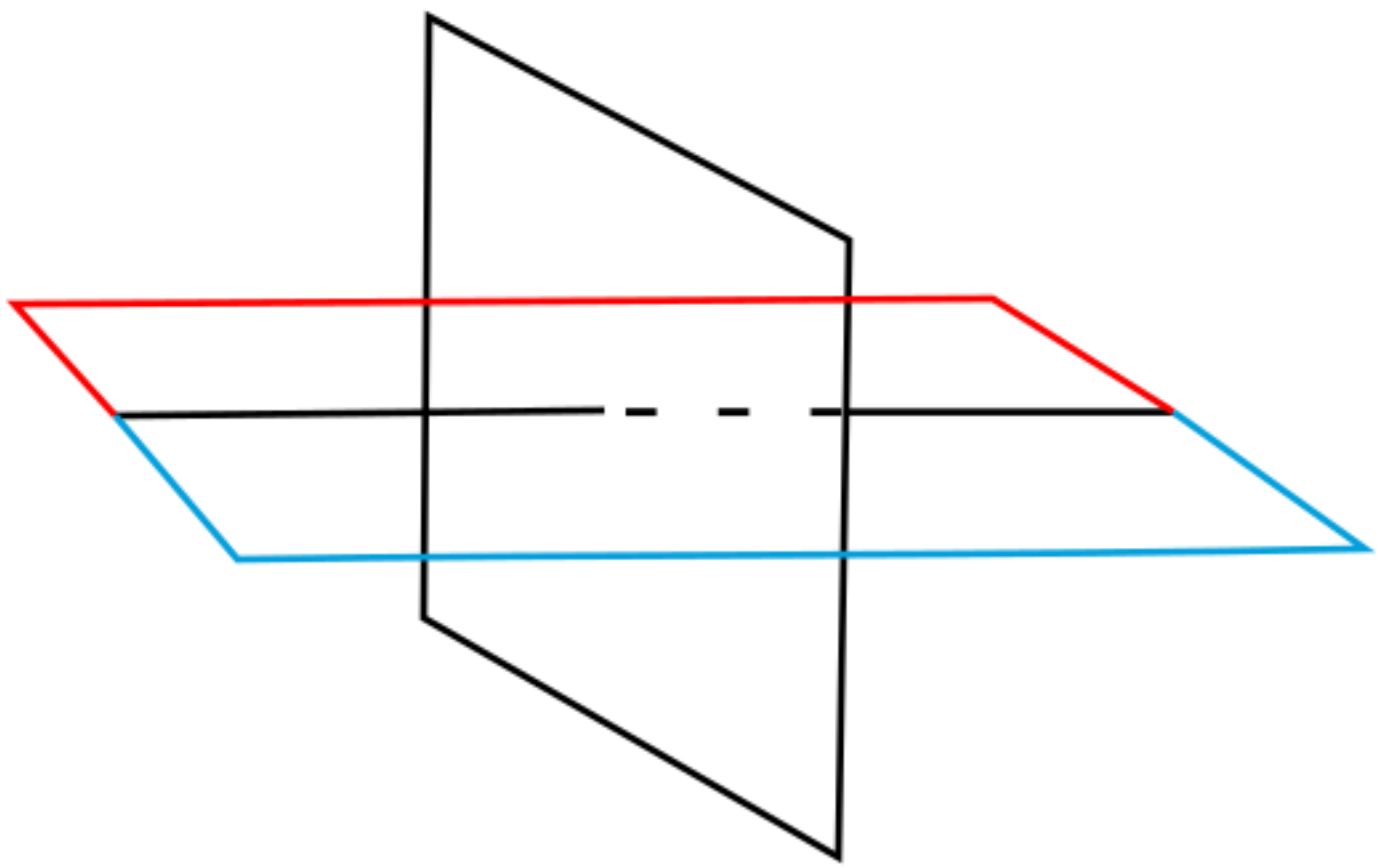

These are two planes intersecting transversally at a point in $\mathbb{R}^4$

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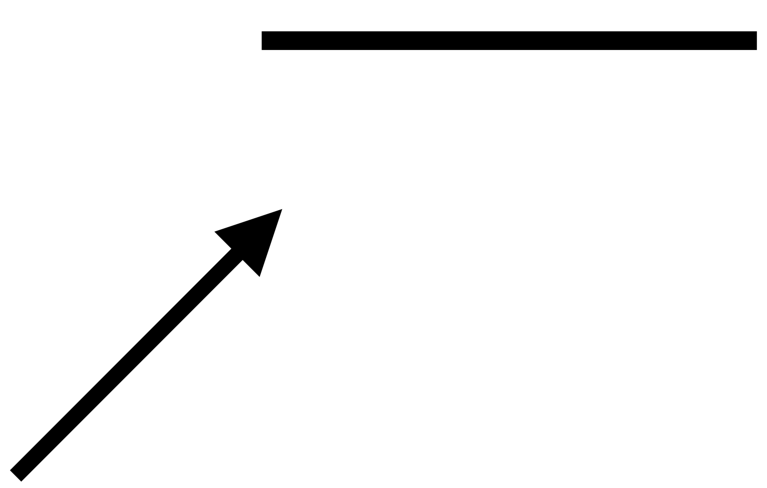

$\mathbb{S}^1$ as an interval with endpoints identified

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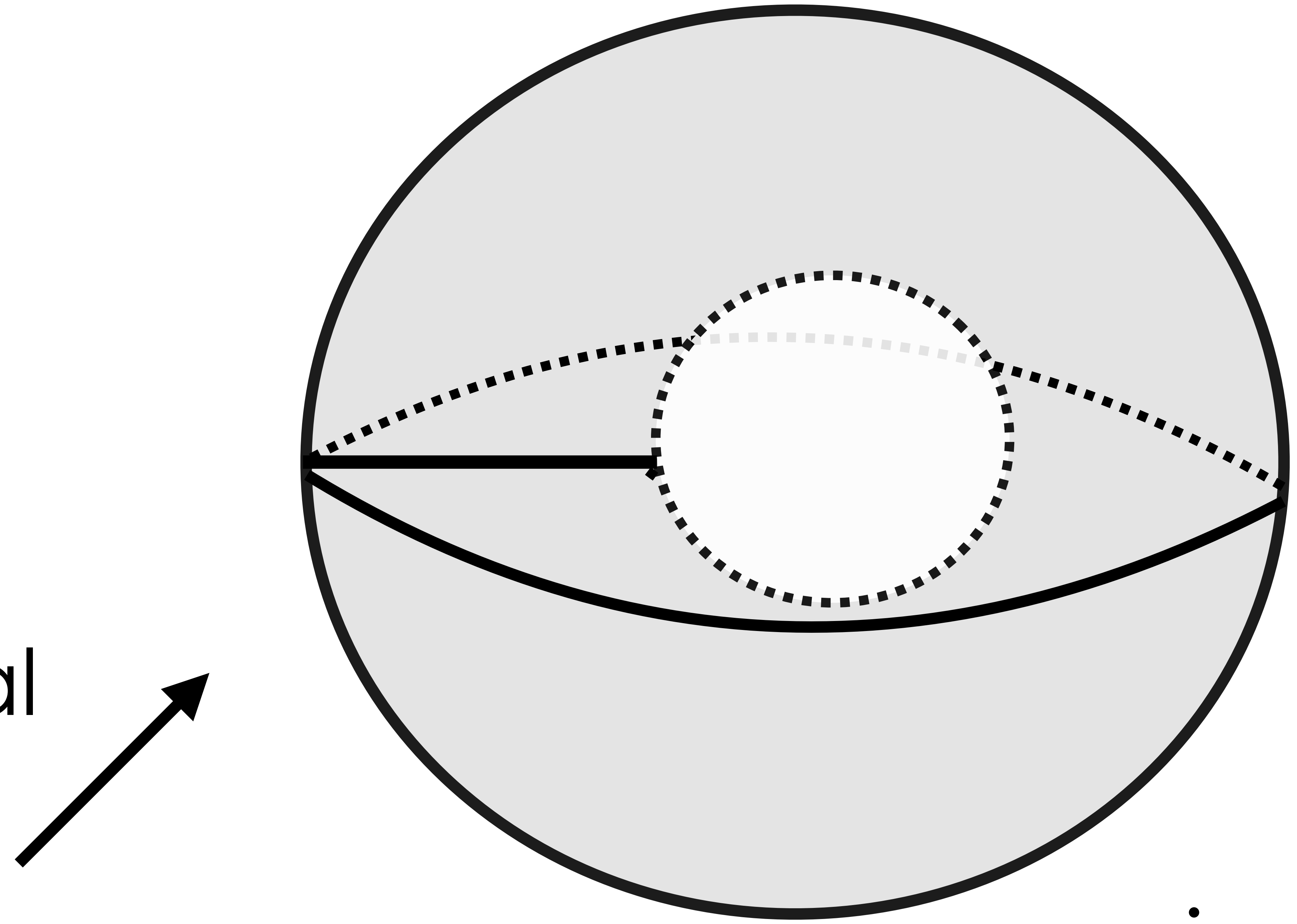

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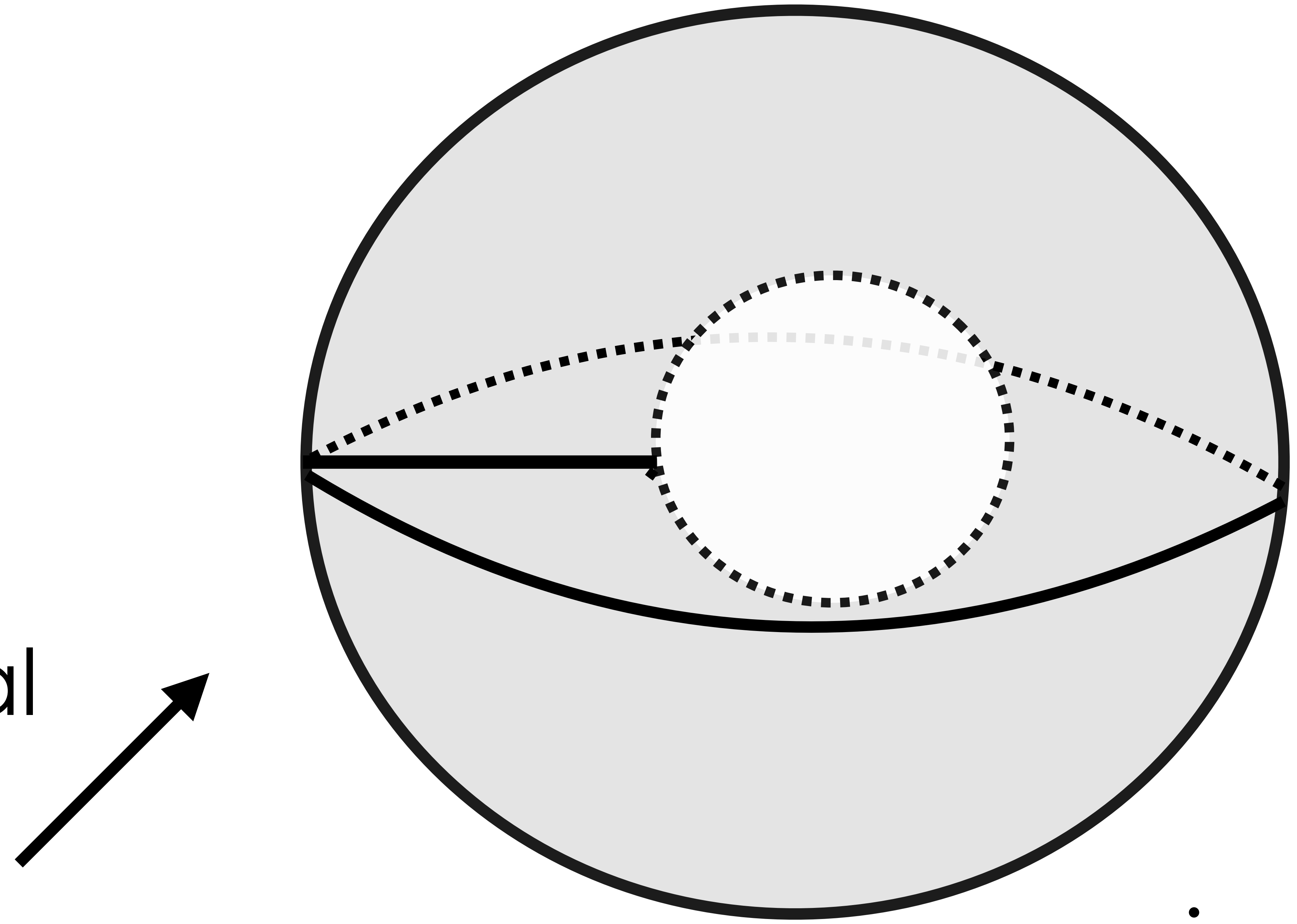

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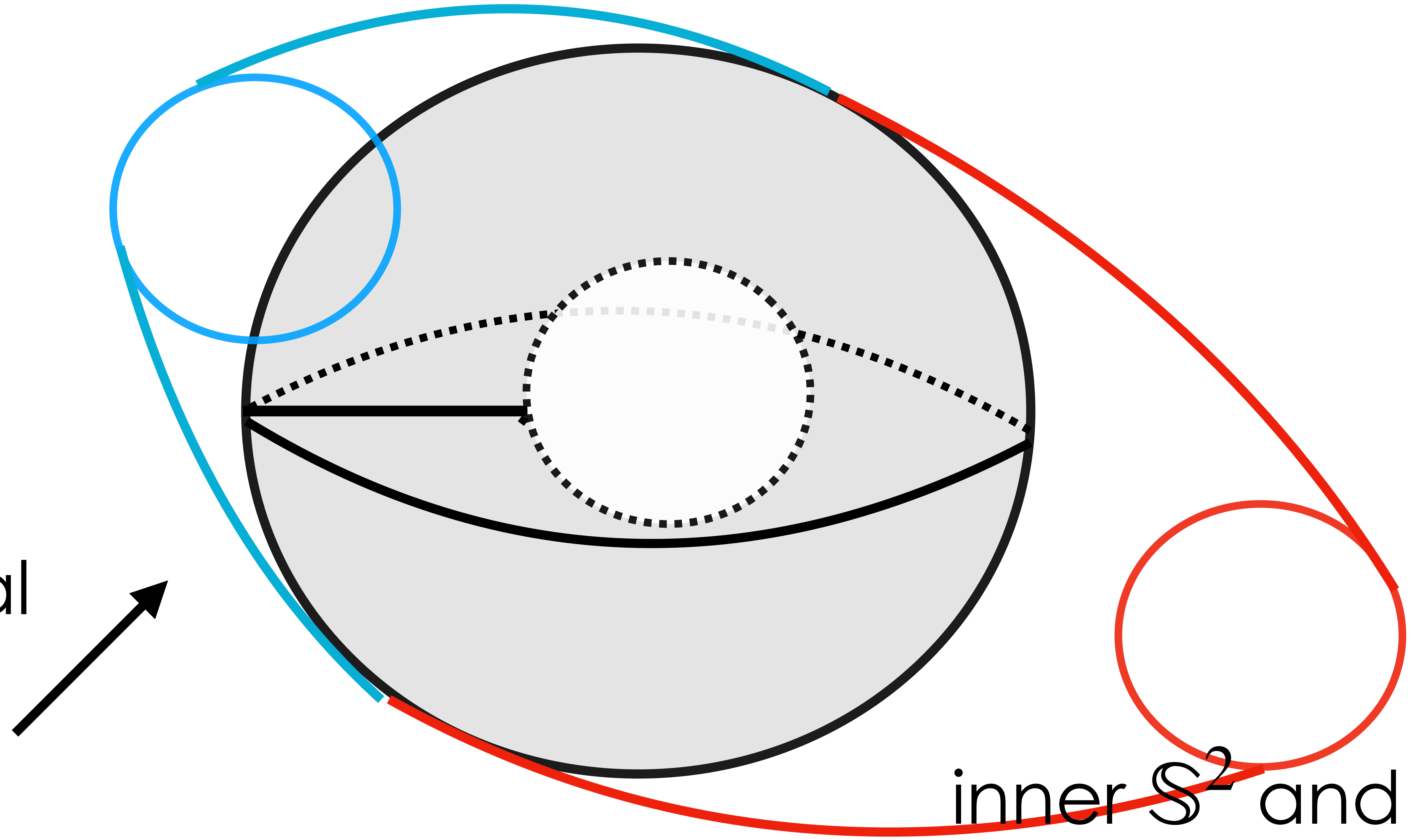

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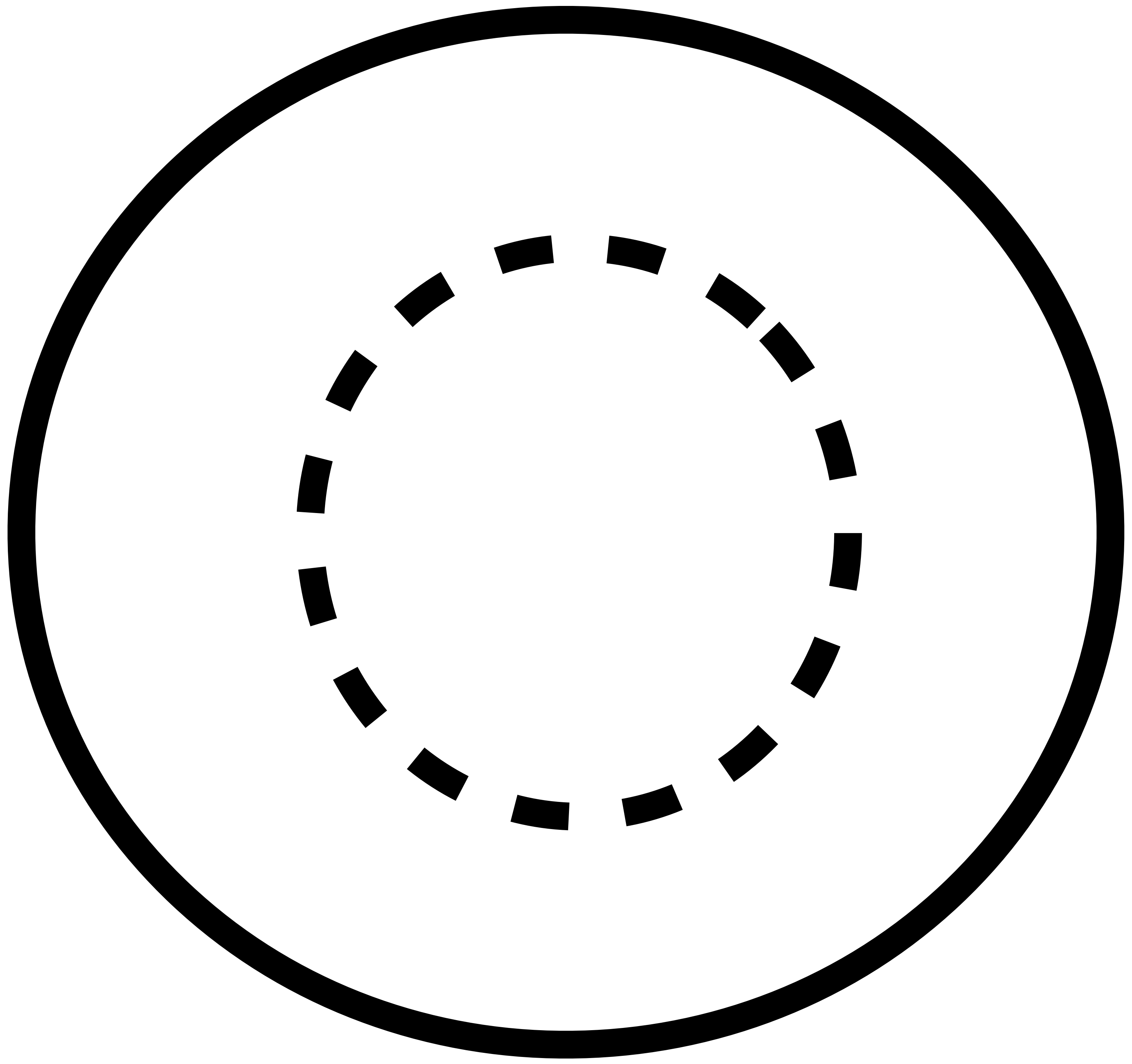

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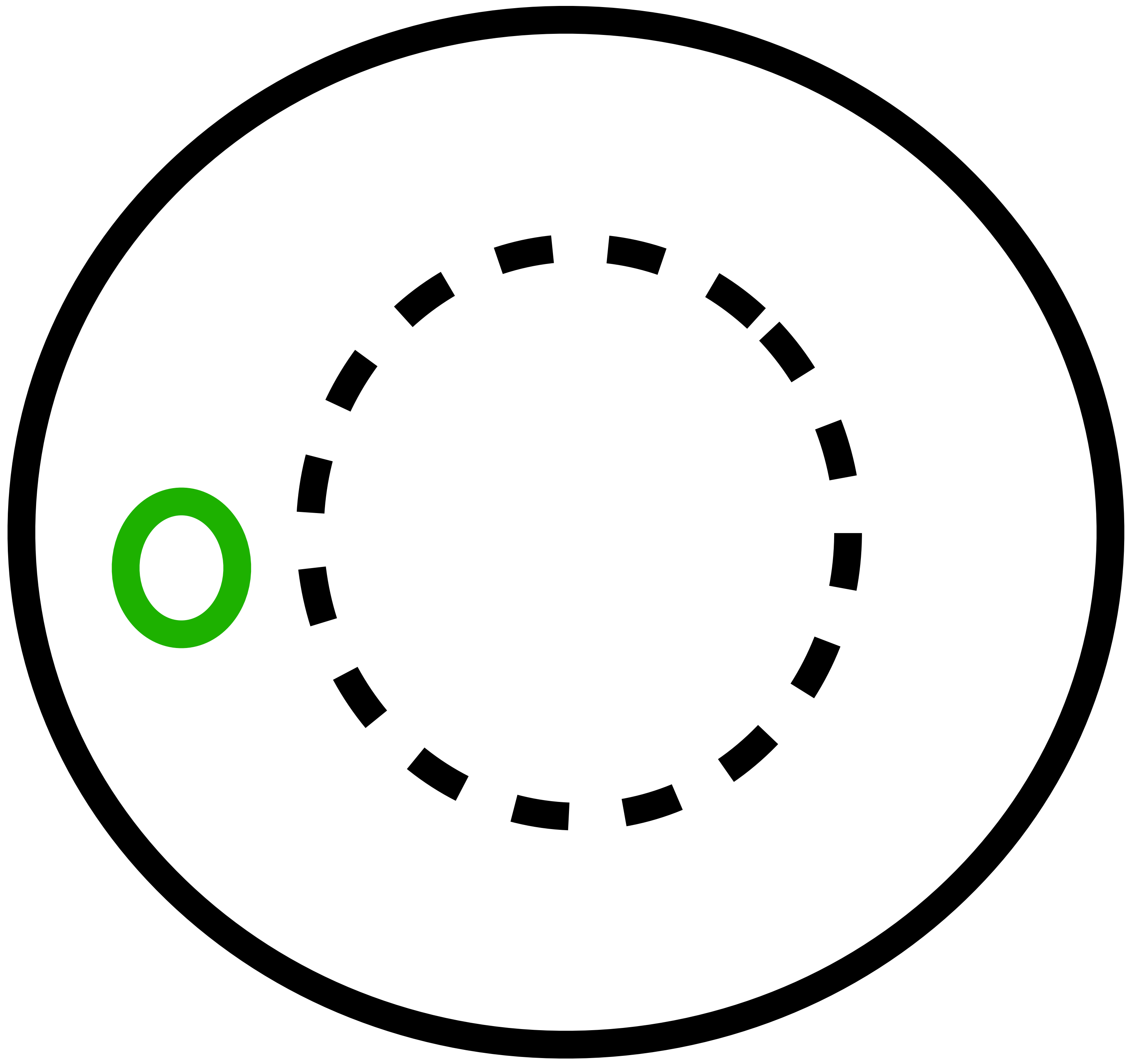

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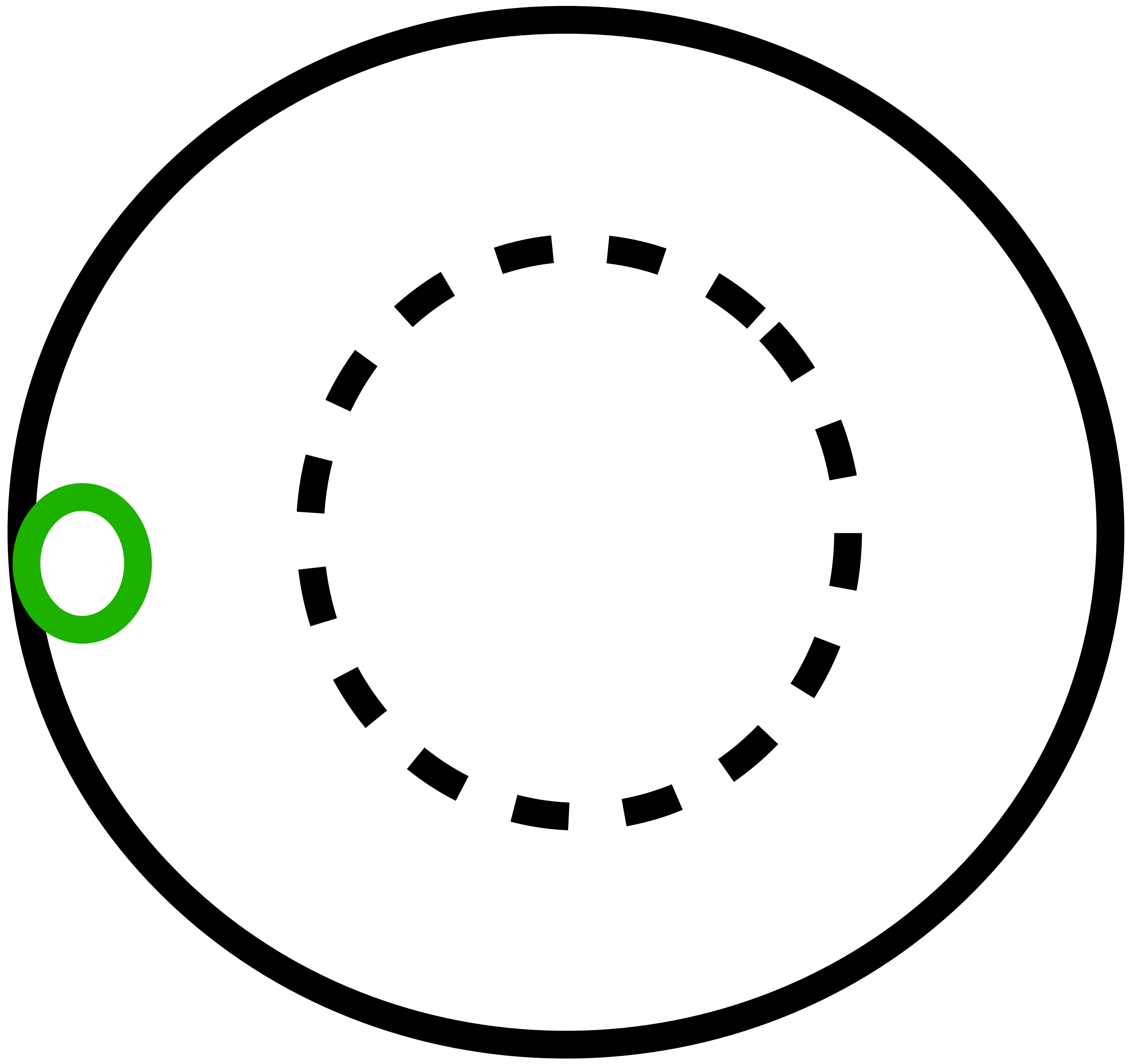

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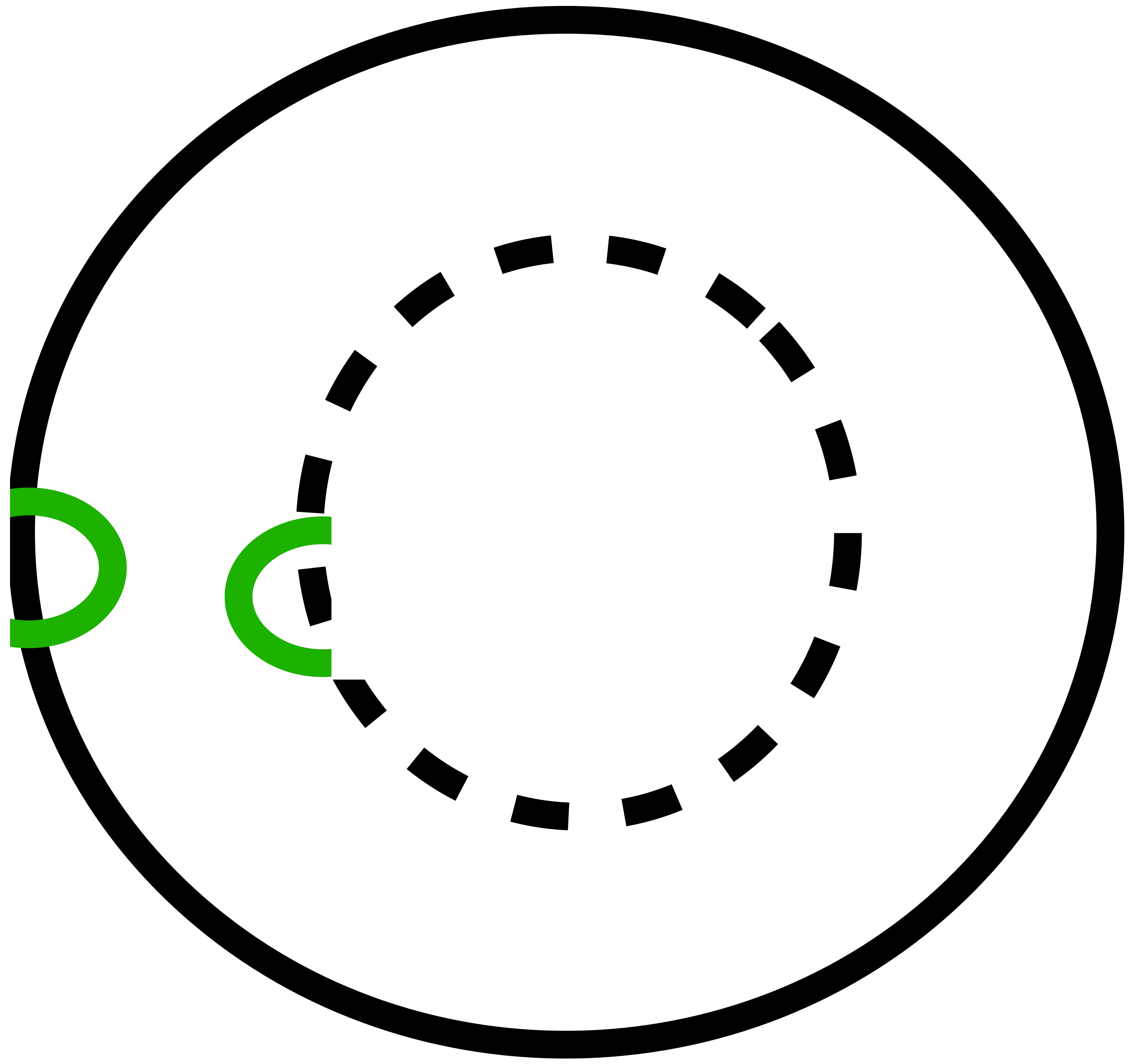

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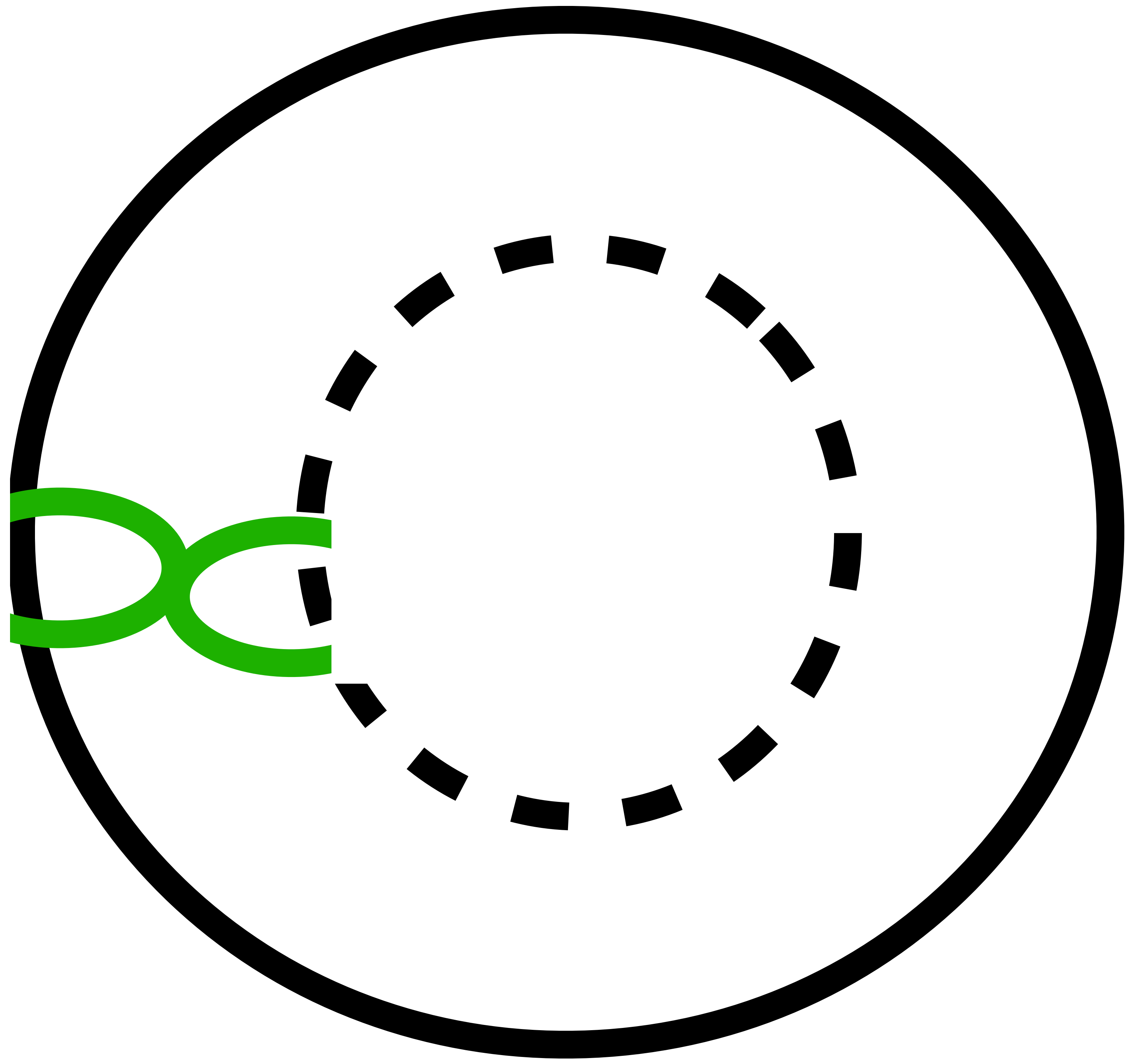

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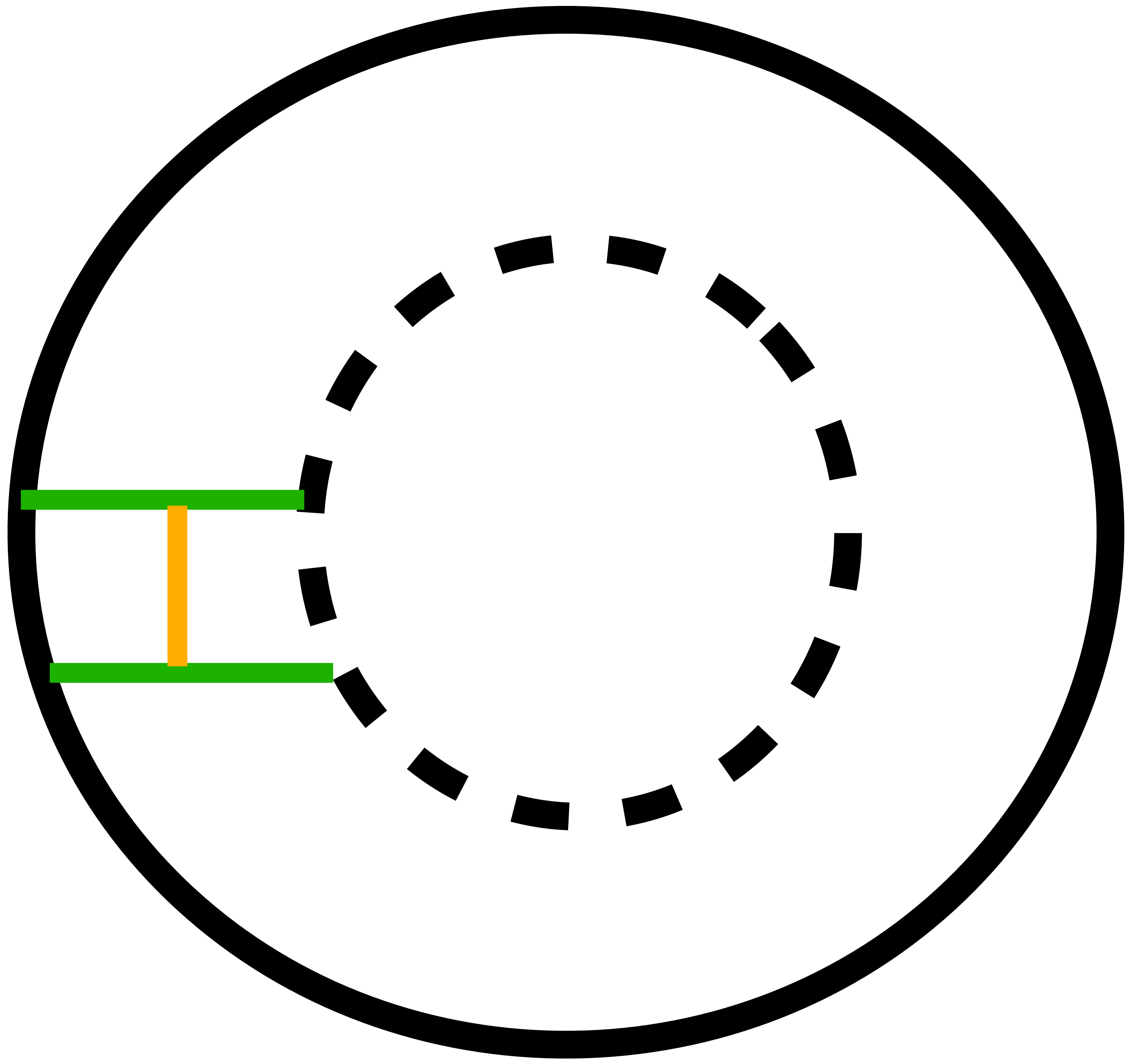

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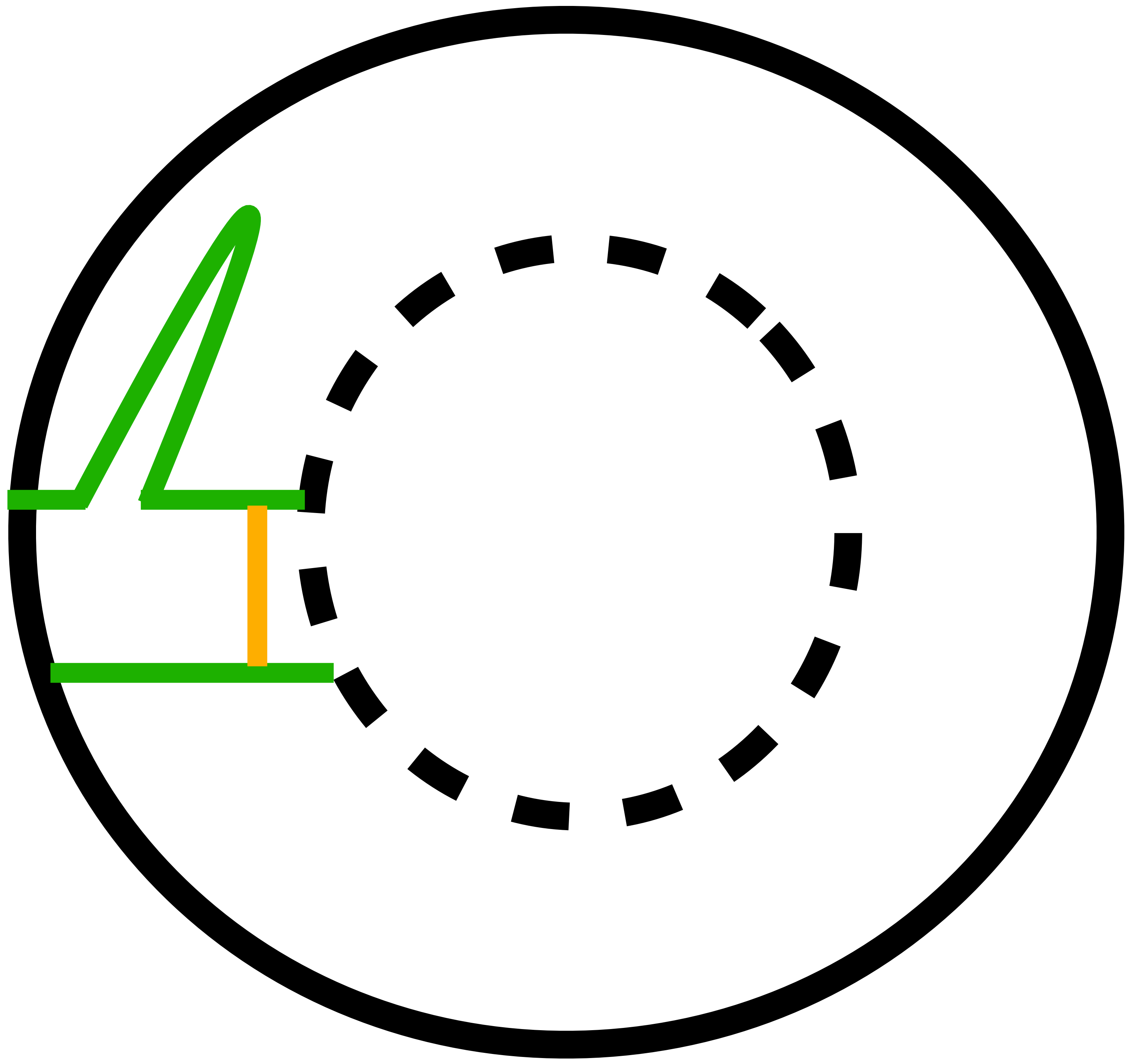

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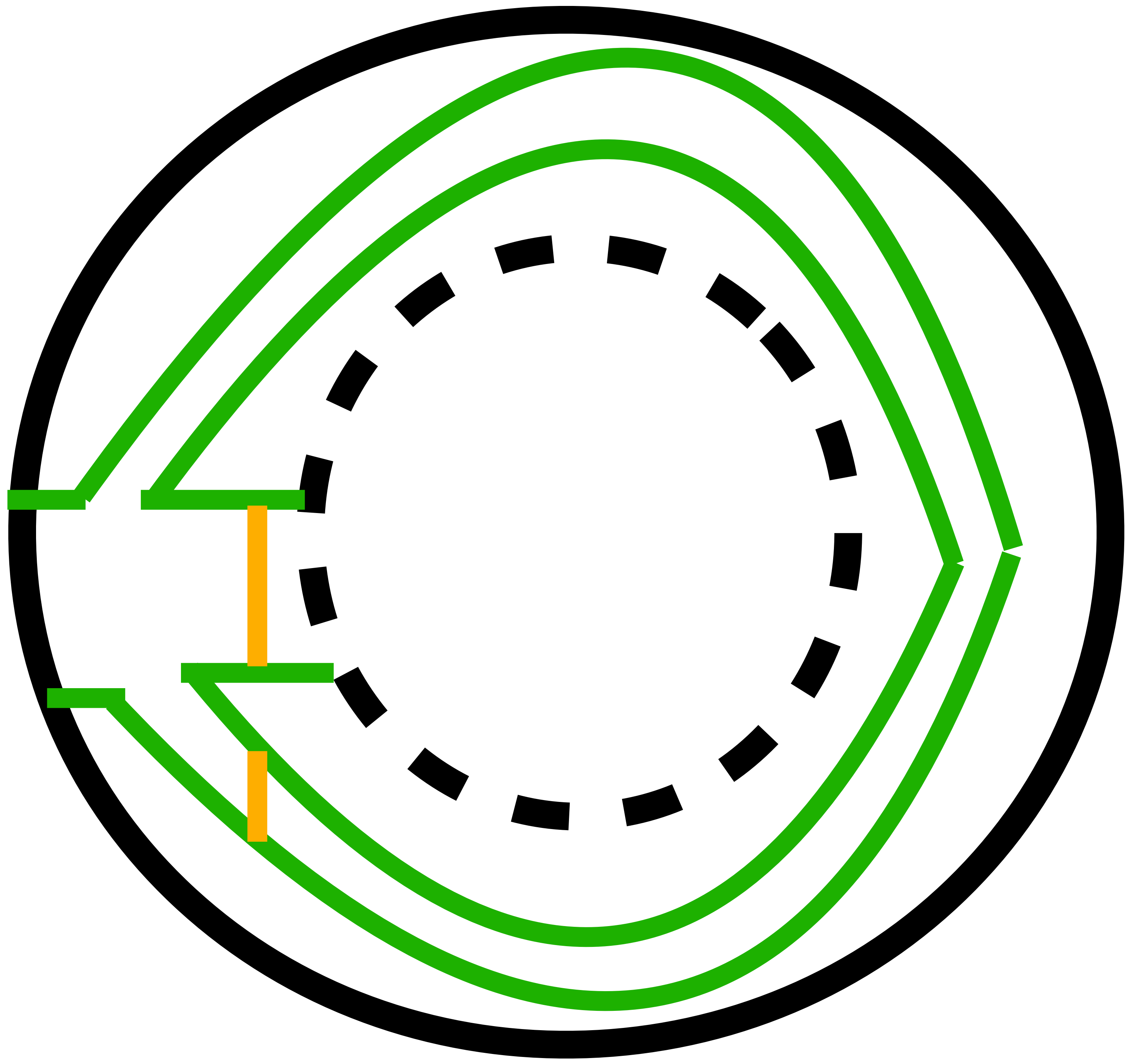

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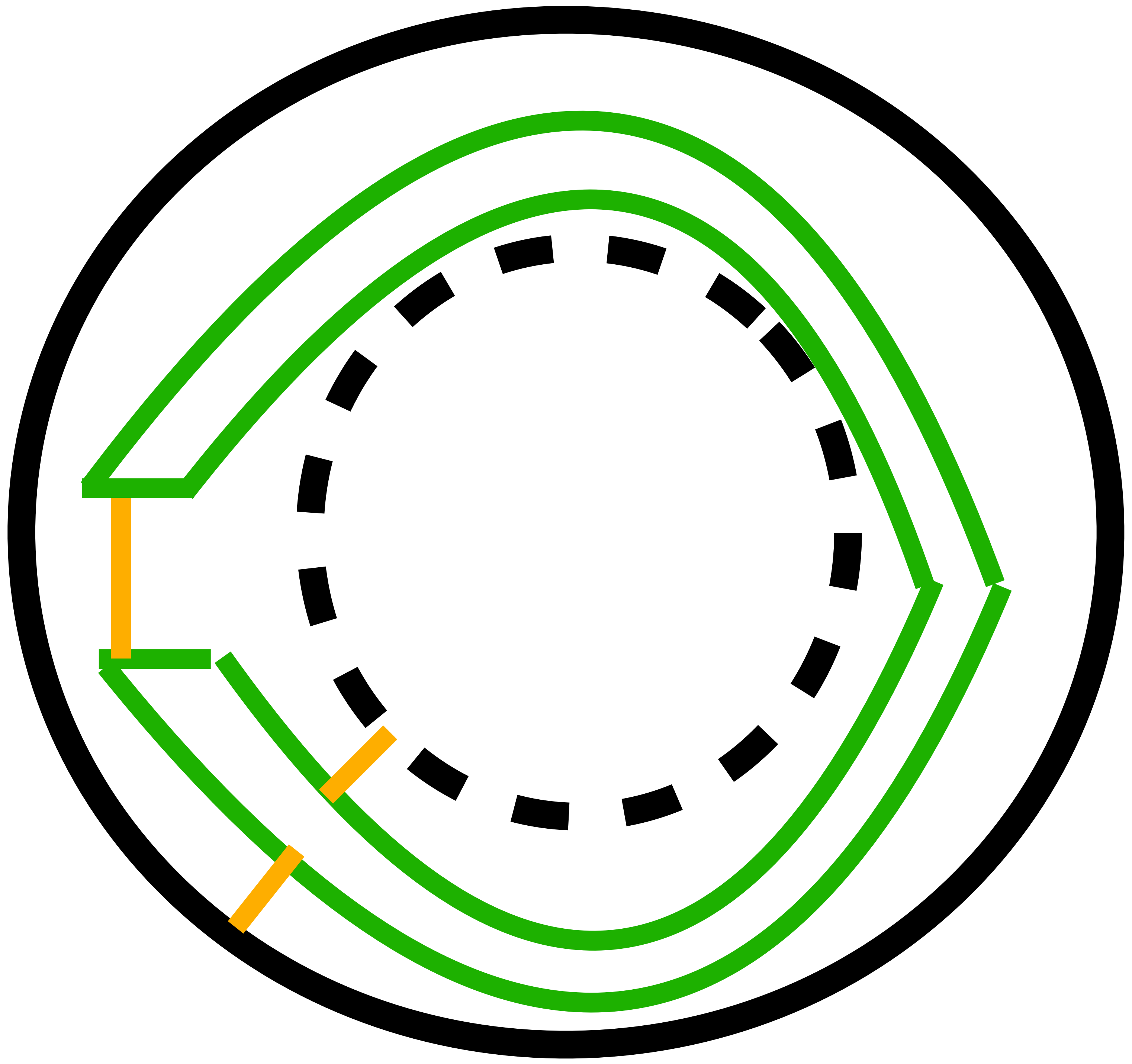

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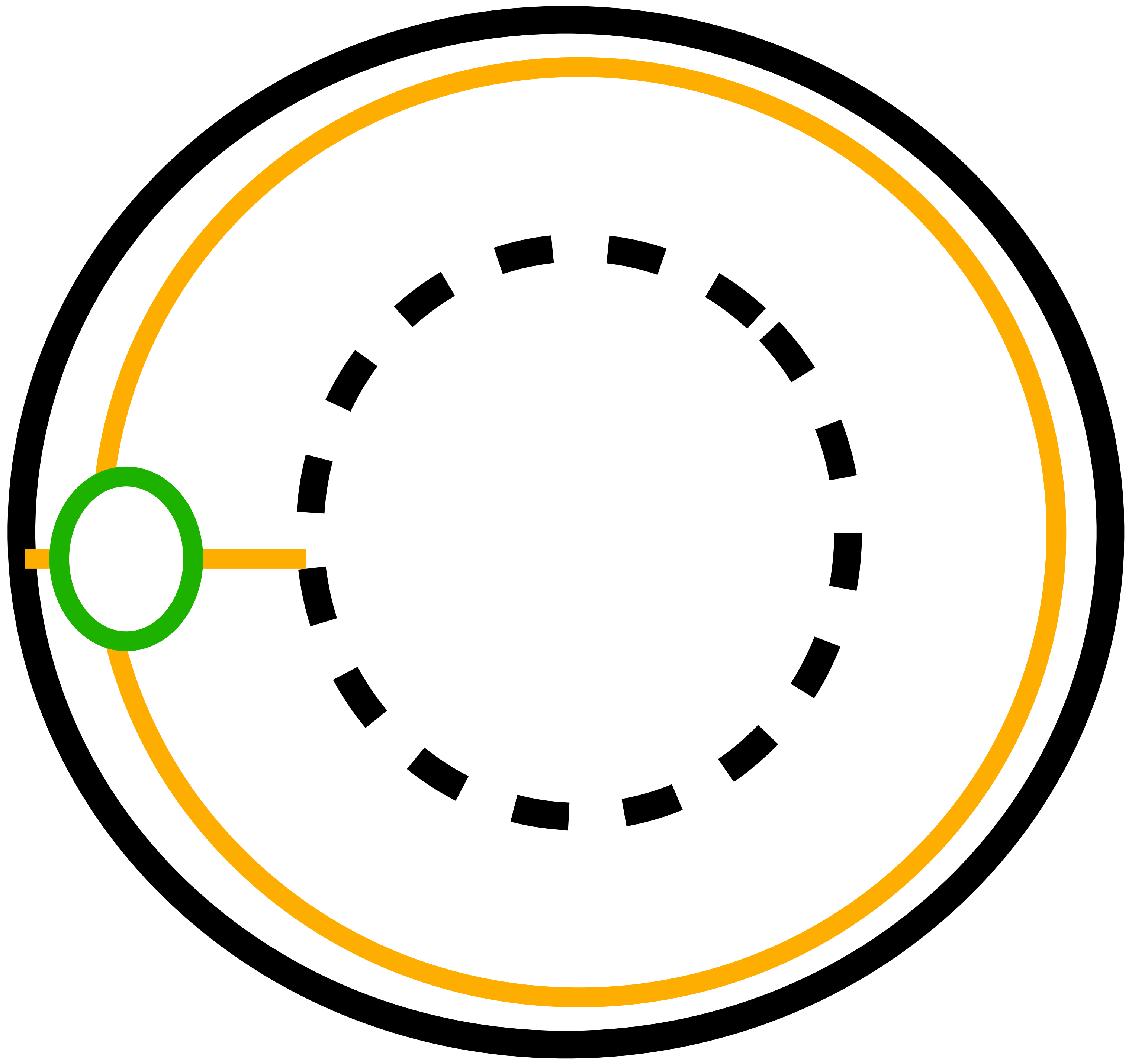

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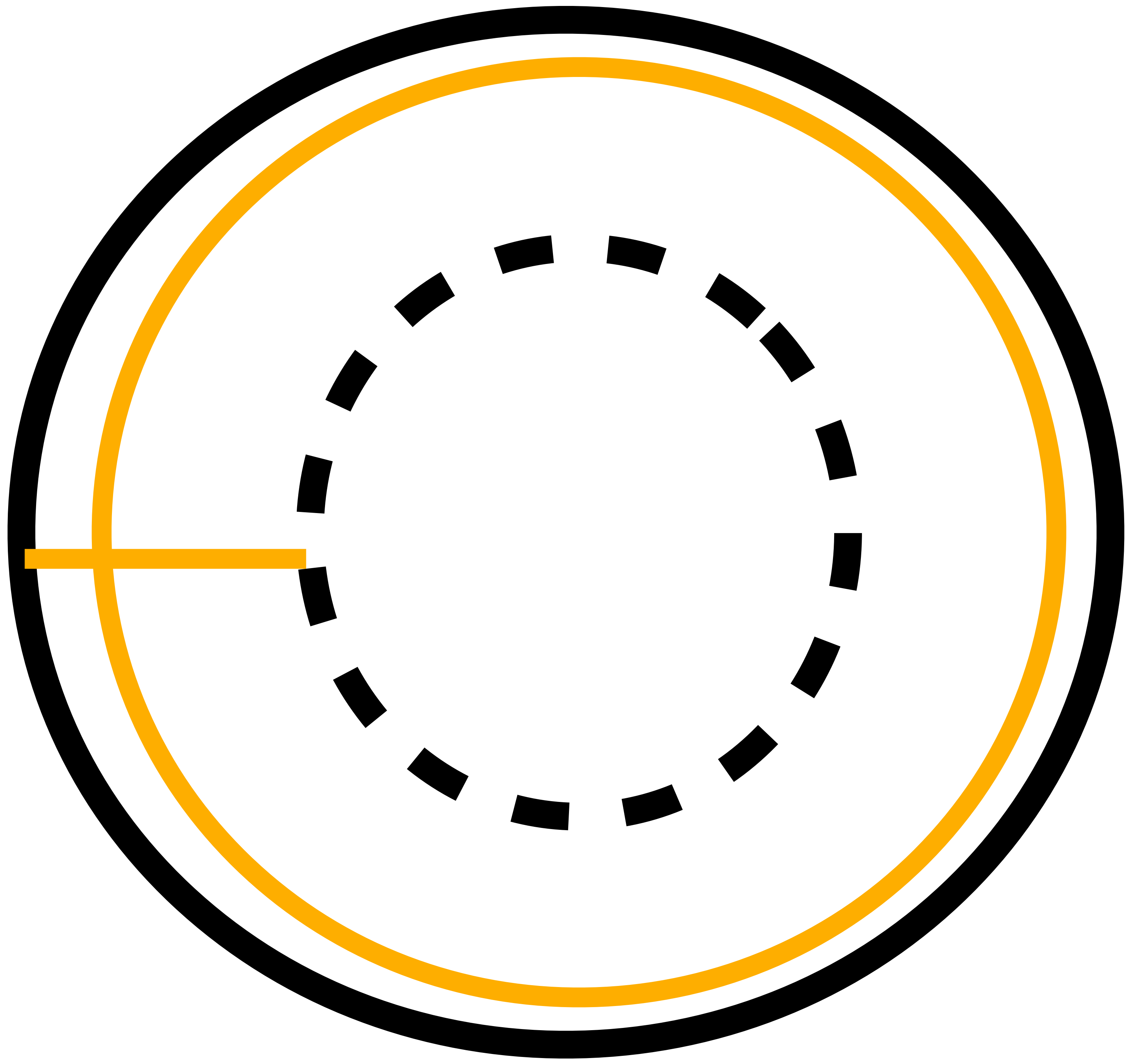

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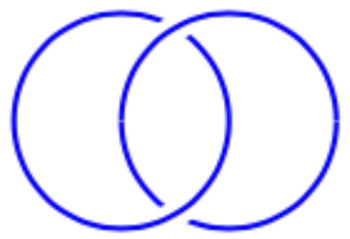
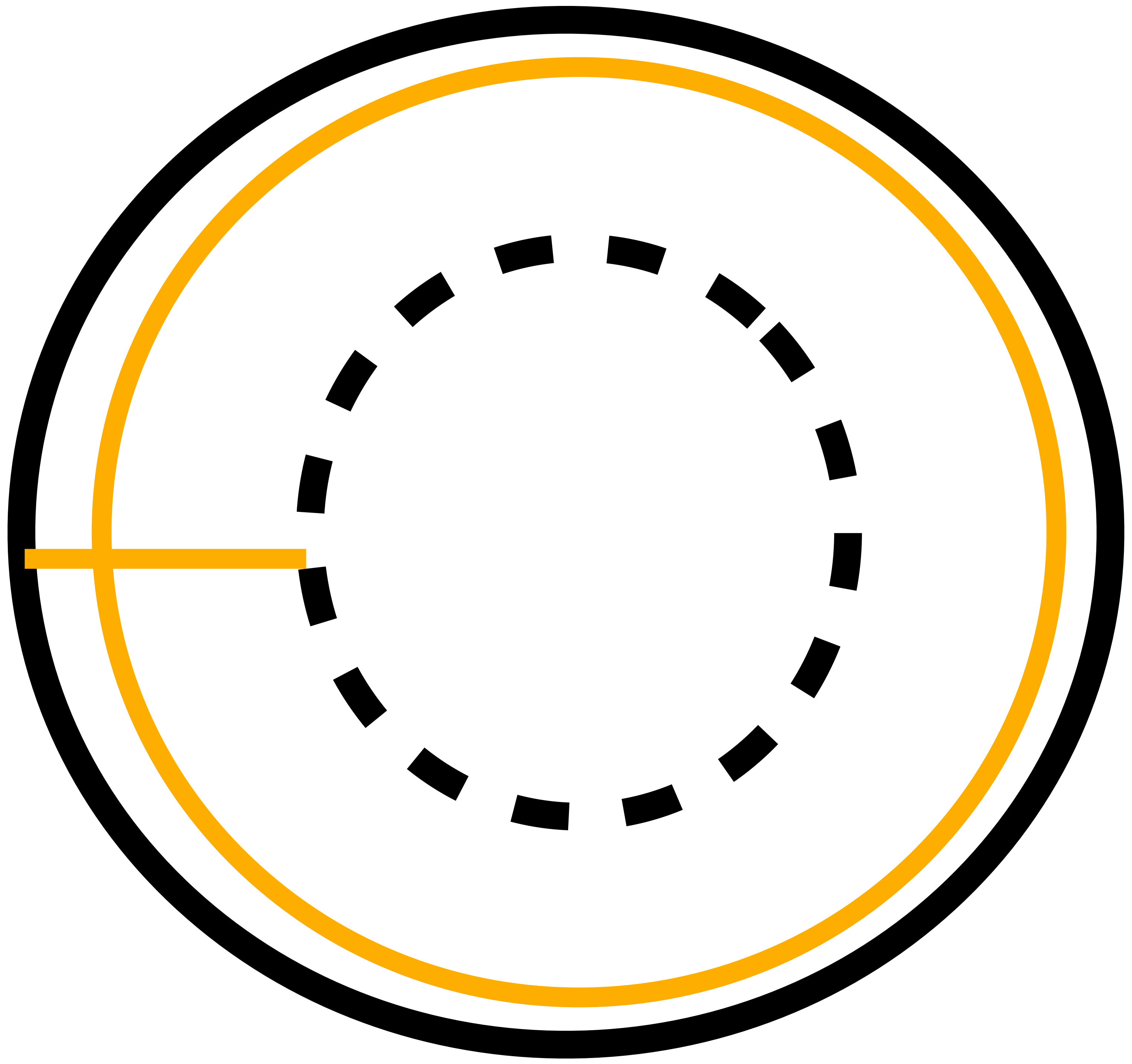
Hopf link correlator of lines in $\mathscr{A}^{N,p}$



$$\mathcal{Z}_{S^2\times S^2} = \frac{1}{N}\sum_{b,c\in\mathbb{Z}_N} \frac{\left\langle L^b \quad L^c \right\rangle_{\mathcal{A}^{N,p}}}{\langle\, \cdot \,\rangle_{\mathcal{A}^{N,p}}}\, \mathcal{Z}[b,c]_{S^2\times S^2}$$



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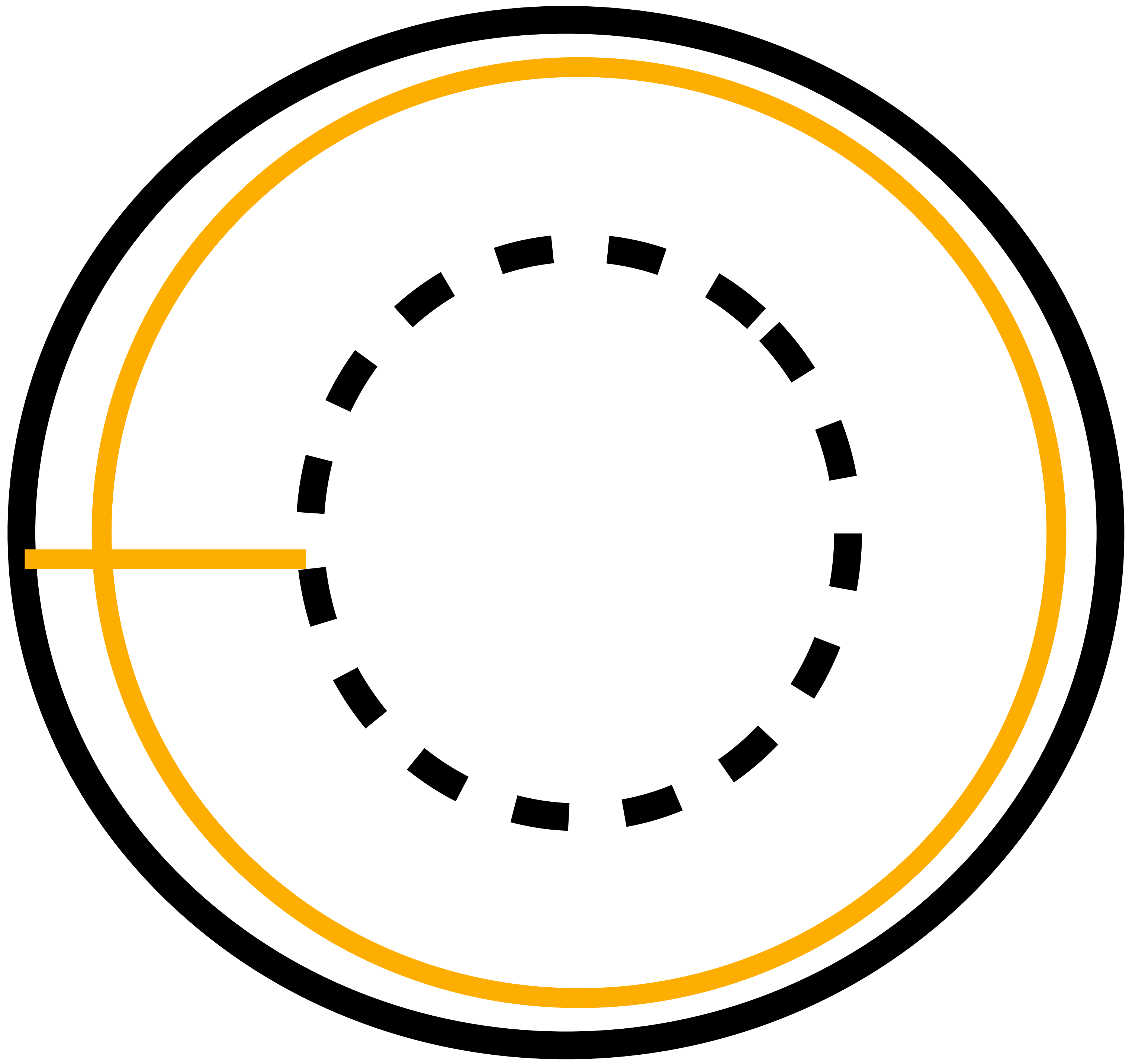

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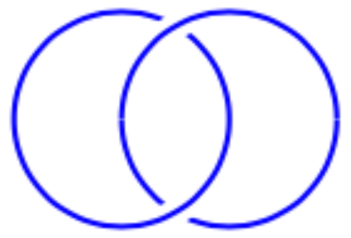

Easy to generalize thanks to Kirby description of 4-manifolds!

Ward Identities and bordisms

Idea is very simple: two ways to look at a compact 4-manifold:

- Null bordism
- Handle decompostion

$$\varnothing \to \mathbb{S}^3 \xrightarrow{H_1} \cdots \xrightarrow{H_n} \varnothing$$

surgery diagram

$\mathbb{S}^2 \times \mathbb{S}^2$ example:

$$\varnothing \to \mathbb{S}^3 \xrightarrow{H_1} \mathbb{S}^1 \times \mathbb{S}^2 \xrightarrow{H_2} \mathbb{S}^3 \to \varnothing$$

Where we are only gluing 2-handles.

For all 4-manifolds with a handle decomposition with 2-handles only the surgery diagram we obtain is a link in $\mathbb{S}^3$: the Ward identity we obtain is the expectation value of such a link, decorated with lines, in the $\mathscr{A}^{N,p}$ 3d TFT.

Executive Summary

Symmetries are a topological sector of the spectrum of operators

The latter is organized by a higher category

We have seen some applications of these ideas

This is just the beginning of a long story

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Hey, but what about **branes** and **strings**?

Maybe I can say something on the blackboard, but for sure I am already out of time…

Thank you for your attention!

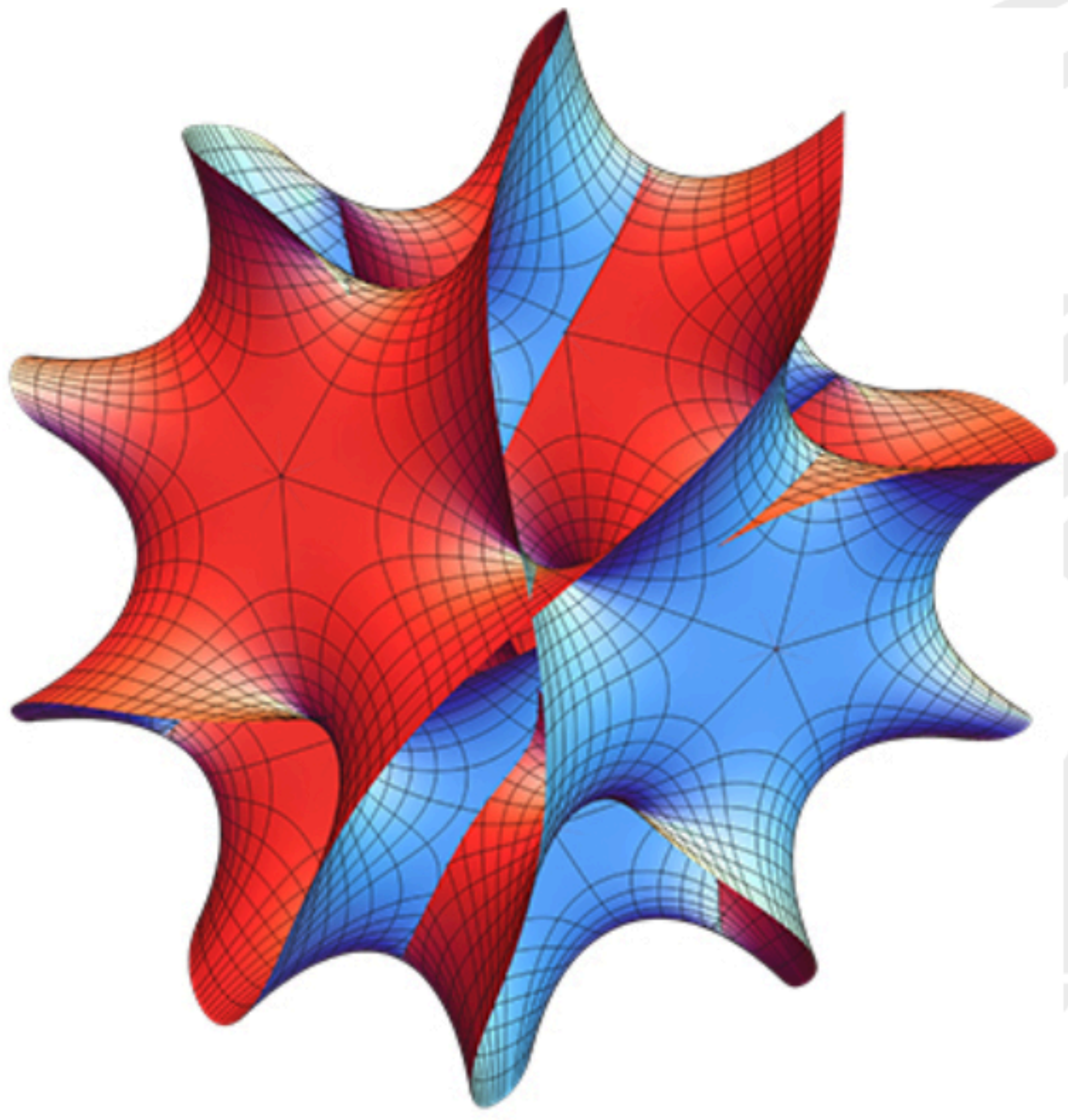
Thank you for your attention!

But before I go let me mention:

Inauguration of the Centre for Geometry and Physics with lecture by honorary doctorate Nikita Nekrasov

Add to your calendar

- Date: 24 January, 13:00–15:00
- Location: Ångströmlaboratoriet, Lägerhyddsvägen 1 , lecture hall Eva von Bahr
- Lecturer: Nikita Nekrasov
- Organiser: Department of Mathematics and Department of Physics and Astronomy
- Contact person: Tobias Ekholm
- Föreläsning



Welcome to the inauguration of the Centre for Geometry and Physics. The centre starts 2024 based on grants from the Swedish Research Council's excellence initiative for projects with great potential for innovative research.

Please register to help us estimate how many people will be attending.