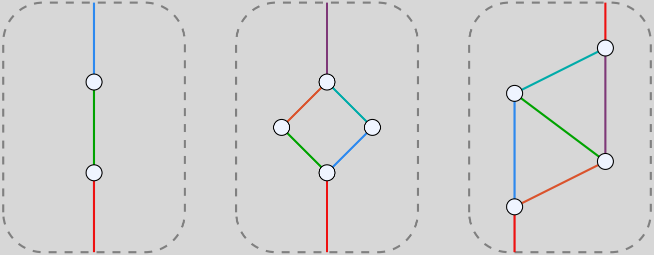
Computing Renormalization Invariant Properties of Levin-Wen Models

Daniel Barter (ANU) Jacob Bridgeman (PI) Corey Jones (OSU)



2D, non-chiral, long range entangled topological phases

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- When $C = \mathbf{Vec}(G)$, the category of G-graded vector spaces, the Levin-Wen model and the Kitaev model define the same phase of matter.

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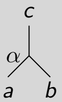
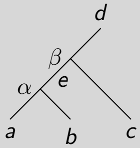
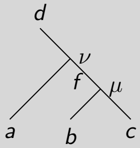


We impose the relation



$$= \sum_{\mu,\nu} F^{\mu,\nu}_{\alpha,\beta}$$



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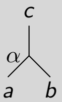
generated by trivalent verticies 

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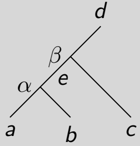

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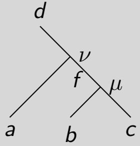

The tensor F must satisfy the pentagon equation, also known as the 3-2 Pachner equation.

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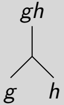

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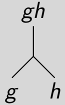

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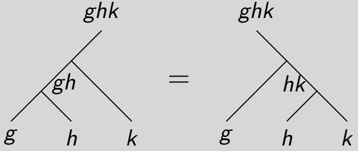

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Let C be a fusion category and Σ an **orientable** 2-dimensional surface possibly with boundary.

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$$Z_C(\Sigma) = \mathbb{C}\left\{\begin{array}{l}\text{Diagrams from } C \text{ drawn on} \\ \Sigma \text{ upto isotopy and relations.} \\ \text{Strings are allowed to terminate} \\ \text{on the boundary.}\end{array}\right\}$$

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In mathematics, Z_C is called a fully extended (2+1)D topological quantum field theory. It captures the renormalization invariant properties of the Levin-Wen model.

Ground states on the torus

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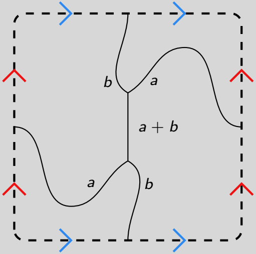

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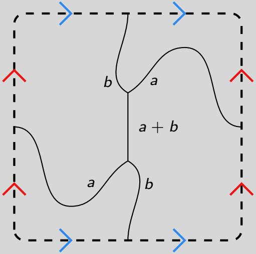

$$\left. \right\}$$

The phase corresponding to A has $|A|^2$ ground states on the torus.

Question

How many domain walls are there between two chunks of the $\mathbb{Z}/2\mathbb{Z}$ phase?

At least 6.

Domain wall	Action on particles
	Condenses e on both sides
	Condenses m on left and e on right
	Condenses e on left and m on right
	Condenses m on both sides
	trivial domain wall
	$e \leftrightarrow m$

Kiteav, Kong and Ostrik

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- **Ostrik's Theorem:**

$$\left\{\begin{matrix}\text{simple } \mathbf{Vec}(G)-\mathbf{Vec}(H) \\ \text{bimodule categories}\end{matrix}\right\} \leftrightarrow \left\{\begin{matrix}\text{subgroups P of } G \times H^{\mathrm{op}} \\ \text{and cohomology classes} \\ \omega \in H^2(P, U(1)) \text{ mod-} \\ \text{ulo conjugation}\end{matrix}\right\}$$

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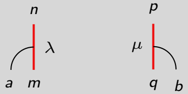
Generated by trivalent vertices 

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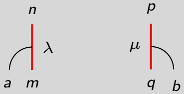

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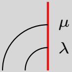
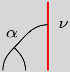
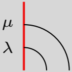
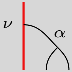


$$= \sum_{\alpha,\nu} L^{\alpha,\nu}_{\lambda,\mu}$$





$$= \sum_{\alpha,\nu} R^{\alpha,\nu}_{\lambda,\mu}$$



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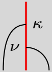

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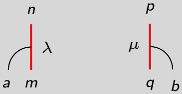
Generated by trivalent vertices 

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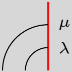

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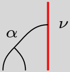

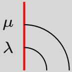

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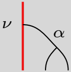

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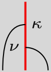
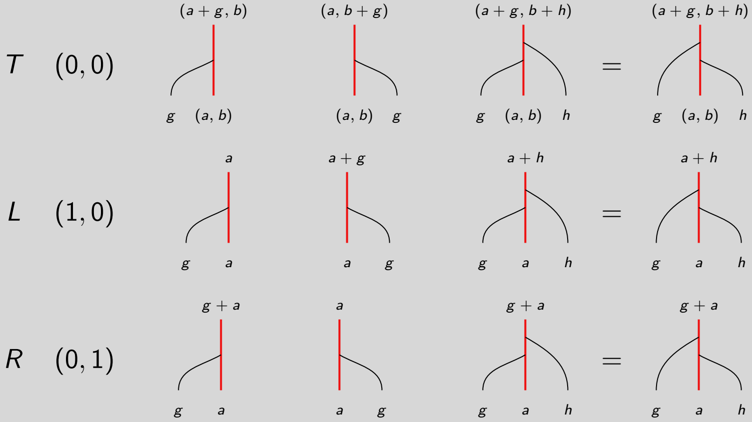


The tensors L, R, C satisfy a dizzying number of coherence equations.

$\mathbf{Vec}(\mathbb{Z}/2\mathbb{Z})$–$\mathbf{Vec}(\mathbb{Z}/2\mathbb{Z})$ bimodules



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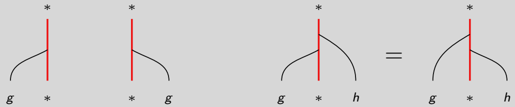
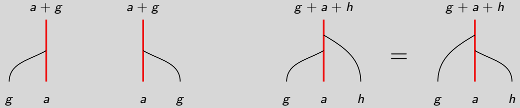
F_0 $(0,1),(1,0)$



X $(1,1)$



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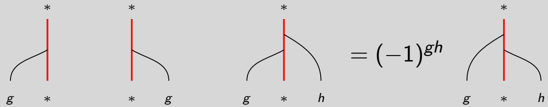


The Correspondence

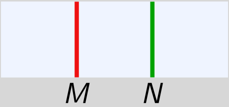
Bimodule	Domain Wall
T	
L	
R	
F_0	
X	
F_1	

Proof:

We can compute the following table in two ways:

$\otimes_{\mathbb{Z}/2\mathbb{Z}}$	T	L	R	F_0	X	F_1
T	$2 \cdot T$	T	$2 \cdot R$	R	T	R
L	$2 \cdot L$	L	$2 \cdot F_0$	F_0	L	F_0
R	T	$2 \cdot T$	R	$2 \cdot R$	R	T
F_0	L	$2 \cdot L$	F_0	$2 \cdot F_0$	F_0	L
X	T	L	R	F_0	X	F_1
F_1	L	T	F_0	R	F_1	X

Method 1: Domain Walls



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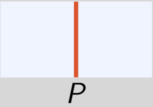

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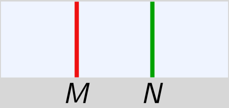

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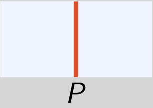
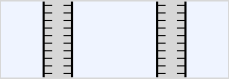
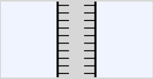




$= \quad 2 \cdot$



$T \otimes_{\mathbb{Z}/2\mathbb{Z}} T = 2 \cdot T$

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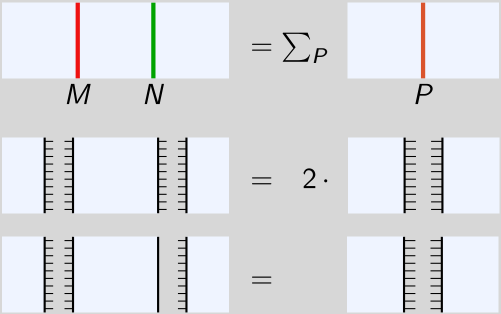

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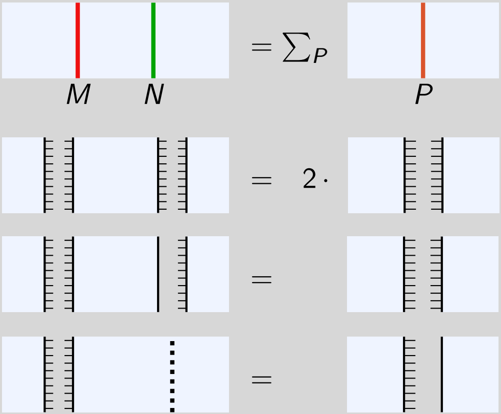

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$$T \otimes_{\mathbb{Z}/2\mathbb{Z}} F_1 = R$$

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- See *Domain walls in topological phases and the Brauer-Picard ring for* $\mathbf{Vec}(\mathbb{Z}/p\mathbb{Z})$, arXiv:1806.01279 for details.

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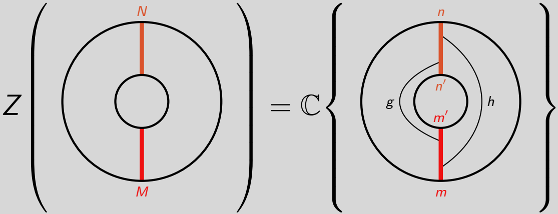
In mathematics, Z is called a defect topological quantum field theory.

Binary Interface Defects



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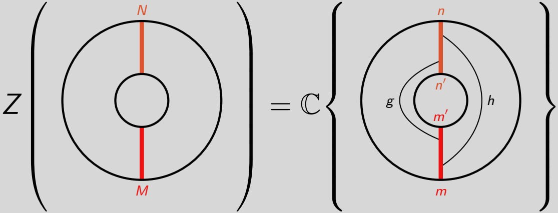

The right hand side is a category. Simple representations of this category parameterize **binary interface defects.**

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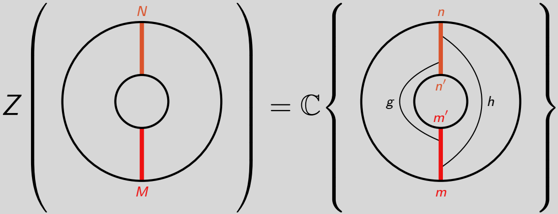

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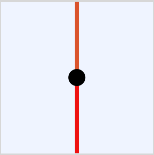
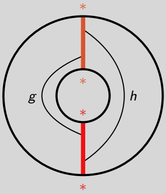


P

Example 1: $\left.\begin{matrix} F_0 \\ F_0 \end{matrix}\right|$

Define $M_{g,h} =$ 

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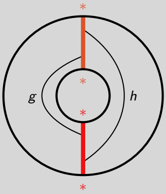

Then $M_{g_0,h_0}M_{g_1,h_1} = M_{g_0+g_1,h_0+h_1}$, so the algebra is isomorphic to $\mathbb{C}\{\mathbb{Z}/2 \times \mathbb{Z}/2\}$. Therefore, there are 4 binary interface defects.

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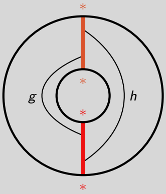
Define $M_{g,h} =$ 

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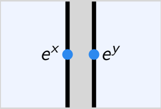

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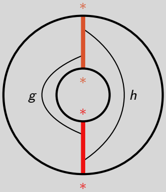
Define $M_{g,h} =$ 

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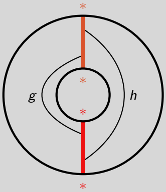
Define $M_{g,h} =$ 

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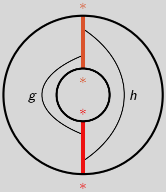
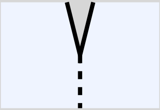


Then $M_{g_0,h_0} M_{g_1,h_1} = (-1)^{h_0 g_1} M_{g_0+g_1,h_0+h_1}$. This algebra is isomorphic to the 2×2 matrix algebra via $M_{g,h} \mapsto X^g Z^h$ (Pauli matrices). The 2×2 matrix algebra only has one simple representation.

$\left.{F_0 \atop F_1}\right| =$



Fusing Binary Interface Defects

- In *Fusing binary interface defects in topological phases: The* **Vec**$(\mathbb{Z}/p\mathbb{Z})$ *case*, arXiv:1810.09469, we give physical interpretations for all binary interface defects in the $\mathbb{Z}/p\mathbb{Z}$-model.
- We also compute all possible vertical and horizontal fusions involving binary interface defects.

$\mathbb{Z}/p\mathbb{Z}$ Horizontal Fusion tables

	$\frac{T}{T}\vert_{(c,d)}$	$\frac{L}{T}\vert_{c}$	$\frac{R}{T}\vert_{c}$	$\frac{F_0}{T}\vert$	$\frac{X_n}{T}\vert_{c}$	$\frac{F_t}{T}\vert$
$\frac{T}{T}\vert_{(a,b)}$	$\delta^{b+c}_{\nu-\mu}\frac{T}{T}\vert^{\mu,\nu}_{(a,d)}$	$\frac{T}{T}\vert^{\mu}_{(a,c)}$	$\delta^{b+c}_{\nu-\mu}\frac{R}{T}\vert^{\mu,\nu}_{a}$	$\frac{R}{T}\vert^{\mu}_{a}$	$\frac{T}{T}\vert^{\mu}_{(a,n^{-1}(b+c+\mu))}$	$\frac{R}{T}\vert^{\mu}_{a}$
$\frac{L}{T}\vert_{a}$	$\delta^{a+c}_{\nu-\mu}\frac{L}{T}\vert^{\mu,\nu}_{d}$	$\frac{L}{T}\vert^{\mu}_{c}$	$\delta^{a+c}_{\nu-\mu}\frac{F_0}{T}\vert^{\mu,\nu}$	$\frac{F_0}{T}\vert^{\mu}$	$\frac{L}{T}\vert^{\mu}_{n^{-1}(\mu+a+c)}$	$\frac{F_0}{T}\vert^{\mu}$
$\frac{R}{T}\vert_{a}$	$\frac{T}{T}\vert^{\mu}_{(a,d)}$	$\frac{T}{T}\vert^{\mu}_{(a,c)}$	$\frac{R}{T}\vert^{\mu}_{a}$	$\frac{R}{T}\vert^{\mu}_{a}$	$\frac{R}{T}\vert^{\mu}_{a}$	$\oplus_\beta\frac{T}{T}\vert^{\mu}_{(a,\beta)}$
$\frac{F_0}{T}\vert$	$\frac{L}{T}\vert^{\mu}_{d}$	$\frac{L}{T}\vert^{\mu,\nu}_{c}$	$\frac{F_0}{T}\vert^{\mu}$	$\frac{F_0}{T}\vert^{\mu,\nu}$	$\frac{F_0}{T}\vert^{\mu}$	$\oplus_\alpha\frac{L}{T}\vert^{\mu}_{\alpha}$
$\frac{X_l}{T}\vert_{a}$	$\frac{T}{T}\vert^{\mu}_{(a+l(\mu+c),d)}$	$\frac{L}{T}\vert^{\mu}_{c}$	$\frac{R}{T}\vert^{\mu}_{a+l(\mu+c)}$	$\frac{F_0}{T}\vert^{\mu}$	$\frac{X_{ln}}{T}\vert^{\mu}_{a+l(c+\mu)}$	$\frac{F_{l^{-1}t}}{T}\vert^{\mu}$
$\frac{F_r}{T}\vert$	$\frac{L}{T}\vert^{\mu}_{d}$	$\oplus_\alpha\frac{T}{T}\vert^{\mu}_{(\alpha,c)}$	$\frac{F_0}{T}\vert^{\mu}$	$\oplus_\alpha\frac{R}{T}\vert^{\mu}_{\alpha}$	$\frac{F_{rn}}{T}\vert^{\mu}$	$\oplus_\alpha\frac{X_{r^{-1}t}}{T}\vert^{\mu}_{\alpha}$
$\frac{T}{L}\vert_{a}$	$\delta^{a+c}_{\nu-\mu}\frac{T}{L}\vert^{\mu,\nu}_{d}$	$\frac{T}{L}\vert^{\mu}_{c}$	$\delta^{a+c}_{\nu-\mu}\frac{R}{L}\vert^{\mu,\nu}$	$\frac{R}{L}\vert^{\mu}$	$\frac{T}{L}\vert^{\mu}_{n^{-1}(\mu+a+c)}$	$\frac{R}{L}\vert^{\mu}$
$\frac{L}{L}\vert_{(a,x)}$	$\delta^{a+c}_{\nu-\mu}\frac{L}{L}\vert^{\mu,\nu}_{(d,x)}$	$\frac{L}{L}\vert^{\mu}_{(d,x)}$	$\delta^{a+c}_{\nu-\mu}\frac{F_0}{L}\vert^{\mu,\nu}_{x}$	$\frac{F_0}{L}\vert^{\mu}_{x}$	$\frac{L}{L}\vert^{\mu}_{(n^{-1}(a+c+\mu,x))}$	$\frac{F_0}{L}\vert^{\mu}_{x}$
$\frac{R}{L}\vert$	$\frac{T}{L}\vert^{\mu}_{d}$	$\frac{T}{L}\vert^{\mu,\nu}_{c}$	$\frac{R}{L}\vert^{\mu}$	$\frac{R}{L}\vert^{\mu,\nu}$	$\frac{R}{L}\vert^{\mu}$	$\oplus_\alpha\frac{T}{L}\vert^{\mu}_{\alpha}$
$\frac{F_0}{L}\vert_{x}$	$\frac{L}{L}\vert^{\mu}_{(d,x)}$	$\frac{L}{L}\vert^{\mu,\nu}_{(d,x)}$	$\frac{F_0}{L}\vert^{\mu}_{x}$	$\frac{F_0}{L}\vert^{\mu,\nu}_{x}$	$\frac{F_0}{L}\vert^{\mu}_{x}$	$\oplus_\alpha\frac{L}{L}\vert^{\mu}_{(\alpha,x)}$
$\frac{X_l}{L}\vert$	$\frac{T}{L}\vert^{\mu}_{d}$	$\oplus_\beta\frac{L}{L}\vert^{\mu}_{(c,\beta)}$	$\frac{R}{L}\vert^{\mu}$	$\oplus_\alpha\frac{F_0}{L}\vert^{\mu}_{\alpha}$	$\frac{X_{ln}}{L}\vert^{\mu}$	$\oplus_\alpha\frac{F_{l^{-1}t}}{L}\vert^{\mu}_{\alpha}$
$\frac{F_r}{L}\vert_{x}$	$\frac{L}{L}\vert^{\mu}_{(d,x+r(c+\mu))}$	$\frac{T}{L}\vert^{\mu}_{c}$	$\frac{F_0}{L}\vert^{\mu}_{x+r(c+\mu)}$	$\frac{R}{L}\vert^{\mu}$	$\frac{F_{rn}}{L}\vert^{\mu}_{x+r\mu}$	$\frac{X_{r^{-1}t}}{L}\vert^{\mu}$
$\frac{T}{R}\vert_{a}$	$\frac{T}{T}\vert^{\nu}_{(a,d)}$	$\frac{T}{T}\vert_{(a,c)}$	$\frac{R}{T}\vert^{\nu}_{a}$	$\frac{R}{T}\vert_{a}$	$\oplus_\beta\frac{T}{T}\vert_{(a,\beta)}$	$\frac{R}{T}\vert_{a}$
$\frac{L}{R}\vert$	$\frac{L}{T}\vert^{\nu}_{d}$	$\frac{L}{T}\vert_{c}$	$\frac{F_0}{T}\vert^{\nu}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{L}{T}\vert_{\alpha}$	$\frac{F_0}{T}\vert$
$\frac{R}{R}\vert_{(a,x)}$	$\frac{T}{T}\vert_{(a,d)}$	$\frac{T}{T}\vert^{\nu}_{(a,c)}$	$\frac{R}{T}\vert_{a}$	$\frac{R}{T}\vert^{\nu}_{a}$	$\frac{R}{T}\vert_{a}$	$\oplus_\beta\frac{T}{T}\vert_{(a,\beta)}$
$\frac{F_0}{R}\vert_{x}$	$\frac{L}{T}\vert_{d}$	$\frac{L}{T}\vert^{\nu}_{c}$	$\frac{F_0}{T}\vert$	$\frac{F_0}{T}\vert^{\nu}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{L}{T}\vert_{\alpha}$
$\frac{X_l}{R}\vert$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,d)}$	$\frac{L}{T}\vert_{c}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{X_{ln}}{T}\vert_{\alpha}$	$\frac{F_{l^{-1}t}}{T}\vert$
$\frac{F_r}{R}\vert_{x}$	$\frac{L}{T}\vert_{d}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\frac{F_{rn}}{T}\vert$	$\oplus_\alpha\frac{X_{r^{-1}t}}{T}\vert_{\alpha}$
$\frac{T}{F_0}\vert$	$\frac{T}{L}\vert^{\nu}_{d}$	$\frac{T}{L}\vert_{c}$	$\frac{R}{L}\vert^{\nu}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{T}{L}\vert_{\alpha}$	$\frac{R}{L}\vert$
$\frac{L}{F_0}\vert_{x}$	$\frac{L}{L}\vert^{\nu}_{(d,x)}$	$\frac{L}{L}\vert_{(c,x)}$	$\frac{F_0}{L}\vert^{\nu}_{x}$	$\frac{F_0}{L}\vert_{x}$	$\oplus_\alpha\frac{L}{L}\vert_{(\alpha,x)}$	$\frac{F_0}{L}\vert_{x}$
$\frac{R}{F_0}\vert_{x}$	$\frac{T}{L}\vert_{d}$	$\frac{T}{L}\vert^{\nu}_{c}$	$\frac{R}{L}\vert$	$\frac{R}{L}\vert^{\nu}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{T}{L}\vert_{\alpha}$
$\frac{F_0}{F_0}\vert_{(x,y)}$	$\frac{L}{L}\vert_{(d,x)}$	$\frac{L}{L}\vert^{\nu}_{(c,x)}$	$\frac{F_0}{L}\vert_{x}$	$\frac{F_0}{L}\vert^{\nu}_{x}$	$\frac{F_0}{L}\vert_{x}$	$\oplus_\alpha\frac{L}{L}\vert_{(\alpha,x)}$
$\frac{X_l}{F_0}\vert_{x}$	$\frac{T}{L}\vert_{d}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\frac{X_{ln}}{L}\vert$	$\oplus_\alpha\frac{F_{l^{-1}t}}{L}\vert_{\alpha}$
$\frac{F_r}{F_0}\vert$	$\oplus_\alpha\frac{L}{L}\vert_{(d,\alpha)}$	$\frac{T}{L}\vert_{c}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{F_{rn}}{L}\vert_{\alpha}$	$\frac{X_{r^{-1}t}}{L}\vert$
$\frac{T}{X_k}\vert_{a}$	$\frac{T}{T}\vert^{\nu}_{(a+k(c-\nu),d)}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$\frac{R}{T}\vert^{\nu}_{a+k(c-\nu)}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,(nk)^{-1}(a-\alpha)+n^{-1}c)}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$
$\frac{L}{X_k}\vert$	$\frac{L}{T}\vert^{\nu}_{d}$	$\frac{L}{T}\vert_{c}$	$\frac{F_0}{T}\vert^{\nu}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{L}{T}\vert_{\alpha}$	$\frac{F_0}{T}\vert$
$\frac{R}{X_k}\vert$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,d)}$	$\oplus_\alpha\frac{T}{T}\vert^{\nu}_{(\alpha,c)}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\oplus_\alpha\frac{R}{T}\vert^{\nu}_{\alpha}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\oplus_{\alpha,\beta}\frac{T}{T}\vert_{(\alpha,\beta)}$
$\frac{F_0}{X_k}\vert_{x}$	$\frac{L}{T}\vert_{d}$	$\frac{L}{T}\vert^{\nu}_{c}$	$\frac{F_0}{T}\vert$	$\frac{F_0}{T}\vert^{\nu}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{L}{T}\vert_{\alpha}$
$\frac{X_k}{X_k}\vert_{(a,x)}$	$\frac{T}{T}\vert_{(a+kc,d)}$	$\frac{L}{T}\vert_{c}$	$\frac{R}{T}\vert_{a+kc}$	$\frac{F_0}{T}\vert$	$\frac{X_{kn}}{T}\vert_{a+kc}$	$\frac{F_{k^{-1}t}}{T}\vert$
$\frac{X_l}{X_k}\vert$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,d)}$	$p\cdot\frac{L}{T}\vert_{c}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$p\cdot\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{X_{ln}}{T}\vert_{\alpha}$	$p\cdot\frac{F_{l^{-1}t}}{T}\vert$
$\frac{F_r}{X_k}\vert_{x}$	$\frac{L}{T}\vert_{d}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\frac{F_{rn}}{T}\vert$	$\oplus_\alpha\frac{X_{r^{-1}t}}{T}\vert_{\alpha}$
$\frac{T}{F_q}\vert$	$\frac{T}{L}\vert^{\nu}_{d}$	$\frac{T}{L}\vert_{c}$	$\frac{R}{L}\vert^{\nu}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{T}{L}\vert_{\alpha}$	$\frac{R}{L}\vert$
$\frac{L}{F_q}\vert_{x}$	$\frac{L}{L}\vert^{\nu}_{(d,x+q(c-\nu))}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$\frac{F_0}{L}\vert^{\nu}_{x+q(c-\nu)}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\oplus_\alpha\frac{L}{L}\vert_{(n^{-1}(q^{-1}(x-\alpha)+c),\alpha)}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$
$\frac{R}{F_q}\vert_{x}$	$\frac{T}{L}\vert_{d}$	$\frac{T}{L}\vert^{\nu}_{c}$	$\frac{R}{L}\vert$	$\frac{R}{L}\vert^{\nu}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{T}{L}\vert_{\alpha}$
$\frac{F_0}{F_q}\vert$	$\oplus_\alpha\frac{L}{L}\vert_{(d,\alpha)}$	$\oplus_\alpha\frac{L}{L}\vert^{\nu}_{(c,\alpha)}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\oplus_\alpha\frac{F_0}{L}\vert^{\nu}_{\alpha}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\oplus_{\alpha,\beta}\frac{L}{L}\vert_{(\alpha,\beta)}$
$\frac{X_l}{F_q}\vert_{x}$	$\frac{T}{L}\vert_{d}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\frac{X_{ln}}{L}\vert$	$\oplus_\alpha\frac{F_{l^{-1}t}}{L}\vert_{\alpha}$
$\frac{F_q}{F_q}\vert_{(x,y)}$	$\frac{L}{L}\vert_{(d,x+qc)}$	$\frac{T}{L}\vert_{c}$	$\frac{F_0}{L}\vert_{x+qc}$	$\frac{R}{L}\vert$	$\frac{F_{qn}}{L}\vert_{x+qc}$	$\frac{X_{q^{-1}t}}{L}\vert$
$\frac{F_r}{F_q}\vert$	$\oplus_\alpha\frac{L}{L}\vert_{(d,\alpha)}$	$p\cdot\frac{T}{L}\vert_{c}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$p\cdot\frac{R}{L}\vert$	$\oplus_\alpha\frac{F_{rn}}{L}\vert_{\alpha}$	$p\cdot\frac{X_{r^{-1}t}}{L}\vert$

	$\frac{T}{L}\vert_{c}$	$\frac{L}{L}\vert_{(c,z)}$	$\frac{R}{L}\vert$	$\frac{F_0}{L}\vert_{z}$	$\frac{X_n}{L}\vert$	$\frac{F_t}{L}\vert_{z}$
$\frac{T}{T}\vert_{(a,b)}$	$\frac{T}{T}\vert^{\nu}_{(a,c)}$	$\frac{T}{T}\vert_{(a,c)}$	$\frac{R}{T}\vert^{\nu}_{a}$	$\frac{R}{T}\vert_{a}$	$\oplus_\beta\frac{T}{T}\vert_{(a,\beta)}$	$\frac{R}{T}\vert_{a}$
$\frac{L}{T}\vert_{a}$	$\frac{L}{T}\vert^{\nu}_{c}$	$\frac{L}{T}\vert_{c}$	$\frac{F_0}{T}\vert^{\nu}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{L}{T}\vert_{\alpha}$	$\frac{F_0}{T}\vert$
$\frac{R}{T}\vert_{a}$	$\frac{T}{T}\vert_{(a,c)}$	$\frac{T}{T}\vert^{\nu}_{(a,c)}$	$\frac{R}{T}\vert_{a}$	$\frac{R}{T}\vert^{\nu}_{a}$	$\frac{R}{T}\vert_{a}$	$\oplus_\beta\frac{T}{T}\vert_{(a,\beta)}$
$\frac{F_0}{T}\vert$	$\frac{L}{T}\vert_{c}$	$\frac{L}{T}\vert^{\nu}_{c}$	$\frac{F_0}{T}\vert$	$\frac{F_0}{T}\vert^{\nu}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{L}{T}\vert_{\alpha}$
$\frac{X_l}{T}\vert_{a}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$\frac{L}{T}\vert_{c}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{X_{ln}}{T}\vert_{\alpha}$	$\frac{F_{l^{-1}t}}{T}\vert$
$\frac{F_r}{T}\vert$	$\frac{L}{T}\vert_{c}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\frac{F_{rn}}{T}\vert$	$\oplus_\alpha\frac{X_{r^{-1}t}}{T}\vert_{\alpha}$
$\frac{T}{L}\vert_{a}$	$\frac{T}{L}\vert^{\nu}_{c}$	$\frac{T}{L}\vert_{c}$	$\frac{R}{L}\vert^{\nu}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{T}{L}\vert_{\alpha}$	$\frac{R}{L}\vert$
$\frac{L}{L}\vert_{(a,x)}$	$\frac{L}{L}\vert^{\nu}_{(c,x)}$	$\frac{L}{L}\vert_{(c,x)}$	$\frac{F_0}{L}\vert^{\nu}_{x}$	$\frac{F_0}{L}\vert_{x}$	$\oplus_\alpha\frac{L}{L}\vert_{(\alpha,x)}$	$\frac{F_0}{L}\vert_{x}$
$\frac{R}{L}\vert$	$\frac{T}{L}\vert_{c}$	$\frac{T}{L}\vert^{\nu}_{c}$	$\frac{R}{L}\vert$	$\frac{R}{L}\vert^{\nu}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{T}{L}\vert_{\alpha}$
$\frac{F_0}{L}\vert_{x}$	$\frac{L}{L}\vert_{(c,x)}$	$\frac{L}{L}\vert^{\nu}_{(c,x)}$	$\frac{F_0}{L}\vert_{x}$	$\frac{F_0}{L}\vert^{\nu}_{x}$	$\frac{F_0}{L}\vert_{x}$	$\oplus_\alpha\frac{L}{L}\vert_{(\alpha,x)}$
$\frac{X_l}{L}\vert$	$\frac{T}{L}\vert_{c}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\frac{X_{ln}}{L}\vert$	$\oplus_\alpha\frac{F_{l^{-1}t}}{L}\vert_{\alpha}$
$\frac{F_r}{L}\vert_{x}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$\frac{T}{L}\vert_{c}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{F_{rn}}{L}\vert_{\alpha}$	$\frac{X_{r^{-1}t}}{L}\vert$
$\frac{T}{R}\vert_{a}$	$\frac{T}{T}\vert^{\mu,\nu}_{(a,c)}$	$\frac{T}{T}\vert^{\mu}_{(a,c)}$	$\frac{R}{T}\vert^{\mu,\nu}_{a}$	$\frac{R}{T}\vert^{\mu}_{a}$	$\oplus_\beta\frac{T}{T}\vert^{\mu}_{(a,\beta)}$	$\frac{R}{T}\vert^{\mu}_{a}$
$\frac{L}{R}\vert$	$\frac{L}{T}\vert^{\mu,\nu}_{c}$	$\frac{L}{T}\vert^{\mu}_{c}$	$\frac{F_0}{T}\vert^{\mu,\nu}$	$\frac{F_0}{T}\vert^{\mu}$	$\oplus_\alpha\frac{L}{T}\vert^{\mu}_{\alpha}$	$\frac{F_0}{T}\vert^{\mu}$
$\frac{R}{R}\vert_{(a,x)}$	$\frac{T}{T}\vert^{\mu}_{(a,c)}$	$\delta^{x+z}_{\nu-\mu}\frac{T}{T}\vert^{\mu,\nu}_{(a,c)}$	$\frac{R}{T}\vert^{\mu}_{a}$	$\delta^{x+z}_{\nu-\mu}\frac{R}{T}\vert^{\mu,\nu}_{a}$	$\frac{R}{T}\vert^{\mu}_{a}$	$\frac{T}{T}\vert^{\mu}_{(a,t^{-1}(\mu+x+z))}$
$\frac{F_0}{R}\vert_{x}$	$\frac{L}{T}\vert^{\mu}_{c}$	$\delta^{x+z}_{\nu-\mu}\frac{L}{T}\vert^{\mu,\nu}_{c}$	$\frac{F_0}{T}\vert^{\mu}$	$\delta^{x+z}_{\nu-\mu}\frac{F_0}{T}\vert^{\mu,\nu}$	$\frac{F_0}{T}\vert^{\mu}$	$\frac{L}{T}\vert^{\mu}_{t^{-1}(\mu+x+z)}$
$\frac{X_l}{R}\vert$	$\oplus_\alpha\frac{T}{T}\vert^{\mu}_{(\alpha,c)}$	$\frac{L}{T}\vert^{\mu}_{c}$	$\oplus_\alpha\frac{R}{T}\vert^{\mu}_{\alpha}$	$\frac{F_0}{T}\vert^{\mu}$	$\oplus_\alpha\frac{X_{ln}}{T}\vert^{\mu}_{\alpha}$	$\frac{F_{l^{-1}t}}{T}\vert^{\mu}$
$\frac{F_r}{R}\vert_{x}$	$\frac{L}{T}\vert^{\mu}_{c}$	$\frac{T}{T}\vert^{\mu}_{(r^{-1}(x+z+\mu,c))}$	$\frac{F_0}{T}\vert^{\mu}$	$\frac{R}{T}\vert^{\mu}_{r^{-1}(x+z+\mu)}$	$\frac{F_{rn}}{T}\vert^{\mu}$	$\frac{X_{r^{-1}t}}{T}\vert^{\mu}_{r^{-1}(x+z+\mu)}$
$\frac{T}{F_0}\vert$	$\frac{T}{L}\vert^{\mu,\nu}_{c}$	$\frac{T}{L}\vert^{\mu}_{c}$	$\frac{R}{L}\vert^{\mu,\nu}$	$\frac{R}{L}\vert^{\mu}$	$\oplus_\alpha\frac{T}{L}\vert^{\mu}_{\alpha}$	$\frac{R}{L}\vert^{\mu}$
$\frac{L}{F_0}\vert_{x}$	$\frac{L}{L}\vert^{\mu,\nu}_{(c,x)}$	$\frac{L}{L}\vert^{\mu}_{(c,x)}$	$\frac{F_0}{L}\vert^{\mu,\nu}_{x}$	$\frac{F_0}{L}\vert^{\mu}_{x}$	$\oplus_\alpha\frac{L}{L}\vert^{\mu}_{(\alpha,x)}$	$\frac{F_0}{L}\vert^{\mu}_{x}$
$\frac{R}{F_0}\vert_{x}$	$\frac{T}{L}\vert^{\mu}_{c}$	$\delta^{x+z}_{\nu-\mu}\frac{T}{L}\vert^{\mu,\nu}_{c}$	$\frac{R}{L}\vert^{\mu}$	$\delta^{x+z}_{\nu-\mu}\frac{R}{L}\vert^{\mu,\nu}$	$\frac{R}{L}\vert^{\mu}$	$\frac{T}{L}\vert^{\mu}_{t^{-1}(\mu+x+z)}$
$\frac{F_0}{F_0}\vert_{(x,y)}$	$\frac{L}{L}\vert^{\mu}_{(c,x)}$	$\delta^{y+z}_{\nu-\mu}\frac{L}{L}\vert^{\mu,\nu}_{(c,x)}$	$\frac{F_0}{L}\vert^{\mu}_{x}$	$\delta^{y+z}_{\nu-\mu}\frac{F_0}{L}\vert^{\mu,\nu}_{x}$	$\frac{F_0}{L}\vert^{\mu}_{x}$	$\frac{L}{L}\vert^{\mu}_{(t^{-1}(y+z+\mu),x)}$
$\frac{X_l}{F_0}\vert_{x}$	$\frac{T}{L}\vert^{\mu}_{c}$	$\frac{L}{L}\vert^{\mu}_{(c,x+l^{-1}(\mu+z))}$	$\frac{R}{L}\vert^{\mu}$	$\frac{F_0}{L}\vert^{\mu}_{x+l^{-1}(\mu+z)}$	$\frac{X_{ln}}{L}\vert^{\mu}$	$\frac{F_{l^{-1}t}}{L}\vert^{\mu}_{x+l^{-1}(\mu+z)}$
$\frac{F_r}{F_0}\vert$	$\oplus_\alpha\frac{L}{L}\vert^{\mu}_{(c,\beta)}$	$\frac{T}{L}\vert^{\mu}_{c}$	$\oplus_\alpha\frac{F_0}{L}\vert^{\mu}_{\alpha}$	$\frac{R}{L}\vert^{\mu}$	$\oplus_\alpha\frac{F_{rn}}{L}\vert^{\mu}_{\alpha}$	$\frac{X_{r^{-1}t}}{L}\vert^{\mu}$
$\frac{T}{X_k}\vert_{a}$	$\frac{T}{L}\vert^{\nu}_{c}$	$\frac{T}{L}\vert_{c}$	$\frac{R}{L}\vert^{\nu}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{T}{L}\vert_{\alpha}$	$\frac{R}{L}\vert$
$\frac{L}{X_k}\vert$	$\oplus_\alpha\frac{L}{L}\vert^{\nu}_{(c,\alpha)}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$\oplus_\alpha\frac{F_0}{L}\vert^{\nu}_{\alpha}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\oplus_{\alpha,\beta}\frac{L}{L}\vert_{(\alpha,\beta)}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$
$\frac{R}{X_k}\vert$	$\frac{T}{L}\vert_{c}$	$\frac{T}{L}\vert^{\nu}_{c}$	$\frac{R}{L}\vert$	$\frac{R}{L}\vert^{\nu}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{T}{L}\vert_{\alpha}$
$\frac{F_0}{X_k}\vert_{x}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$\frac{L}{L}\vert^{\nu}_{(c,x+k^{-1}(z-\nu))}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\frac{F_0}{L}\vert^{\nu}_{x+k^{-1}(z-\nu)}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\oplus_\alpha\frac{L}{L}\vert_{(t^{-1}(k(x-\alpha)+z),\alpha)}$
$\frac{X_k}{X_k}\vert_{(a,x)}$	$\frac{T}{L}\vert_{c}$	$\frac{L}{L}\vert_{(c,k^{-1}(x+z))}$	$\frac{R}{L}\vert$	$\frac{F_0}{L}\vert_{k^{-1}(x+z)}$	$\frac{X_{kn}}{L}\vert$	$\frac{F_{k^{-1}t}}{L}\vert_{k^{-1}(x+z)}$
$\frac{X_l}{X_k}\vert$	$p\cdot\frac{T}{L}\vert_{c}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$p\cdot\frac{R}{L}\vert$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$p\cdot\frac{X_{ln}}{L}\vert$	$\oplus_\alpha\frac{F_{l^{-1}t}}{L}\vert_{\alpha}$
$\frac{F_r}{X_k}\vert_{x}$	$\oplus_\alpha\frac{L}{L}\vert_{(c,\alpha)}$	$\frac{T}{L}\vert_{c}$	$\oplus_\alpha\frac{F_0}{L}\vert_{\alpha}$	$\frac{R}{L}\vert$	$\oplus_\alpha\frac{F_{rn}}{L}\vert_{\alpha}$	$\frac{X_{r^{-1}t}}{L}\vert$
$\frac{T}{F_q}\vert$	$\oplus_\alpha\frac{T}{T}\vert^{\nu}_{(\alpha,c)}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$\oplus_\alpha\frac{R}{T}\vert^{\nu}_{\alpha}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\oplus_{\alpha,\beta}\frac{T}{T}\vert_{(\alpha,\beta)}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$
$\frac{L}{F_q}\vert_{x}$	$\frac{L}{T}\vert^{\nu}_{c}$	$\frac{L}{T}\vert_{c}$	$\frac{F_0}{T}\vert^{\nu}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{L}{T}\vert_{\alpha}$	$\frac{F_0}{T}\vert$
$\frac{R}{F_q}\vert_{x}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$\frac{T}{T}\vert^{\nu}_{(q^{-1}(x+z-\nu),c)}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\frac{R}{T}\vert^{\nu}_{q^{-1}(x+z-\nu)}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,t^{-1}(x+z-q\alpha))}$
$\frac{F_0}{F_q}\vert$	$\frac{L}{T}\vert_{c}$	$\frac{L}{T}\vert^{\nu}_{c}$	$\frac{F_0}{T}\vert$	$\frac{F_0}{T}\vert^{\nu}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{L}{T}\vert_{\alpha}$
$\frac{X_l}{F_q}\vert_{x}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$\frac{L}{T}\vert_{c}$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{X_{ln}}{T}\vert_{\alpha}$	$\frac{F_{l^{-1}t}}{T}\vert$
$\frac{F_q}{F_q}\vert_{(x,y)}$	$\frac{L}{T}\vert_{c}$	$\frac{T}{T}\vert_{(q^{-1}(y+z),c)}$	$\frac{F_0}{T}\vert$	$\frac{R}{T}\vert_{q^{-1}(y+z)}$	$\frac{F_{qn}}{T}\vert$	$\frac{X_{q^{-1}t}}{T}\vert_{q^{-1}(y+z)}$
$\frac{F_r}{F_q}\vert$	$p\cdot\frac{L}{T}\vert_{c}$	$\oplus_\alpha\frac{T}{T}\vert_{(\alpha,c)}$	$p\cdot\frac{F_0}{T}\vert$	$\oplus_\alpha\frac{R}{T}\vert_{\alpha}$	$p\cdot\frac{F_{rn}}{T}\vert$	$\oplus_\alpha\frac{X_{r^{-1}t}}{T}\vert_{\alpha}$

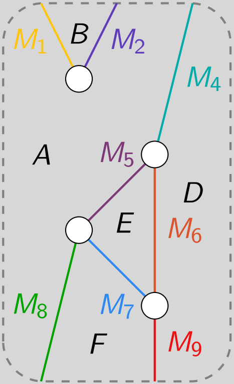
[illegible]

[illegible]

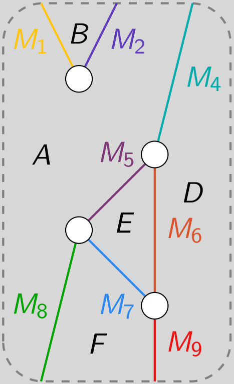
[illegible]

[illegible]

Domain Wall Structures

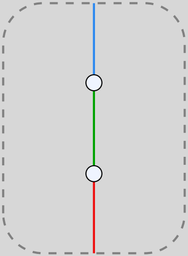


Domain Wall Structures



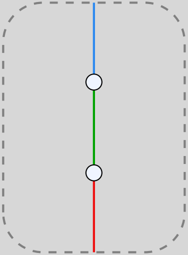
Domain Wall Structure algorithm: Assign defects to all the internal holes. The DWS algorithm computes the resulting compound defect.

Defect Fusion

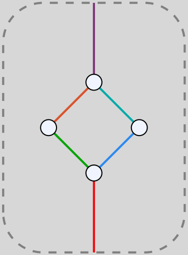


vertical defect fusion.

Defect Fusion



vertical defect fusion.



horizontal defect fusion.

Thank you for Listening!

See *Computing defects associated to bounded domain wall structures: The $\mathbb{Z}/p\mathbb{Z}$ case*, arXiv:1901.08069 for details.