Diagrammatic Categories in Representation Theory

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Acknowledgements

I give my deepest thanks to my supervisor, Anna Romanov, for putting me on this journey of diagrammatics, for teaching me all I know about Soergel bimodules, for organising my disorganisation and for sparking my love for examples; to Daniel Tubbenhauer for the countless hours spent answering my questions and for his enthusiasm and deep knowledge of diagrammatics and categories; and to Arnaud Brothier for all his profound insights into mathematical writing. Without them, this thesis would not be anything.

I also thank my friends and family for their continued encouragement and support.

Abstract

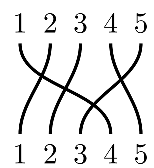
This thesis explores diagrammatic monoidal categories in the examples of one and two-colour Soergel calculus, and its diagrammatic module categories given by the BGG category $\mathcal{O}$ and tilting modules, respectively.

Contents

Chapter 1

Introduction

Visual interpretations of data and objects in mathematics are a tool that aids us in calculations and often provides insights into the mathematics they encode. This diagrammatic philosophy takes form in various settings, and can be defined precisely to help us understand algebraic objects better. A simple example are *string diagrams* for permutations of a *symmetric group*. A permutation can be drawn as strings between two copies of a set determining how the objects are permuted. For example, the permutation (12354) in S_5 has the string diagram (reading from bottom to top)



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Compositions of these permutations is the operation of joining corresponding strings start to end in order to create a larger string diagram representing their product. Related to these are *(Artin) braid groups*, whose elements can be depicted similarly to the symmetric group, but where each crossing of strings can go over or under. As suggested by the name, these string diagrams resemble braids, and are important in knot theory.

A significant example are *planar algebras* in the work of Vaughan Jones and many others. These are certain algebras of planar diagrams that describe operators. The study of the Temperley–Lieb–Jones (planar[1]) algebra lead to the discovery of an important invariant in knot theory [Jon85] in 1983, which we know now as the Jones polynomial. For this and surrounding works Jones received a Fields medal in 1990. This technology of planar algebras have been since used to study subfactors in functional analysis [Jon21][2] with consequences in statistical mechanics and mathematical physics. Although diagrammatics have been around before Jones' work on subfactors (prominent examples by Rumer–Teller–Weyl [WRT32] and Brauer [Bra37]), the diagrammatics of subfactors was what kick-started diagrammatics as a field with the birth of quantum topology.

[1]Many diagrammatic versions of this algebra were independently discovered, for example by Rumer–Teller–Weyl [WRT32] and Kauffman [Kau90].

[2]Originally from 1999, and was recently published.

In representation theory, our main motivational example is given by the proof of the Kazhdan–Lusztig conjecture through the diagrammatics of Soergel bimodules. This conjecture relates Kazhdan–Lusztig polynomials, arising from the Weyl group associated with a Lie algebra, to Jordan–Hölder multiplicities of particular representations of Lie algebras called Verma modules. Proofs were discovered independently by Beilinson–Bernstein and Brylinski–Kashiwara in 1981, both using geometric tools. However these methods had no clear generalisation to general Coxeter groups used in variations of the original conjecture. Around ten years later, Soergel was working toward an algebraic proof using Soergel bimodules, however Soergel hit a technical road block. More recently, in 2010's, Elias and Williamson developed planar diagrams for morphisms on Soergel bimodules (in [EW14] and [EK10]) and were able to overcome the technical point where Soergel got stuck, and prove the conjecture diagrammatically. As a tool, these diagrams provide an intuitive visual language that serve to simplify potentially diffucult algebraic calculations. Moreover, this diagrammatic category can be considered independently from algebraic Soergel bimodules. We will explore this diagrammatic category for the symmetric group S_2 in Section 3.1. Let us stress that these diagrammatics can also be defined for any Coxeter group, including symmetric groups and dihedral groups. A general definition can be found in [Eli+20] along with an introduction to the category of algebraic Soergel bimodules $\mathbb{S}\mathrm{Bim}$. Soergel had also shown that $\mathbb{S}\mathrm{Bim}$ is linked to other categories of representations, such as the Bernstein–Gelfand–Gelfand category $\mathcal{O}$ in [Soe90]. By this, a diagrammatic version of this category of representations can be defined. We see example in more detail in Section 3.2.

One of the advantages of the diagrammatic Soergel bimodules is that it can be defined over $\mathbb{Z}$ and extended to fields of characteristic p where classical Soergel bimodules are ill-behaved. Characters in the category of tilting modules (certain representations of a Lie group or quantum group) can be calculated via Kazhdan–Lusztig polynomials in characteristic zero. However, these polynomials were unknown in characteristic p. Riche and Williamson in [RW18] were able to construct these characteristic p Kazhdan–Lusztig polynomials by considering diagrammatic Soergel bimodules in characteristic p.

In this thesis we present an exposition for existing constructions of diagrammatics in representation theory. Chapter 2 gives an introduction to diagrammatics for monoidal categories, provides a diagrammatic description of Frobenius objects in monoidal categories, then defines module categories and some mechanisms to form an additive idempotent complete category. In Chapter 3 we define the category of diagrammatic Soergel bimodules associated with the symmetric group S_2, construct a basis for its morphism spaces and state the theorem for its equivalence to the category of algebraic Soergel bimodules. We use this diagrammatic category to construct a diagrammatic module category with an extra relation, then prove its equivalence to the category of projective objects in the principle block of the category $\mathcal{O}$. In Chapter 4 we consider the affine symmetric group $\widetilde{S}_2$ to define the diagrammatic Soergel bimodules associated it, construct a basis for its morphism spaces and state the theorem for its equivalence to the category of algebraic Soergel bimodules. The extra generator in $\widetilde{S}_2$, compared with S_2, will introduce some additional complexity to the structure of the category. We then form a module category with two extra relations and provide a proof of its equivalence to the category of tilting modules for quantum $\mathfrak{sl}_2$. In the last chapter we discuss the consequences of diagrammatics in relation to Chapter 3 and Chapter 4, mention some generalisations and further areas of interest.

Note that one of the advantages of diagrammatics is that we don't need to understand these algebraic categories in representation theory to study them. For this reason, we will defer some details in the proofs involving category $\mathcal{O}$ and tilting modules to other sources.

The contents of this thesis are for honours students and future readers with an interest in this topic. The reader is assumed to have some familiarity with undergraduate algebra (such as groups, rings, algebras and fields), basic ideas in representation theory (such as the action of a group or algebra and the equivalence with modules), and basic category theory, including some knowledge of monoidal categories.

Chapter 2

Background

For a category $\mathcal{C}$ we write $\mathrm{ob}(\mathcal{C})$ for the collection of objects, $\mathrm{mor}(\mathcal{C})$ for the collection of all morphisms, and for any pair of objects A, B we write $\mathrm{Hom}(A, B)$ for the collection of morphisms from A to B. The collection of endomorphisms of an object A is written $\mathrm{End}(A) \coloneqq \mathrm{Hom}(A, A)$. Note that our focus of study are particular types of categories, not categories in the abstract sense, so we will assume that all categories we encounter are locally small, that is for any objects A and B, $\mathrm{Hom}(A, B)$ is a set.

2.1 Drawing Monoidal Categories

Monoidal categories are the main context in which we consider diagrammatics. For more details about monoidal categories the reader can refer to [Eti+15], and a survey of diagrams for various types of monoidal categories in [Sel10].

Definition 2.1.1. A *monoidal category* $\mathcal{C}$ is a category equipped with a bifunctor $\otimes : \mathcal{C} \times \mathcal{C} \to \mathcal{C}$ and a unit object $\mathbb{1}$, such that certain associativity and unit relations hold, see [Eti+15, Definition 2.1.1, 2.2.8]. The bifunctor $\otimes$ is called the *tensor* or *monoidal product*. A monoidal category is *strict* if we have equalities $A \otimes (B \otimes C) = (A \otimes B) \otimes C$ and $A = \mathbb{1} \otimes A = A \otimes \mathbb{1}$ for objects and similarly for morphisms.

The functoriality of $\otimes$ means that the monoidal product commutes with composition in both variables.

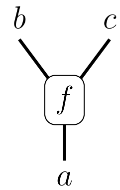
Definition 2.1.2. A functor $F : \mathcal{C} \to \mathcal{D}$ between monoidal categories is called *(strict) monoidal* if it preserves the monoidal product, i.e. $F(A \otimes B) = F(A) \otimes F(B)$. Structure preserving functors for other types of categories can be defined in a similar way.

For this thesis, we will assume that monoidal categories and monoidal functors are strict[1]. This does not pose any problems since all monoidal categories are monoidally

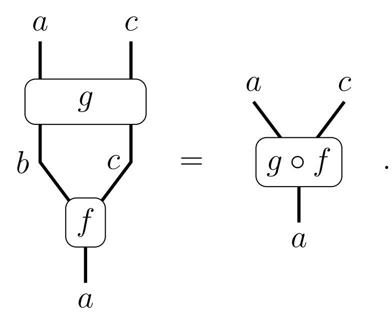
[1] We can also define diagrammatics for non-strict monoidal categories, but drawing isomorphisms composed with each morphism is cumbersome.

equivalent to a strict one[2], and a similar strictification[3] can be applied to the functor. In this context, the details in the coherence relations are trivial.

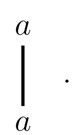
The morphisms of a monoidal category $\mathcal{C}$ can be drawn as string diagrams embedded in a planar strip. We fix the convention that a diagram is a morphism when read from bottom to top; that is, the domain is on the bottom of the strip and the codomain on the top. Morphisms that make up a diagram are drawn as tokens or boxes. For example



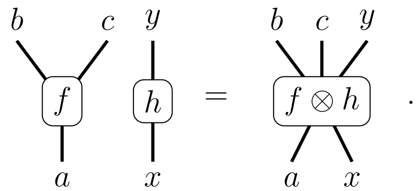
depicts a morphism $f : a \to b \otimes c$. Notice here that tensor products of objects have its factors displayed horizontally. The compositions of morphisms is the vertical stacking of diagrams whenever labels on domains and codomains match. For example, the composition $g \circ f : a \to b \otimes c \to a \otimes c$ of $f : a \to b \otimes c$ with $g : b \otimes c \to a \otimes c$ has the diagram



For identity morphisms we just draw a vertical line, so id_a is the diagram

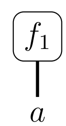


This is a sensible choice since composition with the identity should not change the diagram, which is clear diagrammatically. The tensor product of morphisms is the horizontal concatenation of diagrams, such that strings from separate diagrams don't interact. For example, given $h : x \to y$, the tensor product $f \otimes h : a \otimes x \to b \otimes c \otimes y$ is drawn as

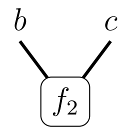


[2]See [ML98, VII.2] or [Eti+15, Theorem 2.8.5].
[3]See [Pow89].

We let the monoidal unit $\mathbb{1}$ be blank and unlabelled, and strings that would join to $\mathbb{1}$ are blank. Particularly, $\mathrm{id}_{\mathbb{1}}$ is an empty diagram. It makes sense to display $\mathbb{1}$ in this way since tensoring with $\mathbb{1}$ (in a strict monoidal category) does nothing to objects and tensoring with $\mathrm{id}_{\mathbb{1}}$ does nothing to morphisms. By this convention, we also have diagrams such as



and

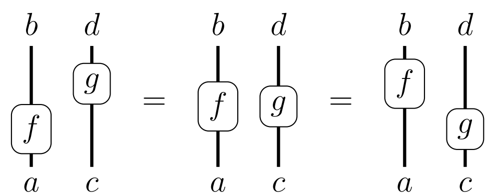


for morphisms $f_1 : a \to \mathbb{1}$ and $f_2 : \mathbb{1} \to b \otimes c$.

The bifunctoriality of $\otimes$ implies the following *interchange law*. For morphisms $f : a \to b$ and $g : c \to d$, we have $(\mathrm{id}_b \otimes g) \circ (f \otimes \mathrm{id}_c) = f \otimes g = (f \otimes \mathrm{id}_d) \circ (\mathrm{id}_a \otimes g)$. In other words the following diagram commutes.

$$\begin{tikzcd}
a \otimes c \arrow[r, "f\otimes \mathrm{id}_c"] \arrow[d, "\mathrm{id}_a \otimes g"'] \arrow[dr, "f\otimes g"] & b \otimes c \arrow[d, "\mathrm{id}_b \otimes g"] \\
a \otimes d \arrow[r, "f\otimes \mathrm{id}_d"] & b \otimes d
\end{tikzcd}$$

Written with string diagrams, this is



which holds up to vertical deformation of the diagram. This is a small taste of isotopy, but only in the vertical direction.

Before looking at an example of a diagrammatic monoidal category, we just mention some definitions.

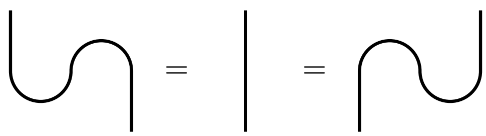
Definition 2.1.3. For a commutative ring R, an *R-linear category* is a category enriched over the category of R-modules. That is, for objects a, b, the set of morphisms $\mathrm{Hom}(a, b)$ is an R-module and the composition of morphisms is R-bilinear. An *R-linear monoidal category* is a category that is both monoidal and R-linear such that the monoidal product on morphisms is R-bilinear. A ($\mathbb{Z}$-)*graded R-linear category* is a category where $\mathrm{Hom}(A, B)$ is a $\mathbb{Z}$-graded R-module. That is, $\mathrm{Hom}(A, B) = \bigoplus_{i\in\mathbb{Z}} \mathrm{Hom}^i(A, B)$ where $\mathrm{Hom}^i(A, B)$ is the homogeneous component of degree i, and for $f \in \mathrm{Hom}^i(A, B)$ and $g \in \mathrm{Hom}^j(B, C)$, the composition $g \circ f$ is in $\mathrm{Hom}^{i+j}(A, C)$.

By the bilinearity of composition and tensor products, $0\otimes f = (0+0)\otimes f = 0\otimes f + 0\otimes f$ and similarly with composition, so composition and tensors with 0 are zero.

Example 2.1.4. The category of vector spaces over a field $\Bbbk$, $\mathbf{Vect}_{\Bbbk}$, is a $\Bbbk$-linear monoidal category given by the usual tensor product of vector spaces and linear maps.

Definition 2.1.5. A monoidal category $\mathcal{C}$ is *generated* by a set G_o of objects and G_m of morphisms, when all non-unit objects are finite tensor products of objects in G_o and all non-identity morphisms are finite combinations of tensors and compositions of morphisms in G_m. Similarly, we define *generated* R-linear monoidal categories such that we also allow R-linear combinations of morphisms.

Example 2.1.6. The Temperley–Lieb–Jones category $\mathcal{TL}$ is a (diagrammatic) strict $\mathbb{Z}$-linear monoidal category whose objects are generated by the vertical line I and morphisms generated by the cup $\cup : \mathbb{1} \to \mathsf{I} \otimes \mathsf{I}$ and cap $\cap : \mathsf{I} \otimes \mathsf{I} \to \mathbb{1}$, with the relation


,

where the composition and tensor product are vertical and horizontal concatenation. This is an isotopy relation allowing us to “straighten out zig-zags”.

Remark 2.1.7. The generating object I is self-dual with adjunction maps $\cup$ and $\cap$ satisfying the adjoint relation given by (2.1.6). In other words, $\mathcal{TL}$ is a free monoidal category on a self-dual object.

The morphisms in this category are $\mathbb{Z}$-linear combinations of diagrams such as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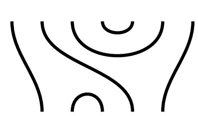
The diagrams in this category are crossingless matchings, i.e. each generator is connected to exactly one line and lines don’t cross, and possibly have floating circles.

The standard definition of the Temperley–Lieb–Jones category has an extra relation that identifies circles with $\delta\,\mathrm{id}_{\mathbb{1}}$, for some fixed constant $\delta \in \mathbb{Z}$. For example, consider the quotient of $\mathcal{TL}$ by the relation

 $= -2\,\mathrm{id}_{\mathbb{1}},$

where $\mathrm{id}_{\mathbb{1}}$ is the blank diagram. In this quotient, the above diagram is

4  .

Remark 2.1.8. This category controls the representation theory of $\mathfrak{sl}_2$.

2.2 Frobenius Objects

The structure of Frobenius objects gives rise to useful diagrammatics that can be defined up to isotopy. This section gives some background to the objects we will encounter in Section 3.1 and beyond.

Let $\mathcal{C}$ be a (strict) monoidal category.

Definition 2.2.1. A *monoid object* in $\mathcal{C}$ is a triple (M, μ, η) for an object $M \in \mathcal{C}$, a *multiplication* map $\mu : M \otimes M \to M$ and a *unit* map $\eta : \mathbb{1} \to M$, such that

$$\begin{tikzcd} & M \otimes M \otimes M \arrow[dl, "\mu\otimes \mathrm{id}_M"'] \arrow[dr, "\mathrm{id}_M \otimes \mu"] & \\ M \otimes M \arrow[dr, "\mu"'] & & M \otimes M \arrow[dl, "\mu"] \\ & M & \end{tikzcd}$$

and

$$\begin{tikzcd} \mathbb{1} \otimes M \arrow[r, "\eta\otimes \mathrm{id}_M"] \arrow[dr, "\mathrm{id}_M"'] & M \otimes M \arrow[d, "\mu"] & M \otimes \mathbb{1} \arrow[l, "\mathrm{id}_M \otimes \eta"'] \arrow[dl, "\mathrm{id}_M"] \\ & M & \end{tikzcd}$$

commute. The first diagram is the *associativity* relation $\mu \circ (\mu \otimes \mathrm{id}_M) = \mu \circ (\mathrm{id}_M \otimes \mu)$ and the second diagram is the *unit* relation $\mathrm{id}_M = \mu \circ (\eta \otimes \mathrm{id}_M) = \mu \circ (\mathrm{id}_M \otimes \eta)$.

Dually, a *comonoid object* in $\mathcal{C}$ is a triple (M, δ, ϵ) for an object $M \in \mathcal{C}$, a *comultiplication* map $\delta : M \to M \otimes M$ and a *counit* map $\epsilon : M \to \mathbb{1}$, satisfying the *coassociativity* relation

$$\begin{tikzcd} & M \otimes M \otimes M & \\ M \otimes M \arrow[ur, "\delta\otimes \mathrm{id}_M"] & & M \otimes M \arrow[ul, "\mathrm{id}_M \otimes \delta"'] \\ & M \arrow[ul, "\delta"] \arrow[ur, "\delta"'] & \end{tikzcd}$$

and *counit* relation

$$\begin{tikzcd} \mathbb{1} \otimes M & M \otimes M \arrow[l, "\epsilon\otimes \mathrm{id}_M"'] \arrow[r, "\mathrm{id}_M \otimes \epsilon"] & M \otimes \mathbb{1} \\ & M \arrow[ul, "\mathrm{id}_M"] \arrow[u, "\delta"] \arrow[ur, "\mathrm{id}_M"'] & \end{tikzcd} .$$

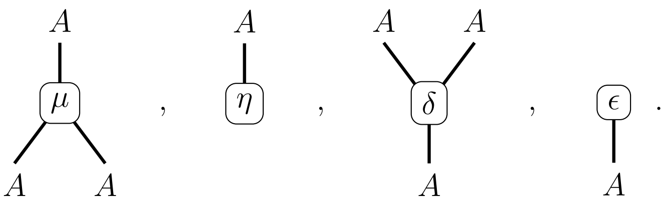
Monoid objects generalise monoids in algebra, i.e. sets with an identity equipped with an associative binary operation.

Definition 2.2.2. A *Frobenius object* in $\mathcal{C}$ is a quintuple $(A, \mu, \eta, \delta, \epsilon)$ such that (A, μ, η) is a monoid object, (A, δ, ϵ) is a comonoid object, and the maps satisfy the *Frobenius relations*

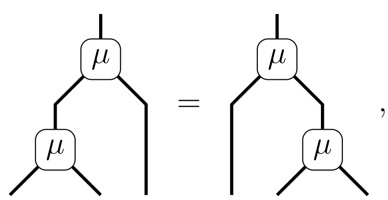
$$\begin{tikzcd}
& A\otimes A \arrow[dl, "\delta\otimes\mathrm{id}_A"'] \arrow[d, "\mu"] \arrow[dr, "\mathrm{id}_A\otimes\delta"] & \\
A\otimes A\otimes A \arrow[dr, "\mathrm{id}_A\otimes\mu"'] & A \arrow[d, "\delta"] & A\otimes A\otimes A \arrow[dl, "\mu\otimes\mathrm{id}_A"] \\
& A\otimes A &
\end{tikzcd},$$

that is $(\mathrm{id}_A \otimes\mu) \circ (\delta \otimes \mathrm{id}_A) = \delta \circ \mu = (\mu \otimes \mathrm{id}_A) \circ (\mathrm{id}_A \otimes\delta)$.

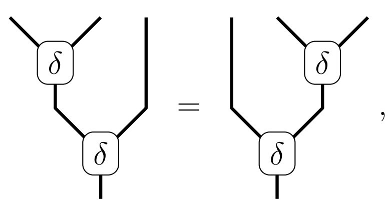
The maps and relations for a Frobenius object $(A, \mu, \eta, \delta, \epsilon)$ have a pleasant description via the diagrams given in Section 2.1. The structure maps are drawn as



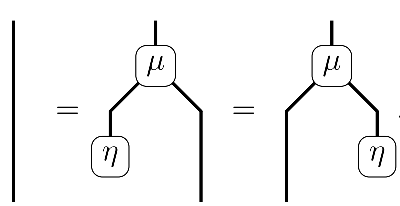
For the rest of this section, we will only work with the Frobenius object A and $\mathbb{1}$. We can stop putting the label A by identifying A with the identity strand $| = \mathrm{id}_A$. Diagrammatically, the associativity relation $\mu \circ (\mu \otimes \mathrm{id}_M) = \mu \circ (\mathrm{id}_M \otimes\mu)$ is



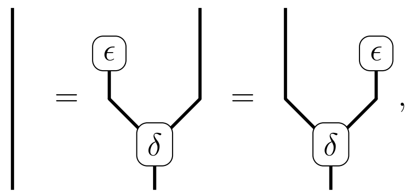
the coassociativity relation $(\delta \otimes \mathrm{id}_A) \circ \delta = (\mathrm{id}_A \otimes\delta) \circ \delta$ is



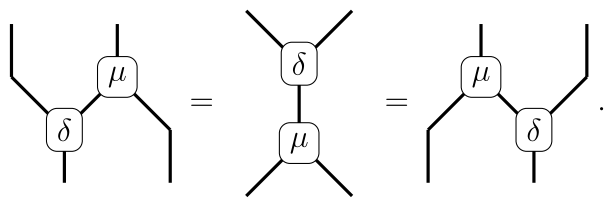
the unit relation $\mathrm{id}_A = \mu \circ (\eta \otimes \mathrm{id}_A) = \mu \circ (\mathrm{id}_A \otimes\eta)$ is



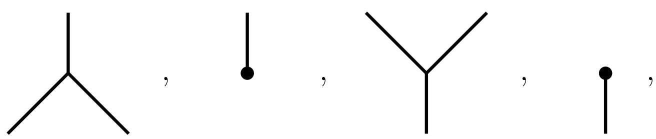
the counit relation $\mathrm{id}_A = (\epsilon \otimes \mathrm{id}_A) \circ \delta = (\mathrm{id}_A \otimes \epsilon) \circ \delta$ is



and the Frobenius relation $(\mathrm{id}_A \otimes \mu) \circ (\delta \otimes \mathrm{id}_A) = \delta \circ \mu = (\mu \otimes \mathrm{id}_A) \circ (\mathrm{id}_A \otimes \delta)$ is

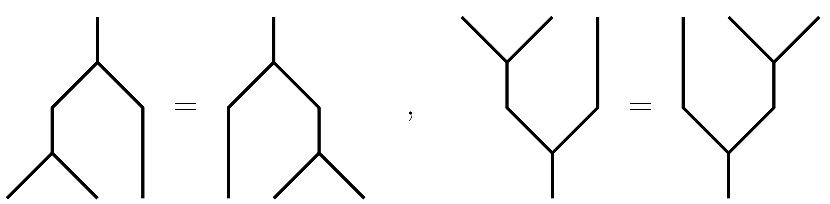


To further simply the diagrams, we stop labelling the morphisms and draw the structure maps as univalent and trivalent vertices

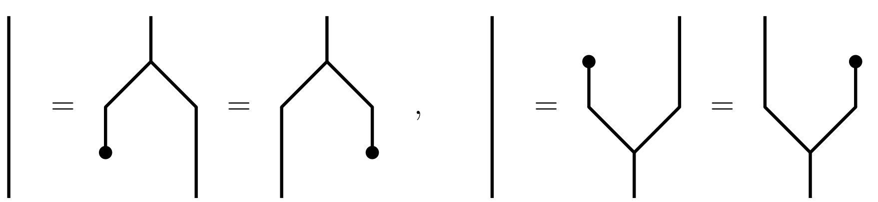


(FrobGen)

where the large dot on the unit and counit indicates that the string stops before reaching the other end. Then the relations become

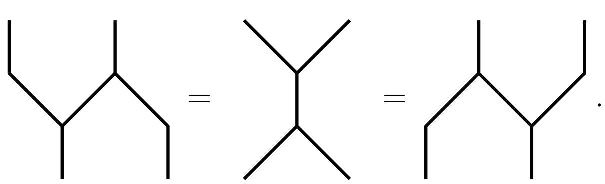


(Frob1)



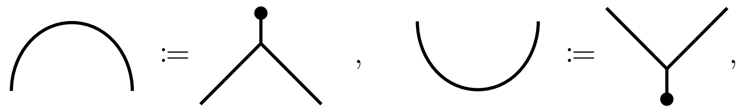
(Frob2)

and



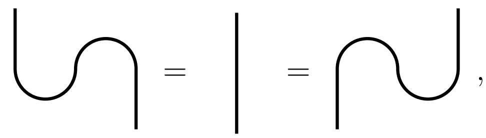
(Frob3)

If we write cups and caps for the diagrams



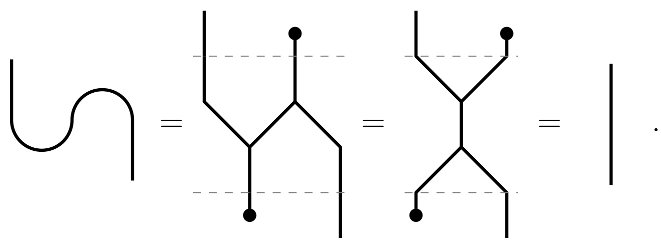
(2.2.3)

then the Frobenius object relations admit a more familiar form of (planar) isotopy by the relations



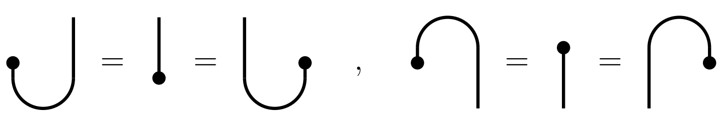
(Iso1)

which we saw in for the Temperley-Lieb-Jones category. For instance the first equality follows from (Frob3) and (Frob2),

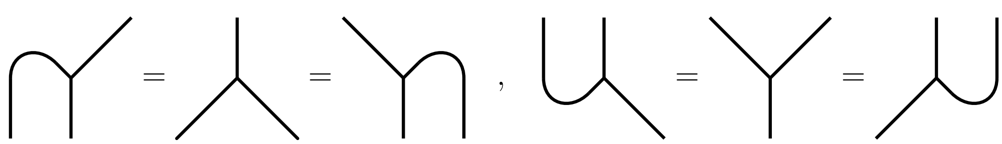


Remark 2.2.4. This implies that Frobenius objects A are dualisable and self-dual, with the unit of duality given by the cap $A \otimes A \to \mathbb{1}$ and the counit given by the cup $\mathbb{1} \to A \otimes A$ above. The triangle identities for duality are exactly the relation (Iso1), which is sometimes called the zig-zag relation. Alternatively, this corresponds to the left tensor functor $A \otimes -$ being self-adjoint by a similar argument.

We can similarly deduce more isotopy relations



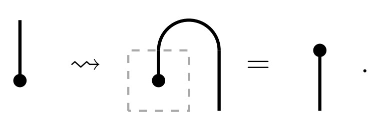
(Iso2)



(Iso3)

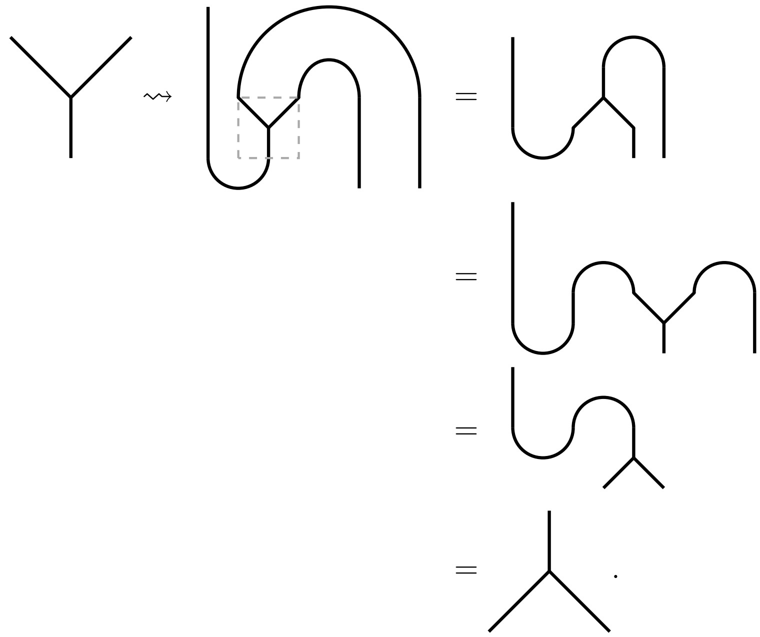
which can be thought of as "rotating vertices". Using these identities, we can rotate entire diagrams by putting caps and cups around it.

Example 2.2.5. The unit relation can be rotated to the counit map



where the equality follows from (Iso2).

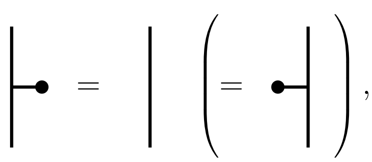
Example 2.2.6. The comultiplication map can be rotated to the multiplication map



where the equality follows from applying (Iso3) three times then (Iso1).

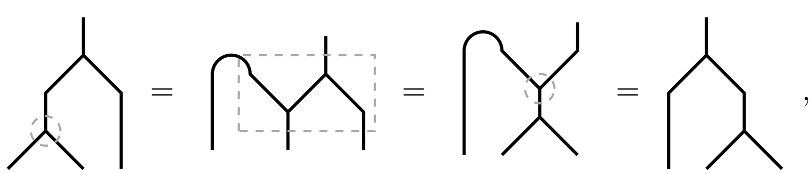
In fact, Frobenius objects satisfy all possible isotopy relations[4]. We can therefore consider the diagrams generated by concatenations of Frobenius structure maps up to planar isotopy. That is, we equate two diagrams if one diagram can be continuously deformed to the other in the plane without crossing. In this way, we can just use our visual intuition in place of applying any specific isotopy relations from (Iso1)-(Iso3).

The Frobenius object relations (Frob1), (Frob2), (Frob3) can be simplified as following. The unit and counit relations are



where the second equality follows from rotating the first one with cups and caps. Here the horizontal line has no innate meaning in the category but isotopically asserts equality between the "bent up" and "bent down" diagrams in (Frob2).

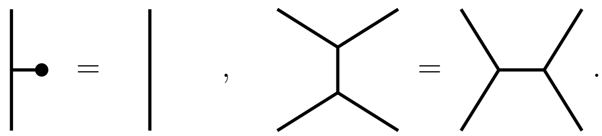
Note that allowing isotopy, the Frobenius relation (Frob3) implies the associativity and coassociativity relations (Frob1). For instance, we have



[4]This is a consequence of the well known connections to 2dTQFTs, see for example [Koc03].

where the second equality is the Frobenius relation. For completeness, this calculation shows the trivalent rotations (Iso3), but the reader is encouraged to think of the first and third equalities as isotopic deformations.

Therefore, up to isotopy, the Frobenius object relations are summed by the unit and Frobenius relation



(FrobRel)

Remark 2.2.7. Let Frob be the monoidal category with objects generated by an object | and morphisms generated by the diagrams (FrobGen) with relations (FrobRel). For any monoidal category $\mathcal{C}$ with a Frobenius object A, there exists a functor[5] Frob $\to$ $\mathcal{C}$ mapping $| \mapsto A$ and the morphisms in (FrobGen) to the corresponding Frobenius structure maps. In other words, Frob is the free monoidal category generated by a Frobenius object.

Remark 2.2.8. Noting Remark 2.2.4, if we define the generating object | to be self-dual, then we automatically get cups and caps as adjunction morphisms[6] satisfying the relation (Iso1). In this case, we can rotate diagrams so we would only need the first two generators in (FrobGen).

These objects will appear again in the context of diagrammatic Soergel bimodules in Section 3.1.

2.3 Module Categories

Module categories are categories equipped with an action of a monoidal category. This generalises the notion of modules over a ring or monoid. In Section 3.2 and Section 4.2, we will see that the categories of interest appear as module categories over the category of Soergel bimodules.

Definition 2.3.1. Let $(\mathcal{M}, \otimes, \mathbb{1})$ be a (strict) monoidal category. A *(left) module category over* $\mathcal{M}$ or $\mathcal{M}$*-module category* is a category $\mathcal{C}$ and a bifunctor $\odot : \mathcal{M} \times \mathcal{C} \to \mathcal{C}$ such that there are natural isomorphisms $(X \otimes Y) \odot A \cong X \odot (Y \odot A)$ and $\mathbb{1} \odot A \cong A$ for $X, Y \in \mathcal{M}$ and $A \in \mathcal{C}$ and similarly for morphisms, satisfying coherence relations analogous to those for monoidal categories (see [Eti+15, Definition 7.1.2]). A (left) $\mathcal{M}$-module category is *strict* if the natural isomorphisms above are identity natural isomorphisms, i.e. we have equality $(X \otimes Y) \odot A = X \odot (Y \odot A)$ and $\mathbb{1} \odot A = A$, and similarly for morphisms. The functor $\odot$ is called the *action of* $\mathcal{M}$ or *the module product*.

[5]This functor need not be full nor faithful, as there may be more morphisms in the target category which could satisfy more relations.

[6]The cups and caps align with the generators by (2.2.3).

In the following examples, the module action is essentially the monoidal product, which we may denote by the same symbol $\otimes$. Note that, in general, module actions are not necessarily an underlying monoidal product.

Example 2.3.2. A monoidal category is a module category over itself, where the action is its tensor product.

Example 2.3.3. Let G be a finite group and $H \subseteq G$ a subgroup. Consider the categories of group representations $\mathbf{Rep}(G)$ and $\mathbf{Rep}(H)$ over a field $\Bbbk$. Recall that $\mathbf{Rep}(G)$ is a category where objects are pairs (V, ρ), for a finite dimensional $\Bbbk$-vector space V and a G-representation $\rho : G \to \mathrm{GL}(V)$, and morphisms are equivariant maps i.e. linear maps that preserve the group action. There is a monoidal structure on $\mathbf{Rep}(G)$ (and similarly $\mathbf{Rep}(H)$) given by

$$(V, \rho_V) \otimes (W, \rho_W) = (V \otimes W, \rho_{V\otimes W})$$

where $V \otimes W$ is the usual tensor of vector spaces, and $\rho_{V\otimes W}$ is defined such that for $v \in V, w \in W$ and $g \in G$,

$$(\rho_{V\otimes W})(g)(v \otimes w) = (\rho_V(g)v) \otimes (\rho_W(g)w)$$

extended linearly. This is well defined by the universal property of tensor products. The monoidal unit is $\Bbbk$ with the trivial representation. The tensor product on morphisms f and g is defined by component-wise application, which is equivariant by the equivariance of f and g.

We have that $\mathbf{Rep}(H)$ is a left module category over $\mathbf{Rep}(G)$ with the following action. For an object (V, ρ) in $\mathbf{Rep}(G)$, we can consider it as a representation over H by the restriction

$$\rho|_H : H \hookrightarrow G \xrightarrow{\rho} \mathrm{GL}(V).$$

The left action of (V, ρ) is the left tensor of $(V, \rho|_H)$ in $\mathbf{Rep}(H)$. On morphisms we apply a similar restriction of equivariant maps.

Definition 2.3.4. A (strict) module category $\mathcal{C}$ over a monoidal category $\mathcal{M}$ is *generated* by a set G_o of objects and G_m of morphisms, when all non-unit objects are of the form $X \odot A$ for $X \in \mathcal{M}$ and $A \in G_o$, and non-identity morphisms in $\mathcal{C}$ are defined similarly.

Definition 2.3.5. Let $\mathcal{M}$ be a (strict) R-linear monoidal category, and $\mathcal{C}$ be a (strict) module category over $\mathcal{M}$. We say that $\mathcal{C}$ is a *(strict) R-linear module category* if $\odot$ is R-bilinear on morphisms.

2.4 Additive Karoubi Envelope

Many interesting categories in representation theory are equivalent to categories of modules over a ring or an algebra. Accordingly, the notion of indecomposable representations, or modules with no non-trivial direct summands, come up in various problems. However the diagrammatic monoidal categories we will define may not innately contain direct sums and direct summands, so we must formally add them in. This can be done by taking the additive closure and Karoubi envelope.

Additive and Karoubian Categories

Definition 2.4.1. A *preadditive category* is a category enriched over the category of abelian groups. That is, for objects A and B, $\mathrm{Hom}(A, B)$ has the structure of an abelian group such that the composition of morphisms is bilinear over the abelian group operation.

In particular, R-linear categories are preadditive because R-modules are defined over abelian groups.

Definition 2.4.2. A *biproduct* of objects of a category is an object that is both a product and a coproduct. An *additive category* is a preadditive category that admits all finite biproducts.

Biproducts are a generalisation of direct sums of modules, so we often write $\oplus$ and say "direct sum". In other words, additive categories are preadditive categories containing all direct sums. An easy example is the category of modules over a ring R.

Definition 2.4.3. An *idempotent* is a endomorphism e such that $e \circ e = e$. We say that a preadditive category is *Karoubian* or *idempotent complete* if for every idempotent $e : X \to X$ there is a direct sum decomposition $X \cong Y \oplus Z$ such that e is a projection onto the component Y.

This is a formal way to say that a category contains all direct summands, as every direct summand is an image of an idempotent given by projection.

Additive Closure and Karoubi Envelope

The additive closure and Karoubi envelope are formal constructions that add direct sums and direct summands into a preadditive category. We will see applications of these in Chapter 3 and Chapter 4.

Definition 2.4.4. Let $\mathcal{C}$ be a preadditive category. The *additive closure* $\mathcal{C}^{\oplus}$ of $\mathcal{C}$ is the category where objects are finite (possibly empty) formal direct sums $\bigoplus_{i=1}^{n} A_i$ for $A_i \in \mathrm{ob}(\mathcal{C})$. We call the empty direct sum the *zero object* 0. A morphism f of $\mathrm{Hom}_{\mathcal{C}^{\oplus}}(\bigoplus_{i=1}^{n} A_i, \bigoplus_{i=1}^{m} B_i)$ is an $m \times n$ matrix $f = (f_{j,i})$ of morphisms $f_{j,i} \in \mathrm{Hom}_{\mathcal{C}}(A_i, B_j)$.

It is clear that $\mathcal{C}$ is a category that embeds in $\mathcal{C}^{\oplus}$ and that $\mathcal{C}^{\oplus}$ is additive. In the case where $\mathcal{C}$ is monoidal, $\mathcal{C}^{\oplus}$ is monoidal by extending the monoidal product to be an additive functor in each input. If $\mathcal{C}$ is R-linear, then $\mathcal{C}^{\oplus}$ is an R-linear category by assuming that the R-action on morphisms applies componentwise. Lastly, if $\mathcal{C}$ is a $\mathcal{M}$-module category, then $\mathcal{C}^{\oplus}$ is a $\mathcal{M}$-module category by additionally assuming that the module action applies componentwise.

Lemma 2.4.5. *The additive closure satisfies the following universal property. For every preadditive functor $F : \mathcal{C} \to \mathcal{D}$ where $\mathcal{D}$ is an additive category, there is a unique additive functor $F' : \mathcal{C}^{\oplus} \to \mathcal{D}$ such that the composition $\mathcal{C} \hookrightarrow \mathcal{C}^{\oplus} \xrightarrow{F'} \mathcal{D}$ is F.*

This is a classical result so we will not provide a proof. It can be observed by extending F to a functor $F^{\oplus} : \mathcal{C}^{\oplus} \to \mathcal{D}^{\oplus}$ defined by applying F componentwise.

Definition 2.4.6. Let $\mathcal{C}$ be a category. The *Karoubi envelope* $\mathrm{Kar}(\mathcal{C})$ of $\mathcal{C}$ is the category where objects are ordered pairs (A, e) for an object A in $\mathcal{C}$ and an idempotent $e \in \mathrm{End}_{\mathcal{C}}(A)$. Morphisms $f : (A, e) \to (A', e')$ are morphisms $f : A \to A'$ in $\mathcal{C}$ such that $f = f \circ e = e' \circ f$, where composition is composition in $\mathcal{C}$. Equivalently, morphisms $f : (A, e) \to (A', e')$ are of the form $e' \circ f \circ e$ for some (not necessarily unique) morphism $f : A \to A'$. The identity morphism on (A, e) is e.

This is also known as the *Karoubian closure* or *idempotent completion*. We should think of the objects (A, e) as "the image of e".

Proposition 2.4.7. *For a preadditive category $\mathcal{C}$, $\mathrm{Kar}(\mathcal{C})$ is Karoubian.*

A proof can be found in [Eli+20, Lemma 11.17].

Lemma 2.4.8. *Every functor $F : \mathcal{C} \to \mathcal{D}$ where $\mathcal{D}$ is Karoubian, extends uniquely (up to isomorphism) to a functor $F' : \mathrm{Kar}(\mathcal{C}) \to \mathcal{D}$.*

This is another classical result. See [Bor94, Proposition 6.5.9 (1)] for a proof.

The structure of monoidal, R-linear, $\mathcal{M}$-module or additive categories, or a combination thereof, can be naturally extended to its Karoubi envelope. If $\mathcal{C}$ is monoidal, the monoidal product extends to $\mathrm{Kar}(\mathcal{C})$ by applying the monoidal product in $\mathcal{C}$ componentwise. If $\mathcal{C}$ is R-linear, then $\mathrm{Kar}(\mathcal{C})$ is naturally R-linear as morphisms are those of $\mathcal{C}$ and composition in $\mathcal{C}$ is R-linear. If $\mathcal{C}$ is a module category over $\mathcal{M}$, then the $\mathcal{M}$-action can be extended to $\mathrm{Kar}(\mathcal{C})$ such that $M \odot (A, e) = (M \odot A, \mathrm{id}_M \odot e)$, where $\mathrm{id}_M \odot e$ is an idempotent by bifunctoriality of $\odot$. We can similarly extend $\mathrm{Kar}(\mathcal{M})$ to a module category over $\mathrm{Kar}(\mathcal{M})$. Finally if $\mathcal{C}$ is additive, then $\mathrm{Kar}(\mathcal{C})$ is additive by applying direct sums componentwise. The *additive Karoubi envelope* of a preadditive category $\mathcal{C}$ is the idempotent complete additive category $\mathrm{Kar}(\mathcal{C}^{\oplus})$ which we denote $\mathrm{Kar}^{\oplus}(\mathcal{C})$.

For diagrammatic monoidal categories $\mathcal{C}$, its additive closure has an easy diagrammatic description by matrices of diagrams. However, in general, diagrams for $\mathrm{Kar}(\mathcal{C})$ or $\mathrm{Kar}^{\oplus}(\mathcal{C})$ are not so simple, since we need to identify every idempotent and place them around morphisms.

Definition 2.4.9. An additive category is *Krull–Schmidt* if every object decomposes into a finite direct sum of objects with local endomorphism rings.

Particularly, all objects decompose into a finite direct sum of indecomposables. The additive Karoubi envelope is not Krull–Schmidt in general. However by results in [Eli+20, Secition 11.3 Appendix 1], the additive Karoubi envelope of the $\Bbbk$-linear diagrammatic categories we will work with are Krull–Schmidt.

Chapter 3

One-colour Diagrammatics

3.1 One-colour Diagrammatic Hecke Category

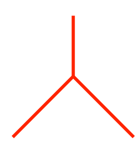
The first one-colour diagrammatic category we explore is the *one-colour (diagrammatic) Hecke category* $\mathcal{H}(S_2)$ for the symmetric group $S_2 = \langle s \mid s^2 = e \rangle$. After describing the category and exploring some properties, we will see that this diagrammatic category is equivalent to the category of Soergel Bimodules under the additive Karoubi envelope.

Remark 3.1.1. All diagrammatics below and in Chapter 4 can also be defined in the language of planar algebras, without mentioning (monoidal) categories, e.g. in [Jon21]. Nevertheless, we study them in the context of categories since they will be seen as diagrammatic versions of important categories in representation theory.

Definition 3.1.2. The *one-colour (diagrammatic) Hecke category* $\mathcal{H}(S_2)$ is a $\mathbb{Z}$-linear monoidal category with the following presentation.

The objects are generated by formal tensors of the non-identity element $s \in S_2$. We will write these tensors as words[1], e.g. s, $ssss =: s^4$, $sssssss =: s^7$, where the tensor product is concatenation. The empty tensor product, i.e. the monoidal identity, will be denoted $\varnothing =: s^0$.

The morphisms are generated, up to isotopy, by the univalent and trivalent vertices

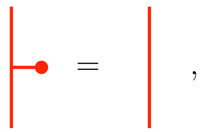
 ,  , (G1)

that are maps $s \to \varnothing$ and $ss \to s$ respectively, and their vertical reflections. Here, we identify the generating object s with its identity morphism $\mathrm{id}_s = |$ to avoid labelling the domain and codomain. We also put a large dot on univalent vertices to signify that the line stops abruptly and does not connect to the top. The composition of such diagrams is appropriate vertical stacking, and the tensor product is horizontal

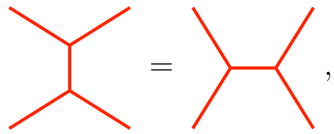
[1]Strings of objects where we do not write the tensor product.

concatenation (without intersection). We can also take formal $\mathbb{Z}$-linear combinations of diagrams. To abuse notation, the empty diagram $\varnothing \to \varnothing$ will be denoted $\varnothing$.

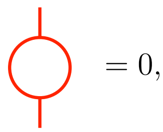
Such diagrams are subject to the following local relations, allowing isotopy,



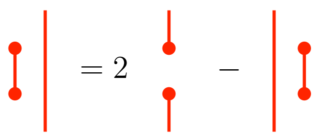
(R1a)



(R1b)



(R1c)

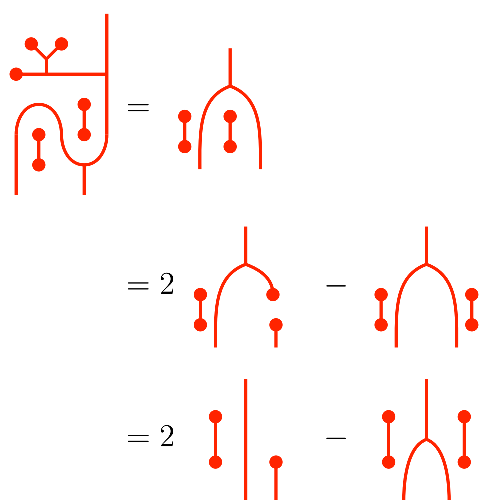


(R1d)

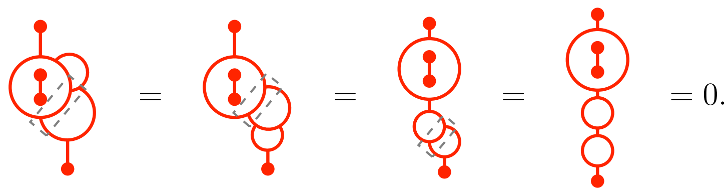
Note that "local" here means that we can apply these relations to any subdiagram. This is called one-colour because we put red for the single generator of S_2.

Remark 3.1.3. It is clear that the s is a Frobenius object in $\mathcal{H}(S_2)$. By the universality of the construction, we see the generators (G1) and their vertical reflections are the unit, multiplication, counit and comultiplication maps, satisfying the Frobenius object relations (R1a) and (R1b).

Example 3.1.4. Using isotopy and the relations in (R1) we can simplify the morphism in $\mathrm{Hom}(ss, s)$,



Example 3.1.5. We can simplify the following morphism in $\mathrm{Hom}(\varnothing, \varnothing)$ to



The first three equalities use the relation (R1b) and the last equality follows from composition with (R1c).

Proposition 3.1.6. *A floating diagram is a diagram in* $\mathrm{Hom}(\varnothing, \varnothing)$*. All floating diagrams are a linear combination of diagrams in which all floating diagrams are barbells.*

Proof. By isotopy and (R1a), floating diagrams can be drawn as barbells with "bubbles" and possibly floating subdiagrams inside each bubble. The Frobenius relation (R1b) allows us to "straighten out" the bubbles to a chain of individual circles. For a floating diagram without floating subdiagrams, it is either 0 by (R1c), or , which can be removed from any floating diagrams containing it via (R1d). Repeating this process produces a linear combination of diagrams where all floating diagrams are barbells. For an example, see the diagram in Example 3.1.5. $\square$

Double Leaves Basis

Let $\mathbb{Z}[\ ]$ be the ring of formal integer polynomials with the variable . The morphism space $\mathrm{Hom}(s^n, s^m)$ has a left (or right) $\mathbb{Z}[\ ]$-basis called the *double leaves* basis, as described in [EW16]. To define this basis, we must first define morphisms known as *light leaves*. This makes use of the group structure of S_2 to reduce words in $\mathcal{H}(S_2)$.

Definition 3.1.7. Let $\phi : (\mathrm{ob}(\mathcal{H}(S_2)), \otimes) \to (S_2, *)$ be the monoid homomorphism[2] mapping $s \mapsto s$ and $\varnothing \mapsto 1$, and $\psi : S_2 \to \mathrm{ob}(\mathcal{H}(S_2))$ be the function that maps $s \mapsto s$ and $1 \mapsto \varnothing$.

The maps ϕ allows words $w = s^n$ to be seen as elements of S_2, and ψ allows $1, s \in S_2$ to be seen as the objects $\varnothing, s \in \mathcal{H}(S_2)$. Clearly, $\phi\psi$ is the identity map on S_2, and the map $\psi\phi : \mathcal{H}(S_2) \to \mathcal{H}(S_2)$ takes objects in the category to one of $\varnothing$ or s in $\mathcal{H}(S_2)$ by considering them as elements in S_2.

Definition 3.1.8. (Subexpression for S_2) Given a word $w = s^n$, a *subexpression* e is a binary word of length n. We can *apply* a subexpression to produce an object $w(e) \in \mathcal{H}(S_2)$, which is w where terms corresponding to 0 in e are replaced with $\varnothing$. For $0 \leq i \leq n$, write $w(e, i)$ for the resultant object of the first i terms in e applied to the first i terms in w. Particularly $w(e, 0) = \varnothing$ and $w(e, n) = w(e)$.

[2]A map that preserves the monoidal product and identity element.

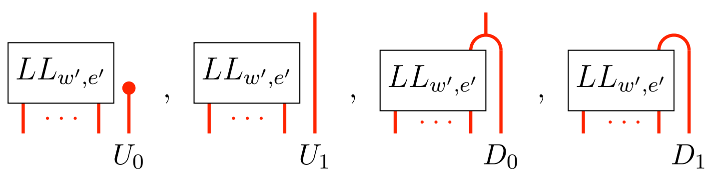
For example, 0000, 0110 and 1011 are subexpressions of $s^4 = ssss$. Applying the third subexpression gives $ssss(1011) = s\varnothing ss = sss$ and $ssss(1011, 3) = sss(101) = s\varnothing s = ss$, by strictness of the monoidal category. Here, each term of the subexpression is a decision to include or exclude the corresponding s in the word, where excluding an s amounts to tensoring with $\varnothing$.

For a word w and subexpression e, we label each term by U_0, U_1, D_0 or D_1. The i-th term is labelled U_* if $\phi(w(e, i-1)) = 1 \in S_2$, and labelled D_* if $\phi(w(e, i-1)) = s \in S_2$. The label's subscript is the corresponding term in e.

Example 3.1.9. For the object $w = ssss$ and subexpression $e = 0101$, we find the labels as recorded in the following table.

Term i	1	2	3	4
Partial w	s	ss	sss	$ssss$
Partial e	0	01	010	0101
$w(e,i)$	$\varnothing$	$\varnothing s = s$	$\varnothing s \varnothing = s$	$\varnothing s \varnothing s = ss$
Labels	U_0	U_0U_1	$U_0U_1D_0$	$U_0U_1D_0D_1$

Definition 3.1.10. The *light leaf* $LL_{w,e} \in \mathrm{Hom}(w, \psi\phi(w(e)))$ for a word w and subexpression e, is defined iteratively as follows. Let $LL_{\varnothing,\varnothing} = \varnothing$ be the empty diagram. Given $LL_{w',e'}$ and $i \in \{0, 1\}$, the light leaf $LL_{w's,e'i}$ is one of

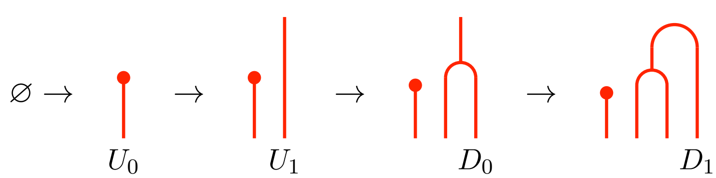


(LL1)

corresponding to the next label, where w' and e' are appropriate subwords[3] of w and e respectively.

Here, the codomain of a light leaf $LL_{w,e}$ is the object $\psi\phi(w(e))$. So if the next label is U_* then the codomain of $LL_{w',e'}$ is $\varnothing$, and when the next label is D_* the codomain of $LL_{w',e'}$ is s. This implies that the recursive definition is consistent.

Example 3.1.11. Following from Example 3.1.9 for $w = ssss$ and $e = 0101$, we have labels $U_0U_1D_0D_1$ so the light leaf $LL_{w,e}$ is built as follows.



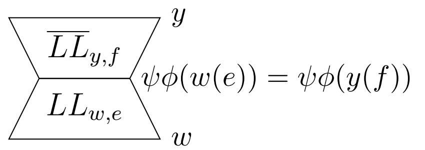
Definition 3.1.12. Let $\overline{LL}_{w,e}$ denote the vertical reflection of $LL_{w,e}$. The *double leaf* for words w, y in $\mathcal{H}(S_2)$ is a composition

$$\mathbb{LL}_{f,e} \coloneqq \overline{LL}_{y,f} \circ LL_{w,e} : w \to y$$

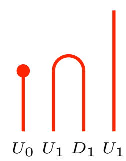
[3] A word with some letters removed.

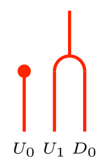
for subexpressions e of w and f of y such that $\psi\phi(w(e)) = \psi\phi(y(f))$.

Visually these are diagrams from w to y factoring through $\psi\phi(w(e)) = \psi\phi(y(f)) \in \{\varnothing, s\}$,



Example 3.1.13. Let $w = ssss$, $y = sss$, $e = 0111$ be a subexpression of w, and $f = 010$ be a subexpression of y. The corresponding light leaves are

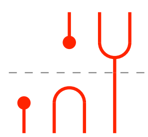
$LL_{w,e} =$ 

and $LL_{y,f} =$ 

.

Then the double leaf $\mathbb{LL}_{f,e} = \overline{LL}_{y,f} \circ LL_{w,e} : ssss \to sss$, factoring through s, is

$\overline{LL}_{y,f}$

$LL_{w,e}$ 
.

Note that these double leaves have no floating diagrams. By Proposition 3.1.6, these all appear as barbells . In order for these double leaves to span morphism spaces, we must insert floating diagrams by taking linear combinations as a left $\mathbb{Z}[\ ]$-module, where the (left) -action is left concatenation by . Since, we can move barbells to the right by isotopy for double leaves factoring through $\varnothing$, or the relation (R1d) if factoring through s, we can equivalently act by $\mathbb{Z}[\ ]$ on the right. Note that for double leaves factoring through s, the "split line" term from (R1d) is also a double leaf with different subexpressions and factoring through $\varnothing$. This leads us to the following theorem.

Theorem 3.1.14 (Elias-Williamson [EW16, Theorem 1.2])**.** *Given objects $w, y \in \mathcal{H}(S_2)$, let $\mathbb{LL}(w, y)$ be the collection of double leaves $\mathbb{LL}_{f,e}$ for subexpressions e of w and f of y, such that $\psi\phi(w(e)) = \psi\phi(y(f))$. Then $\mathbb{LL}(w, y)$ is a basis for* $\mathrm{Hom}(w, y)$ *as a left (or right) $\mathbb{Z}[\ ]$-module.*

A purely diagrammatic proof (of a more general theorem) can be found in [EW16].

Remark 3.1.15. The above light leaves and double leaves, introduced in [EW16], are diagrammatic analogues of Libedinsky's construction in [Lib08].

The morphisms in this category can be graded such that the univalent vertices has degree 1 and trivalent vertices have degree -1. The degree of a diagram is the sum of the degrees of the generators that appear in it. For example, the diagrams from Example 3.1.4 are degree 3. We can easily check that the relations (R1) preserve the grading, so this extends to a $\mathbb{Z}$-grading on $\mathcal{H}(S_2)$.

Equivalence with $\mathbb{S}\mathrm{Bim}$

For a certain polynomial ring R derived from the symmetric group S_2, the category of Bott–Samelson bimodules $\mathbb{BS}\mathrm{Bim}$ is a category of R-R-bimodules generated by a bimodule B_s. Soergel bimodules are R-R-bimodules that appear as direct summands of direct sums of Bott–Samelson bimodules. We remark that the category of Soergel bimodules is a categorification[4] of the Hecke algebra associated to S_2, in which the polynomials in the Kazhdan–Lusztig conjecture appear. These can be defined in more generality, for example see [Eli+20] for details.

The category $\mathrm{Kar}^{\oplus}(\mathcal{H}(S_2))$ is a diagrammatic version of the category of Soergel bimodules $\mathbb{S}\mathrm{Bim}$ for S_2. However $\mathbb{S}\mathrm{Bim}$ is not well behaved with morphisms over $\mathbb{Z}$, so we must first extend the scalars of morphisms spaces in $\mathcal{H}(S_2)$ to[5] $\mathbb{C}$. Formally this is just a left $\mathbb{Z}$-tensor of the morphism spaces with the $\mathbb{C}$-$\mathbb{Z}$-bimodule $\mathbb{C}$, where the right action is induced by the inclusion $\mathbb{Z} \subset \mathbb{C}$. We write $\mathcal{H}_{\mathbb{C}}(S_2)$ for this $\mathbb{C}$-linear monoidal category. This process is quite simple and does not change much about to the category itself. In particular, double leaves in $\mathcal{H}_{\mathbb{C}}(S_2)$ are still $\mathbb{C}[\ ]$-bases[6] for the morphism spaces.

Theorem 3.1.16 (Elias-Williamson [EW16, Theorem 6.30])**.** *The diagrammatic category* $\mathrm{Kar}^{\oplus}(\mathcal{H}_{\mathbb{C}}(S_2))$ *and the category of Soergel Bimodules* $\mathbb{S}\mathrm{Bim}$ *over* S_2 *are equivalent as graded* $\mathbb{C}$*-linear monoidal categories.*

The proof in [EW16] gives an equivalence of graded $\mathbb{C}$-linear monoidal categories $\mathcal{H}_{\mathbb{C}}(S_2) \cong \mathbb{BS}\mathrm{Bim}$. On objects, this sends s to B_s. By construction, $\mathrm{Kar}^{\oplus}(\mathbb{BS}\mathrm{Bim}) \cong \mathbb{S}\mathrm{Bim}$, so this equivalence extends uniquely to $\mathrm{Kar}^{\oplus}(\mathcal{H}_{\mathbb{C}}(S_2)) \cong \mathbb{S}\mathrm{Bim}$.

3.2 Diagrammatic $\mathcal{O}(\mathfrak{sl}_2)$

For this section, our category of interest is the Bernstein-Gelfand-Gelfand category $\mathcal{O}$ for the complex semisimple Lie algebra $\mathfrak{sl}_2(\mathbb{C})$. A description of $\mathcal{O}$ can be found in general in [Hum08, Sections 3.8–3.10], or in [Maz09, Section 5.2] for the case of $\mathfrak{sl}_2(\mathbb{C})$, so we will only give a brief overview. The category $\mathcal{O}$ is a category of certain modules (i.e. representations) over a complex semisimple Lie algebra. It splits into a particular direct sum of subcategories, where, in the case of $\mathfrak{sl}_2$ over $\mathbb{C}$, the non-trivial summands are equivalent as abelian categories to a subcategory $\mathcal{O}_0$ called the principal block of $\mathcal{O}$. Within this, we look to the full subcategory $\mathrm{proj}(\mathcal{O}_0)$ of projective modules in $\mathcal{O}_0$, which, in particular, is additive and idempotent complete.

In [Soe90, Section 2.4], Soergel shows that the category $\mathcal{O}$, and hence the subcategory $\mathrm{proj}(\mathcal{O}_0)$, is a Soergel module category, that is it has an action of the monoidal category $\mathbb{S}\mathrm{Bim}$. By the equivalence in Theorem 3.1.16 we will view $\mathrm{proj}(\mathcal{O})$ as a $\mathcal{H}_{\mathbb{C}}(S_2)$-module

[4] See [Soe07].

[5] The equivalence actually holds in more generality, but we choose $\mathbb{C}$ because it is easy to work with.

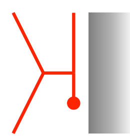
[6] It is easy to check that the set of double leaves tensored with $1 \in \mathbb{C}$ on the left form a basis.

category, extending via the additive Karoubi envelope. Since $\mathcal{H}_{\mathbb{C}}(S_2)$ is diagrammatic, this action allows us to describe $\mathrm{proj}(\mathcal{O}_0)$ (thus essentially $\mathcal{O}_0$ and $\mathcal{O}$) diagrammatically.

Remark 3.2.1. We can pass from $\mathrm{proj}(\mathcal{O}_0)$ to $\mathcal{O}_0$ by observing that the bounded homotopy category $K^b(\mathrm{proj}(\mathcal{O}_0))$ is equivalent to the bounded derived category[7] $D^b(\mathcal{O}_0)$ as graded $\mathbb{C}$-linear monoidal triangulated categories. This is a standard trick in the field, for example see the introduction of [RW18][8]. However, for our purposes, it is not important to understand how this works.

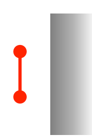
Although we need to work over $\mathbb{C}$ for $\mathrm{proj}(\mathcal{O}_0(\mathfrak{sl}_2))$, the diagrammatic category can be defined over $\mathbb{Z}$.

Definition 3.2.2. Let $\mathcal{DO}_0 \coloneqq \mathcal{DO}_0(\mathfrak{sl}_2)$ be the $\mathbb{Z}$-linear (left) $\mathcal{H}(S_2)$-module category with elements generated by the monoidal identity $\varnothing$ of $\mathcal{H}(S_2)$ and morphisms generated by the empty diagram $\varnothing$. The action of $\mathcal{H}(S_2)$ on the left is left concatenation for both objects and morphisms. In addition to the relations from $\mathcal{H}(S_2)$, the morphisms have one new relation in which diagrams collapse to 0 when there are barbells on the right. To depict this we add a wall on the right of the diagram, i.e. embedding the diagrams in a one-sided planar strip instead of a double-sided strip. For example a morphism may be



.

Therefore we impose the local relation that diagrams are related to the wall by

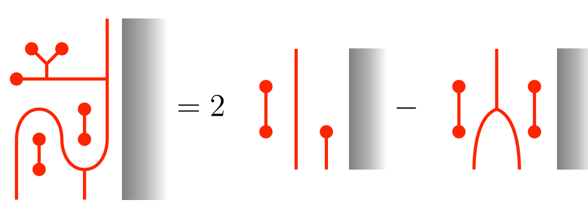


$$= 0. \tag{W1}$$

Note that this local relation applies to any subdiagram *involving the wall*.

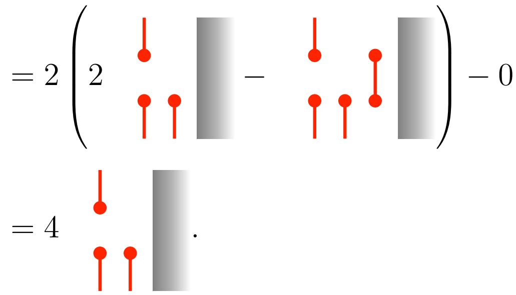
The objects of this category are identical to objects in $\mathcal{H}(S_2)$ and the morphisms are the same modulo the wall relation (W1). Being a left module category, we can only concatenate diagrams on the left by means of the module action. This may seem no different from $\mathcal{H}(S_2)$, however the wall relation (W1) makes right tensors from $\mathcal{H}(S_2)$ inconsistent. For instance, a barbell diagram is 0 and concatenating id_s on the right gives a non-zero diagram. In particular $\mathcal{DO}_0$ is not a monoidal category.

Example 3.2.3. Using the new relation (W1), we can further simplify the morphism in Example 3.1.4 by



[7]These categorical constructions can be found in [Wei94].

[8]A self-contained summary of how diagrammatic categories can be related to abelian categories.



A natural question to ask is whether double leaves still form bases for the morphism spaces here. Notice that double leaves appear in $\mathcal{DO}_0$ by acting on $\varnothing$ by double leaves in $\mathcal{H}(S_2)$. All morphisms in $\mathcal{DO}_0$ are morphisms in $\mathcal{H}(S_2)$ so they can be written as $\mathbb{Z}[\ ]$-linear combinations of double leaves, though some have collapsed to 0. Thus double leaves span the morphism spaces of $\mathcal{DO}_0$ as (left) $\mathbb{Z}[\ ]$-modules. However they may not be linearly independent as neither left nor right modules. For example, any pair of double leaves that factor through $\varnothing$ become 0 when multiplied by on either side (by translating the barbell to the right). Although double leaves are not always a basis for its respective morphism space as $\mathbb{Z}[\ ]$-modules, it turns out they are a basis over $\mathbb{Z}$.

Lemma 3.2.4. *Let $\pi : \mathrm{mor}(\mathcal{H}(S_2)) \to \mathrm{mor}(\mathcal{DO}_0)$ be the projection map which takes a morphism to the result of its action on the empty diagram $\varnothing$. Then the image $\pi(\mathbb{LL}(w, y))$ is a basis for $\mathrm{Hom}_{\mathcal{DO}_0}(w, y)$ as a $\mathbb{Z}$-module.*

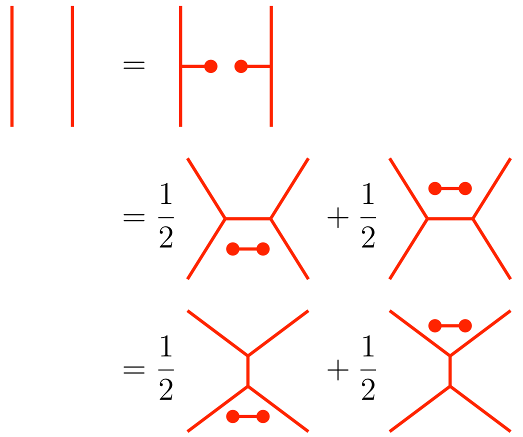
Proof. We consider morphisms $\mathrm{Hom}(w, y)$ in $\mathcal{DO}_0$ for fixed objects w, y, and write $\mathbb{LL} := \pi(\mathbb{LL}(w, y))$ for the set of double leaves in $\mathcal{DO}_0$. Any diagram in $\mathcal{DO}_0$ can be written as a $\mathbb{Z}$-linear combination of morphisms without floating diagrams, by simplifying them to barbells, pulling them to the right and killing them with (W1). We can write each of these as a $\mathbb{Z}[\ ]$-linear combination of double leaves by (3.1.14) with the right action, and reduce it to a $\mathbb{Z}$-linear combination by (W1). This implies that $\mathbb{LL}$ spans $\mathrm{Hom}(w, y)$ as a $\mathbb{Z}$-module. Since the barbell-wall relation (W1) has no effect on $\mathbb{Z}$-linear combinations of $\mathbb{LL}$, it follows from linear independence over $\mathbb{Z}[\ ]$ that they are linearly independent over $\mathbb{Z}$ in $\mathcal{DO}_0$. □

Equivalence with $\mathrm{proj}(\mathcal{O}_0)$

We aim to prove this diagrammatic category is equivalent to $\mathrm{proj}(\mathcal{O}_0)$. To that end, we will shift our focus from $\mathbb{Z}$ to $\mathbb{C}$ for the remainder of this section. From now on, $\mathcal{DO}_0$ is the $\mathbb{C}$-linear $\mathcal{H}_{\mathbb{C}}(S_2)$-module category obtained by extending the scalars from $\mathbb{Z}$ to $\mathbb{C}$. The above discussion and Lemma 3.2.4 still apply to $\mathcal{DO}_0$ over $\mathbb{C}$.

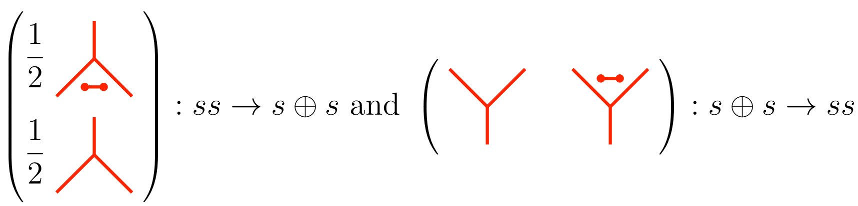
Lemma 3.2.5. *In the additive closure of $\mathcal{H}_{\mathbb{C}}(S_2)$ we have an explicit isomorphism $ss \cong s \oplus s$, as detailed in the following proof. Particularly, these are isomorphisms in the additive closure of $\mathcal{DO}_0$.*

Proof. In $\mathcal{H}_{\mathbb{C}}(S_2)$ we have the relation

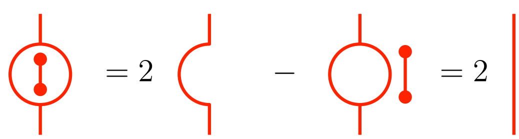


(3.2.6)

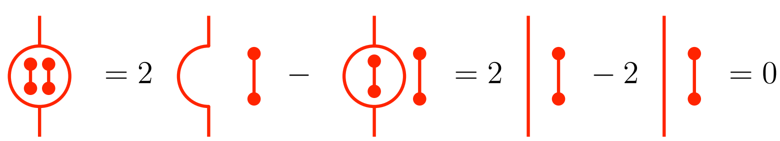
This implies that in $\mathcal{H}_{\mathbb{C}}(S_2)^{\oplus}$, we have maps



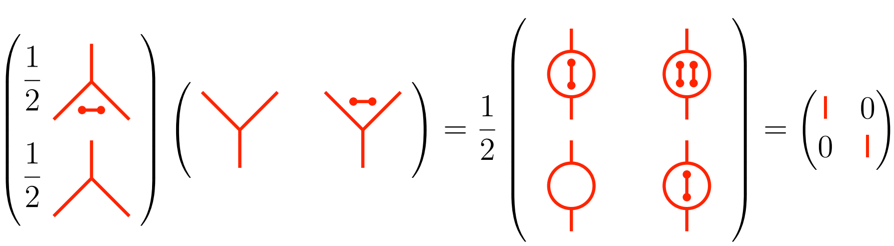
We will check that these maps are inverses. By (R1d) and (R1c),



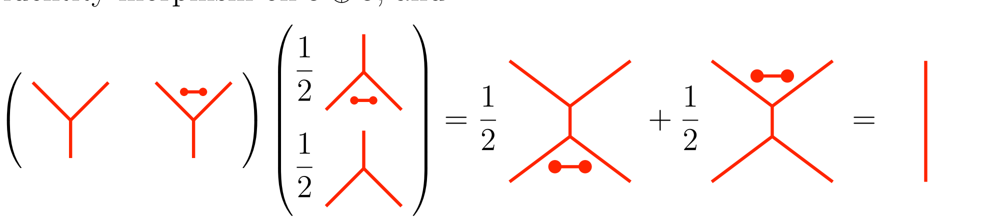
and



Then



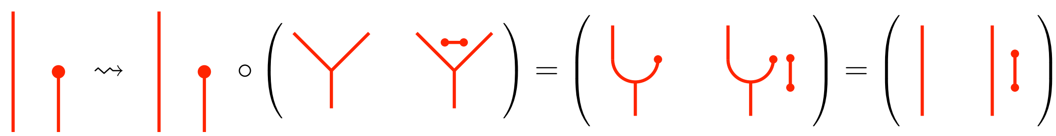
is the identity morphism on $s \oplus s$, and



is the identity morphism on ss, by (3.2.6). □

By composing with these isomorphisms we can view morphisms as matrices of diagrams whose domain and codomain are in $\{\varnothing, s\}$. We can also retrieve the original diagram by composing with the inverse.

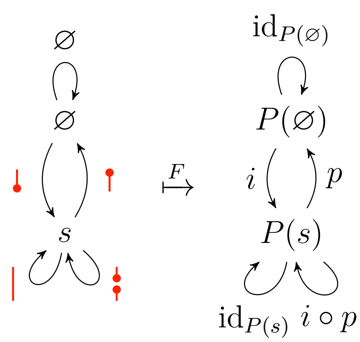
Example 3.2.7. The following morphism in $\mathrm{Hom}(ss, s)$ can be considered as a morphism $s \oplus s \to s$ by precomposing with the above isomorphism $s \oplus s \to ss$.



For larger powers of s, we can apply this repeatedly each entry of the matrix.

As a shorthand, we write $\mathrm{proj}(\mathcal{O}_0)$ for $\mathrm{proj}(\mathcal{O}_0(\mathfrak{sl}_2))$. The work of Soergel in [Soe90, Section 2.4] shows that $\mathrm{proj}(\mathcal{O}_0)$ is a Soergel module, i.e. it has a left action of the category of Soergel bimodules defined by applications of the translation functors $\Theta_\varnothing, \Theta_s \in \mathrm{End}(\mathcal{O})$ in [Maz09, Section 5.8] corresponding to elements in S_2. We will construct a functor that maps faithfully into a full subcategory of $\mathrm{proj}(\mathcal{O}_0)$, which will is entirety of $\mathrm{proj}(\mathcal{O}_0)$ under the additive Karoubi envelope. This is a similar strategy to the proof of Theorem 3.1.16.

Definition 3.2.8. Let $F : \mathcal{DO}_0^{\oplus} \to \mathrm{proj}(\mathcal{O}_0)$ be the $\mathbb{C}$-linear $\mathcal{H}_{\mathbb{C}}(S_2)$-module functor that sends the empty object $\varnothing$ to the trivial module $P(\varnothing)$, and the Soergel module action corresponding to s to the translation functor Θ_s. Then the object s maps to $\Theta_s(P(\varnothing)) =: P(s)$, and for example s^3 maps to $\Theta_s^3(P(\varnothing)) = \Theta_s\Theta_s\Theta_s(P(\varnothing))$, the composition of three Θ_s applied to $P(\varnothing)$. In order for F to be functorial, it must map identity diagrams $s^n \to s^n$ to $\mathrm{id}_{\Theta_s^n(P(\varnothing))}$. On non-identity maps, we let $F(\ )$ be the inclusion $i : P(\varnothing) \to P(s)$ and $F(\ )$ be the projection $p : P(s) \to P(\varnothing)$. We then extend F by composition, additivity and linearity. The mapping of F is depicted by the following picture.



(3.2.9)

Note that extending by composition is not problematic because the module action of $\mathcal{H}(S_2)$ is functorial and and are generators in $\mathcal{H}(S_2)$. Note that the action of the translation functors $\Theta_\varnothing$ and Θ_s on the diagrammatic side looks like a left tensor by the identity morphism $\mathrm{id}_\varnothing$ and id_s, respectively, but we do not need this for the proof.

Lemma 3.2.10. *The functor F is well defined.*

Proof. From [Maz09, Proposition 5.90], there is a natural isomorphism $\Theta_s\Theta_s \cong \Theta_s \oplus \Theta_s$ analogous to the isomorphism $ss \cong s \oplus s$ given in the proof of Lemma 3.2.5. Given a morphism in $\mathcal{DO}_0^{\oplus}$ from s^n to s^m, repeated precomposition and postcomposition with $ss \to s \oplus s$ and $s \oplus s \to ss$ from Lemma 3.2.5 results in a matrix of diagrams with domain and codomain in $\{\varnothing, s\}$. By Lemma 3.2.4 over $\mathbb{C}$, $\mathrm{Hom}(\varnothing, \varnothing)$ has a basis $\{\varnothing = \mathrm{id}_\varnothing\}$, $\mathrm{Hom}(s, \varnothing)$ has a basis $\{\ \}$, $\mathrm{Hom}(\varnothing, s)$ has a basis $\{\ \}$, and $\mathrm{Hom}(s, s)$ has a basis $\{\mathrm{id}_s, \ \circ\ \}$. Therefore, extending by linearity, the picture above completely describes the image of F.

Next we check that all the relations are preserved. From classical results e.g. [Maz09, Proposition 5.84 and Lemma 5.87], it follows that Θ_s is a Frobenius object in the category of endofunctors of $\mathcal{O}$. Then there are unit, counit, multiplication and comultiplication natural transformations satisfying coherence relations in the Frobenius object structure. Applying these to $P(\varnothing)$ result in the same relations in $\mathrm{proj}(\mathcal{O}_0)$ for $P(\varnothing), P(s)$ and $\Theta_s^2(P(\varnothing))$. The projection and inclusion maps above are exactly the unit and counit of Θ_s evaluated at $P(\varnothing)$, and the trivalent vertices provided by projecting the isomorphisms in Lemma 3.2.5 map exactly to the multiplication and comultiplication maps. Hence the Frobenius relations (R1a) and (R1b) are satisfied. It follows from the Soergel module structure in [Soe90, Section 2.4] that the relations (R1c) and (R1d) hold in $\mathrm{proj}(\mathcal{O}_0)$, and that $p \circ i = 0$, which is analogous[9] to the barbell-wall relation (W1). Hence all the relations in $\mathcal{DO}_0$ are preserved by F. By construction, F preserves $\mathbb{C}$-linear combinations and the Soregel module structure in [Soe90], so F is well defined as a functor between $\mathbb{C}$-linear $\mathcal{H}(S_2)$-module categories. □

Theorem 3.2.11 (Soergel, [Soe90, Endomorhihsmensatz 7, Struktursatz 9 and Section 2.4])**.** *The diagrammatic category* $\mathrm{Kar}^{\oplus}(\mathcal{DO}_0(\mathfrak{sl}_2))$ *and* $\mathrm{proj}(\mathcal{O}_0(\mathfrak{sl}_2))$ *are equivalent as additive* $\mathbb{C}$*-linear* $\mathcal{H}(S_2)$*-module categories.*

Proof. First we show that F is full and faithful. The mapping of F on all morphism spaces are determined by those depicted in the picture (3.2.9). So for full and faithfulness, it suffices to compare the $\mathbb{C}$-dimensions of morphism spaces between objects shown in (3.2.9). The double leaves bases mentioned in Lemma 3.2.10 are precisely the diagrams depicted in the image. It follows from the description of $P(\varnothing)$ and $P(s)$ in [Maz09, Section 5.2] that the maps i,p, $i \circ p$ are a basis for morphisms involving $P(\varnothing)$ and $P(s)$ as shown in (3.2.9). Due to $\Theta_s\Theta_s \cong \Theta_s \oplus \Theta_s$, the morphisms p and i are enough to describe all the morphisms in $\mathrm{proj}(\mathcal{O}_0)$, up to conjugating with the isomorphism. From this, it is clear that the dimensions of the Hom spaces coincide. Therefore F is fully faithful.

All objects in $\mathrm{proj}(\mathcal{O}_0)$ appear as direct sums and direct summands of the elements $\Theta_s^n(P(\varnothing))$ for non-negative integers n. Therefore the additive Karoubi envelope induces an equivalence $\mathrm{Kar}^{\oplus}(\mathcal{DO}_0) \cong \mathrm{proj}(\mathcal{O}_0)$ as additive $\mathbb{C}$-linear $\mathcal{H}(S_2)$-module categories. □

[9] This relation extends to the analogue of the local barbell-wall relation, where all "barbell on the right" morphisms in $\mathrm{proj}(\mathcal{O}_0)$ are linear combinations of applications of Θ_s to $p \circ i$, which is 0.

This result is essentially due to Soergel [Soe90, Endomorhihsmensatz 7, Struktursatz 9 and Section 2.4] (see also [Soe98]) but this was not its original formulation. Nevertheless we attribute this theorem to Soergel.

Remark 3.2.12. Noting that the new relations preserve gradings given in $\mathcal{H}(S_2)$, $\mathcal{DO}_0$ is graded by the same grading as $\mathcal{H}(S_2)$ in Section 3.1. Then the equivalence $\mathrm{Kar}^{\oplus}(\mathcal{DO}_0) \cong \mathrm{proj}(\mathcal{O}_0)$ induces a grading on $\mathrm{proj}(\mathcal{O}_0)$ and hence a grading of $\mathcal{O}$, which is otherwise ungraded.

Chapter 4

Two-colour Diagrammatics

4.1 Two-colour Diagrammatic Hecke Category

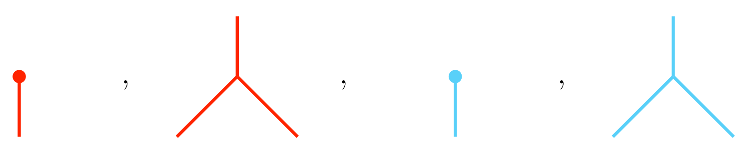
In the previous chapter, the diagrammatic category $\mathcal{H}(S_2)$ is determined by the symmetric group generated by one element S_2, which brought about one-colour diagrammatics. This chapter explores a more complex example by adding an extra generator; that is, another colour. In particular, we consider the affine symmetric group on two elements[1] $\widetilde{S}_2 = \langle s, t \mid s^2 = t^2 = 1 \rangle$.

The definition is similar to the one-colour case, so we will be brief.

Definition 4.1.1. The *two-colour (diagrammatic) Hecke category* $\mathcal{H}(\widetilde{S}_2)$ is a (strict) $\mathbb{Z}$-linear monoidal category given by the following presentation.

Objects in $\mathcal{H}(\widetilde{S}_2)$ are generated by formal tensor products of the non-identity elements $s, t \in \widetilde{S}_2$. As before, we write objects as words such as $sstttst =: s^2t^3st$ where the tensor product is concatenation, and associate the colour red to s and blue to t. The empty word is the monoidal identity, which we write as $\varnothing$.

The morphisms are generated, up to isotopy, by the univalent and trivalent vertices

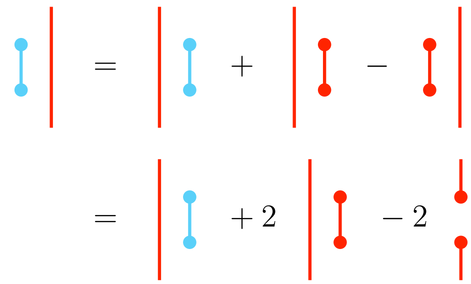
 (G2)

that are maps $s \to \varnothing$, $ss \to s$, $t \to \varnothing$ and $tt \to t$ respectively, and their vertical reflections. As in the one-colour case, tensor product is horizontal concatenation[2], composition is appropriate vertical stacking, and we denote the empty diagram $\varnothing \to \varnothing$ by $\varnothing$. For each colour, these diagrams have the one-colour relations given by (R1). Two

[1] Also known as the infinite dihedral group.

[2] Note that we do not impose any restrictions against tensoring different coloured diagrams.

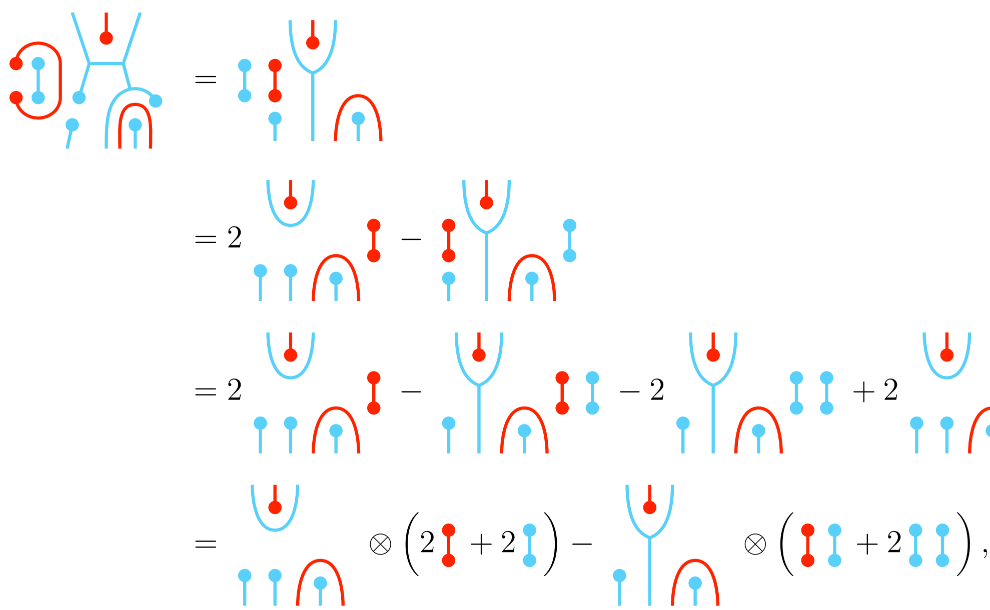
coloured strands relate to each other by the *two-colour relations*



(R2)

and with red and blue swapped.

Example 4.1.2. Using the one-colour and two-colour relations on the following morphism in $\mathrm{Hom}(ttsts, tst)$ we have



where the last line uses linearity of the tensor product.

By restricting to one colour, we see $\mathcal{H}(S_2)$ appears as a full subcategory in red, and in blue.

Remark 4.1.3. Notice that the red and blue lines never cross as no generators allow crossings. This is a consequence of working over affine S_2 in which there are no relations between the generators s and t. In a group such as $S_3 = \langle s, t \mid sts = tst \rangle$, the relation $sts = tst$ provides another generator $sts \to tst$ (and its vertical reflection), depicted as a 6-valent vertex, and a few more diagrammatic relations. On a diagram, these will appear as crossings.

In this two-colour case, Proposition 3.1.6 holds by replacing (R1d) with (R2) in the proof. This handles the new possibility of floating subdiagrams with alternating colours.

Definition 4.1.4. For a group with a presentation in terms of generators and relations, the *length* of a product of generators is the number of generators in the product. We say that a product of generators is *reduced* if it's length cannot be shortened with relations.

In $\widetilde{S}_2$ products can be shortened by the relation $s^2 = t^2 = 1$. For instance, *sttsts* is not reduced because it is equal to ts which is reduced. Notice that for $\widetilde{S}_2$ each element can be written uniquely as a reduced product of generators. This is true since otherwise we have two distinct reduced products for the same element in $\widetilde{S}_2$ so they must be related by $s^2 = t^2$. This means they can be reduced further by $s^2 = t^2 = 1$, which contradicts minimality of their length. It is clear that the reduced products in $\widetilde{S}_2$ are either the identity or alternating products of s and t.

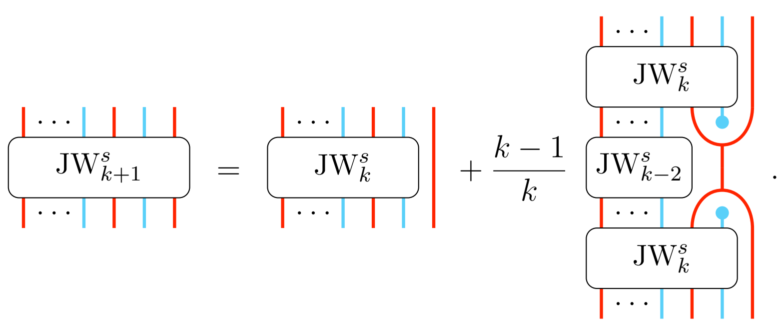
We can put the relations of $\widetilde{S}_2$ onto words in $\mathcal{H}(\widetilde{S}_2)$ similarly to Section 3.1.

Definition 4.1.5. Let $\phi : (\mathrm{ob}(\mathcal{H}(\widetilde{S}_2)), \otimes) \to (\widetilde{S}_2, *)$ be the monoid homomorphism mapping $\varnothing \mapsto 1$, $s \mapsto s$ and $t \mapsto t$. Define $\psi : \widetilde{S}_2 \to \mathrm{ob}(\mathcal{H}(\widetilde{S}_2))$ that maps elements $x \in \widetilde{S}_2$ to the tensor product of s and t in $\mathcal{H}(\widetilde{S}_2)$ corresponding to the reduced product of x in $\widetilde{S}_2$.

The function ψ is well defined because reduced products are unique and two different reduced products cannot equal the same element of $\widetilde{S}_2$. Note that the image $\psi(\widetilde{S}_2)$ is the set containing $\varnothing$ and words of alternating s and t. The composition $\psi\phi : \mathcal{H}(\widetilde{S}_2) \to \mathcal{H}(\widetilde{S}_2)$ maps words w to the tensor of s and t corresponding to the reduced product of $\phi(w)$, and $\phi\psi$ is the identity map on $\widetilde{S}_2$.

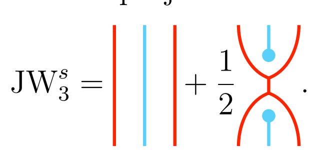
Jones–Wenzl Projectors

Definition 4.1.6. (Jones–Wenzl Projectors) Consider words w in $\mathcal{H}(\widetilde{S}_2)$ corresponding to reduced products in $\widetilde{S}_2$ i.e. alternating s and t. Suppose that the leftmost generator in w is s. Then *Jones–Wenzl projector* $\mathrm{JW}_k^s \in \mathrm{Hom}(w, w)$ is defined recursively such that $\mathrm{JW}_0^s = \mathrm{id}_\varnothing$, $\mathrm{JW}_1^s = \mathrm{id}_s$, $\mathrm{JW}_2^s = \mathrm{id}_{st}$ and for $k \geq 2$ even,

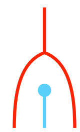


For k odd, we just swap red and blue to the right of the dots. If w starts with t, we can define JW_i^t by swapping all reds and blues in the recursive formula.

Example 4.1.7. The first non-trivial JW-projector is



Definition 4.1.8. A *pitchfork* is a diagram of the form



possibly with the colours swapped or vertically reflected.

Proposition 4.1.9. *The Jones–Wenzl projector is an idempotent, i.e.* $\mathrm{JW}_k \circ \mathrm{JW}_k = \mathrm{JW}_k$*, and is killed by pitchforks on the top and the bottom.*

This result follows from [Eli16, Theorem 5.29] and the below remark.

Remark 4.1.10. Jones–Wenzl projectors are originally defined to be elements in the Temperley–Lieb algebra satisfying certain properties. The above recursive formula was first shown in [Wen87], which we just take for its definition. The functor given in [Eli16, Section 5.3.2] sends them into our diagrammatic category. The proof of the Temperley–Lieb version of Proposition 4.1.9 is a classical result and can be found, for example, in [Wen87] or [Mor15].

The JW-projectors are important idempotents in our category, as their images are all the indecomposables in the additive Karoubi envelope of $\mathcal{H}(\widetilde{S}_2)$, see [Eli16, Section 5.4.2].

Double Leaves Basis

As in the one-colour case, there are bases for morphism spaces in $\mathcal{H}(\widetilde{S}_2)$ given by double leaves, which we will build up to. The following definition is a more general version of Definition 3.1.8.

Definition 4.1.11 (Subexpression)**.** Given a word w of length n, a *subexpression* e is a binary string of length n. A subexpression can be *applied* to produce an word $w(e)$, which is w where terms corresponding to 0 in e are replaced with $\varnothing$. For $1 \leq i \leq n$, we write $w(e, i)$ for the result of the first i terms of e applied to the first i terms in w. Particularly $w(e, 0) = \varnothing$ and $w(e, n) = w(e)$.

For example, in $\mathcal{H}(\widetilde{S}_2)$, if $w = sttts$ and $e = 11001$ then $w(e) = st\varnothing\varnothing s = sts$ and $w(e, 3) = sts(110) = st\varnothing = st$ in $\mathcal{H}(\widetilde{S}_2)$.

Let the *length* of a word be the number of generators in its tensor product. As before, given an object w and a subexpression e of w, we label each of the n terms by one of U_0, U_1, D_0, D_1. Let $i \geq 0$, and write x for the i-th term of w. We label the i-th term U_* if $\psi\phi(w(e, i-1) \otimes x)$ is longer than $\psi\phi(w(e, i-1))$. In other words we write U_* if the next term of w will make $\psi\phi$ applied to the partially evaluated subexpression longer, regardless of the i-term of e. We label D_* if $\psi\phi(w(e, i-1) \otimes x)$ is longer than $\psi\phi(w(e, i-1))$. The label's subscript is the i-th term of e. Note that this construction is well defined because $\psi\phi(w(e, i-1) \otimes x) = \psi(\phi(w(e, i-1)) * \phi(x)) = \psi(\phi(w(e, i-1)) * x)$

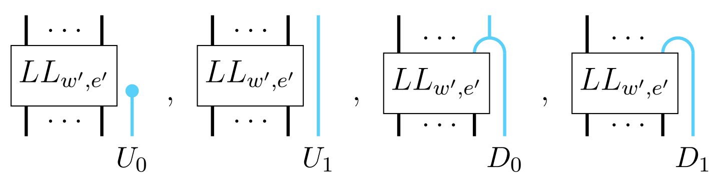
is always either longer or shorter, since the last element of the reduced product is either the same as x or different. When they are the same, the word is shorter via $s^2 = t^2 = 1$, and when they are different it is longer as no relations can make it shorter.

Remark 4.1.12. This description of the labels (via. reduced products) is more akin to the definition in general for Coxeter groups, than in Section 3.1.

Example 4.1.13. Consider the word $w = sttst$ and subexpression $e = 10011$. The labels can be constructed as in the following table.

Term i	1	2	3	4	5
Partial w	s	st	stt	$stts$	$sttst$
Partial e	1	10	100	1001	10011
$w(e,i)$	s	$s\varnothing$	$s\varnothing\varnothing = s$	$s\varnothing\varnothing s = ss$	$s\varnothing\varnothing st = sst$
Labels	U_1	U_1U_0	$U_1U_0U_0$	$U_1U_0U_0D_1$	$U_1U_0U_0D_1U_1$

Definition 4.1.14. The *light leaf* $LL_{w,e} \in \mathrm{Hom}(w, \psi\phi(w(e)))$ for a word w and a subexpression e is defined iteratively as follows. Let $LL_{\varnothing,\varnothing} = \varnothing$ be the empty diagram. Given appropriate subwords w' and e' of w and e respectively, and if the next terms are t in w and i in e, the light leaf $LL_{w'x,e'i}$ is one of

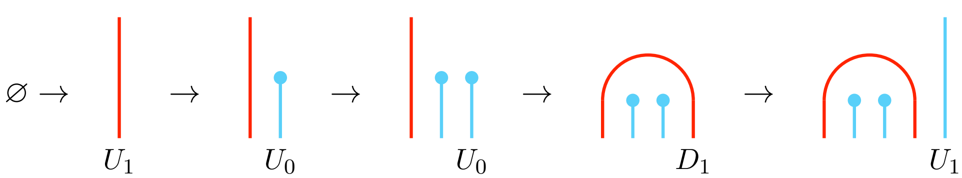


(LL2)

corresponding to the next label. If the next term in w is s, then we have red strands on the right instead.

Notice that the codomain of a light leaf $LL_{w,e}$ is the object $\psi\phi(w(e))$. So if the next label is U_* then the codomain of $LL_{w',e'}$ does not end with the colour corresponding to x, and if the next label is D_* the codomain of $LL_{w',e'}$ ends with a strand with the colour corresponding to x. This implies the recursive definition in the diagram above is consistent. Note that in the case of D_*, one of the black strands in the domain of $LL_{w',e'}$ must have the colour of x in order for the colour to appear in its codomain.

Example 4.1.15. Following from Example 4.1.13, with $w = sttst$, $e = 10011$ and labels $U_1U_0U_0D_1U_1$, the light leaf $LL_{w,e}$ is build as follows.



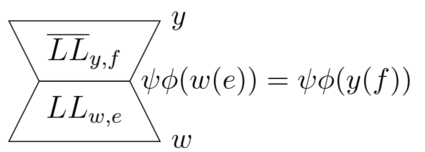
We can define double leaves exactly as we did in Definition 3.1.12.

Definition 4.1.16. Let $\overline{LL}_{w,e}$ denote the vertical reflection of $LL_{w,e}$. The *double leaf* for words w, y in $\mathcal{H}(\widetilde{S}_2)$ is a composition

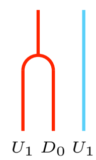
$$\mathbb{LL}_{f,e} \coloneqq \overline{LL}_{y,f} \circ LL_{w,e} : w \to y$$

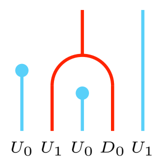
for subexpressions e of w and f of y such that $\psi\phi(w(e)) = \psi\phi(y(f))$.

Diagrammatically these are morphisms from w to y factoring through $\psi\phi(w(e)) = \psi\phi(y(f)) \in \psi(\widetilde{S}_2)$,



Example 4.1.17. Let $w = sst$ with the subexpression $e = 101$ and $y = tstst$ with the subexpression $f = 01001$. The corresponding light leaves are

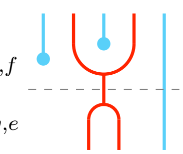
$LL_{w,e} =$ 

and $LL_{y,f} =$ 

.

Then the double leaf $\mathbb{LL}_{f,e} = \overline{LL}_{y,f} \circ LL_{w,e} : sst \to tstst$, factoring through st, is

$\overline{LL}_{y,f}$

$LL_{w,e}$

.

As with the one-colour case, double leaves form a basis up to floating diagrams.

Theorem 4.1.18 (Elias-Williamson [EW16, Theorem 1.2])**.** *Given objects $w, y \in \mathcal{H}(\widetilde{S}_2)$, let $\mathbb{LL}(w, y)$ be the collection of double leaves $\mathbb{LL}_{f,e}$ for subexpressions e of w and f of y, such that $\psi\phi(w(e)) = \psi\phi(y(f))$. Then $\mathbb{LL}(w, y)$ is a basis for* Hom(w, y) *as a left (or right)* $\mathbb{Z}[\ ,\ ]$*-module.*

The category is graded such that the univalent vertices have degree 1 and trivalent vertices have degree -1 for either colour.

Let $\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2)$ be the $\mathbb{C}$-linear monoidal category obtained by extending the scalars of morphisms spaces in $\mathcal{H}(\widetilde{S}_2)$ from $\mathbb{Z}$ with $\mathbb{C}$. All the results above also hold for $\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2)$. Additionally, a result similar to Theorem 3.1.16 holds.

Theorem 4.1.19 (Elias-Williamson [EW16, Theorem 6.30])**.** *The diagrammatic category* $\mathrm{Kar}^{\oplus}(\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2))$ *and the category of Soergel Bimodules* $\mathbb{S}\mathrm{Bim}$ *over $\widetilde{S}_2$ are equivalent as graded $\mathbb{C}$-linear monoidal categories.*

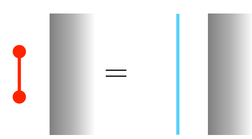
Remark 4.1.20. The construction of the diagrammatic Hecke category, light leaves, Theorem 3.1.14 and Theorem 3.1.16 all generalise to general Coxeter groups. The details can be found in [EW16].

4.2 Diagrammatic $\mathrm{Tilt}(\mathfrak{sl}_2)$

With the two-colour diagrammatic category, we can construct diagrammatics for the category of tilting modules $\mathrm{Tilt}(\mathfrak{sl}_2)$. This category is described in [AT17, Section 2] so we just give a brief introduction. We consider quantum[3] $\mathfrak{sl}_2$ at a primitive complex 2ℓ-th root of unity, for a fixed $\ell \in \mathbb{Z}_{\geq 2}$. An indecomposable module of this algebra is *tilting* if it appears as a direct summand of a tensor product of the defining two-dimensional representation of quantum $\mathfrak{sl}_2$. A general tilting module is a finite direct sum of these indecomposable tilting modules, which collect into the category $\mathrm{Tilt}(\mathfrak{sl}_2)$. This category splits[4] into a direct sum $\mathrm{Tilt}(\mathfrak{sl}_2) \cong \bigoplus_{i\in -1,\ldots,\ell-1} \mathrm{Tilt}_i(\mathfrak{sl}_2)$ such that the categories for indexes -1 and $\ell-1$ are semisimple, where morphisms are trivial by Schur's Lemma, and all other categories are equivalent. We can thus focus on $\mathrm{Tilt}_0(\mathfrak{sl}_2)$, called the principal block of $\mathrm{Tilt}(\mathfrak{sl}_2)$. This category is additive, idempotent complete, Krull–Schmidt and has indecomposables indexed by elements of $\widetilde{S}_2$.

Although we need to be over $\mathbb{C}$ for $\mathrm{Tilt}(\mathfrak{sl}_2)$, the following diagrammatic category can be defined over $\mathbb{Z}$.

Definition 4.2.1. Let $\mathcal{DT}_0 \coloneqq \mathcal{DT}_0(\mathfrak{sl}_2)$ be the $\mathbb{Z}$-linear (left) $\mathcal{H}(\widetilde{S}_2)$-module category with elements generated by the monoidal identity $\varnothing$ of $\mathcal{H}(\widetilde{S}_2)$, and morphisms generated by the empty diagram $\varnothing$. The action of $\mathcal{H}(\widetilde{S}_2)$ on the left is left concatenation for objects and morphisms. The relations on diagrams in $\mathcal{DT}_0(\mathfrak{sl}_2)$ are inherited from those in $\mathcal{H}(\widetilde{S}_2)$. Additionally, we imagine a wall on the right of diagrams and impose the local wall-annihilation relations



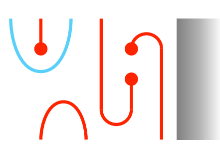
$= 0.$ (W2)

In other words, if a red barbell or blue string can come close to the wall without anything in between, then the diagram is 0. Note that local relations in (W2) must include the wall.

Similar to $\mathcal{DO}_0$, this is not a monoidal category due to the new relations (W2).

Example 4.2.2. In this category, the morphism in Example 4.1.2 collapses to 0 because all the diagrams have either blue or barbell on the right.

Example 4.2.3. Consider the diagram



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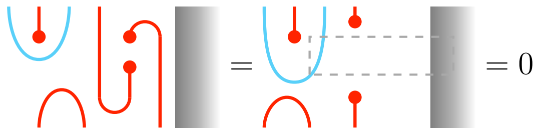
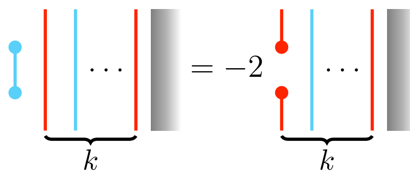
[3]Quantum groups are a generalisation of Lie algebras.
[4]For example, in [AT17, Lemma 2.26].

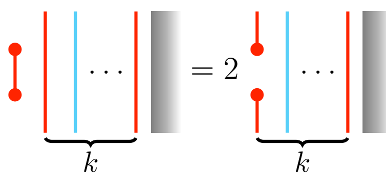
By isotopy and the local relation (W2) we have that



Proposition 4.2.4. *In the following diagrams, the domain and codomain alternate colours and we only depict the case for odd k. For even k, one can swap the colours red and blue on the left of the dots. For integers $k \geq 1$*

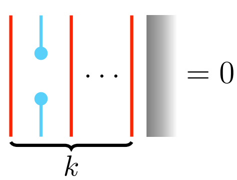


(4.2.4a)



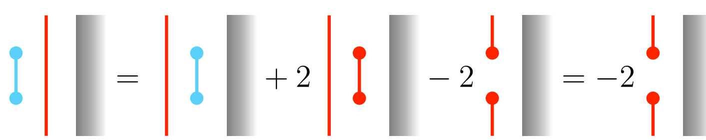
(4.2.4b)

and for $k \geq 3$

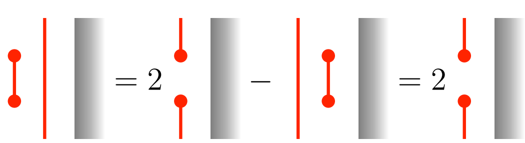


(4.2.4c)

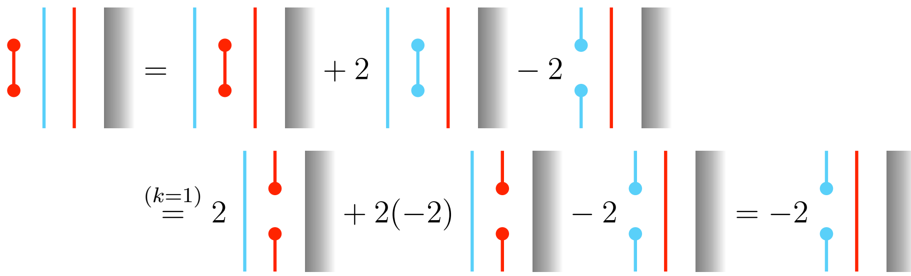
Proof. For $k \in \{1, 2\}$, we check the second two relations by hand. For $k = 1$, pulling the barbell through the line using (R1d) and (R2), then applying (W2) gives us



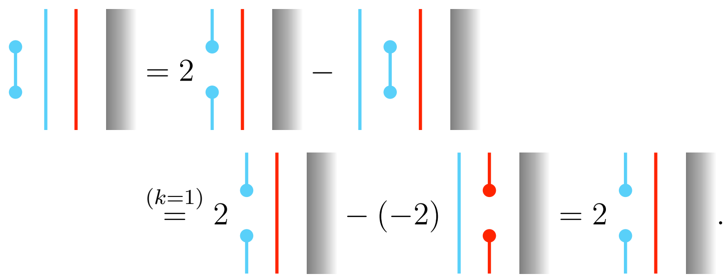
and



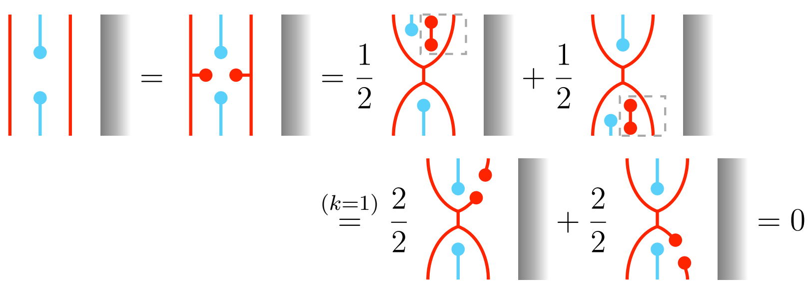
By a similar proof, using the $k = 1$ relations locally, we have for $k = 2$,



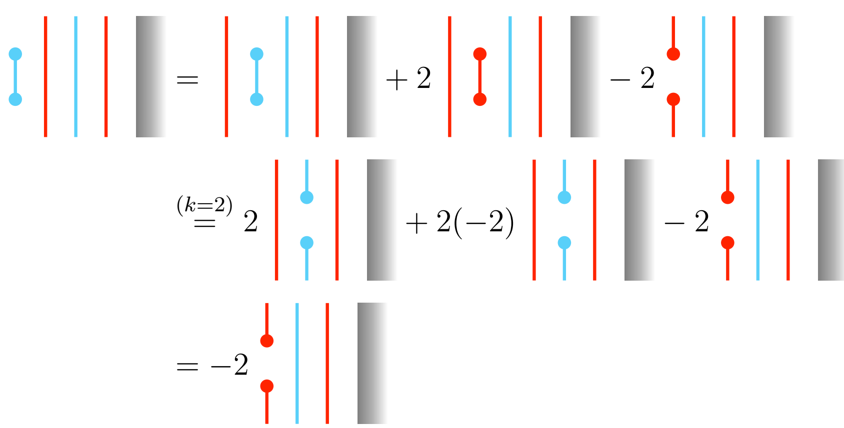
and



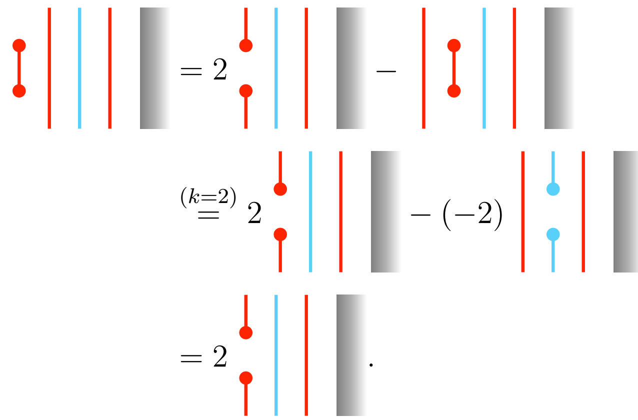
Now we proceed by induction on k. For $k = 3$ we first show (4.2.4c). By a similar argument to (3.2.6) we have



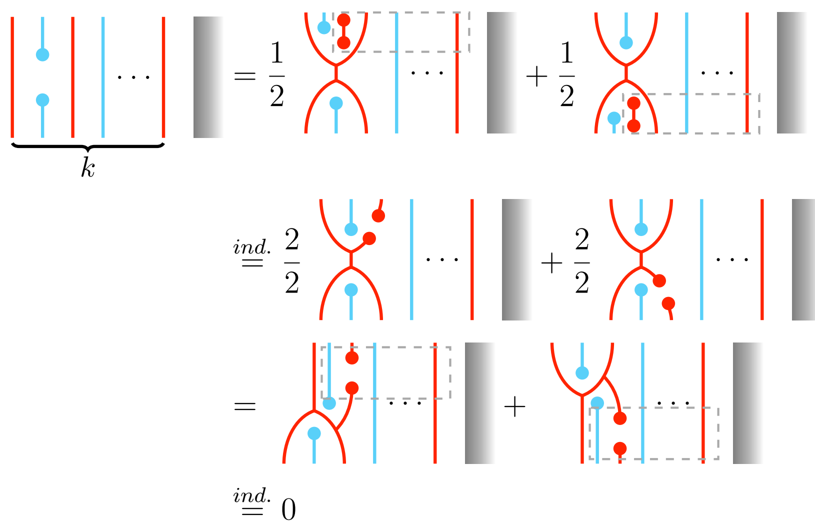
since the wall is accessible by the blue dot. Then



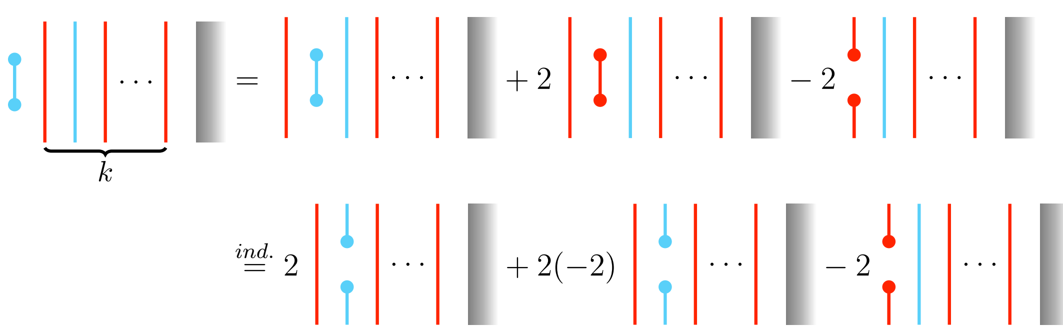
and

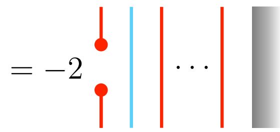


Let $k \geq 4$ and assume the relations hold for diagrams with $k-1, k-2, ..., 1$. We will depict the diagrams with odd k, where the even k case can be retrieved by swapping red and blue to the left of the dots. Again, the argument to (3.2.6) implies

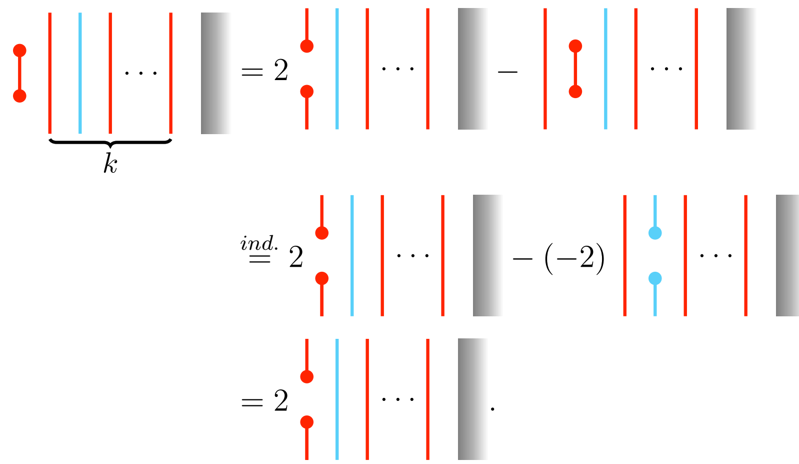


where the string to directly left of the dots is the right red string when $k = 4$. Furthermore, we have





and



$\square$

The objects of this category are identical to objects in $\mathcal{H}(\widetilde{S}_2)$ and the morphisms are the same modulo the wall relations (W2). Naturally, we wonder whether double leaves form bases for the morphism spaces in $\mathcal{DT}_0$. It is easy to see that double leaves appear in $\mathcal{DT}_0$ by acting on $\varnothing$ by double leaves in $\mathcal{H}(\widetilde{S}_2)$. All morphisms in $\mathcal{DT}_0$ are morphisms in $\mathcal{H}(\widetilde{S}_2)$ so they can be written as $\mathbb{Z}[\ ,\ ]$-linear combinations of double leaves, though some of these leaves have collapsed to 0. This makes it clear that double leaves span the morphism spaces of $\mathcal{DT}_0$ as (left) $\mathbb{Z}[\ ,\ ]$-modules. However they may not be linearly independent as neither left nor right modules as with the one-colour case. Although double leaves are not always a basis for its respective morphism space as $\mathbb{Z}[\ ,\ ]$-modules, it turns out a subset of them are a basis over $\mathbb{Z}$.

Lemma 4.2.7. *Let $\pi : \mathrm{mor}(\mathcal{H}(\widetilde{S}_2)) \to \mathrm{mor}(\mathcal{DT}_0)$ be the projection map which takes a morphism to the result of its action on the empty diagram $\varnothing$. Then the image $\pi(\mathbb{LL}(w,y))$ without zero morphisms is a basis for $\mathrm{Hom}_{\mathcal{DT}_0}(w,y)$ as a $\mathbb{C}$-module.*

Proof. Consider morphisms $\mathrm{Hom}(w,y)$ in $\mathcal{DT}_0$ for fixed objects w, y, and write $\mathbb{LL} :=$ $\pi(\mathbb{LL}(w,y))$ for the set of double leaves in $\mathcal{DT}_0$. Any diagram in $\mathcal{DT}_0$ can be written as a $\mathbb{C}$-linear combination of morphisms without floating diagrams by pulling floating diagrams to the right with (R1d) and (R2) then applying the wall relation (W2). We can write each of these as a $\mathbb{Z}[\ ,\ ]$-linear combination of double leaves with a right action, and reduce it to a $\mathbb{Z}$-linear combination by (W2). This implies that $\mathbb{LL}$ spans $\mathrm{Hom}(w,y)$ as a $\mathbb{Z}$-module. Now $\mathbb{LL}$ may not be linearly independent because the two-colour wall relation (W2) reduces all diagrams factoring through a word ending with t

to 0. The set of light leaves after removing morphisms killed by (W2), i.e. $\mathbb{LL} \setminus \{0\}$, still spans $\mathrm{Hom}(w, y)$ by the argument above. This set is linearly independent since, by construction, (W2) has no effect on $\mathbb{Z}$-linear combinations of $\mathbb{LL} \setminus \{0\}$. Then it follows from linear independence over $\mathbb{Z}[\ ,\ ]$ that this set is linearly independent over $\mathbb{Z}$ in $\mathcal{DT}_0$. $\square$

Since there exists light leaves with unbroken red strands on the right, this lemma implies that our category does not collapse by adding the module category structure and the wall relation (W2). Unlike Section 3.2, we will not be using this result to prove the equivalence of categories.

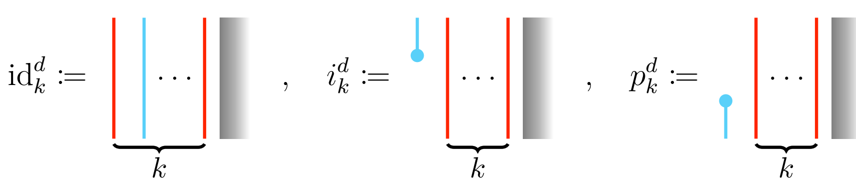
Equivalence with $\mathrm{Tilt}_0(\mathfrak{sl}_2)$

We aim to show that the additive Karoubi envelope of this diagrammatic category is equivalent to $\mathrm{Tilt}_0(\mathfrak{sl}_2)$. From now on, we write $\mathcal{DT}_0$ for the $\mathbb{C}$-linear $\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2)$-module category obtained by extending scalars from $\mathbb{Z}$ with $\mathbb{C}$. All the above discussion and results still apply to $\mathcal{DT}_0$ over $\mathbb{C}$. For brevity we may also write $\mathcal{T}_0$ for $\mathrm{Tilt}_0(\mathfrak{sl}_2)$.

Since $\mathcal{H}_{\mathbb{C}}(S_2)$ appears inside $\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2)$ for each colour, Lemma 3.2.5 provides explicit isomorphisms $ss \cong s \oplus s$ and $tt \cong t \oplus t$ in the additive closure of $\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2)$.

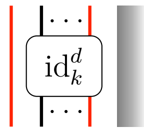
Definition 4.2.8. Let $F : \mathcal{DT}_0^{\oplus} \to \mathrm{Tilt}_0(\mathfrak{sl}_2)$ to be the additive $\mathbb{C}$-linear $\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2)$-module functor defined as follows. Map the empty word $\varnothing$ to the trivial module $T(\varnothing)$. Given a general word $s_n \dots s_1$ in $\mathcal{DT}_0$, for $s_i \in \{s, t\}$, map $F(s_n \dots s_1) = \Theta_{s_n} \dots \Theta_{s_1} T(\varnothing)$ where Θ_s, Θ_t are translation functors[5] associated to generators of $\widetilde{S}_2$.

On morphisms, we define F recursively. Note that we only have red strands on the right since (W2) reduces right blue strands to 0. For $k \geq 0$, define for odd k

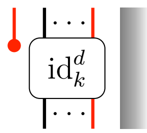


where colours alternate and a red strand on the right when $k \neq 0$. For even k, we define these similarly with colours to the left of the dots swapped. Similarly for $k \geq 0$, we define $\mathrm{id}_k : \Theta_x \dots \Theta_s(T(\varnothing)) \to \Theta_x \dots \Theta_s(T(\varnothing))$, $i_k : \Theta_x \dots \Theta_s(T(\varnothing)) \to \Theta_y\Theta_x \dots \Theta_s(T(\varnothing))$ and $p_k : \Theta_y\Theta_x \dots \Theta_s(T(\varnothing)) \to \Theta_x \dots \Theta_s(T(\varnothing))$ to be the identity, inclusion and projection maps in $\mathcal{T}_0$, where the subscripts alternate s, t and $\Theta_x \dots \Theta_s$ is a composition of k translation functors. Further we write $\tilde{p}_k := (-1)^{k+1}\frac{1}{2^{k+1}}p_k$. Let $F(\mathrm{id}_k^d) = \mathrm{id}_k$. On the generators (G2) of $\mathcal{DT}_0$, map

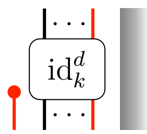
[5] Translation functors for $\mathrm{Tilt}(\mathfrak{sl}_2)$ are defined in [AT17, Definition 2.33].



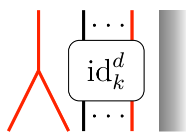
$$\overset{F}{\longmapsto} \begin{cases} \mathrm{id}_{k+1}, & \text{if } k \text{ even,} \\ \begin{pmatrix} \mathrm{id}_k & 0 \\ 0 & \mathrm{id}_k \end{pmatrix}, & \text{if } k \text{ odd,} \end{cases}$$



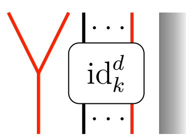
$$\overset{F}{\longmapsto} \begin{cases} \tilde{p}_k, & \text{if } k \text{ even,} \\ \begin{pmatrix} i_{k-1} \circ \tilde{p}_{k-1} \\ \mathrm{id}_k \end{pmatrix}, & \text{if } k \text{ odd,} \end{cases}$$



$$\overset{F}{\longmapsto} \begin{cases} i_k, & \text{if } k \text{ even,} \\ \begin{pmatrix} \mathrm{id}_k & i_{k-1} \circ \tilde{p}_{k-1} \end{pmatrix}, & \text{if } k \text{ odd,} \end{cases}$$

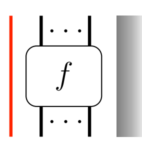


$$\overset{F}{\longmapsto} \begin{cases} \begin{pmatrix} 0 & \mathrm{id}_{k+1} \end{pmatrix}, & \text{if } k \text{ even,} \\ \begin{pmatrix} 0 & 0 & \mathrm{id}_k & 0 \\ 0 & 0 & 0 & \mathrm{id}_k \end{pmatrix}, & \text{if } k \text{ odd,} \end{cases}$$



$$\overset{F}{\longmapsto} \begin{cases} \begin{pmatrix} \mathrm{id}_{k+1} \\ 0 \end{pmatrix}, & \text{if } k \text{ even,} \\ \begin{pmatrix} \mathrm{id}_k & 0 \\ 0 & \mathrm{id}_k \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, & \text{if } k \text{ odd,} \end{cases}$$

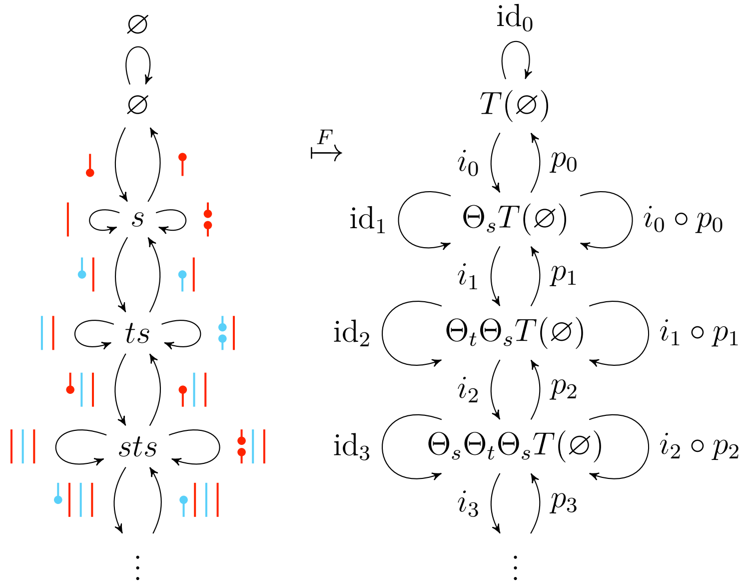
where black strands can be any colour and each entry in the matrix are matrices themselves. For blue generators, the definition is the same with the words even and odd swapped. Putting a red (resp. blue) identity strands on the left of a diagram is applying Θ_s (resp. Θ_t) to the output morphism. Pictorially, for a morphism f in $\mathcal{DT}_0$,



$$\overset{F}{\longmapsto} \Theta_s F(f).$$

We extend the functor by composition, additivity and linearity.

The mappings that don't involve matrices are informally summarised in the picture below.



(4.2.9)

The right wall on each diagram is not shown to reduce clutter.

The definition on generators is a consequence of the isomorphism $\Theta_s\Theta_s \cong \Theta_s \oplus \Theta_s$ analogous to $ss \cong s \oplus s$ (and respectively for t) from Lemma 3.2.5.

Remark 4.2.10. The action of an arbitrary morphism of $\mathcal{H}(\widetilde{S}_2)$ on the left of a morphism in $\mathcal{DT}_0$ is sent to the Godement product[6] of the natural transformations underlying the image of morphisms under F. Taking the Godement product of natural transformations $\Theta_x \dots \Theta_s \to \Theta_y \dots \Theta_s$, when viewed as diagrams in $\mathcal{DT}_0$, is just a left tensor of the corresponding diagrams. Visually, the construction of looks like putting identity morphisms on the left of one morphism on the right of the other, so that the codomains align, and then composing them. In $\mathcal{T}_0$, this is the Kronecker product of matrices.

Lemma 4.2.11. *The functor F is well defined as a functor between additive $\mathbb{C}$-linear $\mathcal{H}(S_2)$-module categories.*

Proof. By Remark 4.2.10, the definition of F defines an action of every morphism in $\mathcal{DT}_0^{\oplus}$. It remains to check that all relations are preserved. It follows from [AT17, Proposition 2.34] that the translation functors Θ_s, Θ_t are Frobenius objects in the category of endofunctors of $\mathcal{T}$ and there are unit, counit, multiplication and comultiplication natural transformations and corresponding relations from the Frobenius object structure. Applying these to $T(\varnothing)$ result in Frobenius object relations in $\mathcal{T}_0$ for $T(\varnothing), \Theta_s T(\varnothing)$ and $\Theta_s^2(T(\varnothing))$, and similarly with Θ_t. Note that and map to i_0 and $\tilde{p}_0$ which are exactly the unit and counit of Θ_s evaluated at $T(\varnothing)$ (up to scaling), and the trivalent vertices defined with id_0^d are mapped exactly to the multiplication and comultiplication maps. The isomorphism Lemma 3.2.5 we use to reduce domain and codomain has an analogue $\Theta_s \circ \Theta_s \cong \Theta_s \oplus \Theta_s$ as in [AT17, Corollary 2.35(a)], and similarly for t. Furthermore, in

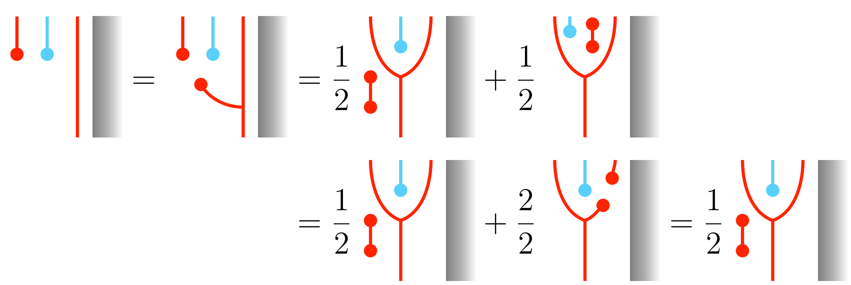
[6]The horizontal composition of natural transformations.

[AT17, Proposition 2.30] we see that $p_0 \circ i_0 = 0$, $p_{k+1} \circ i_{k+1} = i_k \circ p_k$ that are analogous to the relations in Proposition 4.2.4, up to an adjusting scalar given in the definition. From [AT17, Corollary 2.35] the translation functors satisfy properties analogous to the two-colour wall relations (W2). Checking that the remaining relations (R1c), (R1d), (R2) and (W2) hold in $\mathcal{T}_0$ is straightforward (see [AT17, Lemma 4.26]). Therefore all the relations in $\mathcal{DT}_0$ are preserved by F. By construction, F preserves direct sums, $\mathbb{C}$-linear combinations and the Soergel module structure, so F is well defined as a functor between additive $\mathbb{C}$-linear $\mathcal{H}(S_2)$-module categories. $\square$

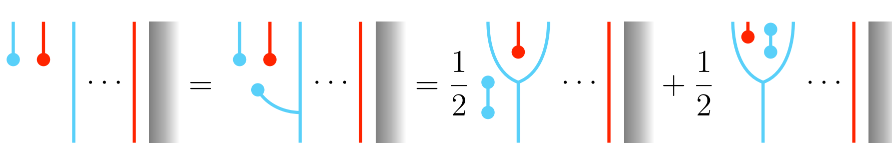
Theorem 4.2.12 (Andersen–Tubbenhauer, [AT17, Theorem 4.27])**.** *The diagrammatic category* $\mathrm{Kar}^{\oplus}(\mathcal{DT}_0(\mathfrak{sl}_2))$ *and* $\mathrm{Tilt}_0(\mathfrak{sl}_2)$ *are equivalent as additive* $\mathbb{C}$*-linear* $\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2)$*-module categories.*

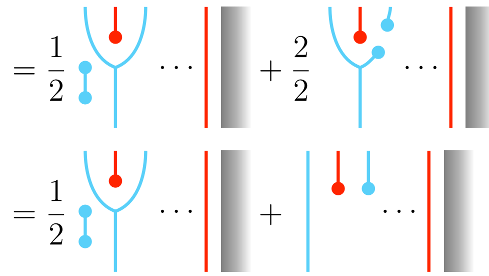
Proof. Since $\mathcal{T}_0$ is additive and Karoubian, our functor F extends uniquely to an additive functor $F' : \mathrm{Kar}^{\oplus}(\mathcal{DT}_0) \to \mathcal{T}_0$. By the argument in [AT17, Theorem 4.27], every element in $\mathcal{T}_0$ is isomorphic to F' applied to a direct sum of images of Jones–Wenzl projectors, so F' is essentially surjective. Particularly, this shows that the images of JW-projectors map exactly to the indecomposable "leading" tilting modules.

By Lemma 3.2.5 and (W2), we just consider words with alternating generators and ending with s. Write $T(...ts)$ for the leading indecomposable summand of $...\Theta_t\Theta_s(T(\varnothing))$ in $\mathcal{T}_0$, and write $b_{...ts}$ for the image of $\mathrm{JW}_{...ts}$. By [Eli16, Section 5.4.2], Jones–Wenzl projectors are primitive idempotents and their images are all the indecomposables in $\mathcal{DT}_0$, and as mentioned above they map to the leading indecomposables in $\mathcal{T}_0$. For full and faithfulness, it is sufficient to check that the dimensions of the morphism spaces between indecomposables $\mathrm{Hom}_{\mathcal{DT}_0}(b_{x...ts}, b_{y...ts})$ and $\mathrm{Hom}_{\mathcal{T}_0}(T(x...ts), T(y...ts))$ coincide. On the diagrammatic side, a morphism $b_{x...ts} \to b_{y...ts}$ is given by $\mathrm{JW}_{y...ts}\, f\, \mathrm{JW}_{x...ts}$ where $f : x...ts \to y...ts$. Since morphisms can be written as a linear combination of double leaves, we consider f to be a double leaf. By Proposition 4.1.9, all double leaves in which pitchfork appear on the top or bottom of the diagram are killed. Since the domain and codomain alternate colours, the remaining diagrams are a tensor and composition of , and identity strands. Notice that we have the relation

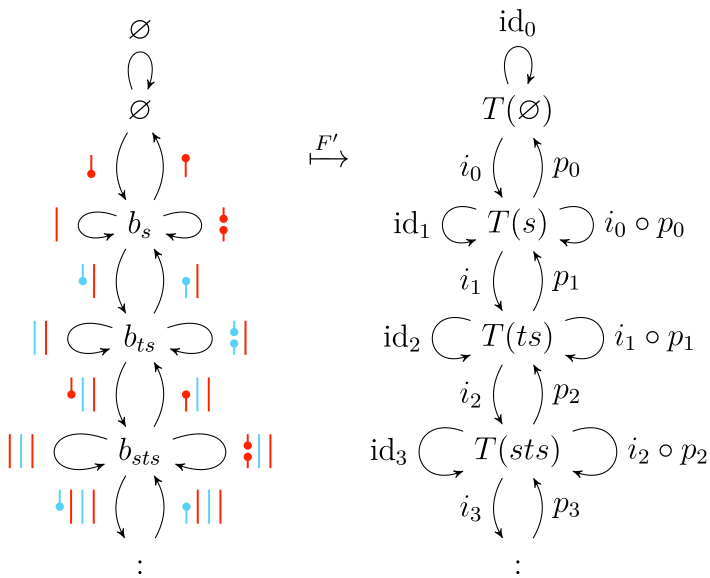


Proceeding inductively on the number of identity strands on the right, we have





for even length domain, where the third equality follows from Proposition 4.2.4. Swapping blue and red strands left of the dots gives us the odd case. By induction the second term is a linear combination of diagrams with pitchforks, hence this diagram is a linear combinations of diagrams with pitchforks. Particularly, these are killed by Jones–Wenzl projectors by Proposition 4.1.9. The same argument holds for the vertically reflected diagram. Along with Proposition 4.2.4, we conclude that the only double leaves we should consider are id_k^d, i_k^d, p_k^d and their composition $i_k^d \circ p_k^d$. This is informally summarised by the diagram below (similar to (4.2.9)).



(4.2.13)

Although not drawn, all the diagrams are flanked by Jones–Wenzl projectors, and the matching morphisms in $\mathcal{T}_0$ are pre and post-composed with the idempotents corresponding to the appropriate JW-projectors. Putting JW-projectors above and below any of these diagrams clearly do not result in zero. Moreover, in the endomorphism space of each non-trivial indecomposable, the morphisms id_k^d and $i_{k-1}^d \circ p_{k-1}^d$, with JW-projectors before and after, can easily be checked to be linearly independent. Hence the bases for the spaces can be read off the picture (4.2.13). In $\mathcal{T}_0$, the analogous bases for the morphism spaces in [AT17, Corollary 2.3.1] have matching dimensions, hence F' is fully faithful. Therefore the categories $\mathrm{Kar}^{\oplus}(\mathcal{DT}_0)$ and $\mathrm{Tilt}_0(\mathfrak{sl}_2)$ are equivalent as (idempotent complete) additive $\mathbb{C}$-linear $\mathcal{H}_{\mathbb{C}}(\widetilde{S}_2)$-module categories. $\square$

This functor is defined similarly to that for $\mathrm{proj}(\mathcal{O}_0)$ in Section 3.2. However this is not apparent since as the corresponding Jones–Wenzl projectors are trivial (the red identity strand).

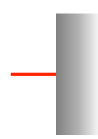
Remark 4.2.14. Similar to Section 3.2, there is a grading for morphism spaces of $\mathcal{DO}_0$ which induces a grading on $\mathrm{Tilt}_0(\mathfrak{sl}_2)$ and hence $\mathrm{Tilt}(\mathfrak{sl}_2)$, which would otherwise be ungraded.

Chapter 5

Future Direction

The diagrammatic descriptions we gave for $\mathcal{O}(\mathfrak{sl}_2)$ and $\mathrm{Tilt}(\mathfrak{sl}_2)$ are integral and graded versions of these categories. These can be studied in contexts where the original categories cannot, for example in characteristic p. In higher ranks such as $\mathfrak{sl}_n$, diagrammatics also exist; for example see [RW18].

A next step is the open problem of constructing diagrammatics for the categorification of the Lusztig–Vogan module by Larson–Romanov [LR22]. In the paper, we see that the category is a Soergel module category, so the diagrammatics are likely similar to those in this thesis. Particularly, we suspect the diagrammatics to be similar to $\mathcal{DT}_0$ with a new generator connecting to the wall



with some (not yet known) relations determining how this generator interacts with other diagrams.

References

[AT17] Henning Haahr Andersen and Daniel Tubbenhauer. “Diagram Categories for $\mathbf{U}_q$-Tilting Modules at Roots of Unity”. In: *Transformation Groups* 22 (2017), pp. 29–89. DOI: 10.1007/s00031-016-9363-z.

[Bor94] Francis Borceux. *Handbook of categorical algebra. 1. Basic category theory.* MR1291599 18-02 (18Axx). Cambridge University Press, 1994.

[Bra37] Richard Brauer. “On Algebras Which are Connected with the Semisimple Continuous Groups”. In: *Annals of Mathematics* 38 (1937), pp. 857–872. DOI: 10.2307/1968843.

[Eli16] Ben Elias. “The two-color Soergel calculus”. In: *Compositio Mathematica* 152.2 (2016), pp. 327–398. DOI: 10.1112/S0010437X15007587.

[EK10] Ben Elias and Mikhail Khovanov. “Diagrammatics for Soergel categories”. In: *International Journal of Mathematics and Mathematical Sciences* 2010 (2010). DOI: 10.1155/2010/978635.

[EW14] Ben Elias and Geordie Williamson. “The Hodge theory of Soergel bimodules”. In: *Annals of Mathematics* 180 (3 2014), pp. 1089–1136. DOI: 10.4007/annals.2014.180.3.6.

[EW16] Ben Elias and Geordie Williamson. “Soergel Calculus”. In: *Representation Theory of the American Mathematical Society* 20 (Oct. 2016). DOI: 10.1090/ert/481.

[Eli+20] Ben Elias et al. *Introduction to Soergel Bimodules*. 1st ed. Vol. 5. RSME Springer Series. Springer Cham, 2020. DOI: https://doi.org/10.1007/978-3-030-48826-0.

[Eti+15] Pavel Etingof et al. *Tensor Categories*. Vol. 205. Mathematical Surveys and Monographs. American Mathematical Society, 2015. DOI: http://dx.doi.org/10.1090/surv/205.

[Hum08] James E. Humphreys. *Representations of Semisimple Lie Algebras in the BGG Category $\mathcal{O}$*. Vol. 94. Graduate Studies in Mathematics. American Mathematical Society, 2008. DOI: http://dx.doi.org/10.1090/gsm/094.

[Jon85] Vaughan F. R. Jones. “A polynomial invariant for links via von Neumann algebras”. In: *Bulletin of the American Mathematical Society* 60 (1985), pp. 103–111.

[Jon21] Vaughan F. R. Jones. "Planar algebras". In: *New Zealand Journal of Mathematics* 52 (2021), pp. 1–107. DOI: 10.53733/172. URL: https://nzjmath.org/index.php/NZJMATH/article/view/172.

[Kau90] Louis H. Kauffman. "An invariant of regular isotopy". In: *Trans. Amer. Math. Soc.* 318.2 (1990), pp. 417–471.

[Koc03] Joachim Kock. *Frobenius Algebras and 2-D Topological Quantum Field Theories*. London Mathematical Society Student Texts. Cambridge University Press, 2003. DOI: 10.1017/CBO9780511615443.

[LR22] Scott Larson and Anna Romanov. *A categorification of the Lusztig–Vogan module*. 2022. arXiv: 2203.09007 [math.RT].

[Lib08] Nicolas Libedinsky. "Sur la catégorie des bimodules de Soergel". In: *Journal of Algebra* 320.7 (2008). (French), pp. 2675–2694. ISSN: 0021-8693. DOI: https://doi.org/10.1016/j.jalgebra.2008.05.027.

[ML98] Saunders Mac Lane. *Categories for the Working Mathematician*. 2nd ed. Vol. 5. Graduate Texts in Mathematics. Springer, 1998. DOI: https://doi.org/10.1007/978-1-4757-4721-8.

[Maz09] Volodymyr Mazorchuk. *Lectures on $\mathfrak{sl}_2(\mathbb{C})$-Modules*. 2nd ed. Vol. 5. Graduate Texts in Mathematics. IMPERIAL COLLEGE PRESS, 2009. DOI: 10.1142/p695.

[Mor15] Scott Morrison. "A Formula for the Jones-Wenzl Projections". In: (2015). arXiv: 1503.00384 [math.QA].

[Pow89] A.J. Power. "A general coherence result". In: *Journal of Pure and Applied Algebra* 57.2 (1989), pp. 165–173. DOI: 10.1016/0022-4049(89)90113-8.

[RW18] Simon Riche and Geordie Williamson. "Tilting Modules and the p-Canonical Basis". In: *Asterisque* 397 (2018). DOI: 10.24033/ast.1041.

[Sel10] P. Selinger. "A Survey of Graphical Languages for Monoidal Categories". In: *New Structures for Physics*. Springer Berlin Heidelberg, 2010, pp. 289–355. DOI: 10.1007/978-3-642-12821-9_4.

[Soe90] Wolfgang Soergel. "Kategorie $\mathcal{O}$, Perverse Garben Und Moduln Uber Den Koinvariantez Zur Weylgruppe". In: *Journal of the American Mathematical Society* 3.2 (1990), pp. 421–445. ISSN: 08940347, 10886834. URL: http://www.jstor.org/stable/1990960.

[Soe98] Wolfgang Soergel. "Combinatorics of Harish-Chandra modules". In: *Representation Theories and Algebraic Geometry*. Ed. by Abraham Broer, A. Daigneault, and Gert Sabidussi. Springer Netherlands, 1998, pp. 401–412. ISBN: 978-94-015-9131-7. DOI: 10.1007/978-94-015-9131-7_10. URL: https://doi.org/10.1007/978-94-015-9131-7_10.

[Soe07] Wolfgang Soergel. “Kazhdan-Lusztig-Polynome Und Unzerlegbare Bimoduln Über Polynomringen”. In: *Journal of the Institute of Mathematics of Jussieu* 6.3 (2007), pp. 501–525. DOI: 10.1017/S1474748007000023.

[Wei94] Charles A. Weibel. *An Introduction to Homological Algebra*. Cambridge University Press, 1994. DOI: https://doi.org/10.1017/CBO9781139644136.

[Wen87] Hans Wenzl. “On Sequences of Projections”. In: *C. R. Math. Rep. Acad. Sci. Canada* 9 (1) (1987). MR 873400 (88k:46070), pp. 5–9.

[WRT32] H. Weyl, G. Rumer, and E. Teller. “Eine für die Valenztheorie geeignete Basis der binären Vektorinvarianten”. In: *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse* 1932 (1932), pp. 499–504. URL: http://eudml.org/doc/59396.