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Alexander Pokorny

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ABSTRACT OF THE DISSERTATION

THESIS TITLE

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In this work, we extend some results from the Kauffman bracket and HOMFLYPT skein theories to the Kuffman (Dubrovnik) skein theory. In particular, a definition is given for special "power sum" type elements $\tilde{P}_k$ in the Dubrovnik skein algebra of the annulus $\mathcal{D}(A)$. It is justified that these elements are the corect generalization for the Chebyshev polynomials (of the first kind) often used when studying Kauffman bracket skein algebras. Threadings of the $\tilde{P}_k$ are used as generators in a presentation of the Dubrovnik skein algebra of the torus $\mathcal{D}(T^2)$, where they are shown to satisfy surprisingly simple relations. This description of $\mathcal{D}(T^2)$ is in turn used to describe the natural action of this algebra on the skein module of the solid torus. Separate from this, we give strong evidence that the universal character rings for the orthogonal and sympletic Lie groups correspond to the skein algebra $\mathcal{D}(A)$ in such a way that the Schur functions of type either B, C or D correspond to annular closures $\tilde{Q}_\lambda$ of minimal idempotents of the Birman-Murakami-Wenzl algebras BMW_n. We also record some miscellaneous applications of the $\tilde{P}_k$, such as commutation relations for the annular closures of BMW symmetrizers $\tilde{Q}_{(n)}$ (and their HOMFLYPT counterparts $Q_{(n)}$) and an expression of central elements of BMW_n in terms of Jucys-Murphy elements.

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Chapter 1

Introduction

Summarize the main background and new results here.

Chapter 2

Skein Theory

2.1 Foundations and General Notions

In this work, we will be forced to discuss a few different variants of skein modules. For this reason, it will be useful to first describe some general framework of skein theory so that each of these variants will be a special case. Unless otherwise stated, we will assume M is an oriented 3-manifold with boundary ∂M (possibly empty), Σ is an oriented surface, I is the real interval $[0, 1]$, R is a commutative and unital ring.

Definition 2.1.1. Let $T_1, T_2 : X \to M$ be smooth embeddings of a smooth manifold X into M. A **smooth ambient isotopy** $H : T_1 \Rightarrow T_2$ is a smooth homotopy of diffeomorphisms $H_t : M \to M$ such that $H_0 = \mathrm{id}_M$ and $H_1 \circ T_1 = T_2$. Furthermore, we demand that the boundary ∂M is fixed by the homotopy.

The relation

$$T_1 \sim T_2 \text{ if and only if there exists a smooth ambient isotopy } H : T_1 \Rightarrow T_2$$

is an equivalence relation. The smoothness requirement of H is important when considering knots. Without it, all knots would be equivalent to the unknot by contracting all of the complexity of the knot to a point.

Definition 2.1.2. Let N be a finite set of points contained in the boundary ∂M. An N-**tangle** in M (or just *tangle* for short) is the smooth ambient isotopy class of a smooth embedding

$$T : \underbrace{\bigsqcup_{j \in J} S^1}_{:=L} \sqcup \underbrace{\bigsqcup_{k \in K} I}_{:=B} \to M$$

for some finite sets J and K such that

1. the image of L lies in the interior of M,

2. the image of the interior of B lies in the interior of M,

3. the image of the boundary of B equals N.

If B is empty, then the result is called a **link** in M. Similarly, if L is empty, then it's called a **braid** in M.

One may also consider *oriented* or *framed* tangles by choosing an orientation or framing for each point in N and for each connected component of L and B such that the choices are compatible with each other with respect to the smooth embedding. If $M = \Sigma \times I$, then we will assume that the points in N are contained in $\Sigma \times \{\frac{1}{2}\}$ and that their framings are thought to be embedded orthogonally to $\Sigma \times \{*\}$.
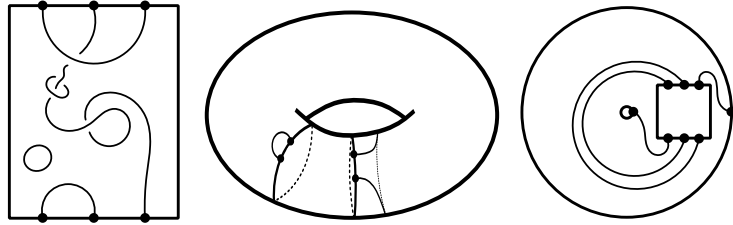
Figure 2.1: Some examples of framed tangle diagrams.

We say a framed tangle in $\Sigma \times I$ has **blackboard framing** if the entire framing is embedded orthogonally to Σ. Every framed link in $\Sigma \times I$ is isotopic to one with a blackboard

framing by turning each twist into a loop with a local blackboard framing:

$$
\vcenter{\hbox{\includegraphics{twist}}} \; = \; \vcenter{\hbox{\includegraphics{loop}}}.
$$

This suggests that we may represent framed links in $\Sigma \times I$ as link diagrams on Σ. Indeed, equivalence under ambient isotopy is captured by the three Reidemeister moves below.

$$
\vcenter{\hbox{\includegraphics{r1}}} \; = \; \vcenter{\hbox{\includegraphics{r1b}}} \tag{2.1}
$$

$$
\vcenter{\hbox{\includegraphics{r2a}}} \; = \; \vcenter{\hbox{\includegraphics{r2b}}} \; = \; \vcenter{\hbox{\includegraphics{r2c}}} \tag{2.2}
$$

$$
\vcenter{\hbox{\includegraphics{r3a}}} \; = \; \vcenter{\hbox{\includegraphics{r3b}}}. \tag{2.3}
$$
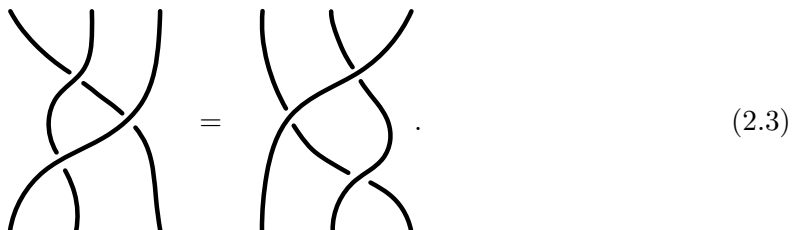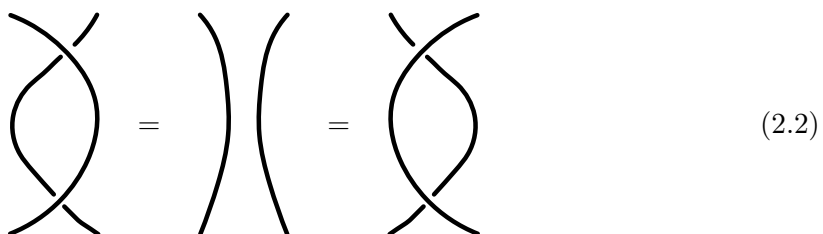
Define the **writhe** of a tangle diagram is the number of positive crossings minus the number of negative crossings. It is easy to see that the Reidemeister moves above preserve the writhe of a diagram, so the concept is well defined. Writhe should be thought of as a grading on the free R-module on the set of tangles in the given space, which provides a good reason to work with framed links over ordinary links. Such a module is a main ingredient of this theory, so let's honor it with a proper discussion.

Definition 2.1.3. Let $\mathcal{T}(M, N)$ be the free R-module generated by the set of framed N-tangles in M. Analagously, we can define $\mathcal{T}^{or}(M, N)$ to be the free R-module generated by the set of oriented framed N-tangles in M. All definitions which are to follow in this section have an analagous definition using oriented tangles. Also, we will formally define $\mathcal{T}_R(\varnothing, \varnothing) := R$.

The construction $\mathcal{T}(-, -)$ is actually a symmetric monoidal functor $\mathcal{T} : \mathsf{C} \to R\text{-}\mathsf{Mod}$ for a careful choice of category C which we now describe. The objects of C are pairs (M, N) of the same type as discussed previously. A morphism $(f, W) : (M', N') \to (M, N)$ is a pair of a smooth, orientation-preserving embedding $f : M' \to M$ such that $M - f(M')$ is either a smooth 3-manifold or the empty set, and choice of $W \in \mathcal{T}(M - f(M'), N \sqcup f(N'))$ (unless $M - f(M')$ is empty, in which case W is a formal symbol for the "empty link" in the empty set). Composition is given by $(g, W') \circ (f, W) = (g \circ f, W' \cup W)$, which is associative since $\circ$ and $\cup$ are associative.
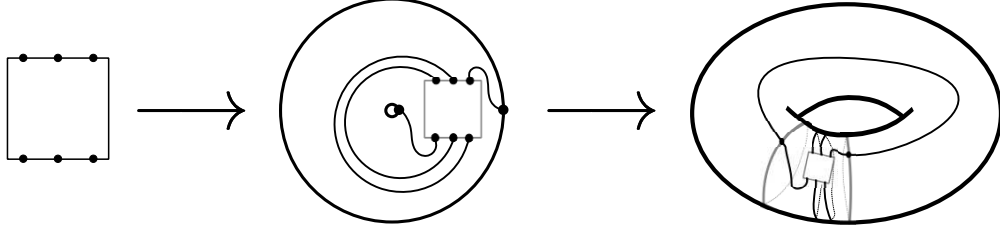
Figure 2.2: An example of how composition works in C.

The induced map denoted $W : \mathcal{T}(M', N') \to \mathcal{T}(M, N)$ is a linear map defined by $W(T) = W \cup T$, and we will refer to such a linear map W as a **wiring**. We are abusing notation by denoting this linear map by W, but it should be clear from the context what f is since it is technically encoded in the data of the element $W \in \mathcal{T}(M - f(M'), N \sqcup f(N'))$. It is true that $\mathcal{T}$ preserves composition and identity morphisms, making and so $\mathcal{T}$ is functorial. C can now be equipped with a symmetric monoidal structure via disjoint union. It is clear that

$$\mathcal{T}_R(M \sqcup M', N \sqcup N') \cong \mathcal{T}_R(M, N) \underset{R}{\otimes} \mathcal{T}_R(M', N')$$

for any sets of framed points $N \subset \partial M$ and $N' \subset \partial M'$. The unit is given by the object $(\varnothing, \varnothing) \in \mathsf{C}$ and define $\mathcal{T}(\varnothing, \varnothing) := R$, which makes $\mathcal{T}$ a symmetric monoidal functor.

Definition 2.1.4. Let B be the smooth closed 3-ball, N_i be a choice of $2i$ boundary points of B, and let $X \subset \bigsqcup_{i \in \mathbb{N}} \mathcal{T}(B, N_i)$ be some (typically finite) set, which we will call a set of **skein relations**. Given any tangle module $\mathcal{T}(M, N_M)$, there exists a submodule $\mathcal{I}(X)$ generated by the set

$$\{W(x) \mid x \in X \text{ and } W : \mathcal{T}(B, N_B) \to \mathcal{T}(M, N_M) \text{ is a wiring diagram}\}.$$

A quotient of the form $\mathcal{S}_X(M, N) := \mathcal{T}(M, N)/\mathcal{I}(X)$ is called a **skein module** of M relative to N. If $N = \varnothing$ is the empty set, we may use the notation $\mathcal{S}_X(M) := \mathcal{S}_X(M, \varnothing)$. Similar definitions may be given using oriented and/or unframed tangles instead.

The construction $\mathcal{S}_X(-, -)$ is a functor in the same way that $\mathcal{T}(-, -)$ is; a smooth, orientation-preserving embedding $f : M \to M'$ and an element $W \in \mathcal{S}_X\big(M - f(M'), N \sqcup f(N')\big)$ (assume N is disjoint from $\mathrm{Im}(f)$) defines a linear map $W : \mathcal{S}_X(M, N) \to \mathcal{S}_X(M', N')$. In fact, the quotient maps $\alpha_{(M,N)} : \mathcal{T}(M, N) \to \mathcal{S}_X(M, N)$ yield a natural transformation. In other words, given a morphism $(M, N) \to (M', N')$ in C, the diagram

$$
\begin{array}{ccc}
\mathcal{T}(M, N) & \xrightarrow{\ W\ } & \mathcal{T}(M', N') \\
\downarrow{\scriptstyle \alpha_{(M,N)}} & & \downarrow{\scriptstyle \alpha_{(M',N')}} \\
\mathcal{S}_X(M, N) & \xrightarrow{\ W\ } & \mathcal{S}_X(M', N')
\end{array}
$$

commutes. Such a functor will be called a **skein theory** (or *oriented* skein theory if the skein relations are based on oriented tangles).

For any oriented surface Σ, we can define a category $\mathsf{Skein}_X(\Sigma)$ which we will call a **skein category**. The objects of this category are finite sets of framed points (together with a choice of orientation if the skein theory is oriented) N in Σ, and the morphisms $N \to N'$ are elements of $\mathcal{S}_X\big(\Sigma \times I, (N \times \{0\}) \sqcup (N' \times \{1\})\big)$, so the category is R-linear. Write composition of morphisms by concatenation. If $y : N \to N'$ and $z : N' \to N''$ are morphisms, then their composite $yz : N \to N''$ is constucted by gluing one end of y to the

other end of z through N' and rescaling the interval coordinate appropriately.
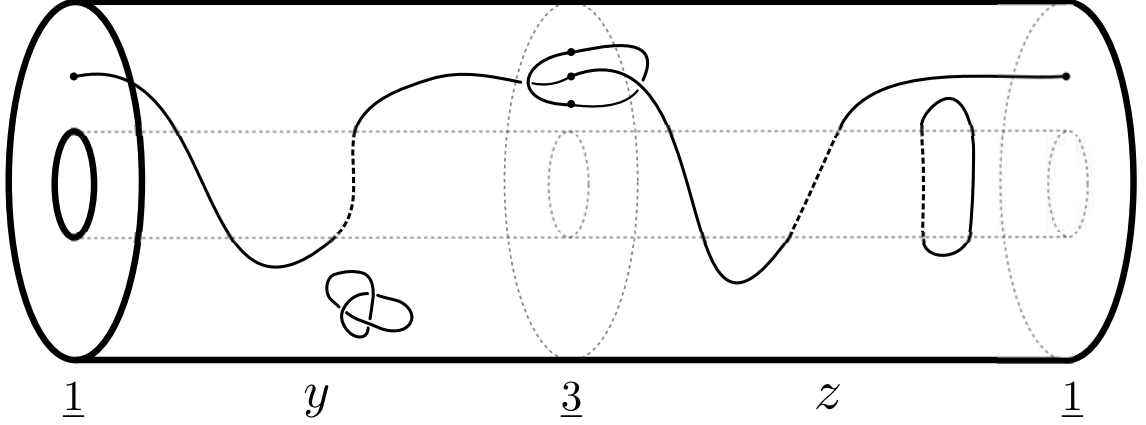
Figure 2.3: A composition of morphisms $y : [1] \to [3]$ and $z : [3] \to [1]$ in the category $\mathsf{Skein}_X(A)$ for an annulus A. The result is an endomorphism yz of $[1]$.

The endomorphism algebras in this category are called **skein algebras** and are denoted by $\mathcal{S}_X(\Sigma, N) := \mathcal{S}_X(\Sigma \times I, (N \times \{0\}) \sqcup (N \times \{1\}))$. If N is the empty set, then we reduce the notation to simply $\mathcal{S}_X(\Sigma)$.

If $f : \Sigma \to \Sigma'$ is a smooth embedding of surfaces, then there is an induced functor

$$\mathsf{Skein}_X(f) : \mathsf{Skein}_X(\Sigma') \to \mathsf{Skein}_X(\Sigma)$$

defined on objects by $\mathsf{Skein}_X(f)(N) = f(N)$ and on morphisms in the following way. First, extend f trivially to $f \times \mathrm{id}_I : \Sigma \times I \to \Sigma' \times I$. Then, in the skein algebra of the complement of the image of $f \times \mathrm{id}_I$, choose the multiplicative identity element $e \in \mathcal{S}_X\big(\Sigma' - \mathrm{Im}(f)\big)$ which is the empty tangle. The pair $(f \times \mathrm{id}_I, e)$ is an object in the category C, which gives rise to a wiring

$$e : \mathcal{S}_X\Big(\Sigma \times I, (N \times \{0\}) \sqcup (N' \times \{1\})\Big) \to \mathcal{S}_X\Big(\Sigma' \times I, (f(N) \times \{0\}) \sqcup (f(N') \times \{1\})\Big)$$

via the functor $\mathcal{S}_X$. Now we may define what $\mathsf{Skein}_X(f)$ does to morphisms: $\mathsf{Skein}_X(f)(y) = e(y)$ for any $y \in \mathcal{S}_X\Big(\Sigma \times I, (N \times \{0\}) \sqcup (N' \times \{1\})\Big)$.
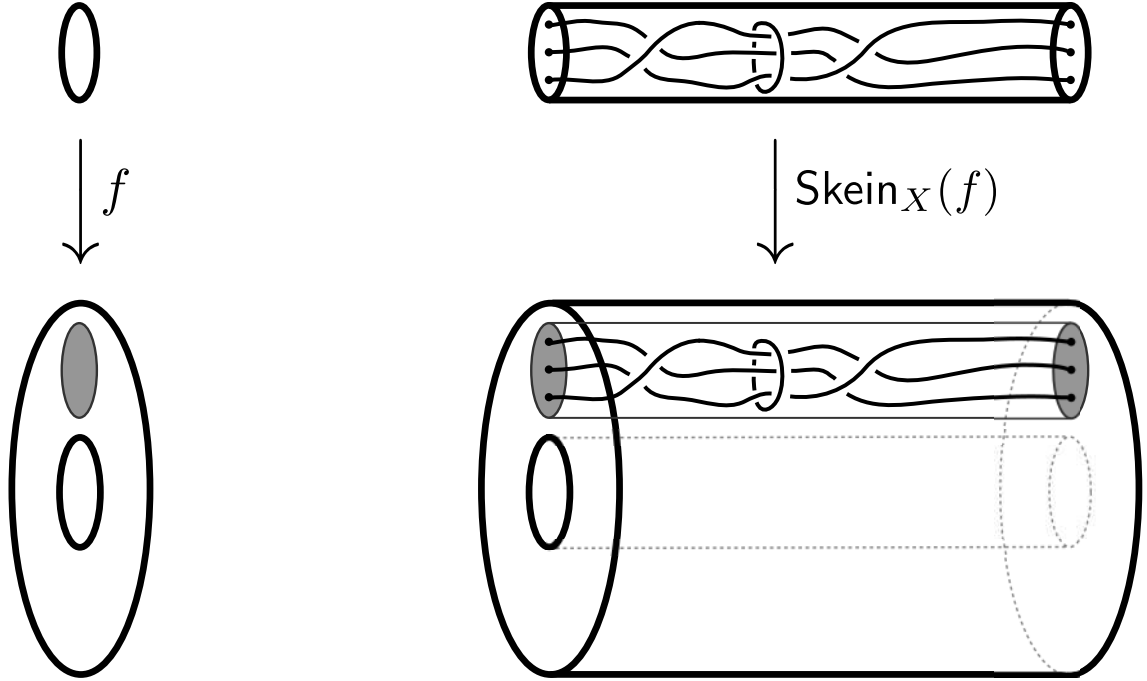
Figure 2.4: On the left is pictured a smooth embedding f of a disk into an annulus. This induces a functor $\mathsf{Skein}_X(f)$ between the skein categories of the disk and the annulus. On the right is an example of a morphism in the skein category of the disk and its image under this functor.

It is clear that $\mathsf{Skein}_X(f)$ preserves composition and identity morphisms. Therefore, if we let $\mathsf{Surf}_{\mathrm{emb}}$ be the category of smooth embeddings between smooth oriented surfaces, we can summarize our last few points by saying we have a functor

$$\mathsf{Skein}_X : \mathsf{Surf}_{\mathrm{emb}} \to \mathsf{Cat}.$$

In particular, $\mathsf{Skein}_X(f)$ defines algebra homomorphisms on the skein algebras

$$e : \mathcal{S}_X\big(\Sigma, N\big) \to \mathcal{S}_X\big(\Sigma', f(N)\big).$$

Remark 2.1.5. The above homomorphisms are a special case of a more general type of map. If N is a set of framed points on Σ, then a smooth embedding $f : \Sigma \to \partial M$ induces a $\mathcal{S}_X(\Sigma, N)$-module structure on $\mathcal{S}_X(M, N')$ for any N' with $f(N) \subseteq N'$. The action is given by "pushing tangles in through the boundary". In other words, the pre-composition of a

smooth embedding of a collar neighborhood $g : \partial M \times I \to M$ with $f \times \mathrm{id}_I : \Sigma \times I \to \partial M \times I$ induces a bilinear map

$$\mathcal{S}_X(\Sigma, N) \times \mathcal{S}_X(M, N') \to \mathcal{S}_X(M, N')$$

because M minus a collar neighborhood is diffeomorphic to itself. Alternatively, a choice of element in $\mathcal{S}_X(\Sigma, N')$ produces a wiring $\mathcal{S}_X(M, N') \to \mathcal{S}_X(M, N')$.
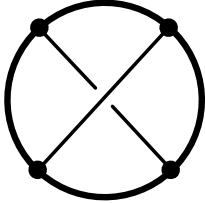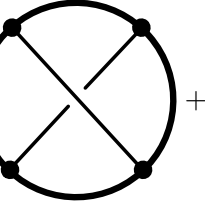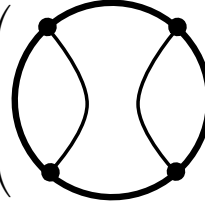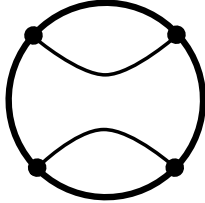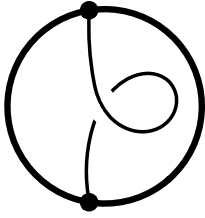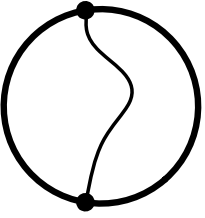
2.2 Examples of Skein Theories

The last section leaves us with an important and unanswered question. Which sets of skein relations X produce interesting skein theories? One class of examples is found by importing sets of relations satisfied by morphisms in a linear ribbon category as skein relations. Ribbon categories are braided monoidal categories which are rigid and equipped with a twist morphism for every object, satisfying some compatibility conditions. The axioms are such that the morphisms may be interpreted as framed braid diagrams. In particular, the morphisms satisfy the Reidemeister moves shown previously. We will discuss three examples of skein theories derived from skein relations which are meant to emulate linear relations satisfied by the braid and twist morphisms in certain ribbon categories coming from the representation theory of quantum groups, a topic which has generated a lot of interest from mathematicians since the 1980s. The categories of representations of quantum groups are ribbon categories with non-involutive braidings and the skein relations below capture how far off the braidings are from being involutive.

Here, we are forced to fix a base ring. For our purposes, R must be a commutative ring containing invertible elements s and v. Typical choices of R are $\mathbb{Z}[s^{\pm 1}, v^{\pm 1}], \mathbb{Q}(s, v)$, or some other ring in between these. In particular, the theorem * Cite BB is stated over this ring, a result we will depend heavily on later on.
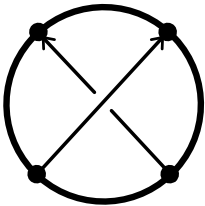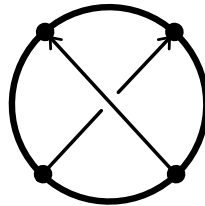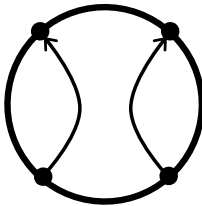
Example 2.2.1 (*Kauffman (Dubrovnik) Skein Relations*)**.** Let X_1 be the set of two unoriented skein relations

(1) $= $ $+ (s - s^{-1}) \left(\text{(diagram)} - \text{(diagram)} \right)$

(2) $= v$.

The functor $\mathcal{D}(-,-) := \mathcal{S}_{X_1}(-,-)$ is the Dubrovnik skein theory (sometimes just called the Kauffman skein theory). We will use the notation $\mathsf{D}(-) := \mathsf{Skein}_{X_1}(-)$ for the Dubrovnik skein categories. Using the Dubrovnik variant is important for us (see Corollary 3.2.2). This theory is related to Dubrovnik polynomials in that the Dubrovnik polynomial of a link is a normalized value of the link in $\mathcal{D}(S^3)$. The normalization is often so that the Dubrovnik polynomial of the unknot is 1, whereas the value of the unknot in $\mathcal{D}(S^3)$ is $\delta_\mathcal{D} := 1 - \frac{v - v^{-1}}{s - s^{-1}}$, which can be deduced from the skein relations.

Example 2.2.2 (*HOMFLYPT Skein Relations*)**.** Next, let X_2 be the set of two oriented skein relations

(1) $=$ $+ (s - s^{-1})$

$$(2) \qquad = v \qquad .$$

The functor $\mathcal{H}(-,-) := \mathcal{S}_{X_2}(-,-)$ is the HOMFLYPT skein theory and we use the notation $\mathsf{H}(-) := \mathsf{Skein}_{X_2}(-)$ for the HOMFLYPT skein categories. As in the Dubrovnik case, this theory is related to HOMFLYPT polynomials so that the HOMFLYPT polynomial of a link is a normalized value of the link in $\mathcal{H}(S^3)$. Again, some often make the choice to normalize this polynomial so that the value of the unknot is 1, but the value of the unknot in $\mathcal{H}(S^3)$ is $\delta_{\mathcal{H}} := -\frac{v - v^{-1}}{s - s^{-1}}$.

Example 2.2.3 (*Kauffman Bracket Skein Relations*)**.** As a final example, let X_3 be the set of two unoriented skein relations

$$(1) \qquad = s \qquad + s^{-1} \qquad$$

$$(2) \qquad = -s^{-3} \qquad .$$

The functor $\mathcal{K}(-,-) := \mathcal{S}_{X_3}(-,-)$ is the Kauffman bracket skein theory (not be confused with the Kauffman skein theory) and we use $\mathsf{K}(-) := \mathsf{Skein}_{X_3}(-)$ to notate the Kauffman bracket skein categories. The value of a link in $\mathcal{K}(S^3)$ is equal to its bracket polynomial, which may be normalized as above to obtain its Jones polynomial. One could choose the framing parameter to be v instead of $-s^{-3}$ like we did before without any obvious

consequences, but it is standard in the literature to make the choice we present here. The value of the unknot is $\delta_\mathcal{K} := -s^2 - s^{-2}$.

Remark 2.2.4. Any linear combination of tangles which satisfy the Dubrovnik skein relations will also satisfy the Kauffman bracket skein relations after making the specialization $v = -s^{-3}$. This can be seen by performing the calculation in the relative skein algebra of the ball with 4 points. Let $\sigma^\pm$ be the diagrams of positive and negative crossings, e the planar diagram with two vertical strands, and c the planar diagram with two horizontal strands. Then the Dubrovnik skein relation is

$$\sigma_\mathcal{D}^+ - \sigma_\mathcal{D}^- - (s - s^{-1})e_\mathcal{D} + (s - s^{-1})c_\mathcal{D} = 0$$

and the Kauffman bracket skein relation implies

$$\sigma_\mathcal{K}^+ = se_\mathcal{K} + s^{-1}c_\mathcal{K}$$
$$\sigma_\mathcal{K}^- = sc_\mathcal{K} + s^{-1}e_\mathcal{K}$$

where the subscript indicates which skein module the diagrams are in. Consider the assignment $d_\mathcal{D} \mapsto d_\mathcal{H}$ for any tangle d in the ball relative to those 4 points. Then observe:

$$
\begin{aligned}
&\sigma_\mathcal{K}^+ - \sigma_\mathcal{K}^- - (s - s^{-1})e_\mathcal{K} + (s - s^{-1})c_\mathcal{K} \\
= \quad &(se_\mathcal{K} + s^{-1}c_\mathcal{K}) - (sc_\mathcal{K} + s^{-1}e_\mathcal{K}) - (s - s^{-1})e_\mathcal{K} + (s - s^{-1})c_\mathcal{K} \\
= \quad &0
\end{aligned}
$$

Therefore, there is a natural transformation of skein theories

$$\eta : \mathcal{D}(-,-) \to \mathcal{K}(-,-)$$

whose components are essentially the identity map, using the same type of assignment as we did above. Note that any component of η corresponding to a skein algebra is an algebra homomorphism since the map preserves the (topological) product structure of the manifold.

In this work, we will be focused on generalizing existing results from the HOMFLYPT and Kauffman bracket skein theories to the Dubrovnik skein theory, but we will state a few facts regarding the HOMFLYPT and Kauffman bracket skein theories when it is valuable for us to do so.

* Maybe add a remark about Turaev's work on deformations of the Goldman Lie algebras? Could potentially say a lot to motivate the topic, but I'm not super familiar with a lot of it.

Remark 2.2.5. For a surface Σ, a link in $\Sigma \times I$ may be considered as a cycle in $H_1(\Sigma \times I, \mathbb{Z}) \cong H_1(\Sigma, \mathbb{Z})$ and applying a HOMFLYPT skein relation to a link results in a linear combination of diagrams, each belonging to the same homology class. The product of two links in the skein algebra descend to the union of the two chains in the homology group. Therefore, the skein algebra $\mathcal{H}(\Sigma)$ is graded by the first (singular) homology group $H_1(\Sigma, \mathbb{Z})$. This isn't true for the skein algebras $\mathcal{D}(\Sigma)$ and $\mathcal{K}(\Sigma)$ because the "cap-cup" resolution diagram in the Dubrovnik and Kauffman bracket skein relations, considered as a chain in $H_1(\Sigma, \mathbb{Z})$, may not belong to the same homology class as the original link. Another problem is that the links in the skein algebras are unoriented, but chains in $H_1(\Sigma, \mathbb{Z})$ are. Both of these problems are resolved by replacing $\mathbb{Z}$ with $\mathbb{Z}/2\mathbb{Z}$. So $\mathcal{D}(\Sigma)$ and $\mathcal{K}(\Sigma)$ are $H_1(\Sigma, \mathbb{Z}/2\mathbb{Z})$-graded algebras.

2.3   Skein Algebras of Tangles in a Cube

In the case where $\Sigma = I^2$, the endomorphism objects of $\mathsf{D}(I^2), \mathsf{H}(I^2)$, and $\mathsf{K}(I^2)$ are known and provide the motivation for why the choices of skein relations are what they are. For an integer $n \geq 1$, let $\underline{n}$ be a set of n points in I^2, chosen to be evenly spaced along the line segment $\{1/2\} \times I$ (choose so that all points share the same orientation if in the context of

an oriented skein theory). Then the endomorphism algebras

$$BMW_n := \text{End}_{\mathsf{D}}(I^2)(\underline{n}), \qquad H_n := \text{End}_{\mathsf{H}}(I^2)(\underline{n}), \qquad TL_n := \text{End}_{\mathsf{K}}(I^2)(\underline{n})$$

are known to be isomorphic to the Birman-Murakami-Wenzl, (Type A) Hecke, and Temperley-Lieb algebras, respectively (* *Add citations).

Let $q \in \mathbb{C}$ be not a root of unity, $U_q(\mathfrak{gl}_N)$ be the Drinfeld-Jimbo quantum group associated to the Lie algebra $\mathfrak{gl}_N$, and V be the natural representation of $U_q(\mathfrak{gl}_N)$ (* cite Chari-Pressley book). Then H_n acts on the n-fold tensor product $V^{\otimes n}$ by $U_q(\mathfrak{gl}_N)$-linear endomorphisms, and this action generates $\text{End}_{U_q(\mathfrak{gl}_N)}(V^{\otimes n})$. This is actually part of the statement of quantum Frobenius-Schur-Weyl duality: $V^{\otimes n}$ is a $U_q(\mathfrak{gl}_N)$-H_n-bimodule, and the action of one algebra generates the linear endomorphisms with respect to the other. So a representation of one algebra determines a representation of the other via tensor product with $V^{\otimes n}$. The Birman-Murakami-Wenzl algebra plays the role of the Hecke algebra for $U_q(\mathfrak{g}_N)$ in the case where $\mathfrak{g}$ is one of the orthogonal or symplectic Lie algebras. For this reason, from a Lie theoretic point of view, the HOMFLYPT skein theory is thought of as a "type A" theory, while the Dubrovnik skein theory is a "types B, C, D" skein theory.

As for the Temperley-Lieb algebra TL_n, it acts on the n-fold tensor power $V^{\otimes n}$ of the natural representation of $U_q(\mathfrak{gl}_2)$ (one may replace $\mathfrak{gl}_2$ with $\mathfrak{sl}_2$). Actually, there is a surjective algebra homomorphism $\pi_{TL} : H_n \to TL_n$ and the action $H_n \to \text{End}_{U_q(\mathfrak{gl}_2)}(V^{\otimes n})$ factors through this homomorphism (see * cite Jimbo). One can conclude that the action of H_n on $V^{\otimes n}$ is not faithful, at least in the case when $N = 2$ and $n \geq 2$.

Much is known about these algebras and some of the results surrounding them are very useful in our context. One of the main ideas is that each of the algebras discussed above has a family of idempotents which provide algebraically nice closures to links in the skein algebra of an annulus. Let's first describe the Hecke algebra in more detail before focusing on the BMW algebra.

For any partition λ of n, there exists an element $y_\lambda \in H_n$ which is idempotent, so that $y_\lambda^2 = y_\lambda$, and minimal in the sense that it generates a minimal left-ideal of H_n (see * cite Aiston-Morton). The elements $y_n := y_{(n)}$ corresponding to single row partitions are called **(Hecke) symmetrizers**. These elements have a certain absorption property which makes them unique, which we will now describe. Let us use $\sigma_i \in H_n$ be the positive crossing between the ith and $(i+1)^{\text{th}}$ strands. The algebra H_n is generated by the σ_i and the symmetrizers are the unique idempotent elements satisfying $\sigma_i y_n = s y_n = y_n \sigma_i$. In this way, y_n corresponds to a 1-dimensional representation of H_n (it is a deformation of the trivial representation of $\mathbb{C}S_n$ where $s = 1$).

A similar story holds for the BMW algebra. Firstly, BMW_n is generated by positive crossing elements σ_i and cap-cup elements c_i. The c_i generate a proper ideal I_n in BMW_n. In (* cite BB), the authors show that the complement of I_n in BMW_n is isomorphic to H_n, giving an isomorphism $BMW_n \cong H_n \oplus I_n$. Then they construct an additive and multiplicative (but non-unital) homomorphism

$$\Gamma_n : H_n \to BMW_n \tag{2.4}$$

which is a section of the natural projection $BMW_n \to H_n$ such that

$$\Gamma_n(x)y = 0 = y\Gamma_n(x) \quad \text{for } x \in H_n, y \in I_n. \tag{2.5}$$

Using this section, one can transport the minimal idempotents $y_\lambda \in H_n$ to minimal idempotents $\tilde{y}_\lambda := \Gamma_n(y_\lambda) \in BMW_n$. The elements $\tilde{y}_n := \tilde{y}_{(n)}$ are called the **(BMW) symmetrizers** and are the unique idempotent elements of BMW_n satisfying the properties of the Hecke symmetrizers and property (2.5). Let $[n]$ be the quantum integers

$$[n] := \frac{s^n - s^{-n}}{s - s^{-1}}$$

and define the constants

$$\beta_n := \frac{1 - s^2}{s^{2n-1}v^{-1} - 1}.$$

By * cite Shelly, the BMW symmetrizers satisfy a very useful recurrence relation

$$(2.6)$$

For what it's worth, this relation descends to a well-known recurrence relation for the $y_n \in H_n$ via the projection map described above ($\tilde{y}_n$ gets sent to y_n and the last diagram on the right-hand side gets sent to 0).

* Come back and add braiding/twist identities from BB if we need them.

2.4   Skein Algebras of the Annulus

Let's use the notation $A := S^1 \times [0,1]$ for the annulus. The thickened annulus represents perhaps the simplest space with non-trivial topology that can harbor links. There are often many different smooth embeddings of the thickened annulus into a given 3-manifold M (one for every element of $\pi_1(M)$, at the very least). Keep in mind that if we have a smooth embedding $f : A \times I \hookrightarrow M$, then we have an induced linear map between skein modules $\mathcal{S}_X(f) : \mathcal{S}_X(A) \to \mathcal{S}_X(M)$, allowing us to prod for information about $\mathcal{S}_X(M)$. One useful type of embedding of A is into a tubular neighborhood of a knot, which is often called *decorating* or *threading* a knot.

A first observation is that any skein algebra of the form $\mathcal{S}_X(A)$ is commutative because the link algebra $\mathcal{S}_\varnothing(A)$ is a commutative algebra. To see this, consider the product of two links L_1 and L_2 in the link algebra and start by stretching L_2 towards the outer boundary

past L_1, followed by moving it down below the furthest point of L_1, and finally contracting L_2 can to its original radial position. This is essentially the Eckmann-Hilton argument.

We'll tackle describing the structure of $\mathcal{K}(A)$ before the others since it is the easiest. The Kauffman bracket skein relation allows one to resolve all crossings in any diagram on any surface Σ. It is a theorem of Pzytycki that the set of non-trivial mutli-curves (non-trivial meaning that no curve bounds a disk), together with the empty link in $A \times \{*\}$ forms a basis of $\mathcal{K}(A)$ (actually, the theorem is stated for any skein algebra, see * cite). There is only one non-trivial curve z and the set $\{z^k\}_{k \in \mathbb{N}}$ exhaust all of the multicurves. Therefore, $\mathcal{K}(A)$ is a polynomial algebra $R[z]$.

The HOMFLYPT and Dubrovnik cases are more complicated because the skein relations do not allow one to resolve all the crossings in a diagram. However, they do allow one to change a diagram with a negative crossing into a diagram with a positive crossing, plus diagrams with a lesser number of crossings. It follows that the skein algebras $\mathcal{H}(A)$ and $\mathcal{D}(A)$ are generated by knots with only positive crossings. Let z_i be a knot in A with winding number i around the annulus. Turaev shows in * cite that the z_i are algebraically independent by showing their HOMFLYPT and Dubrovnik polynomials are algebraically independent. Therefore, $\mathcal{H}(A)$ is a polynomial algebra $R[z_i, i \in \mathbb{Z}_{\neq 0}]$. $\mathcal{D}(A)$ has half as many generators since the z_i in that setting are unoriented, but $\mathcal{D}(A)$ is a polynomial algebra $R[z_i, i \in \mathbb{Z}_{>0}]$ by the same arguments.
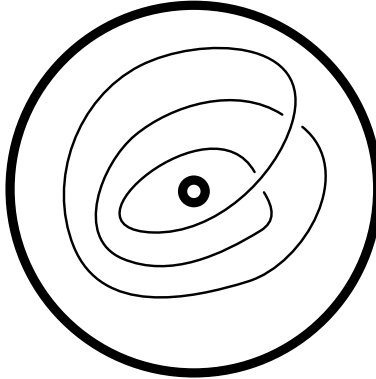
Figure 2.5: The generator $z_2 \in \mathcal{D}(A)$.

The skein algebras of tangles in a cube relate to the skein algebras of the annulus via a wiring cl. We will call the image of an element under this wiring the **annular closure** of the element. This map is surjective and it satisfies the "trace property" $\mathrm{cl}(abc) = \mathrm{cl}(cab)$. Note that is it not unital nor multiplicative, but it is true that $\mathrm{cl}(a \otimes b) = \mathrm{cl}(a)\mathrm{cl}(b)$ where $a \otimes b$ is an element obtained by concatenating elements a and b.
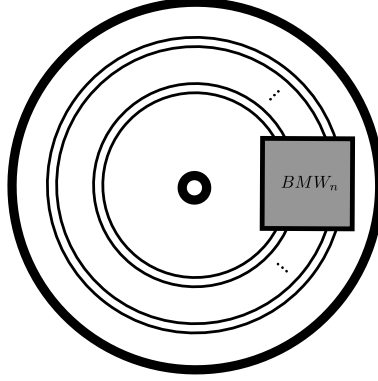
Figure 2.6: This annular closure wiring diagram.

Let $\widetilde{Q}_\lambda := \mathrm{cl}(\tilde{y}_\lambda) \in \mathcal{D}(A)$. Zhong and Lu show in * cite that the set $\{\widetilde{Q}_\lambda\}_\lambda$ forms a basis of $\mathcal{D}(A)$ over the base ring $R = \mathbb{Q}(s, v)$, where λ ranges over all paritions. Actually, it is an eigenbasis with respect to the meridian map $\phi : \mathcal{D}(A) \to \mathcal{D}(A)$ where the eigenvalue of Q_λ is

$$c_\lambda = \delta_\mathcal{D} + (s - s^{-1}) \sum_{\square \in \lambda} v^{-1}s^{2\mathrm{cn}(\square)} - vs^{-2\mathrm{cn}(\square)}$$

and where $\mathrm{cn}(\square) := j - i$ is the *content* of the box in the $\square$ in i^{th} row and j^{th} column of the Young diagram of the partition λ. Two distinct partitions λ and λ' give rise to distinct values of c_λ and c'_λ. Therefore, each of the eigenspaces is 1-dimensional.

The behavior of $\widetilde{Q}_\lambda$ is similar to that of the $Q_\lambda := \mathrm{cl}^+(y_\lambda) \in \mathcal{H}(A)$ where $\mathrm{cl}^+(-)$ is defined by orienting the strands in wiring digram of $\mathrm{cl}(-)$ counter-clockwise. Using the description $\mathcal{H}(A) = R[z_i, i \in \mathbb{Z}_{\neq 0}]$, consider the subalgebras $\mathcal{H}(A)^+ := R[z_i, i \in \mathbb{Z}_{>0}]$ and $\mathcal{H}(A)^- := R[z_i, i \in \mathbb{Z}_{<0}]$. Then the two subalgebras are isomorphic via the linear involution defined by $z_i \mapsto z_{-i}$ and $\mathcal{H}(A) \cong \mathcal{H}(A)^+ \otimes \mathcal{H}(A)^-$. The $\{Q_\lambda\}_\lambda$ forms an eigenbasis of $\mathcal{H}(A)^+$ with resepect to the meridian map and the eigenspaces are 1-dimensional. As a
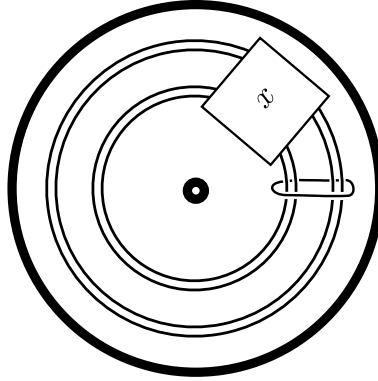
Figure 2.7: The meridian map ϕ applied to the annular closure of some x.

side remark, the linear involution $z_i \mapsto z_{-i}$ may be realized topologically by rotating the thickened annulus π radians around an appropriately centered axis parallel to A and taking the induced skein map. We will call this map the *flip map*.

In * cite Lukac, it's shown how to interpret $\mathcal{H}(A)^+$ as the ring of symmetric functions Λ (also see * cite Morton Murphy Operators). There is an injective algebra homomorphism $\Lambda \to \mathcal{H}(A)^+$ which sends the Schur function s_λ to the minimal idempotent closure Q_λ. This theorem has plenty of implications. For example, the structure constants of Λ in the basis $\{s_\lambda\}_\lambda$ are the Littlewood-Richardson coefficients, which are then sent to structure constants of $\mathcal{H}(A)^+$ in the basis $\{Q_\lambda\}_\lambda$. In Chapter * reference, we discuss partial results surrounding the Dubrovnik analogue of this homomorphism. See Section * reference for a summary about the ring Λ.

Another application of the interpretation of $\mathcal{H}(A)^+$ as Λ is the definition of new special links in the skein algebra. There is a family of elements in Λ known as the power sum symmetric functions, whose counterparts in $\mathcal{H}(A)^+$ we will denote by P_k for integers $k \geq 1$. These elements are algebraically independent in $\Lambda_\mathbb{Q} := \mathbb{Q} \otimes \Lambda$. Therefore, ordered monomials in the P_k form a basis of $\mathcal{H}(A)^+$.

2.5   Skein Algebras of the Torus

The power sum elements P_k described above are known to behave wonderfully in skein theoretic computations. This allows for a simple description of the HOMFLYPT skein algebra of the torus $\mathcal{H}(T^2)$ in terms of generators and relations. First, let's define the generators. Given an r which is either a rational number, or $\pm\infty$, there is an oriented smooth embedding

$$\iota_r : A \hookrightarrow T^2$$

of the annulus into a tubular neighborhood of the line of slope r in the flat torus. Consider the embeddings ι_r and ι_{-r} to be the same embedding with opposite orientations. Now ι_r induces an algebra homomorphism

$$\mathcal{H}(\iota_r) : \mathcal{H}(A) \to \mathcal{H}(T^2)$$

on the level of skein algebras. The ι_r are distinct isotopically (even homotopically) and are exhaustive in the sense that any knot in the thickened torus is may be represented as being contained in the image of an ι_q. Therefore, any basis of $\mathcal{H}(A)^+$ defines a basis of $\mathcal{H}(T^2)$. Let's consider this with respect to the the power-sum monomial basis of $\mathcal{H}(A)^+$. More precisely, for any pair of integers $\mathbf{x} = (a, b)$ where $k = \gcd(\mathbf{x})$, define

$$P_{\mathbf{x}} := \mathcal{H}(\iota_{a/b})(P_k).$$

In * cite MS, Morton and Samuelson prove that the skein algebra $\mathcal{H}(T^2)$ admits a presentation with generators the elements of $\{P_{\mathbf{x}} \mid \mathbf{x} \in \mathbb{Z}^2\}$, subject to the single family of relations

$$[P_{\mathbf{x}}, P_{\mathbf{y}}] = \left(s^{\det(\mathbf{x}, \mathbf{y})} - s^{-\det(\mathbf{x}, \mathbf{y})}\right) P_{\mathbf{x} + \mathbf{y}}.$$

This presentation exhibits a relationship to the elliptic Hall algebra: a 2-parameter family of algebras obtained via Hall algebra decategorification of categories of coherent sheaves over

certain elliptic curves (see * Burban-Schiffman). Along the diagonal of the parameter space, the Burban-Schiffman presentation of the elliptic Hall algebra matches the Morton-Samuelson presentation of the skein algebra of the torus. At the very least, this highlights two things. Firstly, the skein algebra of the torus admits a known deformation. Secondly, skein algebras are connected to surprising areas of mathematics and hence deserve our attention. * Is this paragraph correct?

Next we describe the Kauffman bracket skein algebra of the torus, although the order of exposition is opposite to the historical order of discovery. The story is actually quite similar to the HOMFLYPT case. Recall that $\mathcal{K}(A)$ is a polynomial algebra $R[z]$ where z is the simple closed curve around the hole of the annulus with winding number 1. There exist polynomials known as *Chebyshev polynomials* $T_k \in R[z]$ for all integer $k \geq 1$ which form a basis of $\mathcal{K}(A)$. For any pair of integers $\mathbf{x} = (a, b) \in \mathbb{Z}^2$, define elements $T_\mathbf{x} \in \mathcal{K}(T^2)$ as

$$T_\mathbf{x} := \mathcal{K}(\iota_{a/b})(T_k).$$

Note that $T_\mathbf{x} = T_{-\mathbf{x}}$ because the T_k are fixed under the flip map, which is possible since the Kauffman bracket skein theory is an unoriented skein theory. With this in mind, we may pass to the smaller indexing set $Z^2/\langle \mathbf{x} = -\mathbf{x} \rangle$. Using these elements, Frohman and Gelca * cite prove that the skein algebra $\mathcal{K}(T^2)$ admits a presentation with generators $T_\mathbf{x}$ subject to the relations

$$T_\mathbf{x} T_\mathbf{y} = s^{\det(\mathbf{x},\mathbf{y})} T_{\mathbf{x}+\mathbf{y}} + s^{-\det(\mathbf{x},\mathbf{y})} T_{\mathbf{x}-\mathbf{y}}$$

which the authors call the "product-to-sum" formulas. There is an algebra called the *noncommutative torus*, which is a one-parameter deformation of the algebra of continuous functions on the torus. The Frohman-Gelca presentation of $\mathcal{K}(T^2)$ matches a presentation of the invariant subalgebra of the noncommutative torus with respect to a certain involutive action, as shown in * cite FG. * Is this paragraph correct?

Given the similarity between the presentations of $\mathcal{H}(T^2)$ and $\mathcal{K}(T^2)$, one might suspect that there exists a similar description of the Dubrovnik skein algebra $\mathcal{D}(T^2)$. The answer to this question is affirmative, which is what we discuss in Chapter 3.

2.6 A Relative Skein Algebra of the Annulus

At this point in the story we have introduced special links in the skein algebras of the annulus and described how we can transport these into other skein modules via threading knots. In order to say anything meaningful about these threadings, we ought to know how these special links will interact with other links once in the resulting space. For example, is there an easy way to describe how can we pass a special link through a single strand of another link? To answer this question universally, we should answer it in a certain relative skein algebra which is the endomorphism algebra of one point in the skein category of the annulus. Appropriate wirings from this skein algebra into other skein modules will give us our desired description. Here we will describe this algebra in more detail and summarize what is already known.

First we will restrict ourselves to the HOMFLYPT case, for which we summarize the results from * Morton, Murphy operators. The object we would like to discuss is $\mathcal{A}_{\mathcal{H}} := \mathcal{H}(A, [1])$, which is depicted diagramatically as an annulus with one point on each boundary component. This algebra is closely related to the affine Hecke algebra of type A, $\dot{H}_1$ (see * cite MS). Two of the most basic elements of $\mathcal{A}_{\mathcal{H}}$ are the elements e, the identity of $\mathcal{A}_{\mathcal{H}}$, and a, which is a single strand once around the hole of the annulus. The product in the algebra in this digrammatic notation is given by nesting annuli.

Let $\mathcal{C}_{\mathcal{H}} := \mathcal{H}(A)$. Then, $\mathcal{C}_{\mathcal{H}}$ admits both a left $\mathcal{C}_{\mathcal{H}}$-action by pushing links infront of tangles in $\mathcal{A}_{\mathcal{H}}$. It is known that there is an equality of algebras between $\mathcal{A}_{\mathcal{H}}$ and the Laurent polynomial algebra $\mathcal{C}_{\mathcal{H}}[a, a^{-1}]$. In particular, $\mathcal{A}_{\mathcal{H}}$ is commutative and the left action is determined by how it acts on e. Analagously, there is a right $\mathcal{C}_{\mathcal{H}}$-action by pulling links in behind tangles in $\mathcal{A}_{\mathcal{H}}$. * Orient these diagrams
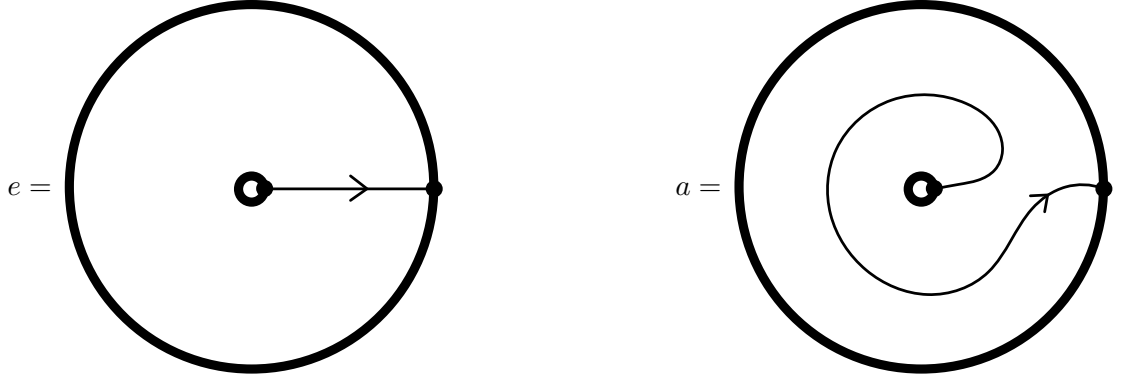
Figure 2.8: On the left is the identity elements $e \in \mathcal{A}_{\mathcal{H}}$. To the right is what we denote by $a \in \mathcal{A}_{\mathcal{H}}$.
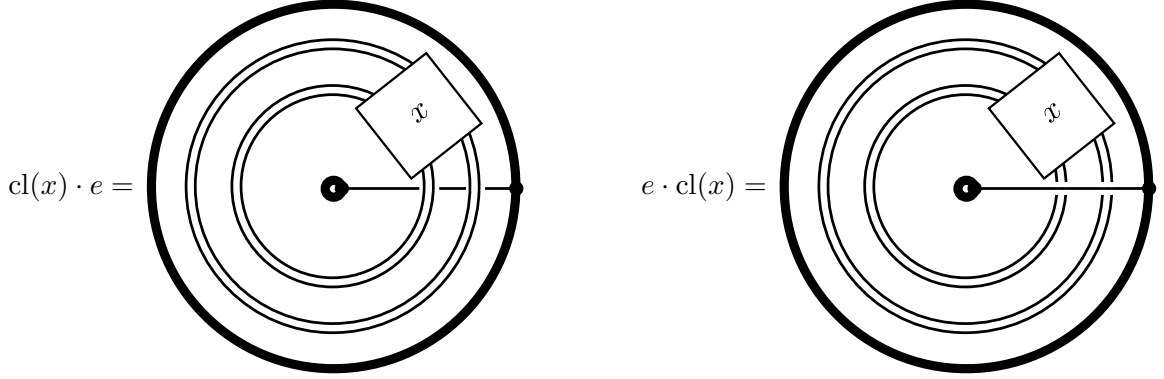
Figure 2.9: Here we have the annular closure of some x acting separately on both the left and right of the identity e.

Both actions are examples of those arising from embeddings into the boundary of the thickened annulus, as described in Remark 2.1.5. The left and right actions obviously commute, endowing $\mathcal{A}_{\mathcal{H}}$ with a $\mathcal{C}_{\mathcal{H}}$-$\mathcal{C}_{\mathcal{H}}$-bimodule structure. It is probably worth pointing out that the left action is not equal to the right action. A simple measurement of how far off the two actions are from being equal would answer our question posed above. The answer is given as a commutator relation

$$e \cdot P_k - P_k \cdot e = (s^k - s^{-k})a^k. \tag{2.7}$$

The proof involves the definition of a certain wiring diagram, defining a linear map $H_n \to \mathcal{A}_{\mathcal{H}}$. The idempotents y_n satisfy a certain recurrence relation, and the commutator relation above

follows from writing P_k in terms of the y_n and calculations involving the image of this recurrence relation.

Eventually we would like to prove a Dubrovnik analogue of Equation (2.7) (see Section 3.1), but we still haven't defined any Dubrovnik analogue of the P_k (see * ref). Nevertheless, we can discuss some of what was previously known about the algebra $\mathcal{A}_{\mathcal{D}} := \mathcal{D}(A, [1])$ (see * Shelly for more details).

Let $\mathcal{C}_{\mathcal{D}} := \mathcal{D}(A)$ and let $a, e \in \mathcal{A}_{\mathcal{D}}$ be the unoriented versions of the elements of the same name above. As in the HOMFLYPT case, there is a left-$\mathcal{C}_{\mathcal{D}}$ action on $\mathcal{A}_{\mathcal{D}}$ and the algebra $\mathcal{A}_{\mathcal{D}}$ is equal to the Laurent polynomial algebra $\mathcal{C}_{\mathcal{D}}[a^{\pm 1}]$. There is also a right-$\mathcal{C}_{\mathcal{D}}$ action on $\mathcal{A}_{\mathcal{D}}$, endowing $\mathcal{A}_{\mathcal{D}}$ with a bimodule structure.
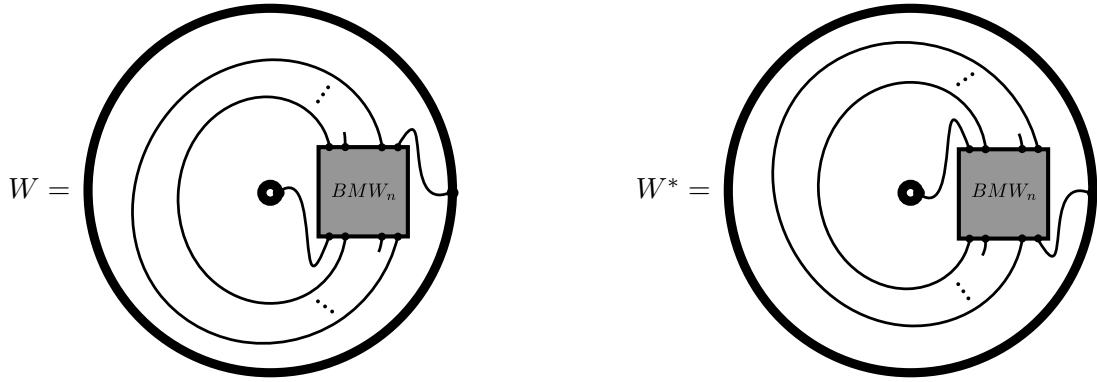
Figure 2.10: Wiring diagrams W and W^* which both define linear maps from the skein algebra of the square to this relative skein algebra of the annulus.

Consider the wiring diagrams pictured above in Figure 2.6 which define linear maps $BMW_n \to \mathcal{A}_{\mathcal{D}}$. Let $W_n := W(\tilde{y}_{n+1})$ and $W_n^* := W^*(\tilde{y}_{n+1})$ where the subscript denotes the "winding number" around A. Taking the image of Equation (2.6) under W gives a relation

$$[n+1]W_n = e \cdot \tilde{h}_n + [n]s^{-1}aW_{n-1} + [n]s^{-1}\beta_n a^{-1}W_{n-1}^* \qquad (2.8)$$

where $\tilde{h}_n := \tilde{Q}_{(n)}$ is the annular closure of the symmetrizer $\tilde{y}_n$.

There are maps

$$(-)^* : BMW_n \to BMW_n \qquad \overline{(-)} : BMW_n \to BMW_n$$

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induced by the diffeomorphisms of the thickened square $(x, y, t) \mapsto (x, 1 - y, 1 - t)$ and $(x, y, t) \mapsto (x, y, 1 - t)$, respectively. The map $\overline{(-)}$ is often called the *mirror map* and is an R-anti-linear involution, while $(-)^*$ will be called the *flip map* and is an R-linear involution. The symmetrizers $\tilde{y}_n$ are fixed under these maps because the mirror and flip maps preserve the properties which make $\tilde{y}_n$ unique. Using the quotient map defined by the equivalence relation $(x, 0, t) \sim (x, 1, t)$, we may analagously define maps

$$(-)^* : \mathcal{A}_{\mathcal{D}} \to \mathcal{A}_{\mathcal{D}}, \qquad \overline{(-)} : \mathcal{A}_{\mathcal{D}} \to \mathcal{A}_{\mathcal{D}}$$

which are linear and anti-linear involutions, respectively. We will also call these the flip map and the mirror map; it will be clear from the context which is being applied. These maps satisfy the relations

$$(W(x))^* = W^*(x^*), \qquad\qquad (y \cdot e)^* = e \cdot y^*,$$

$$\overline{W(x)} = W(\overline{x}), \qquad\qquad \overline{(y \cdot e)} = e \cdot \overline{y}$$

for any $x \in BMW_n$ or $y \in \mathcal{C}_{\mathcal{D}}$. Apply the flip, the mirror, and the composite of the two separately to Equation (2.8) to obtain alternate versions of the original recurrence relation:

$$[n+1]W_n^* = \tilde{h}_n \cdot e + [n]s^{-1}aW_{n-1}^* + [n]s^{-1}\beta_n aW_{n-1}, \tag{2.9}$$

$$[n+1]W_n = \tilde{h}_n \cdot e + [n]saW_{n-1} + [n]s\bar{\beta}_n a^{-1}W_{n-1}^*, \tag{2.10}$$

$$[n+1]W_n^* = e \cdot \tilde{h}_n + [n]sa^{-1}W_{n-1}^* + [n]s^{-1}\bar{\beta}_n aW_{n-1}. \tag{2.11}$$

Rearranging the difference of Equations (2.8) and (2.9) gives a relation

$$\tilde{h}_n \cdot e - e \cdot \tilde{h}_n = (s^n - s^{-n})(a^{-1}W_{n-1}^* - aW_{n-1}) \tag{2.12}$$

which Shelly calls a *fundamental skein relation* in $\mathcal{A}_{\mathcal{D}}$ since it reduces to to usual Dubrovnik skein relation when $n = 1$. * This might also be true in another sense, since there might be

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some connection between the wiring W and something called the "tube algebra", as pointed out by Henry Tucker. In Section 4.1, we will provide a similar relation which amounts to rewriting the right-hand side of the equation in terms of elements of the form $h_i \cdot a^k$ (alternatively $a^k \cdot h_i$).

Chapter 3

The Skein Algebra of the Torus

This chapter is dedicated to the study of the Dubrovnik skein algebra of a torus $\mathcal{D}(T^2)$, the main result being a simple presentation for the algebra, stated in Theorem 3.2.1. The generators $\tilde{P}_{\mathbf{x}}$ are embeddings of certain special elements $\tilde{P}_k \in \mathcal{D}(A)$, which we define in Section 3.1. The $\tilde{P}_k$ generalize both the power sum elements $P_k \in \mathcal{H}(A)$ and the Chebyshev polynomials $T_k \in \mathcal{K}(A)$ which are both used widely in the context of their respective skein theories due to the simple relations they satisfy. In particular, we give a simple formula in Theorem 3.1.1 which explains how to move any embedding of $\tilde{P}_k$ past a single strand in any skein module, which gives us a family of relations between the $\tilde{P}_{\mathbf{x}}$. In Section 3.2, we show how this and another family of relations imply the relations given in the stated presentation.

The definition of the $\tilde{P}_k$ make it clear why these elements generalize their HOMFLYPT counterparts, but the same isn't immediately clear for the Kauffman bracket case for the T_k. In Section 3.3 we justify this claim by showing that the image of $\tilde{P}_k$ is T_k under the A-component of the natural transformation of skein theories $\eta : \mathcal{D} \to \mathcal{K}$ described in the previous chapter (see Remark). A corollary of this is that the presentation we give for $\mathcal{D}(T^2)$ is compatible with $\mathcal{K}(T^2)$ under η. Also described in this section is a "compatibility" of the presentations of $\mathcal{D}(T^2)$ and $\mathcal{H}(T^2)$, given as an injective algebra homomorphism between the two. This homomorphism differs between the previous described $\mathcal{D}(T^2) \to \mathcal{K}(T^2)$ in the sense that it doesn't arise from any natural transformation between skein theories and is

simply defined via generators and relations. However, this map is interesting because we show that $\mathcal{D}(T^2)$ and $\mathcal{H}(T^2)$ are universal enveloping algebras of some Lie algebras, and this homomorphism arises in the image of the universal enveloping algebra functor.

In Section 3.4.3, we give a description of the natural action of $\mathcal{D}(T^2)$ on $\mathcal{D}(D^2 \times S^1)$, which exists because the boundary of the solid torus is T^2. First we give a small generating setof the algebra $\mathcal{D}(T^2)$, consisting of only five elements, together with an algorithm for expressing any $\tilde{P}_{\mathbf{x}}$ in terms of these other generators. Then, we show how these five elements act of $\mathcal{D}(D^2 \times S^1)$, which implicitly describes how each $\tilde{P}_{\mathbf{x}}$ acts.

This chapter includes many, but not all of the details from the paper * MPS which is co-authored by Hugh Morton, Peter Samuelson, and myself. I've included only some parts of the paper which I significantly contributed to. * Is this worded appropriately? Should I say more?

3.1 Power Sum Elements

Recall that there is a injective algebra homomorphism $\Lambda \to \mathcal{H}(A)^+$ which sends the Schur function s_λ to the minimal idempotent closure Q_λ. Use $h_n := Q_{(n)}$ to denote the image of the nth complete homogeneous symmetric function under this homomorphism. In * MS the authors import power sum elements from Λ to $P_k \in \mathcal{H}(A)$. The power sum elements have a concrete definition in Λ, but alternatively they may be defined using an equation of formal power series in the ring $\mathcal{H}(A)[[t]]$ as

$$\sum_{k=1}^{\infty} \frac{P_k}{k} t^k = \ln\left(1 + \sum_{n=1}^{\infty} h_n t^n\right) \tag{3.1}$$

which writes each P_k in terms of the generators h_n.

Using the Beliakova-Blanchet section $\Gamma : H_n \to BMW_n$, we may emulate this definition to define "power sum" elements $\tilde{P}_k \in \mathcal{D}(A)$ by the formal power series equation

$$\sum_{k=1}^{\infty} \frac{\tilde{P}_k}{k} t^k = \ln\left(1 + \sum_{n=1}^{\infty} \tilde{h}_n t^n\right) \tag{3.2}$$

where $\tilde{h}_n := \tilde{Q}_{(n)}$ is the annular closure of the BMW symmetrizers $\tilde{y}_n = \Gamma(y_n)$.

Let's now continue our discussion of Section 2.6 with the following theorem.

Theorem 3.1.1. *For any $k \geq 1$, the relation*

$$e \cdot \tilde{P}_k - \tilde{P}_k \cdot e = (s^k - s^{-k})(a^k - a^{-k}) \tag{3.3}$$

holds. Equivalently,

$$a^i \cdot \tilde{P}_k - \tilde{P}_k \cdot a^i = (s^k - s^{-k})(a^{k+i} - a^{-k+i}) \tag{3.4}$$

for any integer i.

We will split the proof of this theorem into two technical lemmas.

Lemma 3.1.2. *The relations of Theorem 3.1.1 hold if and only if*

$$e \cdot (\tilde{h}_{n+2} + \tilde{h}_n) - (\tilde{h}_{n+2} + \tilde{h}_n) \cdot e = (sa + s^{-1}a^{-1})(e \cdot \tilde{h}_{n+1}) - (s^{-1}a + sa^{-1})(\tilde{h}_{n+1} \cdot e) \tag{3.5}$$

for all integers $n \geq -1$, where $\tilde{h}_0 := 1$ and $\tilde{h}_{-1} := 0$.

Proof. The relations of Theorem 3.1.1 may be organized into a single power series equation

$$\sum_{k=1}^{\infty} \frac{e \cdot \tilde{P}_k - \tilde{P}_k \cdot e}{k} t^k = \sum_{k=1}^{\infty} \frac{(s^k - s^{-k})(a^k - a^{-k})}{k} t^k \tag{3.6}$$

in $\mathcal{A}_{\mathcal{D}}[[t]]$. Rewrite this equation as

$$e \cdot \left(\sum_{k=1}^{\infty} \tilde{P}_k\right) - \left(\sum_{k=1}^{\infty} \tilde{P}_k\right) \cdot e = \sum_{k=1}^{\infty} \frac{(sat)^k}{k} + \sum_{k=1}^{\infty} \frac{(s^{-1}a^{-1}t)^k}{k} - \sum_{k=1}^{\infty} \frac{(s^{-1}at)^k}{k} - \sum_{k=1}^{\infty} \frac{(sa^{-1}t)^k}{k} \tag{3.7}$$

We can make sense of the left-hand side by extending the algebra homomorphism $x \mapsto e \cdot (x)$ to an algebra homomorphism of rings of formal power series

$$\begin{CD}
\mathcal{D}(A) @>e\cdot(-)>> \mathcal{A}_\mathcal{D} \\
@VVV @VVV \\
\mathcal{D}(A)[[t]] @>e\cdot(-)>> \mathcal{A}_\mathcal{D}[[t]]
\end{CD}$$

and similarly for $(-)\cdot e$. Now for shorthand, define

$$H(t) := 1 + \sum_{n=1}^{\infty} \tilde{h}_n t^n$$

and recall the Taylor series expansion

$$-\ln(1-x) = \sum_{k=1}^{\infty} \frac{x^k}{k}$$

which is a variation of the Newton-Mercator series. Then the Equation (3.6) becomes

$$e\cdot\Big(\ln\big(H(t)\big)\Big) - \Big(\ln\big(H(t)\big)\Big)\cdot e = -\ln(1-sat) - \ln(1-s^{-1}a^{-1}t) + \ln(1-s^{-1}at) + \ln(1-sa^{-1}t).$$

$$(3.8)$$

The maps $e\cdot(-)$ and $(-)\cdot e$ commute with the natural logarithm. Use this and other natural log properties to write

$$\ln\Big(e\cdot\big(H(t)\big)\big(1-(sa+s^{-1}a^{-1})t+t^2\big)\Big) = \ln\Big(\big(H(t)\big)\cdot e\big(1-(s^{-1}a+sa^{-1})t+t^2\big)\Big). \quad (3.9)$$

Exponentiating both sides and equating coefficients gives the system of equations defined in the statement of the lemma. Each step of the proof is invertible, and thus the two sets of relations are logically equivalent. $\qquad\square$

Lemma 3.1.3. *The relations of Lemma 3.1.2 hold.*

Proof. If $n = -1$, the relation we would like to show becomes

$$e\cdot\tilde{h}_1 - \tilde{h}_1\cdot e = (s - s^{-1})(a - a^{-1})$$

which is just the Dubrovnik skein relation.

For general values of n, the proof is a technical computation using repeated applications of the recursive formula for the $\tilde{h}_n$. Since we will need them here, let's recall the formulas given in Section 2.6. There are recursive formulas

$$[n+1]W_n = e \cdot \tilde{h}_n + [n]s^{-1}aW_{n-1} + [n]s^{-1}\beta_n a^{-1}W^*_{n-1}, \tag{3.10}$$

$$[n+1]W^*_n = \tilde{h}_n \cdot e + [n]s^{-1}a^{-1}W^*_{n-1} + [n]s^{-1}\beta_n aW_{n-1}, \tag{3.11}$$

$$[n+1]W_n = \tilde{h}_n \cdot e + [n]saW_{n-1} + [n]s\bar{\beta}_n a^{-1}W^*_{n-1}, \tag{3.12}$$

$$[n+1]W^*_n = e \cdot \tilde{h}_n + [n]sa^{-1}W^*_{n-1} + [n]s^{-1}\bar{\beta}_n aW_{n-1} \tag{3.13}$$

and the "fundamental relation"

$$e \cdot \tilde{h}_n - \tilde{h}_n \cdot e = (s^n - s^{-n})(aW_{n-1} - a^{-1}W^*_{n-1}). \tag{3.14}$$

Let's use the shorthand notation

$$\{n\} := s^n - s^{-n}.$$

Start by applying Equation (3.14) to the relation of Lemma 3.1.2 to obtain an equivalent relation

$$\{n+2\}\left(aW_{n+1} - a^{-1}W^*_{n+1}\right) = \left(sa + s^{-1}a^{-1}\right)\left(e \cdot \tilde{h}_{n+1}\right) - \left(sa^{-1} + s^{-1}a\right)\left(\tilde{h}_{n+1} \cdot e\right)$$
$$- \{n\}\left(aW_{n-1} - a^{-1}W^*_{n-1}\right). \tag{3.15}$$

We will show that the left-hand side of this equation may be reduced to the right-hand side by a series of applications of the recursive formulas, which we will signify with an asterisk $*$.

$$\{n+2\}\left(aW_{n+1} - a^{-1}W^*_{n+1}\right)$$
$$\overset{*}{=} \{n+2\}\left(\frac{a}{[n+2]}\left(e \cdot \tilde{h}_{n+1} + [n+1]s^{-1}aW_n + [n+1]s^{-1}\beta_{n+1}a^{-1}W^*_n\right) - \right.$$

$$\frac{a^{-1}}{[n+2]}\left(\tilde{h}_{n+1}\cdot e + [n+1]s^{-1}a^{-1}W_n^* + [n+1]s^{-1}\beta_{n+1}aW_n\right)\bigg)$$

$$= \quad \left(s-s^{-1}\right)\left(\left(a\cdot\tilde{h}_{n+1} + [n+1]s^{-1}a^2W_n + [n+1]s^{-1}\beta_{n+1}W_n^*\right)\right.$$

$$\left.-\left(\tilde{h}_{n+1}\cdot a^{-1} + [n+1]s^{-1}a^{-2}W_n^* + [n+1]s^{-1}\beta_{n+1}W_n\right)\right)$$

$$\overset{*}{=} \quad \left(s-s^{-1}\right)\left(\left(a\cdot\tilde{h}_{n+1} + s^{-2}a\left([n+2]W_{n+1} - \tilde{h}_{n+1}\cdot e - [n+1]s\bar{\beta}_{n+1}a^{-1}W_n^*\right)\right.\right.$$

$$\left.+[n+1]s^{-1}\beta_{n+1}W_n^*\right)$$

$$-\left(\tilde{h}_{n+1}\cdot a^{-1} + s^{-2}a^{-1}\left([n+2]W_{n+1}^* - e\cdot\tilde{h}_{n+1} - [n+1]s\bar{\beta}_{n+1}aW_n\right)\right.$$

$$\left.\left.+[n+1]s^{-1}\beta_{n+1}W_n\right)\right)$$

$$= \quad \left(sa+s^{-1}a^{-1}\right)\left(e\cdot\tilde{h}_{n+1}\right) - \left(sa^{-1}+s^{-1}a\right)\left(\tilde{h}_{n+1}\cdot e\right)$$

$$+ \quad \left(s^{-1}a^{-1}+s^{-3}a\right)\left(\tilde{h}_{n+1}\cdot e\right) - \left(s^{-1}a+s^{-3}a^{-1}\right)\left(e\cdot\tilde{h}_{n+1}\right)$$

$$+ \quad \{n+2\}s^{-2}\left(aW_{n+1}-a^{-1}W_{n+1}^*\right) + \{n+1\}s^{-1}\left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(W_n - W_n^*\right).$$

We break the computation here to note that the first two terms in the last line also appear on the right hand side of (3.15). Thus, we would like to prove the following equality:

$$- \quad \{n\}\left(aW_{n-1}-a^{-1}W_{n-1}^*\right)$$

$$= \quad \left(s^{-1}a^{-1}+s^{-3}a\right)\left(\tilde{h}_{n+1}\cdot e\right) - \left(s^{-1}a+s^{-3}a^{-1}\right)\left(e\cdot\tilde{h}_{n+1}\right)$$

$$+ \quad \{n+2\}s^{-2}\left(aW_{n+1}-a^{-1}W_{n+1}^*\right) - \{n+1\}s^{-1}\left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(W_n - W_n^*\right).$$

We will work the right-hand side of this above equation down to the left-hand side by continuing to apply the same identities. A large number of terms cancel and what remains is the desired relation.

$$\left(s^{-1}a^{-1}+s^{-3}a\right)\left(\tilde{h}_{n+1}\cdot e\right) - \left(s^{-1}a+s^{-3}a^{-1}\right)\left(e\cdot\tilde{h}_{n+1}\right)$$

$$+ \quad \{n+2\}s^{-2}\left(aW_{n+1}-a^{-1}W_{n+1}^*\right) - \{n+1\}s^{-1}\left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(W_n - W_n^*\right)$$

$$= \quad \left(s^{-1}a^{-1}+s^{-3}a\right)\left(\tilde{h}_{n+1}\cdot e\right) - \left(s^{-1}a+s^{-3}a^{-1}\right)\left(e\cdot\tilde{h}_{n+1}\right)$$

$$+ \quad [n+2]\left(s^{-1}-s^{-3}\right)\left(aW_{n+1}-a^{-1}W_{n+1}^*\right)$$

$$+ \quad [n+1]\left(1-s^{-2}\right)\left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(W_n-W_n^*\right)$$

$$= \quad s^{-1}a\left([n+2]W_{n+1}-e\cdot\tilde{h}_{n+1}\right)$$

$$+ \quad s^{-3}a^{-1}\left([n+2]W_{n+1}^*-e\cdot\tilde{h}_{n+1}\right)$$

$$- \quad s^{-3}a\left([n+2]W_{n+1}-\tilde{h}_{n+1}\cdot e\right)$$

$$- \quad s^{-1}a^{-1}\left([n+2]W_{n+1}^*-\tilde{h}_{n+1}\cdot e\right)$$

$$+ \quad [n+1]\left(1-s^{-2}\right)\left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(W_n-W_n^*\right)$$

$$\overset{*}{=} \quad s^{-1}a\left([n+1]s^{-1}aW_n+[n+1]s^{-1}\beta_{n+1}a^{-1}W_n^*\right)$$

$$+ \quad s^{-3}a^{-1}\left([n+1]sa^{-1}W_n^*+[n+1]s\bar{\beta}_{n+1}aW_n\right)$$

$$- \quad s^{-3}a\left([n+1]saW_n+[n+1]s\bar{\beta}_{n+1}a^{-1}W_n^*\right)$$

$$- \quad s^{-1}a^{-1}\left([n+1]s^{-1}a^{-1}W_n^*+[n+1]s^{-1}\beta_{n+1}aW_n\right)$$

$$+ \quad [n+1]\left(1-s^{-2}\right)\left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(W_n-W_n^*\right)$$

$$= \quad [n+1]\left(s^{-2}a^2W_n+s^{-2}\beta_{n+1}W_n^*+s^{-2}a^{-2}W_n^*+s^{-2}\bar{\beta}_{n+1}W_n-s^{-2}a^2W_n\right.$$

$$-s^{-2}\bar{\beta}_{n+1}W_n^*-s^{-2}a^{-2}W_n^*-s^{-2}\beta_{n+1}W_n+\bar{\beta}_{n+1}W_n-\bar{\beta}_{n+1}W_n^*-\beta_{n+1}W_n$$

$$\left.+\beta_{n+1}W_n^*-s^{-2}\bar{\beta}_{n+1}W_n+s^{-2}\bar{\beta}_{n+1}W_n^*+s^{-2}\beta_{n+1}W_n-s^{-2}\beta_{n+1}W_n^*\right)$$

$$= \quad [n+1]\left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(W_n-W_n^*\right)$$

$$= \quad \left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(\left([n+1]W_n\right)-\left([n+1]W_n^*\right)\right)$$

$$\overset{*}{=} \quad \left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(\left(e\cdot\tilde{h}_n+[n]s^{-1}aW_{n-1}+[n]s^{-1}\beta_na^{-1}W_{n-1}^*\right)\right.$$

$$\left.-\left(e\cdot\tilde{h}_n+[n]sa^{-1}W_{n-1}^*+[n]s\bar{\beta}_naW_{n-1}\right)\right)$$

$$= \quad \left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left([n]\left(s^{-1}-s\bar{\beta}_n\right)aW_{n-1}-[n]\left(s-s^{-1}\beta_n\right)a^{-1}W_{n-1}^*\right)$$

$$= \quad [n]\left(\bar{\beta}_{n+1}-\beta_{n+1}\right)\left(s-s^{-1}\beta_n\right)\left(aW_{n-1}-a^{-1}W_{n-1}^*\right)$$

$$= \quad - \quad \{n\}\left(aW_{n-1}-a^{-1}W_{n-1}^*\right).$$

Where the last equality follows from a quick computation in the base ring. This completes the proof. $\qquad\square$

Remark 3.1.4. Theorem 3.1.1 is part of a Dubrovnik generalization of the "Miraculous Cancellations" first proven by Bonahon and Wong in * BW and again by Lê using only skein theoretic methods in * Lê. Under the natural transformation $\eta : \mathcal{D} \to \mathcal{K}$, the $\tilde{P}_k$ are sent to the Chebyshev polynomials T_k (see Section 3.3.1), and the relation of Theorem 3.1.1 is sent to a commutation relation for the T_k. Now, if s is specialized to be a $2k$-th root of unity so that $s^k = s^{-k}$, then the commutation relation implies that any threading of T_k in any skein algebra $\mathcal{K}_{s^{2k}=1}(\Sigma)$ is a central element. More generally, a threading in any skein module $\mathcal{K}_{s^{2k}=1}(M, N)$ is *transparent*, which essentially means it may move freely about the space, past any tangle. This gives rise to the **Chebyshev-Frobenius homomorphism**, first defined for skein algebras in * BW and extended to general relative skein modules in * Le-Paprocki.

It would be nice to say that Theorem 3.1.1 implies a generalization of the Chebyshev-Frobenius homomorphism for Dubrovnik skein modules, but there is a major problem which is that our choice of base ring is $\mathbb{Q}(s, v)$, which doesn't allow for specializations to roots of unity. This choice is also used in * BB and subsequently * ZL, whose results we use here in a fundamental way. Even in the literature regarding HOMFLYPT skein theory, the elements $(s^k - s^{-k})^{-1}$ are adjoined to the base ring. It would be interesting to see if this problem may be resolved somehow, but it is not something we address outside of this remark.

3.2   A Presentation of $\mathcal{D}(T^2)$

In this section we will demonstrate the value of the elements $\tilde{P}_k$ by showing that the skein algebra $\mathcal{D}(T^2)$ admits a very simple presentation. First things first, let's define the generators. Recall that given an extended rational number r, there is a (homotopically) distinct oriented simple closed curve on the flat torus T^2 with slope r, and hence a smooth embedding of the annulus

$$\iota_r : A \hookrightarrow T^2$$

into tubular neighborhood of the curve. This induces an algebra homomorphism

$$\mathcal{D}(\iota_r) : \mathcal{D}(A) \to \mathcal{D}(T^2)$$

on the level of skein algebras. Any knot in $\mathcal{D}(T^2)$ is contained in the image of some $\mathcal{D}(\iota_r)$. Since $\mathcal{D}$ is an unoriented skein theory, let's only consider $r \geq 0$ to avoid redundancy due to the choice of orientations. Given any equivalence class $\mathbf{x} = (a, b)$ in $\mathbb{Z}^2/\langle \mathbf{x} = -\mathbf{x} \rangle$ with $k := \gcd(a, b)$, define the element

$$\tilde{P}_{\mathbf{x}} := \mathcal{D}(\iota_{a/b})(\tilde{P}_k)$$

to be the embedding of the "power sum" element $\tilde{P}_k$ into this tubular neighborhood. Let's state the main theorem of the paper.

Theorem 3.2.1. *The skein algebra $\mathcal{D}(T^2)$ is presented by generators*

$$\{\tilde{P}_{\mathbf{x}} \mid \mathbf{x} \in \mathbb{Z}^2/\langle \mathbf{x} = -\mathbf{x} \rangle\}$$

and relations

$$[\tilde{P}_{\mathbf{x}}, \tilde{P}_{\mathbf{y}}] = (s^{\det(\mathbf{x},\mathbf{y})} - s^{-\det(\mathbf{x},\mathbf{y})})(\tilde{P}_{\mathbf{x}+\mathbf{y}} - \tilde{P}_{\mathbf{x}-\mathbf{y}}). \tag{3.16}$$

Corollary 3.2.2. *The linear span of the set $\{\tilde{P}_{\mathbf{x}} \mid \mathbf{x} \in \mathbb{Z}^2/\langle \mathbf{x} = -\mathbf{x} \rangle\}$ is a Lie algebra, and $\mathcal{D}(T^2)$ is its universal enveloping algebra.*

The full proof of this theorem may be found in the collaboration * MPS. Here, we will be focused on showing that the generators satisfy the relations given in the presentation. We formulate this as a proposition.

Proposition 3.2.3. *The following special cases of Equation* (3.16) *hold*

$$[\tilde{P}_{1,0}, \tilde{P}_{0,n}] = (s^n - s^{-n})(\tilde{P}_{1,n} - \tilde{P}_{1,-n}) \tag{3.17}$$

$$[\tilde{P}_{1,0}, \tilde{P}_{1,n}] = (s^n - s^{-n})(\tilde{P}_{2,n} - \tilde{P}_{0,n}) \tag{3.18}$$

for any $n \geq 1$. Furthermore, these relations generate all of the relations defined by Equation (3.16).

Equation (3.17) is the image of Equation (3.3) under the wiring of $\mathcal{A}_\mathcal{D}$ into $\mathcal{D}(T^2)$ depicted below.

* Picture of wiring.

We will not give the proof of Equation (3.18) here, but it may be found in * MPS. The idea given there is similar to the idea for the proof of Equation (3.17): first show a similar relation holds in the skein algebra of the annulus relative to two points $\mathcal{D}(A, [2])$ via a brute force computation, and then Equation (3.18) is the image of this relation under a simple wiring into $\mathcal{D}(T^2)$.

What's left for us to show here is the second statement of the proposition, that Equations (3.17) and (3.18) imply Equation (3.16). We will devote the rest of this section to doing so, starting with two technical lemmas and ending with Proposition 3.2.8.

We use the notation

$$d(\mathbf{x}, \mathbf{y}) := \det [\mathbf{x} \ \mathbf{y}] \qquad \text{for } \mathbf{x}, \mathbf{y} \in \mathbb{Z}^2,$$

$$d(\mathbf{x}) := gcd(m, n) \qquad \text{when } \mathbf{x} = (m, n).$$

We will also use the following terminology:

$$(\mathbf{x}, \mathbf{y}) \in \mathbb{Z}^2 \times \mathbb{Z}^2 \text{ is } good \text{ if } [\tilde{P}_\mathbf{x}, \tilde{P}_\mathbf{y}] = \{d(\mathbf{x}, \mathbf{y})\} \left(\tilde{P}_{\mathbf{x}+\mathbf{y}} - \tilde{P}_{\mathbf{x}-\mathbf{y}} \right).$$

Remark 3.2.4. Note that because $\tilde{P}_\mathbf{x} = \tilde{P}_{-\mathbf{x}}$, if $(\mathbf{x}, \mathbf{y})$ is good, then the pairs $(\pm\mathbf{x}, \pm\mathbf{y})$ are good as well.

The idea of the proof is to induct on the absolute value of the determinant of the matrix with columns $\mathbf{x}$ and $\mathbf{y}$. To induct, we write $\mathbf{x} = \mathbf{a} + \mathbf{b}$ for carefully chosen vectors $\mathbf{a}, \mathbf{b}$ and then use the following lemma.

Lemma 3.2.5. *Assume* $\mathbf{a} + \mathbf{b} = \mathbf{x}$ *and that* $(\mathbf{a}, \mathbf{b})$ *is good. Further assume that the five pairs of vectors* $(\mathbf{y}, \mathbf{a})$, $(\mathbf{y}, \mathbf{b})$, $(\mathbf{y} + \mathbf{a}, \mathbf{b})$, $(\mathbf{y} + \mathbf{b}, \mathbf{a})$, *and* $(\mathbf{a} - \mathbf{b}, \mathbf{y})$, *are good. Then the pair* $(\mathbf{x}, \mathbf{y})$ *is good.*

Proof. We use the Jacobi identity and the goodness assumptions to compute

$$
\begin{aligned}
&\quad - \{d(\mathbf{a}, \mathbf{b})\}[\tilde{P}_{\mathbf{a}+\mathbf{b}}, \tilde{P}_{\mathbf{y}}] + \{d(\mathbf{a}, \mathbf{b})\}[\tilde{P}_{\mathbf{a}-\mathbf{b}}, \tilde{P}_{\mathbf{y}}] \\
&= \quad - [[\tilde{P}_{\mathbf{a}}, \tilde{P}_{\mathbf{b}}], \tilde{P}_{\mathbf{y}}] \\
&= \quad [[\tilde{P}_{\mathbf{y}}, \tilde{P}_{\mathbf{a}}], \tilde{P}_{\mathbf{b}}] + [[\tilde{P}_{\mathbf{b}}, \tilde{P}_{\mathbf{y}}], \tilde{P}_{\mathbf{a}}] \\
&= \quad \{d(\mathbf{y}, \mathbf{a})\}[\tilde{P}_{\mathbf{y}+\mathbf{a}} - \tilde{P}_{\mathbf{y}-\mathbf{a}}, \tilde{P}_{\mathbf{b}}] + \{d(b, y)\}[\tilde{P}_{\mathbf{b}+\mathbf{y}} - \tilde{P}_{\mathbf{b}-\mathbf{y}}], \tilde{P}_{\mathbf{a}}] \\
&= \quad \{d(\mathbf{y}, \mathbf{a})\}\left(\{d(\mathbf{y}+\mathbf{a}, \mathbf{b})\}\left(\tilde{P}_{\mathbf{y}+\mathbf{a}+\mathbf{b}} - \tilde{P}_{\mathbf{y}+\mathbf{a}-\mathbf{b}}\right) \right. \\
&\qquad\qquad\qquad \left. -\{d(\mathbf{y}-\mathbf{a}, \mathbf{b})\}\left(\tilde{P}_{\mathbf{y}-\mathbf{a}+\mathbf{b}} - \tilde{P}_{\mathbf{y}-\mathbf{a}-\mathbf{b}}\right)\right) \\
&\quad + \{d(\mathbf{b}, \mathbf{y})\}\left(\{d(\mathbf{b}+\mathbf{y}, \mathbf{a})\}\left(\tilde{P}_{\mathbf{b}+\mathbf{y}+\mathbf{a}} - \tilde{P}_{\mathbf{b}+\mathbf{y}-\mathbf{a}}\right)\right. \\
&\qquad\qquad\qquad \left. -\{d(\mathbf{b}-\mathbf{y}, \mathbf{a})\}\left(\tilde{P}_{\mathbf{b}-\mathbf{y}+\mathbf{a}} - \tilde{P}_{\mathbf{b}-\mathbf{y}-\mathbf{a}}\right)\right) \\
&= \quad (\{d(\mathbf{y}, \mathbf{a})\}\{d(\mathbf{y}+\mathbf{a}, \mathbf{b})\} + \{d(\mathbf{b}, \mathbf{y})\}\{d(\mathbf{b}+\mathbf{y}, \mathbf{a})\})\, \tilde{P}_{\mathbf{a}+\mathbf{b}+\mathbf{y}} \\
&\quad + (\{d(\mathbf{y}, \mathbf{a})\}\{d(\mathbf{y}-\mathbf{a}, \mathbf{b})\} - \{d(\mathbf{b}, \mathbf{y})\}\{d(\mathbf{b}-\mathbf{y}, \mathbf{a})\})\, \tilde{P}_{\mathbf{a}+\mathbf{b}-\mathbf{y}} \\
&\quad - (\{d(\mathbf{y}, \mathbf{a})\}\{d(\mathbf{y}+\mathbf{a}, \mathbf{b})\} - \{d(\mathbf{b}, \mathbf{y})\}\{d(\mathbf{b}-\mathbf{y}, \mathbf{a})\})\, \tilde{P}_{\mathbf{a}-\mathbf{b}+\mathbf{y}} \\
&\quad - (\{d(\mathbf{y}, \mathbf{a})\}\{d(\mathbf{y}-\mathbf{a}, \mathbf{b})\} + \{d(\mathbf{b}, \mathbf{y})\}\{d(\mathbf{b}+\mathbf{y}, \mathbf{a})\})\, \tilde{P}_{\mathbf{a}-\mathbf{b}-\mathbf{y}} \\
&=: \quad c_1 \tilde{P}_{\mathbf{a}+\mathbf{b}+\mathbf{y}} + c_2 \tilde{P}_{\mathbf{a}+\mathbf{b}-\mathbf{y}} - c_3 \tilde{P}_{\mathbf{a}-\mathbf{b}+\mathbf{y}} - c_4 \tilde{P}_{\mathbf{a}-\mathbf{b}-\mathbf{y}}.
\end{aligned}
$$

Define constants $\{n\}^+ := s^n + s^{-n}$, and these satisfy the relations

$$
\{n\}\{m\} = \{n + m\}^+ - \{n - m\} + .
$$

Using some simple algebra, we can show

$$
\begin{aligned}
c_1 &= \quad \{d(\mathbf{y}, \mathbf{a})\}\{d(\mathbf{y}+\mathbf{a}, \mathbf{b})\} + \{d(\mathbf{b}, \mathbf{y})\}\{d(\mathbf{b}+\mathbf{y}, \mathbf{a})\} \\
&= \quad \{d(\mathbf{y}, \mathbf{a}) + d(\mathbf{y}+\mathbf{a}, \mathbf{b})\}^+ - \{d(\mathbf{y}, \mathbf{a}) - d(\mathbf{y}+\mathbf{a}, \mathbf{b})\}^+
\end{aligned}
$$

$$+ \quad \{d(\mathbf{b}, \mathbf{y}) + d(\mathbf{b} + \mathbf{y}, \mathbf{a})\}^+ - \{d(\mathbf{b}, \mathbf{y}) - d(\mathbf{b} + \mathbf{y}, \mathbf{a})\}^+$$

$$= \quad \{d(\mathbf{y}, \mathbf{a} + \mathbf{b}) + d(\mathbf{a}, \mathbf{b})\}^+ - \{d(\mathbf{y}, \mathbf{a} - \mathbf{b}) - d(\mathbf{a}, \mathbf{b})\}^+$$

$$+ \quad \{d(\mathbf{y}, \mathbf{a} - \mathbf{b}) - d(\mathbf{a}, \mathbf{b})\}^+ - \{d(\mathbf{a}, \mathbf{b}) - d(\mathbf{y}, \mathbf{a} + \mathbf{b})\}^+$$

$$= \quad \{d(\mathbf{a}, \mathbf{b}) + d(\mathbf{y}, \mathbf{a} + \mathbf{b})\}^+ - \{d(\mathbf{a}, \mathbf{b}) - d(\mathbf{y}, \mathbf{a} + \mathbf{b})\}^+$$

$$= \quad \{d(\mathbf{a}, \mathbf{b})\}\{d(\mathbf{y}, \mathbf{a} + \mathbf{b})\}$$

$$= \quad -\{d(\mathbf{a}, \mathbf{b})\}\{d(\mathbf{x}, \mathbf{y})\}.$$

Similar computations for the other c_i show that

$$\frac{1}{\{d(\mathbf{a}, \mathbf{b})\}}[[\tilde{P}_\mathbf{a}, \tilde{P}_\mathbf{b}], \tilde{P}_\mathbf{y}] = \frac{-1}{\{d(\mathbf{a}, \mathbf{b})\}}\left(c_1\tilde{P}_{\mathbf{a}+\mathbf{b}+\mathbf{y}} + c_2\tilde{P}_{\mathbf{a}+\mathbf{b}-\mathbf{y}} - c_3\tilde{P}_{\mathbf{a}-\mathbf{b}+\mathbf{y}} - c_4\tilde{P}_{\mathbf{a}-\mathbf{b}-\mathbf{y}}\right)$$

$$= \{d(\mathbf{x}, \mathbf{y})\}\left(\tilde{P}_{\mathbf{x}+\mathbf{y}} - \tilde{P}_{\mathbf{x}-\mathbf{y}}\right) - \{d(\mathbf{a} - \mathbf{b}, \mathbf{y})\}\left(\tilde{P}_{\mathbf{a}-\mathbf{b}+\mathbf{y}} - \tilde{P}_{\mathbf{a}-\mathbf{b}-\mathbf{y}}\right)$$

$$= \{d(\mathbf{x}, \mathbf{y})\}\left(\tilde{P}_{\mathbf{x}+\mathbf{y}} - \tilde{P}_{\mathbf{x}-\mathbf{y}}\right) - [\tilde{P}_{\mathbf{a}-\mathbf{b}}, \tilde{P}_\mathbf{y}]. \qquad (3.19)$$

Since the pair $(\mathbf{a}, \mathbf{b})$ is good, we have

$$[\tilde{P}_\mathbf{a}, \tilde{P}_\mathbf{b}] = \{d(\mathbf{a}, \mathbf{b})\}\left(\tilde{P}_\mathbf{x} - \tilde{P}_{\mathbf{a}-\mathbf{b}}\right). \qquad (3.20)$$

Finally, combining equations (3.20) and (3.19) shows that the pair $(\mathbf{x}, \mathbf{y})$ is good. $\qquad \square$

Now we'll need to prove the following elementary lemma (which is a slight modification of [?FG00, Lemma 1] * fix). This is used to make a careful choice of vectors $\mathbf{a}, \mathbf{b}$ so that the previous lemma can be applied.

Lemma 3.2.6. *Suppose $p, q \in \mathbb{N}$ are relatively prime with $q < p$. Then there exist $u, v, w, z \in \mathbb{Z}$ such that the following conditions hold:*

$$0 < u, w < p,$$

$$\det \begin{bmatrix} u & w \\ v & z \end{bmatrix} = 1,$$

$$\begin{bmatrix} u & w \\ v & z \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} p \\ q \end{bmatrix}.$$

Proof. Since p and q are relatively prime, there exist $a, b \in \mathbb{Z}$ with $bq - ap = 1$. This solution can be modified to give another solution $a' = a + q$ and $b' = b + p$, so we may assume $0 \le b < p$. We then define

$$u = b, \quad v = a, \quad w = p - b, \quad z = q - a.$$

By definition, u, v, w, z satisfy $u + w = p$ and $v + z = q$, and the inequalities $0 \le b < p$ and $p > 1$ imply the condition $0 < u, w < p$. To finish the proof, we compute

$$uz - wv = b(q - a) - a(p - b) = bq - ap = 1.$$

$\square$

Remark 3.2.7. The mapping class group of a (smooth) surface Σ is the group of isotopy classes of (smooth) orientation-preserving homeomorphisms $\Sigma \to \Sigma$. Any skein algebra $\mathcal{S}_X(\Sigma)$ is acted on by the mapping class group of Σ: the mapping class group is generated by Dehn twists on Σ and may be extended trivially onto $\Sigma \times I$, which induce algebra endomorphisms on the skein algebra due to functoriality of $\mathcal{S}_X(-)$. Thus, there is an $SL_2(\mathbb{Z})$-action on $\mathcal{D}(T^2)$ and is such that $g \cdot \tilde{P}_{\mathbf{x}} = \tilde{P}_{g\mathbf{x}}$ for any $g \in \mathrm{SL}_2(\mathbb{Z})$. One could choose to extend this to an action of the *extended* mapping class group of Σ (that is, to include orientation-reversing diffeomorphisms) so that $GL_2(Z)$ acts on $\mathcal{D}(T^2)$. If matrices of determinant -1 are to act on $\mathcal{D}(T^2)$ in the same way as before, then they will induce anti-linear algebra anti-homomorphisms on $\mathcal{D}(T^2)$. One could turn these into honest algebra homomorphisms by composing with the mirror map (note that $\tilde{P}_{\mathbf{x}}$ is fixed by the mirror map since the BMW symmetrizers are). It will be important that the orbits of this action on the $\tilde{P}_{\mathbf{x}}$ are the fibers of the assignment $\tilde{P}_{\mathbf{x}} \mapsto d(\mathbf{x})$ (which is essentially the statement of

Lemma 3.2.6). In other words, up to the action of $GL_2(\mathbb{Z})$, vectors in $\mathbb{Z}^2$ are classified by the GCD of their entries.

Proposition 3.2.8. *Suppose A is an algebra with elements $\tilde{P}_{\mathbf{x}}$ for $\mathbf{x} \in \mathbb{Z}^2/\langle -\mathbf{x} = \mathbf{x} \rangle$ that satisfy equations (3.17) and (3.18). Furthermore, suppose that there is a $\mathrm{GL}_2(\mathbb{Z})$-action on A so that $g \cdot \tilde{P}_{\mathbf{x}} = \tilde{P}_{g\mathbf{x}}$ for any $g \in \mathrm{GL}_2(\mathbb{Z})$. Then, any pair $(\mathbf{x}, \mathbf{y})$ is a good pair.*

Proof. The proof proceeds by induction on $|d(\mathbf{x}, \mathbf{y})|$, and the base case $|d(\mathbf{x}, \mathbf{y})| = 1$ is immediate from Remark 3.2.7 and the assumption (3.17) for $\mathbf{x} = (1, 0)$ and $\mathbf{y} = (0, 1)$. We now make the following inductive assumption:

$$\text{For all } \mathbf{x}', \mathbf{y}' \in \mathbb{Z}^2 \text{ with } |d(\mathbf{x}', \mathbf{y}')| < |d(\mathbf{x}, \mathbf{y})|, \text{ the pair } (\mathbf{x}', \mathbf{y}') \text{ is good.} \qquad (3.21)$$

We would like to show that $[\tilde{P}_{\mathbf{x}}, \tilde{P}_{\mathbf{y}}] = \{d(\mathbf{x}, \mathbf{y})\}(\tilde{P}_{\mathbf{x}+\mathbf{y}} - \tilde{P}_{\mathbf{x}-\mathbf{y}})$. By Remark 3.2.7, we may assume

$$\mathbf{y} = \begin{bmatrix} 0 \\ r \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} p \\ q \end{bmatrix}, \quad d(\mathbf{x}) \le d(\mathbf{y}), \quad 0 \le q < p.$$

If $p = 1$, then this equation follows from Equation (3.18), so we may also assume $p > 1$. Furthermore, we may assume that $r > 0$ by Remark 3.2.4.

We will now show that if either $d(\mathbf{x}) = 1$ or $d(\mathbf{y}) = 1$, then $(\mathbf{x}, \mathbf{y})$ is good. By symmetry of the above construction of $\mathbf{x}$ and $\mathbf{y}$, we may assume $d(\mathbf{x}) = 1$, which immediately implies $q > 0$. Furthermore, we may now assume that $r > 1$ by assuming Equation (3.18). We apply Lemma 3.2.6 to p, q to obtain $u, v, w, z \in \mathbb{Z}$ satisfying

$$uz - vw = 1, \quad uq - vp = 1, \quad u + w = p, \quad v + z = q, \quad 0 < u, w < p. \qquad (3.22)$$

We then define vectors $\mathbf{a}$ and $\mathbf{b}$ as follows:

$$\mathbf{a} := \begin{bmatrix} u \\ v \end{bmatrix}, \quad \mathbf{b} := \begin{bmatrix} w \\ z \end{bmatrix}, \quad \mathbf{a} + \mathbf{b} = \mathbf{x}, \quad d(\mathbf{a}, \mathbf{b}) = 1. \qquad (3.23)$$

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Using Lemma 3.2.5 and Assumption (3.21), it is sufficient to show that each of $|d(\mathbf{a}, \mathbf{b})|$, $|d(\mathbf{y}, \mathbf{b})|$, $|d(\mathbf{y}, \mathbf{a})|$, $|d(\mathbf{y} + \mathbf{a}, \mathbf{b})|$, $|d(\mathbf{y} + \mathbf{b}, \mathbf{a})|$, and $|d(\mathbf{a} - \mathbf{b}, \mathbf{y})|$ are strictly less than $pr = |d(\mathbf{x}, \mathbf{y})|$. First, $|d(\mathbf{a}, \mathbf{b})| = 1$ is strictly less than pr since $p > 1$ and $r > 0$. Second, $|d(\mathbf{y}, \mathbf{a})| = ur$ and $|d(\mathbf{y}, \mathbf{b})| = wr$ are strictly less than pr by the inequalities in (3.22). Third, we compute

$$
\begin{aligned}
|d(\mathbf{y} + \mathbf{a}, \mathbf{b})| & = \ |-d(\mathbf{y} + \mathbf{a}, \mathbf{b})| \\
& = \ |-d(\mathbf{y}, \mathbf{b}) - d(\mathbf{a}, \mathbf{b})| \\
& = \ |wr - 1| \\
& = \ wr - 1 \\
& < \ wr \\
& < \ pr.
\end{aligned}
$$

Fourth, we compute

$$
\begin{aligned}
|-d(\mathbf{y} + \mathbf{b}, \mathbf{a})| & = \ |-d(\mathbf{y} + \mathbf{b}, \mathbf{a})| \\
& = \ |-d(\mathbf{y}, \mathbf{a}) - d(\mathbf{b}, \mathbf{a})| \\
& = \ |ur + 1| \\
& = \ ur + 1 \\
& \leq \ (p - 1)r + 1 \\
& = \ pr - r + 1 \\
& < \ pr.
\end{aligned}
$$

Finally, we compute

$$
\begin{aligned}
|d(\mathbf{a} - \mathbf{b}, \mathbf{y})| & = \ |d(\mathbf{a}, \mathbf{y}) - d(\mathbf{b}, \mathbf{y})| \\
& = \ |d(\mathbf{y}, \mathbf{a}) - d(\mathbf{y}, \mathbf{b})|
\end{aligned}
$$

$$
\begin{aligned}
&= \quad |ur - wr| \\
&= \quad |u - w|r \\
&< \quad |u + w|r \\
&= \quad pr.
\end{aligned}
$$

So we have shown that $(\mathbf{x}, \mathbf{y})$ is good if $d(\mathbf{x}) = 1$ or $d(\mathbf{y}) = 1$. Let us now turn our attention to the more general case. We will immediately split this into cases depending on q.

Case 1: Assume $0 < q$.

Let $p' = p/d(\mathbf{x})$ and $q' = q/d(\mathbf{x})$. By the assumption $0 < q$, we see that $d(\mathbf{x}) < p$, so $p' > 1$. We can therefore apply Lemma 3.2.6 to p', q' to obtain $u, v, w, z \in \mathbb{Z}$ satisfying

$$
uz - vw = 1, \quad uq' - vp' = 1, \quad u + w = p', \quad v + z = q', \quad 0 < u, w < p'. \tag{3.24}
$$

In a way similar to the above, we may pick vectors $\mathbf{a}$ and $\mathbf{b}$ like so:

$$
\mathbf{a} := \begin{bmatrix} d(\mathbf{x})u \\ d(\mathbf{x})v \end{bmatrix}, \quad \mathbf{b} := \begin{bmatrix} d(\mathbf{x})w \\ d(\mathbf{x})z \end{bmatrix}, \quad \mathbf{a} + \mathbf{b} = \mathbf{x}, \quad d(\mathbf{a}, \mathbf{b}) = d(\mathbf{x})^2. \tag{3.25}
$$

As before, it is sufficient to show that each of $|d(\mathbf{a}, \mathbf{b})|$, $|d(\mathbf{y}, \mathbf{b})|$, $|d(\mathbf{y}, \mathbf{a})|$, $|d(\mathbf{y} + \mathbf{a}, \mathbf{b})|$, $|d(\mathbf{y} + \mathbf{b}, \mathbf{a})|$, and $|d(\mathbf{a} - \mathbf{b}, \mathbf{y})|$ are strictly less than $pr = |d(\mathbf{x}, \mathbf{y})|$. First,

$$
|d(\mathbf{a}, \mathbf{b})| = d(\mathbf{x})^2 \le d(\mathbf{x})d(\mathbf{y}) = d(\mathbf{x})r < pr
$$

where the last inequality follows from the assumption $0 < q < p$. Second, we can compute $|d(\mathbf{y}, \mathbf{b})| = d(\mathbf{x})wr$ and $|d(\mathbf{y}, \mathbf{a})| = d(\mathbf{x})ur$ are strictly less than pr by the inequalities in (3.24). Third, we compute

$$
\begin{aligned}
|d(\mathbf{y} + \mathbf{a}, \mathbf{b})| &= \quad |-d(\mathbf{y} + \mathbf{a}, \mathbf{b})| \\
&= \quad |-d(\mathbf{y}, \mathbf{b}) - d(\mathbf{a}, \mathbf{b})|
\end{aligned}
$$

$$= \ |d(\mathbf{x})wr - d(\mathbf{x})^2|$$

$$= \ d(\mathbf{x})wr - d(\mathbf{x})^2$$

$$< \ d(\mathbf{x})wr$$

$$\leq \ pr.$$

Finally, we compute

$$|d(\mathbf{y} + \mathbf{b}, \mathbf{a})| \ = \ |-d(\mathbf{y} + \mathbf{b}, \mathbf{a})|$$

$$= \ |-d(\mathbf{y}, \mathbf{a}) - d(\mathbf{b}, \mathbf{a})|$$

$$= \ d(\mathbf{x})ur + d(\mathbf{x})^2$$

$$\leq \ (d(\mathbf{x})u + d(\mathbf{x})) \, d(\mathbf{y})$$

$$= \ (u + 1)d(\mathbf{x})r.$$

Therefore, we will be finished once we show that $(u + 1)d(\mathbf{x})$ is strictly less than p. We now split into subcases:

Subcase 1a: If $u + 1 < p'$, then $(u + 1)d(\mathbf{x})r < p'd(\mathbf{x})r = pr$, and we are done.

Subcase 1b: Assume $u + 1 = p'$. By equation (3.24), we have

$$1 = uq' - vp' = (p' - 1)q' - vp' \implies p'(q' - v) = 1 + q' < 1 + p'.$$

Since $p' > 1$, the last inequality implies $q' - v = 1$, which implies $v = q' - 1$ and $z = 1$ since $v + z = q'$. Now the equation $uz - vw = 1$ implies $(p' - 1) - (q' - 1) = 1$, which implies $q' = p' - 1$. Writing $d = d(\mathbf{x})$ for short, we have

$$|d(\mathbf{y} + \mathbf{b}, \mathbf{a})| = \left| \det \begin{bmatrix} d & p - d \\ d + r & p - 2d \end{bmatrix} \right| = |d(p - 2d) - (p - d)(d + r)| = |rp + d(d - r)|$$

which is at most rp since we are assuming $d(\mathbf{x}) \leq r$. If this inequality is strict, then we are done. Otherwise, we move onto the next subcase.

Subcase 1c: In this subcase, we are reduced to showing the following pair of vectors is good:

$$\mathbf{y} = (0, r), \qquad \mathbf{x} = (rp', rp' - r).$$

If $r = 1$, then $d(\mathbf{y}) = 1$, which makes $(\mathbf{x}, \mathbf{y})$ good. Thus, we may assume that $r > 1$.

We must replace our previous choice of $\mathbf{a}$ and $\mathbf{b}$ with a choice which is better adapted to this particular subcase. We define

$$\mathbf{a} := \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \quad \mathbf{b} := \begin{bmatrix} rp' - 1 \\ rp' - r + 1 \end{bmatrix}.$$

We know that the pairs $(\mathbf{a}, \mathbf{b}), (\mathbf{y}, \mathbf{a}), (\mathbf{y} + \mathbf{b}, \mathbf{a})$ are good since $d(\mathbf{a}) = 1$. Since $r > 1$ and $p' > 1$, we can compute that the determinants of the pairs $(\mathbf{y}, \mathbf{b}), (\mathbf{y} + \mathbf{a}, \mathbf{b}), (\mathbf{a} - \mathbf{b}, \mathbf{y})$ are strictly less than $r^2 p' = |d(\mathbf{x}, \mathbf{y})|$:

$$\begin{aligned} |d(\mathbf{a} - \mathbf{b}, \mathbf{y})| &= |r^2 p' - 2r| \\ &= r^2 p' - 2r \\ &< r^2 p' \end{aligned}$$

$$\begin{aligned} |d(\mathbf{y}, \mathbf{b})| &= |r^2 p' - r| \\ &= r^2 p' - r \\ &< r^2 p' \end{aligned}$$

$$
\begin{aligned}
|d(\mathbf{y} + \mathbf{a}, \mathbf{b})| &= |r^2 p' - (rp' + r - 1)| \\
&= r^2 p' - (rp' + r - 1) \\
&< r^2 p'.
\end{aligned}
$$

This together with Assumption (3.21) and Lemma 3.2.5 shows that $(\mathbf{x}, \mathbf{y})$ is good, which finishes the proof of this subcase and finishes the proof of Case 1.

Case 2: In this case we assume $q = 0$. We define $\mathbf{a}, \mathbf{b}$ similarly to Subcase 1c, so we have

$$
\mathbf{y} = \begin{bmatrix} 0 \\ r \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} p \\ 0 \end{bmatrix}, \quad \mathbf{a} := \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \quad \mathbf{b} := \begin{bmatrix} p - 1 \\ 1 \end{bmatrix}.
$$

Since $d(\mathbf{a}) = d(\mathbf{b}) = 1$, the pairs $(\mathbf{a}, \mathbf{b}), (\mathbf{y}, \mathbf{a}), (\mathbf{y}, \mathbf{b}), (\mathbf{y} + \mathbf{a}, \mathbf{b}), (\mathbf{y} + \mathbf{b}, \mathbf{a})$ are all good. We must check that $|d(\mathbf{a} - \mathbf{b}, \mathbf{y})| < pr = |d(\mathbf{x}, \mathbf{y})|$. If $r = 1$, then the relation (3.17) implies that the pair $(\mathbf{x}, \mathbf{y})$ is good. Thus, we may assume that $r > 1$. We may also assume that $p > 1$. Finally, we check $|d(\mathbf{a} - \mathbf{b}, \mathbf{y})| = |rp - 2r| = rp - 2r < rp$. By using Assumption (3.21) and Lemma 3.2.5, this completes Case 2 which completes the proof. $\qquad\square$

3.3   Relationships With $\mathcal{K}(T^2)$ and $\mathcal{H}(T^2)$

3.3.1   The Kauffman Bracket Case

Recall that the Dubrovnik skein relations satisfy the Kauffman Bracket skein relations, and hence there is a natural transformation of functors

$$
\eta : \mathcal{D} \to \mathcal{K}
$$

whose components are essentially the identity map (more details are given in Section 2.2). In particular, there is an algebra homomorphism from the Birman-Murakami-Wenzl algebra to the Temperley-Lieb algebra.

Theorem 3.3.1. *Under the algebra homomorphism*

$$\eta_{(I^2,\underline{n})} : BMW_n \to TL_n$$

the BMW symmetrizer $\tilde{y}_n$ is sent to the Jones-Wenzl idempotent JW_n.

Proof. The element JW_n is the unique element of TL_n satisfying the properties

1. $JW_n \neq 0$,

2. $JW_n^2 = JW_n$,

3. $JW_n c_i = c_i JW_n = 0$ for all cap-cup generators c_i.

Let's abuse some notation by using η instead of $\eta_{(I^2,\underline{n+1})}$ since it should be clear from context what we mean. Since η is an algebra map, it is true that $\eta(\tilde{y}_n)$ are idempotent and absorb c_i in the same way as JW_n, but it is not clear if these images are non-zero. If $n = 1$, then the statement is true since $\tilde{y}_1$ and JW_1 are the simply the identity, a single strand. We will proceed assuming the induction hypothesis, that $\eta(\tilde{y}_k) = JW_k$ for all $k \leq n$. The Jones-Wenzl idempotents satisfy the recurrence relation

$$(3.26)$$

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(see * Morrison paper and substitute $q = s^2$) and recall the recurrence relation for the BMW symmetrizers

$$[n+1] \boxed{\tilde{y}_{n+1}} = [n]s^{-1} \boxed{\tilde{y}_n / \tilde{y}_n} + \boxed{\tilde{y}_n} + [n]s^{-1}\beta_n \boxed{\tilde{y}_n / \tilde{y}_n} \tag{3.27}$$

where

$$\beta_n = \frac{1 - s^2}{s^{2n-1}v^{-1} - 1}.$$

We finish the proof by showing that the image of Equation (3.27) is Equation (3.26) under η. So specialize $v = -s^{-3}$ and apply η to Equation (3.27) and use the induction hypothesis to get

$$[n+1] \boxed{\eta(\tilde{y}_{n+1})} = [n]s^{-1} \boxed{JW_n / JW_n} + \boxed{JW_n} + \frac{s^n - s^{-n}}{s^{2n+2} + 1} \boxed{JW_n / JW_n} \tag{3.28}$$

which is true after calculating $\eta([n]s^{-1}\beta_n)$. First, let's work with the second diagram on the right-hand side.

$$\boxed{JW_n} = \boxed{JW_n / JW_n} = s \boxed{JW_n / JW_n} + s^{-1} \boxed{JW_n / JW_n}$$

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since $\sigma_i JW_n = JW_n\sigma_i = sJW_n$ for a positive crossing σ_i. So Equation (3.28) becomes

$$(3.29)$$

Let's divide both sides of Equation (3.29) by $[n+1]$ and simplify the constants slightly.

$$(3.30)$$

Take the first diagram on the right-hand side and rewrite it using the following technique.

We can also rewrite the second diagram on the right-hand side of Equation (3.30) in a similar way.

Then Equation (3.30) becomes

$$(3.31)$$

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Multiply both sides of the equation by $\sigma_n \cdots \sigma_1$ to get the equation

$$\tag{3.32}$$

On the left-hand side, the crossings are absorbed and scale the diagram by s^n. Divide both sides by s^n. One can show that the equality of scalars

$$s^{-n}\left(s^{n-2} - \frac{1 - s^{-2n-4} + s^{-2} - s^{-2n-2}}{s^{n+2} - s^{-n-2} - s^n + s^{-n}}\right) = \frac{s^{2n} - s^{-2n}}{s^{2n+2} - s^{-2n-2}}$$

hold in the base ring. The right-hand side of the resulting equation is precisely the right-hand side of Equation (3.26). Therefore, $\eta(\tilde{y}_{n+1}) = JW_{n+1}$, which completes the proof. $\qquad\square$

Remark 3.3.2. In * Shelly, it is pointed out that, under the composition of algebra maps $BMW_n \to H_n \to TL_n$ (see Section 2.3), the BMW symmetrizer $\tilde{y}_n$ is sent to the Jones-Wenzl idempotent JW_n. However, these maps are defined abstractly on generators, and so *a priori* they are not induced by any natural transformations of skein theories. Furthermore, the diagram

does not commute since $\pi_H(c_i) = 0$. However, Theorem 3.3.1 shows that restricting the maps of the diagram on the relevant idempotents *does* commute.

It was mentioned in Section 2.2 that *Chebyshev polynomials* are imporant elements of the skein algebra $\mathcal{K}(A) = R[z]$. Let's now elaborate what that means. The **Chebyshev**

polynomials of the second kind $C_n^S = C_n^S(z)$ are defined recursively as

$$C_0^U = 1, \qquad C_1^U = 2z, \qquad C_n^U = 2zC_{n-1}^U - C_{n-2}^U.$$

Let's consider slightly modified versions $U_n := C_n^U(z/2)$. These polynomials have amazing properties, most of which we won't discuss here. One such fact is that the annular closure of the Jones-Wenzl idempotent JW_n is equal to $U_n(z)$. This can be shown by taking the annular closure of Equation (3.26), the recurrence relation for the JW_n, and using some well-known identities to show that the result is the same as the recurrence relation $U_{n+1} = zU_n - U_{n-1}$.

There are also **Chebyshev polynomials of the first kind** $C_k^T = C_k^T(z)$ which are defined recursively as

$$C_0^T = 1, \qquad C_1^T = z, \qquad C_k^T = 2zC_{k-1}^T - C_{k-2}^T.$$

Again, we will need slightly modified versions of these, $T_k := 2C_k^T(z/2)$.

Corollary 3.3.3. *Under the algebra homomorphism*

$$\eta_A : \mathcal{D}(A) \to \mathcal{K}(A)$$

the image of the special element $\tilde{P}_k$ is equal to the Chebyshev polynomial T_k.

Proof. Since η is natural, the closure into the annulus induces a commuting square

$$
\begin{array}{ccc}
BMW_n & \xrightarrow{\;\text{cl}\;} & \mathcal{D}(A) \\
\downarrow{\scriptstyle \eta} & & \downarrow{\scriptstyle \eta} \\
TL_n & \xrightarrow{\;\text{cl}\;} & \mathcal{K}(A)
\end{array}
$$

Recall the $\tilde{P}_k$ are uniquely determined by the power series equation

$$\sum_{k=1}^{\infty} \frac{\tilde{P}_k}{k} t^k = \ln\left(1 + \sum_{n=1}^{\infty} \tilde{h}_n t^n\right).$$

If we show that the following equality holds

$$\sum_{k=1}^{\infty} \frac{T_k}{k} t^k = \ln\left(1 + \sum_{n=1}^{\infty} U_n t^n\right)$$

then the proof is complete since $\eta_A(\tilde{h}_n) = U_n$. The Chebyshev polynomials admit well-known generating functions (see Wikipedia, for example)

$$\sum_{n\geq 0} C_n^U(z) t^n = \frac{1}{1 - 2tz + t^2}$$

$$\sum_{k\geq 1} C_k^T(z) \frac{t^k}{k} = \ln\left(\frac{1}{\sqrt{1 - 2tz + t^2}}\right).$$

These imply

$$\sum_{n\geq 0} C_n^U(z/2) t^n = \frac{1}{1 - tz + t^2}$$

$$\sum_{k\geq 1} C_k^T(z/2) \frac{t^k}{k} = \ln\left(\frac{1}{\sqrt{1 - tz + t^2}}\right).$$

Multiply the second equation by 2 to get

$$\sum_{k\geq 1} 2C_k^T(z/2) \frac{t^k}{k} = \ln\left(\frac{1}{1 - tz + t^2}\right)$$

which implies the desired equation since $T_k = 2C_k^T(z/2)$ and $U_n := C_n^U(z/2)$. $\square$

Recall once more the embedding of the annulus

$$\iota_r : A \hookrightarrow T^2$$

into a tubular neighborhood of the simple closed curve of rational slope $r = a/b$ for (a, b) considered as an element of $\mathbb{Z}^2/\langle \mathbf{x} = -\mathbf{x} \rangle$. These embeddings induce naturality squares

$$\begin{CD} \mathcal{D}(A) @>{\mathcal{D}(\iota_r)}>> \mathcal{D}(T^2) \\ @V{\eta}VV @VV{\eta}V \\ \mathcal{K}(A) @>{\mathcal{K}(\iota_r)}>> \mathcal{K}(T^2) \end{CD}$$

which imply that $\eta_{T^2}(\tilde{P}_{\mathbf{x}}) = T_{\mathbf{x}}$ for any $\mathbf{x}$ where the $T_{\mathbf{x}}$ are the generators in the Frohman-Gelca presentation of $\mathcal{K}(T^2)$. Indeed, one can check that the T_k satisfy the relations Theorem 3.2.1:

$$\begin{aligned} [T_{\mathbf{x}}, T_{\mathbf{y}}] &= T_{\mathbf{x}}T_{\mathbf{y}} - T_{\mathbf{y}}T_{\mathbf{x}} \\ &= (s^{\det(\mathbf{x},\mathbf{y})}T_{\mathbf{x}+\mathbf{y}} + s^{-\det(\mathbf{x},\mathbf{y})}T_{\mathbf{x}-\mathbf{y}}) - (s^{\det(\mathbf{y},\mathbf{x})}T_{\mathbf{y}+\mathbf{x}} + s^{-\det(\mathbf{y},\mathbf{x})}T_{\mathbf{y}-\mathbf{x}}) \\ &= (s^{\det(\mathbf{x},\mathbf{y})}T_{\mathbf{x}+\mathbf{y}} + s^{-\det(\mathbf{x},\mathbf{y})}T_{\mathbf{x}-\mathbf{y}}) - (s^{-\det(\mathbf{x},\mathbf{y})}T_{\mathbf{x}+\mathbf{y}} + s^{\det(\mathbf{x},\mathbf{y})}T_{\mathbf{x}-\mathbf{y}}) \\ &= (s^{\det(\mathbf{x},\mathbf{y})} - s^{-\det(\mathbf{x},\mathbf{y})})(T_{\mathbf{x}+\mathbf{y}} - T_{\mathbf{x}-\mathbf{y}}) \end{aligned}$$

Let's summarize this discussion with a corollary.

Corollary 3.3.4. *The presentation of $\mathcal{D}(T^2)$ is compatible with the Frohman-Gelca presentation of $\mathcal{K}(T^2)$ under the algebra homomorphism*

$$\eta_{T^2} : \mathcal{D}(T^2) \to \mathcal{K}(T^2).$$

It should probably be emphasized that this homomorphism is defined topologically on the level of diagrams, and not simply via an abstract assignment of generators. This is important because skein theoretic methods will translate through these types of homomorphisms.

3.3.2 The HOMFLYPT Case

Recall that $\mathcal{H}(T^2)$ is presented by generators

$$\{P_{\mathbf{x}} \mid \mathbf{x} \in \mathbb{Z}^2\}$$

and relations

$$[P_{\mathbf{x}}, P_{\mathbf{y}}] = (s^{\det(\mathbf{x}, \mathbf{y})} - s^{-\det(\mathbf{x}, \mathbf{y})}) P_{\mathbf{x}}.$$

This implies that the span of the generators is a Lie algebra and $\mathcal{H}(T^2)$ is its universal enveloping algebra. Let's use the notation

$$\mathfrak{g}_{\mathcal{H}} := R\{P_{\mathbf{x}} \mid \mathbf{x} \in \mathbb{Z}^2\} \qquad \mathfrak{g}_{\mathcal{D}} := R\{\tilde{P}_{\mathbf{x}} \mid \mathbf{x} \in \mathbb{Z}^2 / \langle \mathbf{x} = -\mathbf{x} \rangle\}.$$

Proposition 3.3.5. *There is an injective Lie algebra homomorphism*

$$\varphi : \mathfrak{g}_{\mathcal{D}} \to \mathfrak{g}_{\mathcal{H}}$$

defined by $\varphi(\tilde{P}_{\mathbf{x}}) = P_{\mathbf{x}} + P_{-\mathbf{x}}$. *This induces an algebra homomorphism*

$$U(\varphi) : \mathcal{D}(T^2) \to \mathcal{H}(T^2)$$

where $U(-)$ *is the universal enveloping algebra functor. Furthermore, the restrition of this homomorphism to an annulus provides an identification for* $\mathcal{D}(A)$ *as a subalgebra of* $\mathcal{H}(A)$.

Proof. The assignment is linear since it's defined on basis elements. Let's check that

$$\varphi([\tilde{P}_{\mathbf{x}}, \tilde{P}_{\mathbf{y}}]) = [\varphi(\tilde{P}_{\mathbf{x}}), \varphi(\tilde{P}_{\mathbf{y}})]$$

for any $\mathbf{x}$ and $\mathbf{y}$. The left-hand side is

$$
\begin{aligned}
&\varphi([\tilde{P}_{\mathbf{x}}, \tilde{P}_{\mathbf{y}}]) \\
=\;& \varphi\big((s^{\det(\mathbf{x}, \mathbf{y})} - s^{-\det(\mathbf{x}, \mathbf{y})})(\tilde{P}_{\mathbf{x}+\mathbf{y}} - \tilde{P}_{\mathbf{x}-\mathbf{y}})\big) \\
=\;& (s^{\det(\mathbf{x}, \mathbf{y})} - s^{-\det(\mathbf{x}, \mathbf{y})})\big(\varphi(\tilde{P}_{\mathbf{x}+\mathbf{y}}) - \varphi(\tilde{P}_{\mathbf{x}-\mathbf{y}})\big) \\
=\;& (s^{\det(\mathbf{x}, \mathbf{y})} - s^{-\det(\mathbf{x}, \mathbf{y})})\big(P_{\mathbf{x}+\mathbf{y}} + P_{-\mathbf{x}-\mathbf{y}} - P_{\mathbf{x}-\mathbf{y}} - P_{-\mathbf{x}+\mathbf{y}}\big) \\
=\;& (s^{\det(\mathbf{x}, \mathbf{y})} - s^{-\det(\mathbf{x}, \mathbf{y})})P_{\mathbf{x}+\mathbf{y}} + (s^{\det(\mathbf{x}, \mathbf{y})} - s^{-\det(\mathbf{x}, \mathbf{y})})P_{-\mathbf{x}-\mathbf{y}}
\end{aligned}
$$

$$- \left(s^{\det(\mathbf{x},\mathbf{y})} - s^{-\det(\mathbf{x},\mathbf{y})}\right) P_{\mathbf{x}-\mathbf{y}} - \left(s^{\det(\mathbf{x},\mathbf{y})} - s^{-\det(\mathbf{x},\mathbf{y})}\right) P_{-\mathbf{x}+\mathbf{y}}$$

$$= \left(s^{\det(\mathbf{x},\mathbf{y})} - s^{-\det(\mathbf{x},\mathbf{y})}\right) P_{\mathbf{x}+\mathbf{y}} + \left(s^{\det(-\mathbf{x},-\mathbf{y})} - s^{-\det(-\mathbf{x},-\mathbf{y})}\right) P_{-\mathbf{x}-\mathbf{y}}$$

$$- \left(s^{-\det(\mathbf{x},-\mathbf{y})} - s^{\det(\mathbf{x},-\mathbf{y})}\right) P_{\mathbf{x}-\mathbf{y}} - \left(s^{-\det(-\mathbf{x},\mathbf{y})} - s^{\det(-\mathbf{x},\mathbf{y})}\right) P_{-\mathbf{x}+\mathbf{y}}$$

$$= [P_{\mathbf{x}}, P_{\mathbf{y}}] + [P_{-\mathbf{x}}, P_{-\mathbf{y}}] + [P_{\mathbf{x}}, P_{-\mathbf{y}}] + [P_{-\mathbf{x}}, P_{\mathbf{y}}]$$

$$= [P_{\mathbf{x}} + P_{-\mathbf{x}}, P_{\mathbf{y}} + P_{-\mathbf{y}}]$$

$$= [\varphi(\tilde{P}_{\mathbf{x}}), \varphi(\tilde{P}_{\mathbf{y}})].$$

Note that $\varphi(\tilde{P}_{\mathbf{x}}) = \varphi(\tilde{P}_{-\mathbf{x}})$, so the map is well-defined. This completes the proof. $\square$

Remark 3.3.6. It's worth pointing out that this homomorphism is defined abstractly on generators. It is not clear whether or not this map is induced by something topological in nature, as was the case for the map $\eta_{T^2} : \mathcal{D}(T^2) \to \mathcal{K}(T^2)$. After all, we are relating an unoriented skein theory with an oriented one. If this map were to arise from topology, it would have to involve a choice of orientations for each component of each link. All attempts to find such a choice has been unsuccessful.

3.4 An Action $\mathcal{D}(T^2) \curvearrowright \mathcal{D}(D^2 \times I)$

Recall that the skein algebra of the boundary of a 3-manifold acts on the skein module of that manifold, Hence $\mathcal{D}(D^2 \times I)$ carries the structure of a $\mathcal{D}(T^2)$-module. In this section we give an implicit description of this action. The first step is to show that $\mathcal{D}(T^2)$ is generated by five specific elements, where proof may be viewed as an algorithm to write each basis element as a product of generators. Next, formulas are given for how each of those generators act. Note that $\mathcal{D}(D^2 \times I)$ also carries an algebra structure and is isomorphic to $\mathcal{D}(A)$ as algebras, but the $\mathcal{D}(T^2)$ action does not commute with the product. Thus, we consider $\mathcal{D}(D^2 \times I)$ simply as a vector space with basis $\{\tilde{y}_\lambda\}_\lambda$.

3.4.1   A Small Generating Set of $\mathcal{D}(T^2)$

Recall the presentation of $\mathcal{D}(T^2)$ given in Theorem 3.2.1. To make formulas nicer, we will use slightly different generators

$$B_{\mathbf{x}} := \tilde{P}_{\mathbf{x}} + c_{\mathbf{x}}$$

where

$$c_{\mathbf{x}} = \begin{cases} 0 & \gcd(\mathbf{x}) = 1 \pmod 2 \\ 1 & \gcd(\mathbf{x}) = 0 \pmod 2 \end{cases}$$

which also present the algebra subject to the same relations of Theorem 3.2.1. This generating set is infinite, but Proposition 3.4.2 shows that the algebra is finitely generated by a small subset of these generators. First, we prove a technical lemma.

Lemma 3.4.1. *Let* $\mathbf{x}, \mathbf{y}, \mathbf{z} \in \mathbb{Z}^2$ *be such that* $\mathbf{x} = \mathbf{y} - \mathbf{z}$ *and so* $d := \det(\mathbf{y}, \mathbf{z})$ *is non-zero. Then* $B_{\mathbf{x}+n\mathbf{z}}$ *is generated by* $B_{\mathbf{x}}, B_{\mathbf{y}}, B_{\mathbf{z}}$ *for all* $n \in \mathbb{Z}$.

Proof. The statement is trivial if $n = 0$. By induction on positive n, one can express $B_{\mathbf{y}+n\mathbf{z}}$ as

$$B_{\mathbf{y}+n\mathbf{z}} = \{d\}^{-1}\Big([B_{\mathbf{y}+(n-1)\mathbf{z}}, B_{\mathbf{z}}] + \{d\} B_{\mathbf{y}+(n-2)\mathbf{z}} \Big)$$

which holds for $n = 1$ by Theorem 3.2.1. Since $B_{\mathbf{z}} = B_{-\mathbf{z}}$, we can repeat a similar induction to generate $B_{\mathbf{y}-n\mathbf{z}}$:

$$B_{\mathbf{y}-n\mathbf{z}} = \{d\}^{-1}\Big([B_{\mathbf{y}-(n-1)\mathbf{z}}, B_{-\mathbf{z}}] + \{d\} B_{\mathbf{y}-(n-2)\mathbf{z}} \Big)$$

where now the base case can be any $n \geq 1$. $\qquad\qquad\qquad\qquad\qquad\qquad\square$

The above lemma may the thought of geometrically as a way of generating the integer points of a line with rational slope in the lattice $\{B_{n,m} | (n,m) \in \mathbb{Z}^2\}$, given the right initial conditions.

Proposition 3.4.2. *The algebra* $\mathcal{D}(T^2)$ *is generated by the elements* $B_{0,0}, B_{1,0}, B_{0,1}, B_{1,1}, B_{2,0}$.

Proof. Let's visualize and keep track of which $B_{n,m}$ we've generated by dots on a lattice. So, we start with the configuration below.
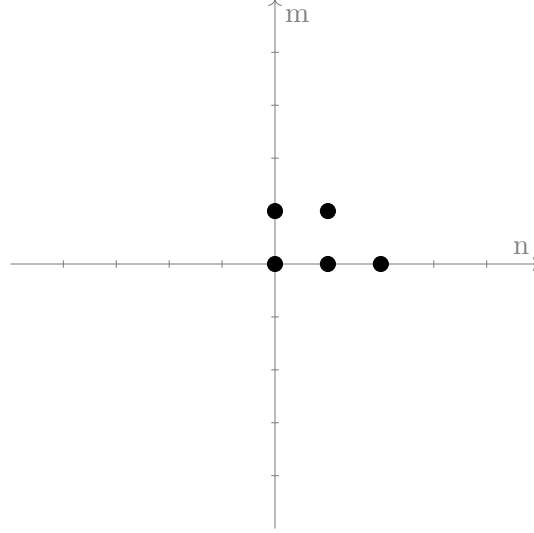
First, we generate the element

$$B_{1,-1} = \{1\}^{-1}\Big([B_{1,0}, D_{0,1}] + \{1\}^{-1}D_{1,1}\Big).$$
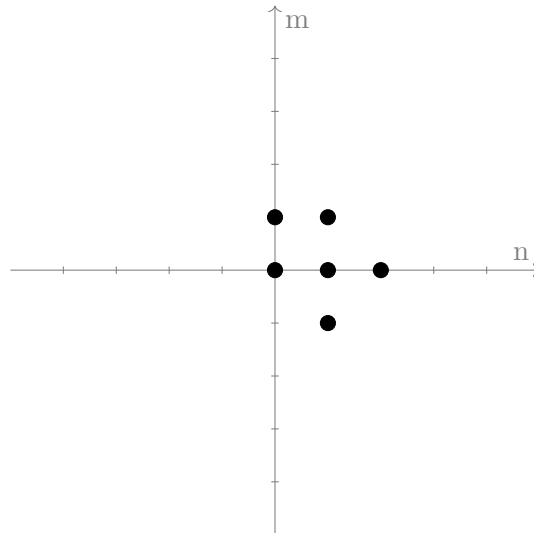
Then, we can generate two parallel lines of minimal distance apart by applying 3.4.1 to the two sets of values

$$\mathbf{x}_1 = (0,1), \quad \mathbf{y}_1 = (1,0), \quad \mathbf{z}_1 = (1,-1)$$

$$\mathbf{x}_2 = (0,2), \quad \mathbf{y}_2 = (1,1), \quad \mathbf{z}_2 = (1,-1)$$

thus generating $B_{n,1-n}, B_{n,2-n}$ for all $n \in \mathbb{Z}$.
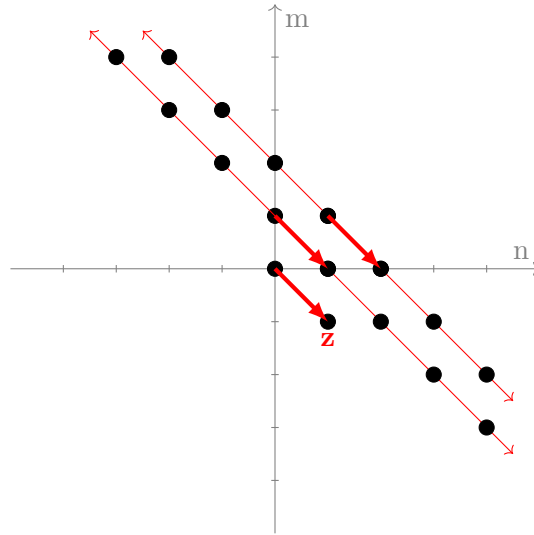
Then for any $n \neq 0$, we may apply Lemma 3.4.1 to the triple

$$\mathbf{x} = (n, 1-n), \quad \mathbf{y} = (n, 2-n), \quad \mathbf{z} = (0,1)$$

to generate the vertical line of points through $(n,0)$.

Finally, any $B_{0,m}$ for $m \neq 0$ can be expressed as

$$B_{0,m} = \{m\}^{-1}\Big([B_{1,m}, B_{-1,0}] + \{m\}B_{2,m}\Big)$$

which generates the last of what is left of the $B_{n,m}$. This completes the proof. □

Remark 3.4.3. The proof above provides an algorithm for expressing any $B_{n,m}$ in terms of the five generators. Of course, this expression is complicated and not very convenient to work with in practice, but it is not surprising since the generating set is so small.

3.4.2   Recalling Some Formulas From the Literature

Let $\Lambda = (\Lambda_1, \ldots, \Lambda_n)$ be a sequence of Young diagrams such that $|\Lambda_1| = 1$, $|\Lambda_{i+1}| = |\Lambda_i| \pm 1$, and $\Lambda_n = \lambda$. We will call such a sequence an *up-down tableau* of length n and shape $\lambda(\Lambda) := \Lambda_n$. If $\Lambda = (\Lambda_1, \ldots, \Lambda_{n-1}, \Lambda_n)$, then define $\Lambda' = (\Lambda_1, \ldots, \Lambda_{n-1})$. In particular, $|\lambda(\Lambda)| = |\lambda(\Lambda')| \pm 1$. Following * BB01, recursively define morphisms $\mathfrak{a}_\Lambda$ and $\mathfrak{b}_\Lambda$ by:

$$\mathfrak{a}_1 := \mathrm{id}_1 =: \mathfrak{b}_1$$

and if $|\Lambda_n| = |\Lambda_{n-1}| + 1$, then

$$\mathfrak{a}_\Lambda := (\mathfrak{a}_{\Lambda'} \otimes 1_1)\tilde{y}_{\Lambda(\Lambda)}$$

$$\mathfrak{b}_\Lambda := \tilde{y}_{\lambda(\Lambda)}(\mathfrak{b}_{\Lambda'} \otimes 1_1)$$

and if $|\Lambda_n| = |\Lambda_{n-1}| - 1$, then

$$\mathfrak{a}_\Lambda := \frac{\langle \Lambda_n \rangle}{\langle \Lambda_{n-1} \rangle}(\mathfrak{a}_{\Lambda'} \otimes 1_1)(\tilde{y}_{\lambda(\Lambda)} \otimes \cap)$$

$$\mathfrak{b}_\Lambda := (\tilde{y}_{\lambda(\Lambda)} \otimes \cup)(\mathfrak{b}_{\Lambda'} \otimes 1_1)$$

where $\langle \lambda \rangle$ is the Kauffman polynomial of the closure of $\tilde{y}_\lambda$ in S^3, the morphisms $\cup \in$ $\mathrm{Hom}_{\mathsf{D}(I^2)}\big(\varnothing, [2]\big)$ and $\cap \in \mathrm{Hom}_{\mathsf{D}(I^2)}\big([2], \varnothing\big)$ are the obvious cup and cap morphisms, and $\otimes$ is the monoidal product of $\mathsf{D}(I^2)$ induced by some standard embedding $I^2 \sqcup I^2 \to I^2$.

Theorem 3.4.4 (* BB01, Section 5). *Let $d_\lambda^{(n)}$ be the number of up-down tableaux of length n and shape λ. Let $\mathcal{M}_{d_\lambda}$ denote the $d_\lambda^{(n)} \times d_\lambda^{(n)}$ matrix algebra. Also, let*

$$q_\Lambda := \alpha_\Lambda \beta_\Lambda, \qquad z_\lambda^{(n)} := \sum_{\lambda(\Lambda) = \lambda} q_\Lambda$$

1. *There is an algebra isomorphism*

$$\rho : \bigoplus_{|\lambda| = n, n-2, \dots} \mathcal{M}_{d_\lambda^{(n)}} \xrightarrow{\sim} BMW_n$$

   such that the image of a standard basis element is $\rho(e_{\Lambda,\Xi}^\lambda) = \alpha_\Lambda \beta_\Xi$ where $\lambda(\Lambda) = \lambda = \lambda(\Xi)$. It follows that the $z_\lambda^{(n)}$ are central idempotents of BMW_n.

2. *(Branching formula)*

$$q_\Lambda \otimes 1_1 = \sum_{\Xi' = \Lambda} q_\Xi$$

   for all up-down tableaux Λ.

3.

$$\mathfrak{b}_\Lambda \mathfrak{a}_\Lambda = \tilde{y}_{\lambda(\Lambda)}$$

for all up-down tableaux Λ.

Remark 3.4.5. Recall our notation $\tilde{Q}_\lambda := \text{cl}(\tilde{y}_\lambda)$. Then Theorem 3.4.4 implies

$$\text{cl}(q_\Lambda) = \text{cl}(\mathfrak{a}_\Lambda \mathfrak{b}_\Lambda) = \text{cl}(\mathfrak{b}_\Lambda \mathfrak{a}_\Lambda) = \text{cl}(\tilde{y}_{\lambda(\Lambda)}) = \tilde{Q}_{\lambda(\Lambda)},$$

so therefore $\text{cl}(z_\lambda^{(n)})$ is a positive integer multiple of $\tilde{Q}_{\lambda(\Lambda)}$.

Let's formally restate a theorem which was mentioned in Section 2.4.

Theorem 3.4.6 (* ZL01, Corollary 2, Proposition 2.1)**.**

1. The elements $\tilde{Q}_\lambda$ form a basis of the skein module of a solid torus $\mathcal{D}(I^2 \times S^1)$, where λ ranges over all Young diagrams.

2. Let $\phi : \mathcal{C} \to \mathcal{C}$ be the meridian map so that $\phi(x)$ is a simple loop wrapped around x. Then

$$\phi(\tilde{Q}_\lambda) = c_\lambda \tilde{Q}_\lambda$$

where

$$c_\lambda = \delta + (s - s^{-1}) \left(v^{-1} \sum_{x \in \lambda} s^{2\text{cn}(x)} - v \sum_{x \in \lambda} s^{-2\text{cn}(x)} \right)$$

This is the basis we will choose to act by $\mathcal{D}(T^2)$ on in Section 3.4.3.

3.4.3 Showing How Generators Act

We will fix the convention that $B_{1,0}$ acts as a meridian link and $B_{0,1}$ acts as a longitude link. This next proposition shows how each element of the generating set of Proposition 3.4.2 act.

Proposition 3.4.7. *In the basis* $\{\tilde{Q}_\lambda\}_\lambda$ *of* $\mathcal{D}(I^2 \times S^1)$*, the action of* $\mathcal{D}(T^2)$ *is determined by the following equations*

$$B_{1,0} \cdot \tilde{Q}_\lambda = \left(\langle B_1 \rangle + \{1\}\left(v^{-1} \sum_{x \in \lambda} s^{2\mathrm{cn}(x)} - v \sum_{x \in \lambda} s^{-2\mathrm{cn}(x)} \right) \right) \tilde{Q}_\lambda \qquad (3.33)$$

$$B_{2,0} \cdot \tilde{Q}_\lambda = \left(\langle B_2 \rangle + \{2\}\left(v^{-2} \sum_{x \in \lambda} s^{4\mathrm{cn}(x)} - v^2 \sum_{x \in \lambda} s^{-4\mathrm{cn}(x)} \right) \right) \tilde{Q}_\lambda \qquad (3.34)$$

$$B_{0,1} \cdot \tilde{Q}_\lambda = \sum_{\substack{\nu \supset \lambda \\ |\mu|=|\lambda|+1}} \tilde{Q}_\lambda + \sum_{\substack{\mu \subset \lambda \\ |\mu|=|\lambda|-1}} \tilde{Q}_\lambda \qquad (3.35)$$

$$B_{1,1} \cdot \tilde{Q}_\lambda = v^{-1} \sum_{\substack{\nu \supset \lambda \\ |\mu|=|\lambda|+1 \\ \nu=\lambda+x}} s^{2\mathrm{cn}(x)} \tilde{Q}_\nu + v \sum_{\substack{\mu \subset \lambda \\ |\mu|=|\lambda|-1 \\ \mu=\lambda-x}} s^{-2\mathrm{cn}(x)} \tilde{Q}_\mu \qquad (3.36)$$

Proof. The equation (3.33) follows by considering the annular closure of the branching rule formula of Theorem 3.4.4, together with Remark 3.4.5. Also, (3.35) is precisely the result of the meridian map eigenvalue computation of Theorem 3.4.6. Equation (3.34) follows from Proposition 4.3.2 for $k = 2$.

Finally, we show (3.36) by invoking the branching rule and applying an identity coming from the proof of the branching rule, seen in [?BB01]:

(* Need to make diagrams for proof.) $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\square$

Proposition 3.4.8. *In the BMW algebra,*

$$B_{n,1} \cdot \tilde{y}_\lambda =$$

Chapter 4

More Formulas and Partial Results

4.1 Commutation Relations For BMW and Hecke Symmetrizer Closures

This next theorem follows directly from Equation (4.13), which makes it equivalent to Theorem 3.1.1 in some sense. This expresses the left $\mathcal{D}(A)$-action on $\mathcal{A}_\mathcal{D}$ in terms of the right action, and vice versa. This implies a commutation relation for the closures of the BMW symmetrizers in terms of either the elements of the set $\{\tilde{h}_j \cdot a^i\}_{j,i}$ or $\{a^i \cdot \tilde{h}_j\}_{j,i \geq 0}$ which are subsets of the bases $\{\widetilde{Q}_\lambda \cdot a^i\}_{i \geq 0,\lambda}$ and $\{a^i \cdot \widetilde{Q}_\lambda\}_{i \geq 0,\lambda}$ of $\mathcal{A}_\mathcal{D}$, respectively. These supersets are bases since $\mathcal{A}_\mathcal{D} = \mathcal{D}(A)[a, a^{-1}]$ as algebras in the category of left $\mathcal{D}(A)$-modules and because the map defined by $\widetilde{Q}_\lambda \cdot a^i \mapsto a^i \cdot \widetilde{Q}_\lambda$ is an invertible algebra homomorphism.

Theorem 4.1.1. *For any $n \geq 1$, the relations*

$$\tilde{h}_n \cdot e = \sum_{i=0}^{n} d_i (e \cdot \tilde{h}_{n-i}) \tag{4.1}$$

and

$$e \cdot \tilde{h}_n = \sum_{i=0}^{n} \bar{d}_i (\tilde{h}_{n-i} \cdot e) \tag{4.2}$$

hold in $\mathcal{A}_\mathcal{D}$, where

$$d_0 = 1,$$

$$d_i = \sum_{l=0}^{i-1}(1-s^2)s^{2l-i}a^{i-2l} + (1-s^{-2})s^{i-2l}a^{2l-i} \qquad \forall i \geq 1,$$

$$\bar{d}_i = \sum_{l=0}^{i-1}(1-s^{-2})s^{i-2l}a^{i-2l} + (1-s^2)s^{2l-i}a^{2l-i} \qquad \forall i \geq 1.$$

Equivalently,

$$e \cdot \tilde{h}_n - \tilde{h}_n \cdot e = \sum_{i=1}^{n}\bar{d}_i(\tilde{h}_{n-i} \cdot e) \tag{4.3}$$

or

$$\tilde{h}_n \cdot e - e \cdot \tilde{h}_n = \sum_{i=1}^{n}d_i(e \cdot \tilde{h}_{n-i}). \tag{4.4}$$

Proof. The formula for the d_i were discovered experimentally by coding a solver using the SymPy package in Python. The second equation is just the mirror map applied to the first equation, so we will just prove the first equation.

The idea of the proof depends on a reformulation of Equation (4.13) as

$$\tilde{h}_n \cdot e = e \cdot \tilde{h}_n - (sa + s^{-1}a^{-1})(e \cdot \tilde{h}_{n-1}) + e \cdot \tilde{h}_{n-2} + (s^{-1}a + sa^{-1})\tilde{h}_{n-1} \cdot e - \tilde{h}_{n-2} \cdot e$$

and a recursive application of this formula to its last two terms on the right-hand side of the equation.

The case of $n = 0$ is trivial. For $n = 1$, just apply the Kauffman skein relation. Now assume the induction hypothesis, that the formula in the statement is true for all $k \leq n - 1$. Then apply this assumption to Equation (4.13):

$$\tilde{h}_n \cdot e = e \cdot \tilde{h}_n - (sa + s^{-1}a^{-1})(e \cdot \tilde{h}_{n-1}) + e \cdot \tilde{h}_{n-2} + (s^{-1}a + sa^{-1})(\tilde{h}_{n-1} \cdot e) - \tilde{h}_{n-2} \cdot e$$

$$= e \cdot \tilde{h}_n - (sa + s^{-1}a^{-1})(e \cdot \tilde{h}_{n-1}) + e \cdot \tilde{h}_{n-2} + (s^{-1}a + sa^{-1})\sum_{i=0}^{n-1}d_i(e \cdot \tilde{h}_{n-1-i})$$

$$-\sum_{i=0}^{n-2} d_i(e \cdot \tilde{h}_{n-2-i})$$

$$= e \cdot \tilde{h}_n + d_1(e \cdot \tilde{h}_{n-1}) + (s^{-1}a + sa^{-1}) \sum_{i=1}^{n-1} d_i(e \cdot \tilde{h}_{n-1-i}) - \sum_{i=1}^{n-2} d_i(e \cdot \tilde{h}_{n-2-i})$$

$$= e \cdot \tilde{h}_n + d_1(e \cdot \tilde{h}_{n-1}) + (s^{-1}a + sa^{-1}) \sum_{i=0}^{n-2} d_{i+1}(e \cdot \tilde{h}_{n-2-i}) - \sum_{i=1}^{n-2} d_i(e \cdot \tilde{h}_{n-2-i})$$

$$= e \cdot \tilde{h}_n + d_1(e \cdot \tilde{h}_{n-1}) + (s^{-1}a + sa^{-1})d_1(e \cdot \tilde{h}_{n-2})$$

$$+ \sum_{i=1}^{n-2} \left((s^{-1}a + sa^{-1})d_{i+1} - d_i \right)(e \cdot \tilde{h}_{n-2-i}).$$

It is a straightforward computation to show that $(s^{-1}a + sa^{-1})d_1 = d_2$:

$$(s^{-1}a + sa^{-1})d_1 = (s^{-1}a + sa^{-1})\left((1-s^2)s^{-1}a + (1+s^{-2})sa^{-1}\right)$$

$$= (1-s^2)s^{-2}a^2 + (1-s^{-2})s^0a^0 + (1-s^2)s^0a^0 + (1-s^{-2})s^2a^{-2}$$

$$= d_2.$$

It's slightly more tedious to show that $(s^{-1}a + sa^{-1})d_{i+1} - d_i = d_{i+2}$ for all $i \geq 1$:

$$(s^{-1}a + sa^{-1})d_{i+1} - d_i$$

$$= (s^{-1}a + sa^{-1}) \sum_{l=0}^{i} (1-s^2)s^{2l-i}a^{i-2l} + (1-s^{-2})s^{i-2l}a^{2l-i}$$

$$- \sum_{l=0}^{i-1} (1-s^2)s^{2l-(i-1)}a^{(i-1)-2l} + (1-s^{-2})s^{(i-1)-2l}a^{2l-(i-1)}$$

$$= \sum_{l=0}^{i} (1-s^2)s^{2l-(i+1)}a^{(i+1)-2l} + (1-s^{-2})s^{(i+1)-2l}a^{2l-(i+1)}$$

$$+ \sum_{l=0}^{i} (1-s^2)s^{2l-(i-1)}a^{(i-1)-2l} + (1-s^{-2})s^{(i-1)-2l}a^{2l-(i-1)}$$

$$- \sum_{l=0}^{i-1} (1-s^2)s^{2l-(i-1)}a^{(i-1)-2l} + (1-s^{-2})s^{(i-1)-2l}a^{2l-(i-1)}$$

$$= \sum_{l=0}^{i}(1-s^2)s^{2l-(i+1)}a^{(i+1)-2l} + (1-s^{-2})s^{(i+1)-2l}a^{2l-(i+1)}$$

$$+ \ (1-s^2)s^{i+1}a^{-1-i} + (1-s^{-2})s^{-1-i}a^{i+1}$$

$$= d_{i+2}.$$

This completes the proof of the statement. $\qquad\square$

Remark 4.1.2. There exists an algebra homomorphism from $\mathcal{D}(A)$ to the ring of symmetric functions Λ_R (see Section 4.2). Conjecturally, this map is an isomorphism, which would imply that the sets $\{\tilde{h}_\lambda \cdot a^i\}_{\lambda,i}$ and $\{a^i \cdot \tilde{h}_\lambda\}_{\lambda,i}$ over integers i and partitions λ, where $\tilde{h}_\lambda := \tilde{h}_{\lambda_1}\cdots\tilde{h}_{\lambda_r}$, form bases of $\mathcal{A}_\mathcal{D} = \mathcal{D}(A)[a,a^{-1}]$ * or is this already known separately somehow?. If so, then Theorem 4.1.1 provides transition formulas between these two bases, and therefore giving a full description of $\mathcal{A}_\mathcal{D}$ as a $\mathcal{D}(A)$-$\mathcal{D}(A)$-bimodule.

One might expect similar formulas to hold in the HOMFLYPT case. To our knowledge, there is no HOMFLYPT analogue of Theorem 4.1.1 written down in the literature. Let's do that here.

Lemma 4.1.3. *For all integers n, the following relation holds in $\mathcal{A}_\mathcal{H}$*

$$e \cdot h_n - h_n \cdot e = sa \cdot h_{n-1} - h_{n-1} \cdot s^{-1}a \tag{4.5}$$

where we use the convention $h_0 = 1$ and $h_n = 0$ if $n < 0$.

Proof. Recall the power sum elements P_k satisfy the power series equation

$$\sum_{k=1}^{\infty}\frac{P_k}{k}x^k = \ln\Big(\sum_{n=0}^{\infty}h_n x^n\Big) \tag{4.6}$$

By [?Mor02b, Theorem 4.2]* fix, the power sum elements satisfy a commutation relation in $\mathcal{A}_\mathcal{H}$

$$e \cdot P_k - P_k \cdot e = (s^k - s^{-k})a^k \tag{4.7}$$

which may be rephrased as a power series equation

$$e \cdot \Big(\sum_{k=1}^{\infty} P_k x^k \Big) - \Big(\sum_{k=1}^{\infty} P_k x^k \Big) \cdot e = \sum_{k=1}^{\infty} s^k a^k - \sum_{k=1}^{\infty} s^{-k} a^k.$$

On the left-hand side, use the defining equation (4.6). Use the power series formulation of natual log on the right-hand side. So we have

$$\ln \Big(e \cdot \Big(\sum_{k=0}^{\infty} h_k x^k \Big) \Big) - \ln \Big(\Big(\sum_{k=0}^{\infty} h_k x^k \Big) \cdot e \Big) = \ln(1 - sax) - \ln(1 - s^{-1}ax).$$

After moving terms around, using properties of natural log, and exponentiating both sides, we arrive at the equation

$$\Big(\sum_{n=0}^{\infty} (h_n \cdot e) x^n \Big) (1 - sax) = \Big(\sum_{n=0}^{\infty} (e \cdot h_n) x^k \Big) (1 - s^{-1}ax)$$

which implies the statement of the lemma. $\qquad\qquad\square$

Recall that the algebra $\mathcal{A}_\mathcal{H}$ is equal to the Laurent polynomial ring $\mathcal{H}(A)^+[a, a^{-1}]$. Under the isomorphism between $\mathcal{H}(A)^+$ and the ring of symmetric functions Λ_R, the h_n identify with the complete homogeneous symmetric functions. It is well-known that ordered monomials in the complete homogeneous symmetric functions form a basis of Λ, hence the sets $\{h_\lambda \cdot a^i\}_{\lambda, i}$ and $\{a^i \cdot h_\lambda\}_{\lambda, i}$ over integers i and partitions λ, where $h_\lambda := h_{\lambda_1} \cdots h_{\lambda_r}$, form bases of $\mathcal{A}_\mathcal{H}$. The following theorem gives transition formulas between these two bases.

Theorem 4.1.4. *The Hecke symmetrizers h_n satisfy the equations*

$$h_n \cdot e = e \cdot h_n + (1 - s^2) \sum_{l=1}^{n} s^{-l} (a^l \cdot h_{n-l})$$

and

$$e \cdot h_n = h_n \cdot e + (1 - s^{-2}) \sum_{l=1}^{n} s^l (h_{n-l} \cdot a^l).$$

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Proof. We will prove the first equality. The second is completely analagous. Proceed by induction. When $n = 1$, the statement follows from the HOMFLY skein relation.

We can rearrange the terms of Lemma 4.1.3 to get

$$h_n \cdot e = e \cdot h_n + s^{-1}a(h_{n-1} \cdot e) - sa(e \cdot h_{n-1}). \tag{4.8}$$

By the induction hypothesis,

$$
\begin{aligned}
h_n \cdot e &= e \cdot h_n + s^{-1}a(h_{n-1} \cdot e) - sa(e \cdot h_{n-1}) \\
&= e \cdot h_n + s^{-1}a\left(e \cdot h_{n-1} + (1 - s^2)\sum_{j=1}^{n-1} s^{-j}a^j(e \cdot h_{n-1-j})\right) - sa(e \cdot h_{n-1}) \\
&= e \cdot h_n + (s^{-1} - s)a(e \cdot h_{n-1}) + (1 - s^2)\sum_{j=1}^{n-1} s^{-j-1}a^{j+1}(e \cdot h_{n-1-j}) \\
&= e \cdot h_n + (1 - s^2)s^{-1}a(e \cdot h_{n-1}) + (1 - s^2)\sum_{j=1}^{n-1} s^{-(j+1)}a^{j+1}(e \cdot h_{n-(j+1)}) \\
&= e \cdot h_n + (1 - s^2)\sum_{l=1}^{n} s^{-l}a^l(e \cdot h_{n-l})
\end{aligned}
$$

where the last equality follows from the substitution $j = l + 1$. $\qquad\square$

4.2 Type B/C/D Schur Functions and BMW Idempotent Closures

In * Lukac, it is shown using skein theory techniques that there is an algebra isomorphism between the ring of symmetric functions Λ and the positive part of the skein algebra of the annulus $\mathcal{H}(A)^+$. The isomorphism is defined on generators by sending the complete homogeneous symmetric functions to the annular closures of Hecke symmetrizers. Futhermore, it is shown that the image of the Schur function s_λ is the idempotent closure Q_λ. This fact has many implications. For example, the structure constants of $\mathcal{H}(A)^+$ in the basis $\{Q_\lambda\}_\lambda$ are the Littlewood-Richardson constants. Also, the definition of P_k implies that

these elements truly correspond with the power sum symmetric functions. Through this isomorphism, one could transfer structure of Λ to $\mathcal{H}(A)^+$, such as the Hopf algebra structure or the plethysm structure (see * Morton-Manchon).

From a Lie-theoretic perspective, the ring of symmetric polynomials Λ_N in N variables is the ring of polynomial representations of $GL_n(\mathbb{C})$. There are maps of graded rings $\Lambda_n \to \Lambda_{n-1}$ defined by specializing the Nth variable to 0, which together form an inverse system whose inverse limit in the category of graded rings is isomorphic to Λ. This strengthens the existing relationship between the HOMFLYPT skein theory and $GL_n(\mathbb{C})$ (recall that the skein relations are modeled after relations of morphisms in $U_q(\mathfrak{gl}_n)$-Mod).

This section is an attempt to emulate Lukac's argument in the Dubrovnik case. First we will review some of the theory behind character rings of the orthogonal and symplectic groups. In particula, they are isomorphic as rings and there are "Schur functions" indexed over partitions for the different types. Next, for any of the character rings, we can define a homomorphism to $\mathcal{D}(A)$. We conjecture that the Schur functions are sent to the annular closures of the BMW idempotents $\tilde{Q}_\lambda$, and we prove the conjecture when the length of λ is at most 2.

4.2.1 Universal Character Rings of Orthogonal and Symplectic Type

Here we will summarize some results from * Koike-Terada. Recall that a character of a (finite-dimensional) group representation is the post-composition of the representation with the trace function. The character of a direct sum of representations is the pointwise sum of the individual characters. Also, the character of a tensor product of representations is the pointwise product of the individual characters. For compact connected Lie groups G, two representations of G are isomorphic only if their characters are equal. In this way, the character ring of G is a decategorification of the category of finite-dimensional representations of G. Let $R(B_n)$, $R(C_n)$, and $R(D_n)$ denote the character rings of the Lie groups $SO_{2n+1}\mathbb{C}$, $SP_{2n}\mathbb{C}$, and $SO_{2n}\mathbb{C}$ respectively (the type D_n case will require some subtle care, see * KT for details).

The irreducible representations of $SO_{2n+1}\mathbb{C}$ and $SP_{2n}\mathbb{C}$ are indexed by partitions λ of length at most n, and denote their respective characters by $sb_{n,\lambda}$ and $sc_{n,\lambda}$ respectively. The type D_n case requires some subtle care, but let $sd_{n,\lambda}$ denote the character of the restriction of the appropriate irreducible representation of $O_{2n}\mathbb{C}$ to $SO_{2n}\mathbb{C}$ (see * KT for details). These are called the **Schur polynomials** of types B_n, C_n, and D_n.

Let G be any of $SO_{2n+1}\mathbb{C}$, $SP_{2n}\mathbb{C}$, and $SO_{2n}\mathbb{C}$. A character of G is determined by its value on a maximal torus of G, which may be chosen to be a set of diagonal matrices.

$$B_n: \qquad T = \{\mathrm{diag}(t_1, \ldots, t_n, 1, t_n^{-1}, \ldots, t_1^{-1})\}$$

$$C_n: \qquad T = \{\mathrm{diag}(t_1, \ldots, t_n, t_n^{-1}, \ldots, t_1^{-1})\}$$

$$D_n: \qquad T = \{\mathrm{diag}(t_1, \ldots, t_n, t_n^{-1}, \ldots, t_1^{-1})\}$$

Furthermore, it can be shown that $R(G) = \mathbb{Z}[t_1^{\pm 1}, \ldots, t_n^{\pm 1}]^{\mathbb{Z}_2^n \rtimes \mathfrak{S}_n} = \mathbb{Z}[t_1 + t_1^{-1}, \ldots, t_n + t_n^{-1}]^{\mathfrak{S}_n}$. This is isomorphic to the ring of symmetric polynomials $\Lambda_n = \mathbb{Z}[c_1, \ldots, c_n]^{S_n}$ under the identification $c_i = t_i + t_i^{-1}$.

Let V be the natural representation of the group G. Let $h_{G,i} := \mathrm{Sym}^i(V)$ and $e_{G,i} := \mathrm{Alt}^i(V)$ be the symmetric and alternating powers of V. Also, let $h_{G,i}^\circ = h_{G,i} - h_{G_i - 2}$ and $e_{G,i}^\circ = e_{G,i} - e_{G_i - 2}$. The following statements are true.

1. The characters $h_{B_n,i}^\circ$ and $e_{B_n,i}$ are irreducible, and

$$R(B_n) = \mathbb{Z}[h_{B_n,1}^\circ, \ldots, h_{B_n,n}^\circ] = \mathbb{Z}[e_{B_n,1}, \ldots, e_{B_n,n}].$$

2. The characters $h_{C_n,i}$ and $e_{C_n,i}^\circ$ are irreducible, and

$$R(C_n) = \mathbb{Z}[h_{C_n,1}, \ldots, h_{C_n,n}] = \mathbb{Z}[e_{C_n,1}^\circ, \ldots, e_{C_n,n}^\circ].$$

3. The characters $h_{D_n,i}^{\circ}$ are irreducible, $e_{D_n,i}$ is irreducible if $i \neq n$, and

$$R(D_n) = \mathbb{Z}[h_{D_n,1}^{\circ}, \ldots, h_{D_n,n}^{\circ}] = \mathbb{Z}[e_{D_n,1}, \ldots, e_{D_n,n}].$$

The characters $h_{G,i}$ are equal to the Schur polynomials corresponding to a single row, and e_{G_i}, a single column.

The ring Λ_n is called the ring of symmetric polynomials in n indeterminates, and it may be identified with the character ring of finite-dimensional polynomial representations of the Lie group $GL_n\mathbb{C}$. The projection maps $\Lambda_n \to \Lambda_{n-1}$ form an inverse system in the category of graded rings, whose inverse limit is what we call the **ring of symmetric functions** Λ. The ring Λ may be concretely defined as the restriction of the ring of formal power series in countable many indeterminates to those series which have bounded degree and which are invariant under permutations of the indeterminates.

There are symmetric functions $sb_\lambda = sd_\lambda$ (they are equal) which project to the Schur polynomials $sb_{n,\lambda}$ and $sd_{n,\lambda}$ under the projections. Similarly, there are sc_λ which project to $sc_{n,\lambda}$. These symmetric functions are called Schur functions of types B, C, and D.The sets $\{sb_\lambda\}_\lambda$ and $\{sc_\lambda\}_\lambda$ form $\mathbb{Z}$-bases of Λ. Furthermore, there is an involutive algebra automorphism defined by $\omega(sb_\lambda) = sc_{\lambda^t}$ where λ^t is the transpose partition of λ. This implies that the structure constants for both bases totally coincide, i.e. if

$$sb_\mu sb_\nu = \sum_\lambda b_{\mu\nu}^\lambda sb_\lambda$$

and

$$sc_\mu sc_\nu = \sum_\lambda c_{\mu\nu}^\lambda sc_\lambda$$

then $c_{\mu\nu}^\lambda = b_{\mu^t\nu^t}^{\lambda^t}$. In particular, if we let $hb_i := sb_{(i)}$ be the Schur functions of type B corresponding to one row and $ec_i := sc_{(1^i)}$ be the Schur functions of type C corresponding to one column, then

$$\omega(hb_i) = ec_i. \tag{4.9}$$

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Let $hb_i^\circ := hb_i - hb_{i-2}$. For a partition $\lambda = (\lambda_0, \lambda_1, \ldots, \lambda_{r-1})$ of length r, set $hb_\lambda^\circ(i,j) :=$ $hb_{\lambda_i-i+j}^\circ + hb_{\lambda_i-i-j}^\circ$. The classical Jacobi-Trudi formula for the type A case generalizes to the type B case as

$$sb_\lambda = \frac{1}{2} \det \left(hb_\lambda(i,j) \right)_{0 \le i,j \le r-1} \tag{4.10}$$

which implies a type C generalization by applying Equation (4.9). The $1/2$ is there simply to compensate for the first column for when $j = 0$.

4.2.2 Determinantal Calculations

The computations in this section will be very technical. Let's fix some notation to hopefully make everything slightly easier to read. First, let

$$t_n := \tilde{h}_n \cdot e - e \cdot \tilde{h}_n,$$
$$h(n,k) := \tilde{h}_{n+k} + \tilde{h}_{n-k},$$
$$t(n,k) := t_{n+k} + t_{n-k} = h(n,k) \cdot e - e \cdot h(n,k).$$

Let's also define the 'skew commutator' elements

$$\varsigma^+(n,k) := s^{-1}h(n,k) \cdot a - sa \cdot h(n,k)$$
$$\varsigma^-(n,k) := sh(n,k) \cdot a^{-1} - s^{-1}a^{-1} \cdot h(n,k).$$

It might be worth pointing out these simple relations:

$$t(n,-k) = t(n,k),$$
$$h(n,-k) = h(n,k),$$
$$\varsigma^\pm(n,-k) = \varsigma^\pm(n,k), \tag{4.11}$$
$$t(n,0) = 2t_n,$$
$$h(n,0) = 2\tilde{h}_n.$$

There is a way to write a commutator in terms of skew commutators. This is given by the equation

$$t(n,k) = \frac{-1}{s-s^{-1}}\left(a^{-1}\varsigma^+(n,k) - a\varsigma^-(n,k)\right) \tag{4.12}$$

for all $k \geq 0$. Also, we may restate the identity of Lemma 3.1.2 in terms of this new notation.

$$t(n,1) = \frac{1}{2}\varsigma^+(n,0) + \frac{1}{2}\varsigma^-(n,0) \tag{4.13}$$

Lemma 4.2.1. *For all $k \geq 0$, the following holds in $\mathcal{A}$.*

$$t(n,k+1) = \varsigma^+(n,k) + \varsigma^-(n,k) - t(n,k-1)$$

Proof. The base case is 2 times Equation 4.13 since $t(n,1) = t(n,-1)$. To show the general case, use equation (4.13) twice.

$$
\begin{aligned}
t(n,k+1) &= t_{n+(k+1)} + t_{n-(k+1)} \\
&= \left((s^{-1}\tilde{h}_{n+k}\cdot e - se\cdot\tilde{h}_{n+k})a + (s\tilde{h}_{n+k}\cdot e - s^{-1}e\cdot\tilde{h}_{n+k})a^{-1} - t_{n+(k-1)}\right) \\
&\quad + \left((s^{-1}\tilde{h}_{n-k}\cdot e - se\cdot\tilde{h}_{n-k})a + (s\tilde{h}_{n-k}\cdot e - s^{-1}e\cdot\tilde{h}_{n-k})a^{-1} - t_{n-(k-1)}\right) \\
&= \left(s^{-1}h(n,k)\cdot e - se\cdot h(n,k)\right)a + \left(sh(n,k)\cdot e - s^{-1}e\cdot h(n,k)\right)a^{-1} \\
&\quad - t(n,k-1) \\
&= \varsigma^+(n,k) + \varsigma^-(n,k) - t(n,k-1)
\end{aligned}
$$

$\square$

Remark 4.2.2. An alternate formulation of the first statement of the lemma above is

$$t(n,k+1) + t(n,k-1) = \varsigma^+(n,k) + \varsigma^-(n,k) \tag{4.14}$$

which is a generalization of Equation (4.13). Also, one may apply the identity to itself recursively to get a closed form for the $t(n,k)$ in terms of skew-commutators, but the closed

form splits into cases depending on k. Thirdly, this lemma yields a kind of recursive formula for the skew commutators, given as

$$\varsigma^+(n,k)+\varsigma^-(n,k) = \frac{-1}{s-s^{-1}}\Big(a^{-1}\big(\varsigma^+(n,k+1)+\varsigma^+(n,k-1)\big)-a\big(\varsigma^-(n,k+1)+\varsigma^-(n,k-1)\big)\Big)$$

(4.15)

which follows from Equation (4.12)

Lemma 4.2.3. *The following identities hold in $\mathcal{A}$.*

1.
$$\begin{vmatrix} h(n,k)\cdot e & \varsigma^+(n,k) \\ h(m,k)\cdot e & \varsigma^+(m,k) \end{vmatrix} = s^2 \begin{vmatrix} e\cdot h(n,k) & \varsigma^+(n,k) \\ e\cdot h(m,k) & \varsigma^+(m,k) \end{vmatrix}$$

2.
$$\begin{vmatrix} h(n,k)\cdot e & \varsigma^-(n,k) \\ h(m,k)\cdot e & \varsigma^-(m,k) \end{vmatrix} = s^{-2} \begin{vmatrix} e\cdot h(n,k) & \varsigma^-(n,k) \\ e\cdot h(m,k) & \varsigma^-(m,k) \end{vmatrix}$$

Proof. Here is the computation for the first item. The proof of the second runs completely parallel. First, expand the determinants.

$$\big(h(n,k)\cdot e\big)\varsigma^+(m,k) - \big(h(m,k)\cdot e\big)\varsigma^+(n,k) = s^2\big(e\cdot h(n,k)\big)\varsigma^+(m,k) - s^2\big(e\cdot h(m,k)\big)\varsigma^+(n,k)$$

Collect terms in the following way.

$$\big(h(n,k)\cdot e - s^2 e\cdot h(n,k)\big)\varsigma^+(m,k) = \big(h(m,k)\cdot e - s^2 e\cdot h(m,k)\big)\varsigma^+(n,k)$$

The right-hand side is equal to the left-hand side with the indices n and m interchanged. So the equation holds if and only if the left hand side is invariant under permuting n and m. Let $P(n,m)$ equal the left-hand side. Expand the product in $P(n,m)$ using the definition of $\varsigma^+(m,k)$

$$P(n,m) = \big(h(n,k)\cdot e - s^2 e\cdot h(n,k)\big)\varsigma^+(m,k)$$

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$$= \big(h(n,k) \cdot e - s^2 e \cdot h(n,k)\big)\big(s^{-1}h(n,k) \cdot a - sa \cdot h(n,k)\big)$$

$$= \Big(s^{-1}\big(h(n,k)h(m,k)\big) \cdot e + s^3 e \cdot \big(h(n,k)h(m,k)\big)$$

$$- sh(n,k) \cdot e \cdot h(m,k) - sh(m,k) \cdot e \cdot h(n,k)\Big)a$$

Use that $\mathcal{C}$ is commutative to get that $P(n,m) - P(m,n) = 0$. This completes the proof. $\square$

Remark 4.2.4. It may be worth pointing out that the factor of a in $\varsigma^+(n,k)$ and the factor of a^{-1} in $\varsigma^-(n,k)$ don't affect the identities above. In other words, scaling identity (1) by a^{-1} gives

$$\begin{vmatrix} h(n,k) \cdot e & s^{-1}h(n,k) \cdot e - se \cdot h(n,k) \\ h(m,k) \cdot e & s^{-1}h(m,k) \cdot e - se \cdot h(m,k) \end{vmatrix} = s^2 \begin{vmatrix} e \cdot h(n,k) & s^{-1}h(n,k) \cdot e - se \cdot h(n,k) \\ e \cdot h(m,k) & s^{-1}h(m,k) \cdot e - se \cdot h(m,k) \end{vmatrix}$$

$$(4.16)$$

and scaling identity (2) by a gives

$$\begin{vmatrix} h(n,k) \cdot e & sh(n,k) \cdot e - s^{-1}e \cdot h(n,k) \\ h(m,k) \cdot e & sh(m,k) \cdot e - s^{-1}e \cdot h(m,k) \end{vmatrix} = s^{-2} \begin{vmatrix} e \cdot h(n,k) & sh(n,k) \cdot e - s^{-1}e \cdot h(n,k) \\ e \cdot h(m,k) & sh(m,k) \cdot e - s^{-1}e \cdot h(m,k) \end{vmatrix}.$$

$$(4.17)$$

The previous two lemmas together imply the next lemma.

Lemma 4.2.5. *For all $k \geq 0$, we have*

$$\begin{vmatrix} h(n,k) \cdot e & t(n,k+1) \\ h(m,k) \cdot e & t(m,k+1) \end{vmatrix}$$

$$= \begin{vmatrix} e \cdot h(n,k) & s^2\varsigma^+(n,k) + s^{-2}\varsigma^-(n,k) - t(n,k-1) \\ e \cdot h(m,k) & s^2\varsigma^+(m,k) + s^{-2}\varsigma^-(m,k) - t(m,k-1) \end{vmatrix}$$

$$+ \sum_{l=1}^{k} \begin{vmatrix} e \cdot h(n,k-l) & (s^2-1)\varsigma^+(n,k-l) + (s^{-2}-1)\varsigma^-(n,k-l) \\ e \cdot h(m,k-l) & (s^2-1)\varsigma^+(m,k-l) + (s^{-2}-1)\varsigma^-(m,k-l) \end{vmatrix}.$$

Proof. First, when $k = 0$, the statement should be read as

$$\begin{vmatrix} h(n,0) \cdot e & t(n,1) \\ h(m,0) \cdot e & t(m,1) \end{vmatrix} = \frac{1}{2} \begin{vmatrix} e \cdot h(n,k) & s^2 \varsigma^+(n,0) + s^{-2} \varsigma^-(n,0) \\ e \cdot h(m,k) & s^2 \varsigma^+(m,0) + s^{-2} \varsigma^-(m,0) \end{vmatrix}$$

which follows straightforwardly by applying Equation 4.13 to the entries $t(n,1)$ and $t(m,1)$ before applying Lemma 4.2.3. In general, use Lemma 4.2.1 to write

$$\begin{vmatrix} h(n,k) \cdot e & t(n,k+1) \\ h(m,k) \cdot e & t(m,k+1) \end{vmatrix} = \begin{vmatrix} h(n,k) \cdot e & \varsigma^+(n,k) \\ h(m,k) \cdot e & \varsigma^+(m,k) \end{vmatrix} + \begin{vmatrix} h(n,k) \cdot e & \varsigma^-(n,k) \\ h(m,k) \cdot e & \varsigma^-(m,k) \end{vmatrix}$$

$$+ \begin{vmatrix} h(n,k) \cdot e & -t(n,k-1) \\ h(m,k) \cdot e & -t(m,k-1) \end{vmatrix}.$$

On the first two summands, apply Lemma 4.2.3 to switch the order of the action in the first columns at the price of the specified scalar. For the third summand, observe

$$\begin{vmatrix} h(n,k) \cdot e & -t(n,k-1) \\ h(m,k) \cdot e & -t(m,k-1) \end{vmatrix} = \begin{vmatrix} t(n,k-1) & h(n,k) \cdot e \\ t(m,k-1) & h(m,k) \cdot e \end{vmatrix}$$

$$= \begin{vmatrix} t(n,k-1) & t(n,k) \\ t(m,k-1) & t(m,k) \end{vmatrix} + \begin{vmatrix} t(n,k-1) & e \cdot h(n,k) \\ t(m,k-1) & e \cdot h(m,k) \end{vmatrix}$$

$$= \begin{vmatrix} h(n,k-1) \cdot e & t(n,k) \\ h(m,k-1) \cdot e & t(m,k) \end{vmatrix} - \begin{vmatrix} e \cdot h(n,k-1) & t(n,k) \\ e \cdot h(m,k-1) & t(m,k) \end{vmatrix}$$

$$+ \begin{vmatrix} e \cdot h(n,k) & -t(n,k-1) \\ e \cdot h(m,k) & -t(m,k-1) \end{vmatrix}.$$

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Thus, for all $k \geq 0$, we have

$$
\begin{vmatrix} h(n,k) \cdot e & t(n,k+1) \\ h(m,k) \cdot e & t(m,k+1) \end{vmatrix} = \begin{vmatrix} e \cdot h(n,k) & s^2 \varsigma^+(n,k) + s^{-2} \varsigma^-(n,k) - t(n,k-1) \\ e \cdot h(m,k) & s^2 \varsigma^+(m,k) + s^{-2} \varsigma^-(m,k) - t(m,k-1) \end{vmatrix}
$$
$$
- \begin{vmatrix} e \cdot h(n,k-1) & t(n,k) \\ e \cdot h(m,k-1) & t(m,k) \end{vmatrix} + \begin{vmatrix} h(n,k-1) \cdot e & t(n,k) \\ h(m,k-1) \cdot e & t(m,k) \end{vmatrix}.
$$

$$(4.18)$$

Next, recursively apply Equation 4.18 its own trailing term k times so that the right-hand side becomes

$$
\sum_{l=0}^{k-1} \left(\begin{vmatrix} e \cdot h(n,k-l) & s^2 \varsigma^+(n,k-l) + s^{-2} \varsigma^-(n,k-l) - t(n,k-1-l) \\ e \cdot h(m,k-l) & s^2 \varsigma^+(m,k-l) + s^{-2} \varsigma^-(m,k-l) - t(m,k-1-l) \end{vmatrix} \right.
$$
$$
\left. - \begin{vmatrix} e \cdot h(n,k-1-l) & t(n,k-l) \\ e \cdot h(m,k-1-l) & t(m,k-l) \end{vmatrix} \right) + \begin{vmatrix} h(n,0) \cdot e & t(n,1) \\ h(m,0) \cdot e & t(m,1) \end{vmatrix}.
$$

Through some careful reindexing work, we rewrite this as

$$
\begin{vmatrix} e \cdot h(n,k) & s^2 \varsigma^+(n,k) + s^{-2} \varsigma^-(n,k) - t(n,k-1) \\ e \cdot h(m,k) & s^2 \varsigma^+(m,k) + s^{-2} \varsigma^-(m,k) - t(m,k-1) \end{vmatrix}
$$
$$
+ \sum_{l=1}^{k-1} \begin{vmatrix} e \cdot h(n,k-l) & s^2 \varsigma^+(n,k-l) + s^{-2} \varsigma^-(n,k-l) - t(n,k-1-l) - t(n,k+1-l) \\ e \cdot h(m,k-l) & s^2 \varsigma^+(m,k-l) + s^{-2} \varsigma^-(m,k-l) - t(m,k-1-l) - t(m,k+1-l) \end{vmatrix}
$$
$$
- \begin{vmatrix} e \cdot h(n,0) & t(n,1) \\ e \cdot h(m,0) & t(m,1) \end{vmatrix} + \begin{vmatrix} h(n,0) \cdot e & t(n,1) \\ h(m,0) \cdot e & t(m,1) \end{vmatrix}.
$$

Apply Lemma 4.2.1 to the terms in the entries in the second column of each matrix in the

big sum. Finally, observe the following applications of Lemmas 4.2.3 and 4.2.1:

$$
-\begin{vmatrix} e \cdot h(n,0) & t(n,1) \\ e \cdot h(m,0) & t(m,1) \end{vmatrix} + \begin{vmatrix} h(n,0) \cdot e & t(n,1) \\ h(m,0) \cdot e & t(m,1) \end{vmatrix}
$$

$$
= -\begin{vmatrix} e \cdot h(n,0) & t(n,1) \\ e \cdot h(m,0) & t(m,1) \end{vmatrix} + \begin{vmatrix} e \cdot h(n,0) & s^2\varsigma^+(n,0) + s^{-2}\varsigma^-(n,0) - t(n,-1) \\ e \cdot h(m,0) & s^2\varsigma^+(m,0) + s^{-2}\varsigma^-(m,0) - t(m,-1) \end{vmatrix}
$$

$$
= \begin{vmatrix} e \cdot h(n,0) & s^2\varsigma^+(n,0) + s^{-2}\varsigma^-(n,0) - 2t(n,1) \\ e \cdot h(m,0) & s^2\varsigma^+(m,0) + s^{-2}\varsigma^-(m,0) - 2t(m,1) \end{vmatrix}
$$

$$
= \begin{vmatrix} e \cdot h(n,0) & (s^2-1)\varsigma^+(n,0) + (s^{-2}-1)\varsigma^-(n,0) \\ e \cdot h(m,0) & (s^2-1)\varsigma^+(m,0) + (s^{-2}-1)\varsigma^-(m,0) \end{vmatrix}
$$

where we use $t(n,1) = t(n,-1)$. This completes the proof. $\qquad\square$

Remark 4.2.6. Using a parallel technique as in the proof of Lemma 4.2.5, one can show

that

$$
\begin{vmatrix} e \cdot h(n,k) & t(n,k+1) \\ e \cdot h(m,k) & t(m,k+1) \end{vmatrix}
$$

$$
= \begin{vmatrix} h(n,k) \cdot e & s^{-2}\varsigma^+(n,k) + s^2\varsigma^-(n,k) - t(n,k-1) \\ h(m,k) \cdot e & s^{-2}\varsigma^+(m,k) + s^2\varsigma^-(m,k) - t(m,k-1) \end{vmatrix}
$$

$$
+ \sum_{l=1}^{k} \begin{vmatrix} h(n,k-l) \cdot e & (s^{-2}-1)\varsigma^+(n,k-l) + (s^2-1)\varsigma^-(n,k-l) \\ h(m,k-l) \cdot e & (s^{-2}-1)\varsigma^+(m,k-l) + (s^2-1)\varsigma^-(m,k-l) \end{vmatrix}.
$$

Corollary 4.2.7.

$$
\begin{vmatrix} t(n,k) & t(n,k+1) \\ t(m,k) & t(m,k+1) \end{vmatrix} = \sum_{l=0}^{k} \begin{vmatrix} e \cdot h(n,k-l) & (s^2-1)\varsigma^+(n,k-l) + (s^{-2}-1)\varsigma^-(n,k-l) \\ e \cdot h(m,k-l) & (s^2-1)\varsigma^+(m,k-l) + (s^{-2}-1)\varsigma^-(m,k-l) \end{vmatrix}
$$

$$= \sum_{l=0}^{k} \begin{vmatrix} h(n, k-l) \cdot e & (1 - s^{-2})\varsigma^+(n, k-l) + (1 - s^2)\varsigma^-(n, k-l) \\ h(m, k-l) \cdot e & (1 - s^{-2})\varsigma^+(m, k-l) + (1 - s^2)\varsigma^-(m, k-l) \end{vmatrix}.$$

Proof. We prove the first equality. The second follows by using Remark 4.2.6.

$$\begin{vmatrix} t(n, k) & t(n, k+1) \\ t(m, k) & t(m, k+1) \end{vmatrix}$$

$$= - \begin{vmatrix} e \cdot h(n, k) & t(n, k+1) \\ e \cdot h(m, k) & t(m, k+1) \end{vmatrix} + \begin{vmatrix} h(n, k) \cdot e & t(n, k+1) \\ h(m, k) \cdot e & t(m, k+1) \end{vmatrix}$$

$$= - \begin{vmatrix} e \cdot h(n, k) & \varsigma^+(n, k) + \varsigma^-(n, k) - t(n, k-1) \\ e \cdot h(m, k) & \varsigma^+(m, k) + \varsigma^-(m, k) - t(m, k-1) \end{vmatrix}$$

$$+ \begin{vmatrix} e \cdot h(n, k) & s^2\varsigma^+(n, k) + s^{-2}\varsigma^-(n, k) - t(n, k-1) \\ e \cdot h(m, k) & s^2\varsigma^+(m, k) + s^{-2}\varsigma^-(m, k) - t(m, k-1) \end{vmatrix}$$

$$+ \sum_{l=1}^{k} \begin{vmatrix} e \cdot h(n, k-l) & (s^2 - 1)\varsigma^+(n, k-l) + (s^{-2} - 1)\varsigma^-(n, k-l) \\ e \cdot h(m, k-l) & (s^2 - 1)\varsigma^+(m, k-l) + (s^{-2} - 1)\varsigma^-(m, k-l) \end{vmatrix}$$

$$= \sum_{l=0}^{k} \begin{vmatrix} e \cdot h(n, k-l) & (s^2 - 1)\varsigma^+(n, k-l) + (s^{-2} - 1)\varsigma^-(n, k-l) \\ e \cdot h(m, k-l) & (s^2 - 1)\varsigma^+(m, k-l) + (s^{-2} - 1)\varsigma^-(m, k-l) \end{vmatrix}$$

$\square$

Let $\mathrm{cl}_{\mathcal{A}} : \mathcal{A} \to \mathcal{C}$ be the wiring which connects the two boundary points of $\mathcal{A}$ by an arc above the annulus.
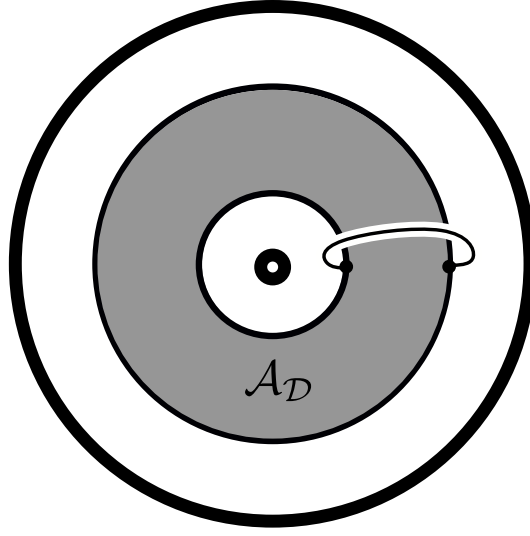
Figure 4.1: The wiring diagram which defines $\mathrm{cl}_{\mathcal{A}} : \mathcal{A} \to \mathcal{C}$.

This map is not unital nor multiplicative, but it is a right $\mathcal{C}$-module homomorphism so that $\mathrm{cl}_{\mathcal{A}}(e \cdot x) = \delta_{\mathcal{D}} x$. Furthermore, the closure $\mathrm{cl}_{\mathcal{A}}(x \cdot e)$ is the element $\phi(x)$ which is the meridian map ϕ applied to x. The following identity is a generalization of Lemma 8.3 in Lukac.

Lemma 4.2.8. *Let*

$$\alpha_n := \{n\} \left(v^{-1} s^{n-1} - v s^{1-n} \right).$$

Then,

$$cl_{\mathcal{A}} \left(\frac{1}{2} t(n, 0) \right) = cl_{\mathcal{A}}(t_n) = \alpha_n \tilde{h}_n$$

and hence

$$cl_{\mathcal{A}}\big(t(n, k) \big) = \alpha_{n+k} \tilde{h}_{n+k} + \alpha_{n-k} \tilde{h}_{n-k}.$$

Proof. Recall Equation (2.12), which we restate here using different notation:

$$t_n = \{n\} a^{-1} W_{n-1}^* - \{n\} a W_{n-1}.$$

Apply the closure to both sides. Apply the framing relation to the diagrams on the right to pick up the framing parameter terms. Use the property that the BMW idempotents

absorb crossings to a factor of s for positive crossings and s^{-1} for negative crossings. This completes the proof. $\square$

Lemma 4.2.9. *Define the constants*

$$\omega_n^+ := -\{n\}s^{1-n}v,$$

$$v_n^+ := s^n[n+1](\bar{\beta}_{n+1} - \beta_{n+1})(\delta_{\mathcal{D}} + s^{n-1}[n](sv^{-1} + \beta_n)),$$

$$\omega_n^- := \{n\}s^{n-1}v^{-1},$$

$$v_n^- := -s^{-n}[n+1](\bar{\beta}_{n+1} - \beta_{n+1})(\delta_{\mathcal{D}} + s^{n-1}[n](sv^{-1} + \beta_n)).$$

Then the following identities hold in $\mathcal{C}$ for all $n \geq 0$

$$cl_{\mathcal{A}}\left(\frac{1}{2}\varsigma^+(n,0)\right) = \quad cl_{\mathcal{A}}(s^{-1}\tilde{h}_n \cdot a - sa \cdot \tilde{h}_n) \quad = \omega_{n+1}^+ \tilde{h}_{n+1} + v_{n-1}^+ \tilde{h}_{n-1},$$

$$cl_{\mathcal{A}}\left(\frac{1}{2}\varsigma^-(n,0)\right) = cl_{\mathcal{A}}(s\tilde{h}_n \cdot a^{-1} - s^{-1}a^{-1} \cdot \tilde{h}_n) = \omega_{n+1}^- \tilde{h}_{n+1} + v_{n-1}^- \tilde{h}_{n-1}$$

which implies that

$$cl_{\mathcal{A}}(\varsigma^+(n,k)) = \omega_{n+k+1}^+ \tilde{h}_{n+k+1} + v_{n+k-1}^+ \tilde{h}_{n+k-1} + \omega_{n-k+1}^+ \tilde{h}_{n-k+1} + v_{n-k-1}^+ \tilde{h}_{n-k-1},$$

$$cl_{\mathcal{A}}(\varsigma^-(n,k)) = \omega_{n+k+1}^- \tilde{h}_{n+k+1} + v_{n+k-1}^- \tilde{h}_{n+k-1} + \omega_{n-k+1}^- \tilde{h}_{n-k+1} + v_{n-k-1}^- \tilde{h}_{n-k-1}.$$

Proof. Apply Equations (3.12) and (3.10) :

$$(s^{-1}\tilde{h}_n \cdot e - se \cdot \tilde{h}_n)a$$

$$= \left(s^{-1}([n+1]W_n - [n]saW_{n-1} - [n]s\bar{\beta}_n a^{-1}W_{n-1}^*)\right.$$

$$\left. - s([n+1]W_n - [n]s^{-1}aW_{n-1} - [n]s^{-1}\beta_n a^{-1}W_{n-1}^*)\right)a$$

$$= -\{n+1\}aW_n - (\bar{\beta}_n - \beta_n)[n]W_{n-1}^*.$$

The identities below hold in $\mathcal{C}$. Use [?She16, Lemma 21] * *** for the second two.

$$\mathrm{cl}_{\mathcal{A}}(aW_n) = s^{-n}v\tilde{h}_{n+1}$$

$$\mathrm{cl}_{\mathcal{A}}(a^{-1}W_n^*) = s^n v^{-1}\tilde{h}_{n+1}$$

$$\mathrm{cl}_{\mathcal{A}}(W_n) = -s^{-n}\big(\delta_{\mathcal{D}} + s^{n-1}[n](sv^{-1} + \beta_n)\big)\tilde{h}_n$$

$$= [n+1]^{-1}\big(\delta_{\mathcal{D}} + [n]s^{-1}(s^{-(n-1)}v - \beta_n s^{n-1}v^{-1})\big)\tilde{h}_n$$

$$\mathrm{cl}_{\mathcal{A}}(W_n^*) = s^n\big(\delta_{\mathcal{D}} + s^{n-1}[n](sv^{-1} + \beta_n)\big)\tilde{h}_n$$

Then applying $\mathrm{cl}_{\mathcal{A}}$ to the above gives

$$\mathrm{cl}_{\mathcal{A}}\big(s^{-1}\tilde{h}_n \cdot a - sa \cdot \tilde{h}_n\big)$$

$$= -\{n+1\}\mathrm{cl}_{\mathcal{A}}(aW_n) - (\bar{\beta}_n - \beta_n)[n]\mathrm{cl}_{\mathcal{A}}(W_{n-1}^*)$$

$$= -\{n+1\}s^{-n}v\tilde{h}_{n+1} - (\bar{\beta}_n - \beta_n)[n]s^{n-1}\big(\delta_{\mathcal{D}} + s^{n-2}[n-1](sv^{-1}\beta_{n-1})\big)\tilde{h}_{n-1}$$

$$= \omega_{n+1}^+ \tilde{h}_{n+1} + \upsilon_{n-1}^+ \tilde{h}_{n-1}.$$

The proof of the other statement is similar. $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\square$

Remark 4.2.10. As a quick corollary of this lemma, apply $\mathrm{cl}_{\mathcal{A}}$ to Equation (4.14) with $k = 0$, so

$$\mathrm{cl}_{\mathcal{A}}\big(2t(n,1)\big) = \mathrm{cl}_{\mathcal{A}}\big(\varsigma^+(n,0) + \varsigma^-(n,0)\big)$$

and apply the previous two Lemmas and divide by 2 to get

$$\alpha_{n+1}\tilde{h}_{n+1} + \alpha_{n-1}\tilde{h}_{n-1} = (\omega_{n+1}^+ + \omega_{n+1}^-)\tilde{h}_{n+1} + (\upsilon_{n-1}^+ + \upsilon_{n-1}^-)\tilde{h}_{n-1}.$$

Since the $\tilde{h}_n$ are linearly independent, it's true that

$$\alpha_n = \omega_n^+ + \omega_n^- = \upsilon_n^+ + \upsilon_n^- \qquad\qquad\qquad (4.19)$$

for any n.

Consider the algebra homomorphism $\Lambda \to \mathcal{D}(A)$ defined by the assignment $hb_i \mapsto \tilde{h}_i$. This map is well defined since Λ is generated freely as a commutative ring by the set $\{hb_i\}_i$. Let S_λ be the image of sb_λ under this assignment. Now we are ready to state the main conjecture of this section.

Conjecture 4.2.11. Let $\phi : \mathcal{C} \to \mathcal{C}$ be the meridian map. Then

$$\phi(S_\lambda) = c_\lambda S_\lambda \tag{4.20}$$

where

$$c_\lambda = \delta_{\mathcal{D}} + (s - s^{-1})\left(v^{-1}\sum_{x\in\lambda} s^{2\mathrm{cn}(x)} - v\sum_{x\in\lambda} s^{-2\mathrm{cn}(x)}\right) \tag{4.21}$$

and where $\mathrm{cn}(x)$ is the content of the cell x of the Young diagram of λ in the $(i,j)^{\text{th}}$ position, defined by $\mathrm{cn}(x) := j - i$.

If true, then this conjecture may be used to prove that $S_\lambda = \tilde{Q}_\lambda$, following the same arguement from * Lukac. Essentially, Conjecture 4.2.11 states that S_λ and Q_λ are in the same eigenspace with respect to ϕ. These eigenspaces each have dimension 1 by * Zhong-Lu, so S_λ would be a scalar multiple of Q_λ. Following Lukac, a simple induction argument involving the branching formula of * BB shows that this scalar is 1. Next, let's give some evidence for why this conjecture should be true.

Proposition 4.2.12. *The conjecture holds when λ has length at most 2.*

Proof. The statement is trivial if λ has length 1 by definition of the map. Assume $\lambda = (a, b)$. Apply Equation (**??**).

$$S_\lambda = \begin{vmatrix} \frac{1}{2}\tilde{h}_\lambda(0,0) & \tilde{h}_\lambda(0,1) \\ \frac{1}{2}\tilde{h}_\lambda(1,0) & \tilde{h}_\lambda(1,1) \end{vmatrix}$$

Use multilinearity of the determinant as we did above to decompose the commutator $S_\lambda \cdot e - e \cdot S_\lambda$.

$$S_\lambda \cdot e - e \cdot S_\lambda = \begin{vmatrix} \frac{1}{2}t_\lambda(0,0) & e \cdot \tilde{h}_\lambda(0,1) \\ \frac{1}{2}t_\lambda(1,0) & e \cdot \tilde{h}_\lambda(1,1) \end{vmatrix} + \begin{vmatrix} \frac{1}{2}\tilde{h}_\lambda(0,0) \cdot e & t_\lambda(0,1) \\ \frac{1}{2}\tilde{h}_\lambda(1,0) \cdot e & t_\lambda(1,1) \end{vmatrix}$$

The entries in the second column of the second determinant need to be split using Equation (4.13) into a form which is compatible with Lemma 4.2.3. The right-hand side becomes

$$\begin{vmatrix} \frac{1}{2}t_\lambda(0,0) & e \cdot \tilde{h}_\lambda(0,1) \\ \frac{1}{2}t_\lambda(1,0) & e \cdot \tilde{h}_\lambda(1,1) \end{vmatrix} + \begin{vmatrix} \frac{1}{2}\tilde{h}_\lambda(0,0) \cdot e & \frac{1}{2}\varsigma_\lambda^+(0,0) \\ \frac{1}{2}\tilde{h}_\lambda(1,0) \cdot e & \frac{1}{2}\varsigma_\lambda^+(1,0) \end{vmatrix} + \begin{vmatrix} \frac{1}{2}\tilde{h}_\lambda(0,0) \cdot e & \frac{1}{2}\varsigma_\lambda^-(0,0) \\ \frac{1}{2}\tilde{h}_\lambda(1,0) \cdot e & \frac{1}{2}\varsigma_\lambda^-(1,0) \end{vmatrix}.$$

Apply Lemma 4.2.3 to the second two terms:

$$\begin{vmatrix} \frac{1}{2}t_\lambda(0,0) & e \cdot \tilde{h}_\lambda(0,1) \\ \frac{1}{2}t_\lambda(1,0) & e \cdot \tilde{h}_\lambda(1,1) \end{vmatrix} + s^2 \begin{vmatrix} e \cdot \frac{1}{2}\tilde{h}_\lambda(0,0) & \frac{1}{2}\varsigma_\lambda^+(0,0) \\ e \cdot \frac{1}{2}\tilde{h}_\lambda(1,0) & \frac{1}{2}\varsigma_\lambda^+(1,0) \end{vmatrix} + s^{-2} \begin{vmatrix} e \cdot \frac{1}{2}\tilde{h}_\lambda(0,0) & \frac{1}{2}\varsigma_\lambda^-(0,0) \\ e \cdot \frac{1}{2}\tilde{h}_\lambda(1,0) & \frac{1}{2}\varsigma_\lambda^-(1,0) \end{vmatrix}.$$

Now apply $\text{cl}_\mathcal{A}$ and use the property that it is a right $\mathcal{C}$-module homomorphism to remove e from the $\tilde{h}_i$ terms. Apply Lemmas 4.2.8 and 4.2.9 for the second equality.

$$\text{cl}_\mathcal{A}(S_\lambda \cdot e - e \cdot S_\lambda)$$

$$= \begin{vmatrix} \text{cl}_\mathcal{A}\left(\frac{1}{2}t_\lambda(0,0)\right) & \tilde{h}_\lambda(0,1) \\ \text{cl}_\mathcal{A}\left(\frac{1}{2}t_\lambda(1,0)\right) & \tilde{h}_\lambda(1,1) \end{vmatrix} + s^2 \begin{vmatrix} \frac{1}{2}\tilde{h}_\lambda(0,0) & \text{cl}_\mathcal{A}\left(\frac{1}{2}\varsigma_\lambda^+(0,0)\right) \\ \frac{1}{2}\tilde{h}_\lambda(1,0) & \text{cl}_\mathcal{A}\left(\frac{1}{2}\varsigma_\lambda^+(1,0)\right) \end{vmatrix}$$

$$+ s^{-2} \begin{vmatrix} \frac{1}{2}\tilde{h}_\lambda(0,0) & \text{cl}_\mathcal{A}\left(\frac{1}{2}\varsigma_\lambda^-(0,0)\right) \\ \frac{1}{2}\tilde{h}_\lambda(1,0) & \text{cl}_\mathcal{A}\left(\frac{1}{2}\varsigma_\lambda^-(1,0)\right) \end{vmatrix}$$

$$= \begin{vmatrix} \text{cl}_\mathcal{A}\left(\frac{1}{2}t(a,0)\right) & \tilde{h}(a,1) \\ \text{cl}_\mathcal{A}\left(\frac{1}{2}t(b-1,0)\right) & \tilde{h}(b-1,1) \end{vmatrix} + s^2 \begin{vmatrix} \frac{1}{2}\tilde{h}(a,0) & \text{cl}_\mathcal{A}\left(\frac{1}{2}\varsigma^+(a,0)\right) \\ \frac{1}{2}\tilde{h}(b-1,0) & \text{cl}_\mathcal{A}\left(\frac{1}{2}\varsigma^+(b-1,0)\right) \end{vmatrix}$$

$$+ s^{-2} \begin{vmatrix} \frac{1}{2}\tilde{h}(a,0) & \text{cl}_\mathcal{A}\left(\frac{1}{2}\varsigma^-(a,0)\right) \\ \frac{1}{2}\tilde{h}(b-1,0) & \text{cl}_\mathcal{A}\left(\frac{1}{2}\varsigma^-(b-1,0)\right) \end{vmatrix}$$

$$
= \begin{vmatrix} \alpha_a \tilde{h}_a & \tilde{h}_{a+1} + \tilde{h}_{a-1} \\ \alpha_{b-1}\tilde{h}_{b-1} & \tilde{h}_b + \tilde{h}_{b-2} \end{vmatrix} + s^2 \begin{vmatrix} \tilde{h}_a & \omega_{a+1}^+ \tilde{h}_{a+1} + \upsilon_{a-1}^+ \tilde{h}_{a-1} \\ \tilde{h}_{b-1} & \omega_b^+ \tilde{h}_b + \upsilon_{b-2}^+ \tilde{h}_{b-2} \end{vmatrix}
$$

$$
+ s^{-2} \begin{vmatrix} \tilde{h}_a & \omega_{a+1}^- \tilde{h}_{a+1} + \upsilon_{a-1}^- \tilde{h}_{a-1} \\ \tilde{h}_{b-1} & \omega_b^- \tilde{h}_b + \upsilon_{b-2}^- \tilde{h}_{b-2} \end{vmatrix}
$$

$$
= \big(\alpha_a \tilde{h}_a (\tilde{h}_b + \tilde{h}_{b-2}) - \alpha_{b-1}\tilde{h}_{b-1}(\tilde{h}_{a+1} + \tilde{h}_{a-1}) \big)
$$

$$
+ s^2 \big(\tilde{h}_a (\omega_b^+ \tilde{h}_b + \upsilon_{b-2}^+ \tilde{h}_{b-2}) - \tilde{h}_{b-1}(\omega_{a+1}^+ \tilde{h}_{a+1} + \upsilon_{a-1}^+ \tilde{h}_{a-1}) \big)
$$

$$
+ s^{-2} \big(\tilde{h}_a (\omega_b^- \tilde{h}_b + \upsilon_{b-2}^- \tilde{h}_{b-2}) - \tilde{h}_{b-1}(\omega_{a+1}^- \tilde{h}_{a+1} + \upsilon_{a-1}^- \tilde{h}_{a-1}) \big)
$$

$$
= (\alpha_a + s^2 \omega_b^+ + s^{-2} \omega_b^-)\tilde{h}_a \tilde{h}_b + (\alpha_a + s^2 \upsilon_{b-2}^+ + s^{-2} \upsilon_{b-2}^-)\tilde{h}_a \tilde{h}_{b-2}
$$

$$
- (\alpha_{b-1} + s^2 \omega_{a+1}^+ + s^{-2} \omega_{a+1}^-)\tilde{h}_{a+1} \tilde{h}_{b-1} - (\alpha_{b-1} + s^2 \upsilon_{a-1}^+ + s^{-2} \upsilon_{a-1}^-)\tilde{h}_{a-1} \tilde{h}_{b-1}
$$

The conjecture claims that all of these coefficients are equal to the appropriate eigenvalue minus the value of the unknot $c_\lambda - \delta_{\mathcal{D}}$. At first glance, it's not at all obvious that these coefficients are even equal to each other. Nevertheless, we will show it is true by looking at each coefficient one by one, going in the order in which they are written. Firstly, observe:

$$
\alpha_a + s^2 \omega_b^+ + s^{-2}\omega_b^- = \{a\}(v^{-1}s^{a-1} - vs^{1-a}) - \{b\}vs^{3-b} + \{b\}v^{-1}s^{b-3}
$$

$$
= (s^a - s^{-a})(v^{-1}s^{a-1} - vs^{1-a}) - (s^b - s^{-b})(vs^{3-b} - v^{-1}s^{b-3})
$$

$$
= (v^{-1}s^{2a-1} - vs - v^{-1}s^{-1} + vs^{1-2a}) -
$$

$$
(vs^3 - v^{-1}s^{2b-3} - vs^{3-2b} + v^{-1}s^{-3})
$$

$$
= v^{-1}\big((s^{2a-1} - s^{-1}) + (s^{2b-3} - s^{-3})\big) - v\big((s - s^{1-2a}) + (s^3 - s^{3-2b})\big)
$$

$$
= v^{-1}\left((s - s^{-1})\sum_{i=0}^{a-1} s^{2a-2-2i} + (s - s^{-1})\sum_{i=0}^{b-1} s^{2b-4-2i} \right)
$$

$$
v\left((s - s^{-1})\sum_{i=0}^{a-1} s^{-2i} + (s - s^{-1})\sum_{i=0}^{b-1} s^{2-2i} \right)
$$

$$
= (s - s^{-1})\left(v^{-1}\sum_{x \in \lambda} s^{2\mathrm{cn}(x)} - v\sum_{x \in \lambda} s^{-2\mathrm{cn}(x)} \right)
$$

$$
= c_\lambda - \delta_{\mathcal{D}}.
$$

Therefore, the first coefficient is what we claimed. Now we can simply show the other coefficients are equal to the first. Let's show the second coefficient is equal to the first:

$$
\begin{aligned}
&- \alpha_{b-1} - s^2 \omega_{a+1}^{+} - s^{-2} \omega_{a+1}^{-} \\
&= -\{b-1\}(v^{-1}s^{b-2} - vs^{2-b}) + \{a+1\}vs^{2-a} - \{a+1\}v^{-1}s^{a-2} \\
&= (s^{1-b} - s^{b-1})(v^{-1}s^{b-2} - vs^{2-b}) + (s^{a+1} - s^{a+1})(vs^{2-a} - v^{-1}s^{a-2}) \\
&= (v^{-1}s^{-1} - v^{-1}s^{2b-3} - vs^{3-2b} + vs) - (vs^3 - vs^{1-2a} - v^{-1}s^{2a-1} + v^{-1}s) \\
&= v^{-1}\big((s^{2a-1} - s^{-1}) + (s^{2b-3} - s^{-3})\big) - v\big((s - s^{1-2a}) + (s^3 - s^{3-2b})\big) \\
&= c_\lambda - \delta_{\mathcal{D}}
\end{aligned}
$$

The next two are slightly different. We will avoid the complexity of $v_i^{\pm}$ by using the relation $v_i^{+} + v_i^{-} = \alpha_i$. Observe:

$$
\begin{aligned}
&\alpha_a + s^2 v_{b-2}^{+} + s^{-2} v_{b-2}^{-} \\
&= \{a\}(v^{-1}s^{a-1} - vs^{1-a}) + (s^b - s^{-b})[b-1](\bar{\beta}_{b-1} - \beta_{b-1})\big(\delta_{\mathcal{D}} + s^{b-3}[b-2](sv^{-1} + \beta_{b-2})\big) \\
&= \{a\}(v^{-1}s^{a-1} - vs^{1-a}) \\
&\quad + (s^b - s^{-b})(s^{b-2} - s^{2-b})^{-1}(s^{b-2} - s^{2-b})[b-1](\bar{\beta}_{b-1} - \beta_{b-1})\big(\delta_{\mathcal{D}} + s^{b-3}[b-2](sv^{-1} + \beta_{b-2})\big) \\
&= \{a\}(v^{-1}s^{a-1} - vs^{1-a}) + (s^b - s^{-b})(s^{b-2} - s^{2-b})^{-1}(v_{b-2}^{+} + v_{b-2}^{-}) \\
&= \{a\}(v^{-1}s^{a-1} - vs^{1-a}) + (s^b - s^{-b})(s^{b-2} - s^{2-b})^{-1}\alpha_{b-2} \\
&= \{a\}(v^{-1}s^{a-1} - vs^{1-a}) - (s^b - s^{-b})(s^{b-2} - s^{2-b})^{-1}(s^{b-2} - s^{2-b})(vs^{3-b} - v^{-1}s^{b-3}) \\
&= (s^a - s^{-a})(v^{-1}s^{a-1} - vs^{1-a}) - (s^b - s^{-b})(vs^{3-b} - v^{-1}s^{b-3}) \\
&= c_\lambda - \delta_{\mathcal{D}}
\end{aligned}
$$

and a similar computation holds for the final coefficient. This completes the proof. $\qquad\square$

4.3 Meridians and Jucys-Murphy Elements of BMW_n

Consider the elements $M_{n,i} = \sigma_{i-1} \cdots \sigma_1 \sigma_1 \cdots \sigma_{i-1} \in BMW_n$ for $2 \leq i \leq n$ and set $M_{n,1} = \mathrm{id}_n$. The set of $M_{n,i}$ in BMW_n are called the **BMW Jucys-Murphy elements**, which are invertible and which generate a commutative subalgebra (see * Isaev-Ogievetsky for more details). These generalize the well-known Jucys-Murphy elements of the symmetric
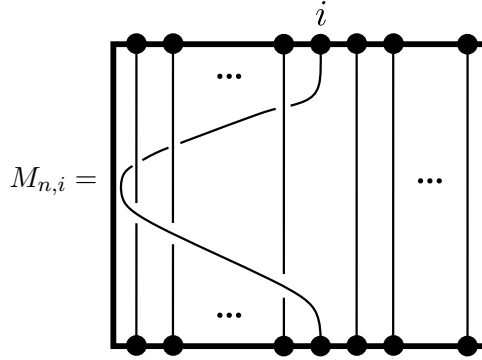

Figure 4.2: The Jucys-Murphy element wraps the ith strand around the first $i-1$ strands.

group algebra $\mathbb{C}[S_n]$, where symmetric polynomials in the Jucys-Murphy elements generate the center $Z(\mathbb{C}[S_n])$.

There is a homomorphism $\psi_n : \mathcal{D}(A) \to BMW_n$ defined so that $\psi_n(x)$ is the element x threaded by a meridian around the identity of BMW_n. The image of ψ_n clearly lies in the center of BMW_n. In the next proposition, we give a simple application which expresses
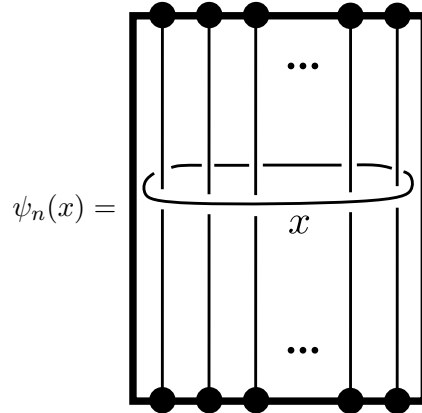
Figure 4.3: The image of x under the homomorphism ψ_n.

$\psi_n(\tilde{P}_k)$ as a linear combination of the BMW Jucys-Murphy elements, their inverses, and the identity. One way to interpret the proposition is that we express $(s^k - s^{-k})^{-1}\big(\psi_n(\tilde{P}_k) - \langle\tilde{P}_k\rangle\mathrm{id}_n\big)$ as a power sum symmetric polynomial in the elements $\{v^{\pm 1}M_{n,i}^{\pm 1}\}_i$. This is a Dubrovnik generalization of the HOMFLYPT counterpart found in * Morton.

Proposition 4.3.1. *For any $k \geq 1$, and any $n \geq 1$, we may represent $\psi_n(\tilde{P}_k)$ as*

$$\psi_n(\tilde{P}_k) = \langle\tilde{P}_k\rangle\mathrm{id}_n + (s^k - s^{-k})\sum_{i=1}^{n} v^{-k}M_{n,i}^k - v^k M_{n,i}^{-k} \tag{4.22}$$

where $\langle\tilde{P}_k\rangle$ is the evaluation of $\tilde{P}_k$ in a 3-ball.

Proof. Induct on n. For $n = 1$, simply apply Theorem 3.1.1 and apply framing relations to get the desired expression (imagine removing the first $n - 1$ strands from the diagrams which follow). Assume the induction hypothesis, that the statement is true for all $n < i$. Apply Theorem 3.1.1 to move $\tilde{P}_k$ past the nth strand and apply framing relations.

$$= \psi_{n-1}(\tilde{P}_k) \otimes \mathrm{id}_1 + (s^k - s^{-k})(v^{-k}M_{n,n}^k - v^k M_{n,n}^{-k})$$

$$= \left(\langle \tilde{P}_k \rangle \mathrm{id}_{n-1} + (s^k - s^{-k}) \sum_{i=2}^{n-1} v^{-k} M_{n-1,i}^k - v^k M_{n-1,i}^{-k} \right) \otimes \mathrm{id}_1$$

$$+ (s^k - s^{-k})(v^{-k} M_{n,n}^k - v^k M_{n,n}^{-k})$$

$$= \langle \tilde{P}_k \rangle \mathrm{id}_{n-1} \otimes \mathrm{id}_1 + (s^k - s^{-k}) \sum_{i=2}^{n-1} \left(v^{-k} M_{n-1,i}^k \otimes \mathrm{id}_1 - v^k M_{n-1,i}^{-k} \otimes \mathrm{id}_1 \right)$$

$$+ (s^k - s^{-k})(v^{-k} M_{n,n}^k - v^{-k} M_{n,n}^{-k})$$

$$= \langle \tilde{P}_k \mathrm{id}_n + (s^k - s^{-k}) \sum_{i=2}^{n-1} \left(v^{-k} M_{n,i}^k - v^k M_{n,i}^{-k} \right) + (s^k - s^{-k})(v^{-k} M_{n,n}^k - v^k M_{n,n}^{-k})$$

$$= \langle \tilde{P}_k \rangle \mathrm{id}_n + (s^k - s^{-k}) \sum_{i=2}^{n} v^{-k} M_{n,i}^k - v^k M_{n,i}^{-k}$$

$\square$

Let for a minimal idempotent $\tilde{y}_\lambda \in BMW_n$, let $\tilde{P}_k \cdot \tilde{y}_\lambda := \psi_n(\tilde{P}_k) \tilde{y}_\lambda$, which is essentially a meridian threaded by $\tilde{P}_k$ wrapped around $\tilde{y}_\lambda$. The next proposition shows that $\tilde{y}_\lambda$ is an eigenvector with respect to the assignment $\tilde{y}_\lambda \mapsto \tilde{P}_k \cdot \tilde{y}_\lambda$. Note that all the eigenvalues are distinct from each other. The annular closure of these eigenvalue equations generalize the result found in * ZL, which they show for $k = 1$.

Proposition 4.3.2. *In* BMW_n, *we have that*

$$\tilde{P}_k \cdot \tilde{y}_\lambda = \left(\langle \tilde{P}_k \rangle \mathrm{id}_n + (s^k - s^{-k}) \sum_{\square \in \lambda} \left(v^{-k} s^{2\mathrm{cn}(\square)} - v^k s^{-2\mathrm{cn}(x)} \right) \right) \tilde{y}_\lambda$$

where $\mathrm{cn}(\square)$ *is the content of the cell* $\square$ *in the Young diagram of* λ.

Proof. We will prove the formula by inducting on the size of λ. For $|\lambda| = 1$, we have that $\tilde{y}_\lambda = \mathrm{id}_1$, so simply apply Proposition 4.3.1 and verify that the fomulae coincide. Now proceed assuming the induction hypothesis. Let μ be the partition obtained by removing a choice of cell x from the Young diagram of λ. First apply the branching formula (see Corollary 5.3 in * BB). Then apply Theorem 3.1.1 to move $\tilde{P}_k$ past the nth strand and apply

framing relations.

The first diagram is equal to $\left(\langle \tilde{P}_k \rangle \mathrm{id}_n + (s^k - s^{-k}) \sum_{\square \in \mu} \left(v^{-k} s^{2\mathrm{cn}(\square)} - v^k s^{-2\mathrm{cn}(x)}\right)\right) \tilde{y}_\lambda$ by the induction hypothesis. The second diagram is equal to $s^{2k\mathrm{cn}(x)} \tilde{y}_\lambda$, which may be shown by repeating the main computation found in the proof of Theorem 5.5 of * Aiston-Morton k times. The third diagram is is mirror map applied to the second diagram, so it is equal to $s^{-2k\mathrm{cn}(x)} \tilde{y}_\lambda$. This completes the proof. $\square$

References