

Conformal Embeddings of G_2 via Graph Planar Algebra Embeddings

Cain's notes

- Show off \mathcal{D}_i in the intro. Theorem: skein cats like this exist
- don't oversell and say "these will be of great use." Define and then show utility.
- Delete lots of prelim material. Just cite.
- Delete final proof. Cite Cain and Noah
- Overall style not academic enough. Dry it out.

CONTENTS

1. Introduction	1
2. Preliminaries	2
2.1. Unoriented Planar Algebras	2
2.2. Unitarity and inner products	3
2.3. The Unoriented Graph Planar Algebra	4
2.4. Algebra and Module Objects	4
3. Skein Theory Generalities	6
4. Methods: GPA Embeddings	10
4.1. Trivalent Vertex	11
4.2. Projection and its relations	12
5. Results: Level 3	13
5.1. GPA Embedding and Relations	13
5.2. Theorem and proof	15
6. Results: Level 4	17
References	18

1. INTRODUCTION

This paper gives generators-and-relations presentations for two categories

$$\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3} \quad \text{and} \quad \overline{\text{Rep}(U_{q_4}(\mathfrak{g}_2))}_{A_4}$$

where A_3 and A_4 are the commutative Etale algebras corresponding, respectively, to the conformal embeddings $G_{2,3} \subseteq E_{6,1}$ and $G_{2,4} \subseteq D_{7,1}$ of affine Lie algebras. The correspondence $\mathcal{C}(\mathfrak{g}, k) \leftrightarrow \overline{\text{Rep}(U_{q_k}(\mathfrak{h}))}$ between affine Lie algebra representations and quantum group representations **need citation** allows one, in the course of studying conformal embeddings, to move freely from the perspective of affine Lie algebras to that of quantum groups. We will initialize our statements in the language of affine Lie algebras, and then translate into quantum groups.

By *presentation* we mean the following standard sequence of steps. Let \mathcal{P} be the planar algebra generated by some object of the tensor category \mathcal{C} . Then we show \mathcal{P} is monoidally equivalent to some skein category \mathcal{E} , and that $\text{Ab}(\mathcal{E})$ is monoidally equivalent to \mathcal{C} . The presentations we give are extensions of Kuperberg's $\mathcal{G}_2(q)$ skein theory by strands of type \mathbb{Z}_3 (level 3) and \mathbb{Z}_2 (level 4).

The novel methodology offered here is the use of graph planar algebra (GPA) embeddings to deduce relations. Computing, e.g., the relation (Change of Basis) purely in the context of quantum group representations is daunting, to say the least. With a GPA embedding in hand, however, this becomes an elementary linear algebra problem. This approach is counter to the usual approach take by, say, Copeland and Edie-Michell in [2]. Those authors move from generators-and-relations presentations to GPA embeddings for the purpose of constructing module categories over $\overline{\text{Rep}(U_q(\mathfrak{sl}_N))}$ categories.

Even work with the same aim as this paper, e.g., presenting categories \mathcal{C}_A of algebras has, thus far, taken a markedly different form. The closest example is the recent work of Edie-Michell and Snyder [8],

which gives presentations for categories of the form $\overline{\text{Rep}(U_q(\mathfrak{sl}_N))}_A$. The methods used by these authors is purely representation theoretic; that is, all of the skein relations for those categories can be deduced from first principles. **At this time there seems to be no clear path from pure representation theory to the presentations we give. ***More tools are needed.*****

The present work is organized as follows. Section 2 sets up most of the theory needed, referencing that which we do not exposit here. This includes unoriented planar algebras, unoriented graph planar algebras, internal algebra and module objects, and some assorted theoretical devices and results. Section 3 then goes on to define a general class of categories of which our examples are members. We expect this class of categories to be of great use for those researchers intent on conjuring examples of exotic new tensor categories. We then show this class of categories to be evaluable. Section 4 then goes on to discuss what the details of the process of using GPA embeddings looks like. Subsection 4.1 details the techniques used to arrive at GPA embeddings of trivalent categories. Subsection 4.2 shows how we go beyond these embeddings of trivalent categories, and how we use GPA embeddings to explore relations in extensions of trivalent categories. Finally, Sections 5 and 6 give the structure constants for the newly constructed categories. Section 5 details the argument used to prove that we truly have found full presentations. This covariant Galois-esque argument also appears in [8].


2. PRELIMINARIES

Here we define the players in this game. We begin with planar algebras, in the spirit of [15].

2.1. Unoriented Planar Algebras. We begin by recalling the theory of **rigid** monoidal categories detailed in [13]. To put it succinctly, rigid monoidal categories have duals. Duals, and the associated evaluation and coevaluation maps, give us the cups and caps ubiquitous in planar algebras. A rigidity assumption gives us the ability to isotope diagrams. The generators we will use for our planar algebras will be symmetrically self-dual. We also assume pivotality throughout.

Let X be a (symmetrically self-dual) tensor generator for the tensor category \mathcal{C} ; that is, every object of \mathcal{C} is isomorphic to a subobject of some tensor power $X^{\otimes n}$. Let $\mathcal{P}_{X;\mathcal{C}}$ be the full subcategory of \mathcal{C} whose objects are tensor powers $\mathbb{1} = X^{\otimes 0}, X, X^{\otimes 2}, \dots$; we call this the (unoriented) **planar algebra** generated by X in \mathcal{C} . Since we assumed X tensor generates \mathcal{C} , it follows that $\mathcal{C} \cong \text{Ab}(\mathcal{P}_{X;\mathcal{C}})$, the abelian envelope of $\mathcal{P}_{X;\mathcal{C}}$. The universal property of $\text{Ab}(\mathcal{P}_{X;\mathcal{C}})$ therefore implies that studying $\mathcal{P}_{X;\mathcal{C}}$ is sufficient to understand \mathcal{C} . The planar algebra $\mathcal{P}_{X;\mathcal{C}}$ is **evaluable** if $\dim \text{End}_{\mathcal{P}_{X;\mathcal{C}}}(\mathbb{1}) = 1$.

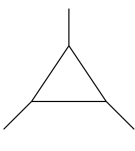
We will be presenting our two new categories as extensions of $\mathcal{G}_2(q)$ skein theories, in the spirit of Kuperberg [14]. Up to a rescaling by a factor of $k = \sqrt{[7] - 1}$ we use the same skein theory (note the sign error in the Pentagon relation of [14]). That is, we define the planar algebra $\mathcal{G}_2(q)$ generated by a trivalent vertex, with the skein relations

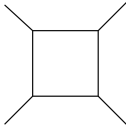
(Loop)  $= q^{10} + q^8 + q^2 + 1 + q^{-2} + q^{-8} + q^{-10}$

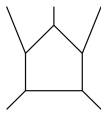
(Lollipop)  $= 0$

(Rotate) $r \left(\begin{array}{c} | \\ \diagup \quad \diagdown \\ | \end{array} \right) = \begin{array}{c} | \\ \diagdown \quad \diagup \\ | \end{array}$

(Bigon)  $= k^2 \left| \begin{array}{c} | \\ | \\ | \\ | \end{array} \right|$

(Trigon)  $= -(q^4 + 1 + q^{-4}) \begin{array}{c} | \\ \diagdown \quad \diagup \\ | \end{array}$

(Tetragon)  $= (q^2 + q^{-2}) \left(\text{Y-junction} + \text{X-junction} \right) + (q^2 + 1 + q^{-2}) \left(\text{Cup} + \text{Cap} \right)$

(Pentagon)  $= - \sum_{i=0}^4 r^i \left(\text{Cup} \right) - \sum_{i=0}^4 r^i \left(\text{Cap} \right)$

Here, the notation $r^i(\mathcal{E})$ means an i -click right rotation of the diagram \mathcal{E} . For instance,

$$r^1 \left(\begin{array}{|} \hline \hline \end{array} \right) = \text{Cup} \quad \text{and} \quad r^2 \left(\begin{array}{|} \hline \hline \end{array} \right) = \begin{array}{|} \hline \hline \end{array}.$$

The value of q is given in [6] and depends on the level k :

$$q = e^{\frac{2\pi i}{3(4+k)}}.$$

Thus at level 3 we have $q_3 = e^{\frac{2\pi i}{42}}$ and at level 4 we have $q_4 = e^{\frac{2\pi i}{48}}$.

2.2. Unitarity and inner products. Recall that a **dagger** category is one endowed with an involution, denoted by a superscript \dagger . The dagger operation gives us the useful ability to reverse any morphism. This will be of use when, for example, we need a way to pair parallel *or* antiparallel morphisms.

The categorical trace of a morphism $f : X \rightarrow X$ is defined by

$$\text{tr}(f) := \text{ev}_X \circ (f \otimes \text{id}_{X^*}) \circ \text{coev}_X.$$

Informally, the trace “caps off” an endomorphism and returns the resulting scalar (since we assume $\dim \text{Hom}(\mathbb{1} \rightarrow \mathbb{1}) \cong \mathbb{C}$).

We use trace to define two different notions of pairing of morphisms:

$$\langle f, g \rangle^\dagger := \text{tr}(g^\dagger \circ f)$$

for parallel morphisms and

$$\langle \varphi, \psi \rangle := \text{tr}(\psi \circ \varphi)$$

for antiparallel morphisms.

Unitarity gives two tools. Computationally, it allows us to do computations by “capping” diagrams. It also has useful theoretical consequences.

Definition 1. A category \mathcal{C} is **unitary** if it is a dagger category and the two conditions

- if $\langle f, f \rangle^\dagger = 0$, then $f = 0$
- for every $f : X \rightarrow Y$, there is some $g : X \rightarrow X$ such that $f f^\dagger = g g^\dagger$

are satisfied.

On a related note, we also make the following definition

Definition 2. A morphism $f : X \rightarrow Y$ in a dagger category \mathcal{C} is **negligible** if $\langle f, g \rangle = 0$ for all $g : Y \rightarrow X$.

It is a fact that the negligible morphisms in a category \mathcal{C} form an ideal, called the **negligible idea** and denoted by $\mathcal{N}(\mathcal{C})$. We may form the semisimple quotient $\overline{\mathcal{C}} := \mathcal{C}/\mathcal{N}(\mathcal{C})$.

Proposition 1. Let \mathcal{C} and \mathcal{D} be pivotal, with \mathcal{D} unitary, and $F : \mathcal{C} \rightarrow \mathcal{D}$ a pivotal dagger functor. Then F descends to a faithful pivotal functor $\overline{F} : \overline{\mathcal{C}} \rightarrow \mathcal{D}$ such that the diagram

$$\begin{array}{ccc} \mathcal{C} & \xrightarrow{F} & \mathcal{D} \\ \downarrow & \nearrow \overline{F} & \\ \overline{\mathcal{C}} & & \end{array}$$

is commutative.

Proof. Compute directly:

$$\begin{aligned}
\langle F(f), F(f) \rangle^\dagger &= \text{tr}(F(f)^\dagger \circ F(f)) \\
&= \text{tr}(F(f^\dagger) \circ F(f)) \\
&= F(\text{tr}(f^\dagger \circ f)) \\
&= F(0) = 0
\end{aligned}$$

since we assumed f was negligible. \square

As one might expect, and as was alluded to above, unitarity interacts nicely with the negligible ideal.

Proposition 2. *Let \mathcal{C} and \mathcal{D} be unitary, and suppose $F : \mathcal{C} \rightarrow \mathcal{D}$ is a pivotal dagger functor. Then there is a faithful $\tilde{F} : \bar{\mathcal{C}} \rightarrow \bar{\mathcal{D}}$ such that*

$$\begin{array}{ccc}
\mathcal{C} & \xrightarrow{F} & \mathcal{D} \\
\downarrow & & \downarrow \\
\bar{\mathcal{C}} & \xrightarrow{\tilde{F}} & \bar{\mathcal{D}}
\end{array}$$

If F is faithful, so is \tilde{F} .

Proof. Compose \bar{F} of Proposition 1 with the functor $\mathcal{D} \rightarrow \bar{\mathcal{D}}$. ?? \square

2.3. The Unoriented Graph Planar Algebra. We will study the quantum subgroups of type G_2 by embedding their skein theories into appropriate graph planar algebras. This serves two purposes:

- Giving us solid ground on which to do computations, allowing us to uncover relations by finding them in the GPA hom-spaces, and
- Implying some nice general properties for the quantum subgroups (i.e., unitarity)

In this work we have no use for generalized GPAs, such as the *oriented* [2] or *multi-color* GPA, so we consider only the unoriented case.

Definition 3. *Let $\Gamma = (V, E)$ be a finite graph. For an edge $e = (u, v) \in E$, let $\bar{e} = (v, u) \in E$. The graph planar algebra on Γ , denoted $\text{GPA}(\Gamma)$, is the strictly pivotal rigid monoidal category whose objects are nonnegative integers, and whose hom-spaces have basis*

$$\text{Hom}_{\text{GPA}(\Gamma)}(m \rightarrow n) := \mathbb{C} \left\{ (p, q) \mid \begin{array}{l} p \text{ an } m\text{-path} \quad s(p) = s(q) \\ q \text{ and } n\text{-path} \quad t(p) = t(q) \end{array} \right\},$$

with composition law

$$(p, q) \circ (p', q') := \delta_{q=p'}(p, q'),$$

and rigidity maps

$$ev = \sum_e \sqrt{\frac{\lambda_{t(e)}}{\lambda_{s(e)}}} \langle e\bar{e}, s(e) \rangle, \quad coev = \sum_e \sqrt{\frac{\lambda_{t(e)}}{\lambda_{s(e)}}} \langle s(e)e\bar{e} \rangle.$$

Monoidal product on objects is addition, and for morphisms is defined by

$$(p, q) \otimes (p', q') := \delta_{s(p')=t(p)}(pp', qq').$$

We will be finding GPA embeddings of certain planar algebras. The following implies unitarity of these planar algebras.

Lemma 1. *For Γ a finite graph, $\text{GPA}(\Gamma)$ is unitary.*

Proof. \square

2.4. Algebra and Module Objects. Our ultimate goal is to find skein theoretic descriptions of two categories $\overline{\text{Rep}}(U_{q_3}(\mathfrak{g}_2))_{A_3}$ and $\overline{\text{Rep}}(U_{q_4}(\mathfrak{g}_2))_{A_4}$ of modules over algebra objects A_3 and A_4 coming from the conformal embeddings $\mathfrak{g}_2 \subseteq \hat{\mathfrak{e}}_6$ and $\mathfrak{g}_2 \subseteq \hat{\mathfrak{d}}_7$. In this subsection we define algebra and module objects. See [16] for a full description. Unless otherwise stated, we will be studying braided tensor categories.

Definition 4. *An algebra object of a braided tensor category \mathcal{C} is an object A along with two maps*

$$\begin{aligned}
m : A \otimes A &\rightarrow A \\
e : \mathbb{1} &\rightarrow A
\end{aligned}$$

such that the following three diagrams

$$\begin{array}{ccccc}
 (A \otimes A) \otimes A & \xrightarrow{a} & A \otimes (A \otimes A) & \xrightarrow{id_A \otimes m} & A \otimes A \\
 \downarrow m \otimes id_A & & & & \downarrow m \\
 A \otimes A & \xrightarrow{m} & & & A
 \end{array}$$

and

$$\begin{array}{ccccc}
 & & A & & \\
 & \swarrow & & \searrow & \\
 1 \otimes A & \xrightarrow{e} & A \otimes A & \xleftarrow{e} & A \otimes 1 \\
 & \searrow & \downarrow m & \swarrow & \\
 & & A & &
 \end{array}$$

commute (where a is the associator for \mathcal{C}). Given that \mathcal{C} has braiding c , the algebra A is **commutative** if $m \circ c_{A,A} = m$.

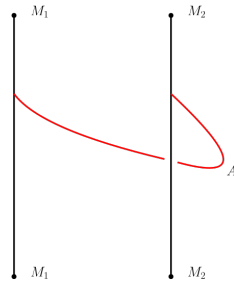
Once we have algebra objects one naturally defines modules over them.

Definition 5. Given an algebra object A of \mathcal{C} , an object M of \mathcal{C} is said to be a **right A -module** if there is a map $s : M \otimes A \rightarrow A$ such that the diagram

$$\begin{array}{ccc}
 (M \otimes A) \otimes A & \xrightarrow{a} & M \otimes (A \otimes A) \xrightarrow{s} M \otimes A \\
 \downarrow a & & \downarrow s \\
 M \otimes A & \xrightarrow{s} & M
 \end{array}$$

commutes. We define \mathcal{C}_A to be the category of right A -module objects in \mathcal{C} .

The braiding on \mathcal{C} allows one to give a right A -module the structure of a left A -module. Once this has been done, we may define a tensor product on \mathcal{C}_A by defining $M_1 \otimes_{\mathcal{C}_A} M_2$ to be the object projected onto by the idempotent



Monoidal functors interact with algebra objects in the ways we would hope.

Proposition 3. Let $\mathcal{F} : \mathcal{C} \rightarrow \mathcal{D}$ be a lax-monoidal functor, and let A be an algebra object of \mathcal{C} . Then $\mathcal{F}A$ has algebra structure induced by \mathcal{F} .

Proof. The approach is to use the lax-monoidal structure on \mathcal{F} and its functoriality to translate diagrams in \mathcal{C} to diagrams in \mathcal{D} . See [12] for the full argument. \square

The following proposition gives us license to make similar statements about adjoints of monoidal functors.

Proposition 4. Monoidal functors between semisimple categories have lax-monoidal right adjoints.

The free module functor $\mathcal{F}_A : \mathcal{C} \rightarrow \mathcal{C}_A$ given by $X \mapsto X \otimes A$ has a monoidal structure induced by the braiding on \mathcal{C} . Its right adjoint is given by the forgetful functor $\mathcal{F}^\vee : \mathcal{C}_A \rightarrow \mathcal{C}$ which is the identity on objects. In the sequel we will be interested in using facts about the restriction of \mathcal{F}_A to a planar algebra whose Karoubi completion is \mathcal{C} . The following fact, which is a restatement of [1][Proposition 5.1], will turn out to be key.

Proposition 5. *Let $\mathcal{F} : \mathcal{C} \rightarrow \mathcal{D}$ be a monoidal functor with faithful exact right adjoint R . If we define $A := R(\mathbb{1})$, then there is an isomorphism K such that the diagram*

$$\begin{array}{ccc} \mathcal{C} & \xrightarrow{\mathcal{F}} & \mathcal{D} \\ & \searrow \mathcal{F}_A & \downarrow K \\ & & \mathcal{C}_A \end{array}$$

commutes up to natural isomorphism.

Remark 1. *Affine Lie algebras and conformal embeddings will only be used to obtain algebra objects for the quantum subgroups, so we briefly recall the correspondence*

$$\mathcal{C}(\mathfrak{g}, k) \cong \overline{\text{Rep}(U_q(\mathfrak{g}))}$$

of [[empty citation](#)], where k is the level. For our purposes this fact translates to

$$(1) \quad \mathcal{C}(\mathfrak{g}_2, k) \cong \overline{\text{Rep}(U_{e^{\frac{2\pi i}{3(4+k)}}}(\mathfrak{g}_2))} \cong \overline{\text{Kar}(\mathcal{G}_2(e^{\frac{2\pi i}{3(4+k)}}))}$$

as given in [6].

We find the algebra objects and fundamental graphs for GPAs from [3].

3. SKEIN THEORY GENERALITIES

The goal of this section is to develop the tools needed to prove evaluability in a certain class of extensions of trivalent categories. Namely we define the concept of a \mathbb{Z}_n -like extension of an Euler-evaluable trivalent category. We expect this class of extensions to be helpful in the search for novel categories. For example, there is work underway by the present author and Edie-Michell to use the techniques of this paper to construct a possibly infinitely large class of examples of near-group categories [9]. This work on near-group categories [7] extends an underlying $SO(3)_q$ trivalent skein theory. The present author has also begun work [11] on a family of extensions of $SP(4)_q$, which, despite its skein theory being generated by a braid, is of the same essence.

This all begs the question of which leaves on the “tree of life” [15] may be extended in this way. We expect this tree to bear much fruit of this variety. Already we have extended both categories ($SO(3)_q$ and Fib) covered by [15, Theorem A] by group-like objects. This paper deals with all but one of the categories covered by [15, Theorem B]. The categories one might next attempt such an extension of include:

- The remaining category ABA of [15, Theorem B]
- The category H_3 of [15, Theorem C]

Now let us get to work defining the class of extensions we’ve been alluding to. Both of the categories studied in this paper are extensions of trivalent categories by a colored, directed, \mathbb{Z}_n -like strand. The trivalent categories we deal with have evaluation algorithms based on the standard Euler characteristic argument. One way to capture this evaluability is by considering dimensions of box spaces.

Definition 6. *In a trivalent category we define a **box space** $B(k, f)$ to be the span of diagrams $k \rightarrow 0$ with f internal faces. If \mathcal{C} is a trivalent category such that, for $k = 1, \dots, 5$, the constraint*

$$\dim B(k, 1) \leq \dim B(k, 0)$$

*holds, we will refer to \mathcal{C} as **Euler-evaluable**.*

General methods for demonstrating evaluability of a skein theory involve identifying some measure of complexity for a closed diagram, then showing the known relations allow one to strictly decrease this measure. For our underlying trivalent categories, Euler-evaluability allows us to decrement one measure of complexity: number of internal faces. With the new strand type, we have another measure: number of colored strands.

The following notation will be useful in writing down relations in \mathbb{Z}_n -like extensions.

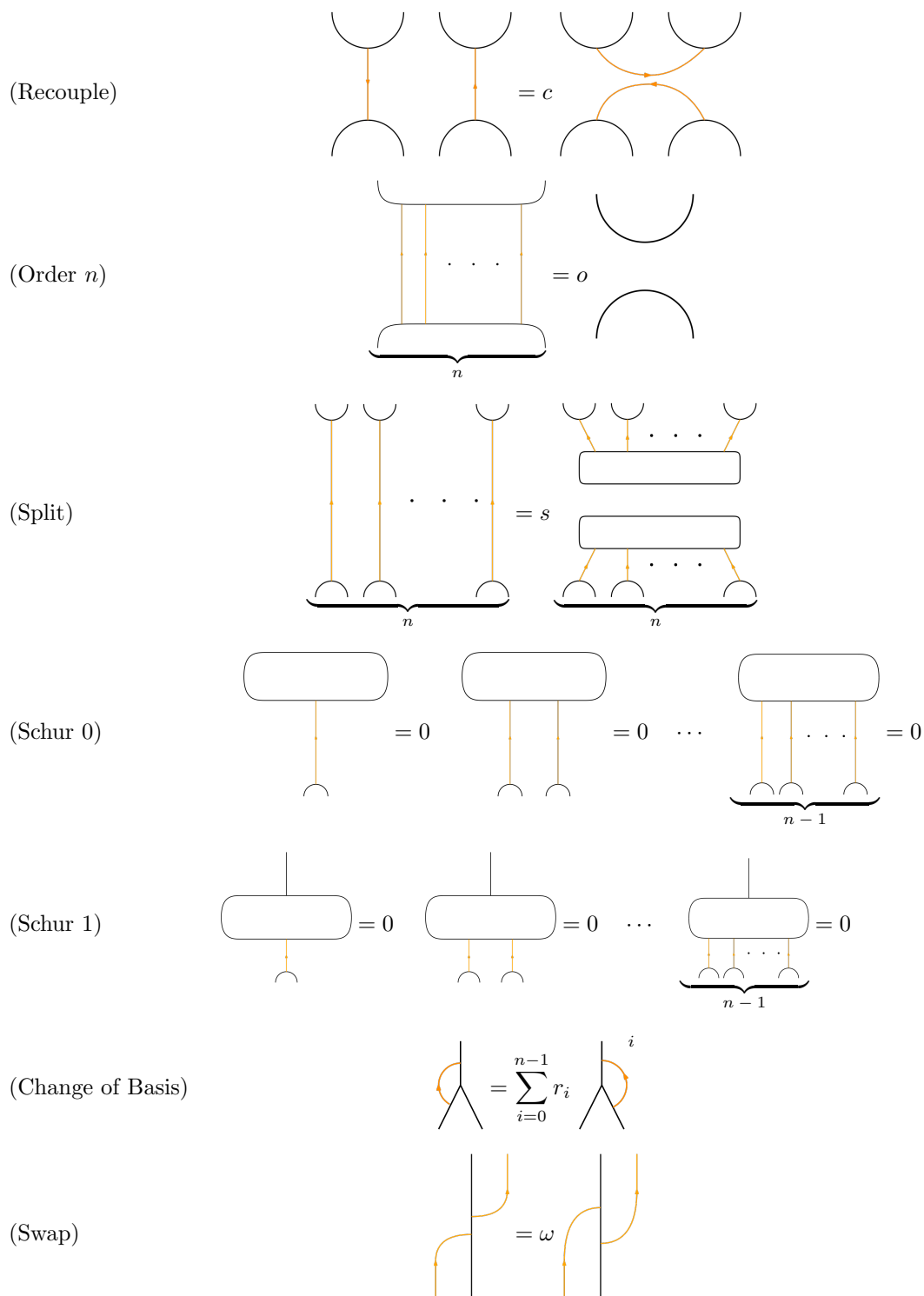
Definition 7. *Suppose a diagram E has m boundary points. We define $dec_i(E)$ to be the i -th external single clockwise decorations of E . For example,*

$$dec_1 \left(\begin{array}{c} | \\ \diagup \quad \diagdown \\ | \end{array} \right) = \begin{array}{c} | \\ \diagup \quad \diagdown \\ | \end{array} \text{ with a clockwise arc on the left strand}, \quad \text{and} \quad \sum_{i=1}^m dec_i \left(\begin{array}{c} | \\ \diagup \quad \diagdown \\ | \end{array} \right) = \begin{array}{c} | \\ \diagup \quad \diagdown \\ | \end{array} \text{ with a clockwise arc on the left strand} + \begin{array}{c} | \\ \diagup \quad \diagdown \\ | \end{array} \text{ with a clockwise arc on the right strand} + \begin{array}{c} | \\ \diagup \quad \diagdown \\ | \end{array} \text{ with a clockwise arc on the bottom strand}$$

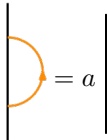
We adopt the convention that $\text{dec}_0(E) = E$.

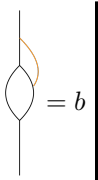
Finally we define the class of categories we will be working with, and show they are evaluable in general.

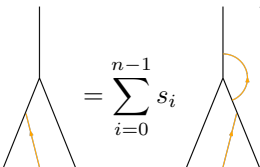
Definition 8. Let $\mathcal{C} = \langle \text{trivalent diagrams} \rangle$ be a trivalent category that is Euler-evaluable. Call \mathcal{D} a \mathbb{Z}_n -like extension of \mathcal{C} if $\mathcal{D} = \langle \text{trivalent diagrams}, \text{orange arrows} \rangle$ and enjoys the following relations¹:

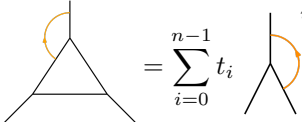


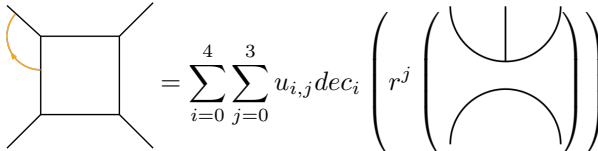
¹Conditions from [4].

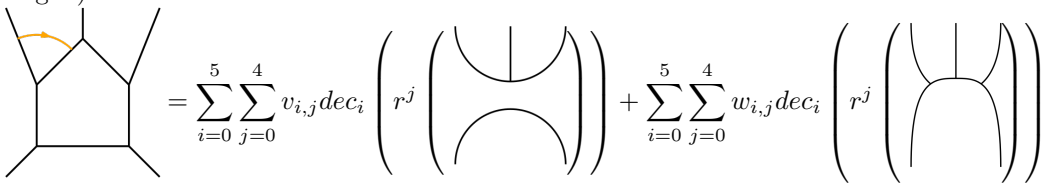
(decStick) 

(decBigon) 

(Slide) 

(decTrigon) 

(decTetragon) 

(decPentagon) 

Remark 2. A quick sketch shows that using (Order) followed by repeated applications of (Recouple) and (decStick) allows one to swap an up-oriented strand for $n - 1$ down-oriented strand. This means that, upon reversing the orientations of the lefthand sides of the relations in Definition 8 will give similar relations. This fact will be used in the proof of Lemma 2.

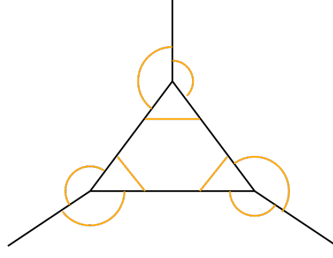
Remark 3. It is worth noting the following standard abuse of language. A diagrammatically presented category such as a \mathbb{Z}_n -like extension has hom-spaces which are formal spans of diagrams. When applying a relation such as (decTrigon) locally, the result is clearly a linear combination of diagrams. Usually, though, this linear combination has some desirable quality, such as a smaller number of internal faces in each summand. In this instance, we prefer to say something along the lines of, “applying (decTrigon) decreases the number of internal faces,” instead of, for instance, the more wordy, “applying (decTrigon) turns this diagram into a linear combination of diagrams with fewer internal faces.”

Diagrams inside a \mathbb{Z}_n -like extension exhibit the following nice property, which will be key in proving their evaluability. Essentially, we use the following lemma to exchange decorated faces for singly-externally-decorated faces. The defining relations for a \mathbb{Z}_n -like extension then pop the singly-decorated faces.

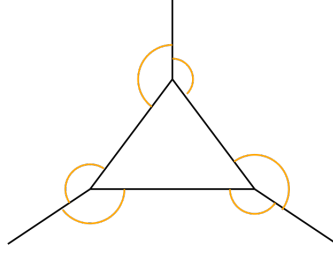
Lemma 2. A decorated diagram may be expressed as a combination of externally decorated diagrams

Proof. We prove the lemma for a decorated trigon, and leave the remaining cases to the reader. We begin with a maximally-decorated trigon. All less decorated cases are absorbed along the way in this

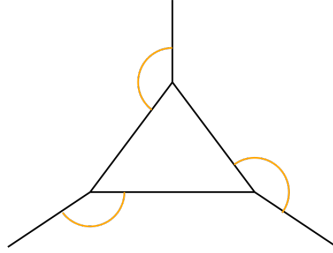
analysis. Now, a maximally-decorated trigon is of the form:



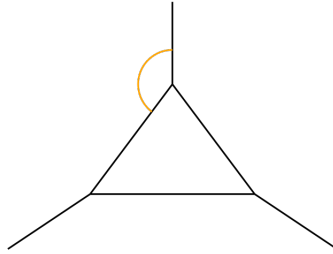
with any labeling on the colored strands. We apply the relations (Swap) and (Slide) on the internal colored strands to obtain a combination of diagrams of the form



Now apply (Change of Basis) to reduce to a combination of diagrams of the form



By another application of (Slide) and (Change of Basis) we arrive at a diagram of the form



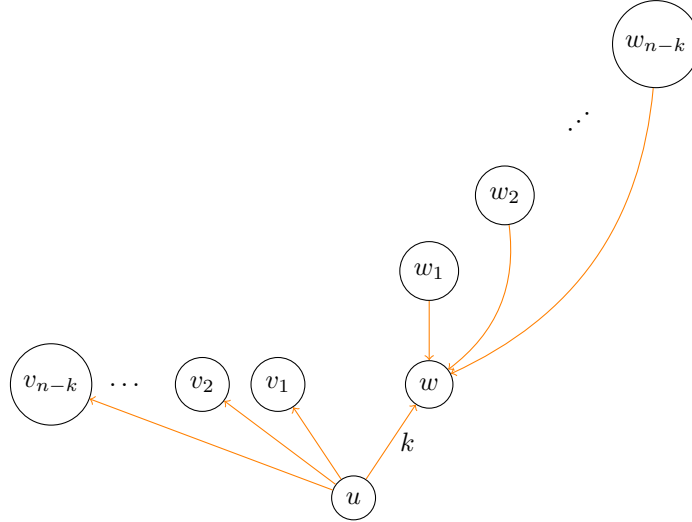
During this last step, we pick up colored strands between the black “spokes”; one may happily move these out of the diagram. \square

Lemma 3. *A planar diagram \mathcal{E} consists only of black loops and colored oriented edges between them, such that (Order n) and (Recouple) hold. Suppose furthermore that each loop of \mathcal{E} has either exactly n strands or exactly n strands leaving. Then the diagram \mathcal{E} evaluates to a scalar.*

Proof. First note that any oriented edges starting and ending from the same black loop may be removed using (Swap) and (decStick). So assume there are only oriented edges between distinct black loops. We’ll use graph theoretic language, with black loops playing the role of nodes, and oriented edges playing the role of, well, oriented edges.

If a node has exactly one neighbor, use (Order n) to remove both. So assume every node has at least two neighbors. Pick one node and call it u . Choose an orientation for its neighbors. Call the rightmost neighbor by w ; assume $\deg(u \rightarrow w) = k < n$. From right to left, call the remaining neighbors by v_1, \dots, v_{n-k} , noting that these need not be distinct. From left to right, call the neighbors of w by w_1, \dots, w_{n-k} , again noting that these need not be distinct.

The diagram is planar, so without loss, we may isotope it to look, locally, like



Now apply (Recouple), exchanging pairs of edges $u \rightarrow v_i$ and $w_i \rightarrow w$ for pairs of edges $u \rightarrow w$ and $w_i \rightarrow v_i$. This changes $\deg(u \rightarrow w)$ to n , allowing us, using (Order), to exchange a pair of nodes for a scalar. Continue ad nauseum. \square

Proposition 6. *A \mathbb{Z}_n -like extension of an Euler-evaluable trivalent category is evaluable.*

Proof. Suppose we begin with a diagram given by a closed, decorated planar trivalent graph. Begin by applying relations from the underlying trivalent category's evaluation algorithm to any undecorated faces; this decreases the number of trivalent vertices. By the standard Euler characteristic calculation, there must remain some black n -gon with $n \in \{2, \dots, 5\}$. Choose one such face and apply Lemma 2 to reduce it to a singly-externally-decorated n -gon. Now one of the relations (decBigon), (decTrigon), (decTetragon), or (decPentagon) allows us to pop the face. This process decreases the number of faces (ignoring colored strands) in diagrams by at least 1 at every step, but also may increase the number of connected components in any summand. Continue this process until only decorated loops, or decorated loops connected by colored strands remain. If only decorated loops remain, apply (decStick).

Our diagram now consists of a number of black loops, connected by colored strands. Use (Recouple) and (Order n) to make it so every black loop has either only in-strands or only out-strands attached to it. If any black loop has more or less than n strands entering or exiting (Schur 0) implies the whole diagram is zero. So suppose each black loop has exactly n strands entering or exiting. Apply Lemma 3 to evaluate the remaining graph for a scalar. \square

For each quantum subgroup we construct, we will find planar algebras satisfying the conditions of Proposition 6, and thus will know the planar algebras are evaluable.

4. METHODS: GPA EMBEDDINGS

The defining relations for \mathcal{D}_3 and \mathcal{D}_4 were not computed theoretically. Instead, we deduced them from embedding the planar algebras $\mathcal{P}_{Y_4; \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}}$ and $\mathcal{P}_{Y_4; \overline{\text{Rep}(U_{q_4}(\mathfrak{g}_2))}_{A_4}}$ into graph planar algebras.

One may give a functor $F : \mathcal{P}_Y \rightarrow \text{GPA}(\Gamma)$ by giving the image of the morphism

$$F \left(\bigwedge \right) \in \text{Hom}_{\text{GPA}(\Gamma)}(2 \rightarrow 1).$$

This amounts to giving a list of $M := \text{tr}(\Gamma^2 \cdot \Gamma)$ complex scalars, say a_1, \dots, a_M . These complex numbers satisfy equations in the a_i and \bar{a}_i . If we assume for now that each a_i is real, then this reduces the system to a collection of polynomials in the a_i ². Once we have the image of the trivalent vertex in hand, we have found an embedding of the planar algebra it generates. We can then solve for the image

$$F \left(\bigvee \right) \in \text{Hom}_{\text{GPA}(\Gamma)}(2 \rightarrow 2).$$

²This assumption is useful only if it turns out to help us solve the system. In fact, any assumptions we make about this system, if they yield solutions, are in some way valid.

4.1. Trivalent Vertex. The goal of this subsection is to describe in more detail the process of finding the image of the trivalent vertex. We will walk through the details for the level 4 case. The level 3 case follows the same process, but is somewhat less instructive. See Sections ?? to find the exact graph used at level 4.

Let

$$(p_1, q_1), \dots, (p_M, q_M)$$

be the defining basis for $\text{Hom}_{\text{GPA}(\Gamma)}(2 \rightarrow 1)$ ($M = 88$ at level 4). Then it must be that

$$F \left(\bigvee \right) = a_1(p_1, q_1) + \dots + a_M(p_M, q_M).$$

The Bigon relation, when sent through F , becomes the system

$$\sum_{i=1}^M a_i(p_i, q_i) \circ \sum_{j=1}^M a_j(q_j, p_j) = k^2 \sum_{e \in E(\Gamma)} (e, e).$$

This system is quadratic in the a_i since it involves up to two trivalent vertices on either side. The Lollipop and Rotate relations therefore determine a system of linear equations; the others give cubic, quartic, and quintic equations. It is often useful to solve the linear subsystem first and substitute the solution into the quadratic equations. For example, at level 4, discussed in Section ??, we solve the linear subsystem, substitute the solution, and isolate the following resulting equations:

$$\begin{aligned} a_8^2 + a_{85}^2 &= 4 - \sqrt{2} + 2\sqrt{3} - \sqrt{6} \\ a_{69}^2 + \left(1 + \sqrt{\frac{3}{2}}\right) a_8^2 &= \frac{3 + \sqrt{3} + \sqrt{6}}{\sqrt{2}} \\ a_{69}^2 \left((2 + \sqrt{6}) a_8^2 + (2 + \sqrt{6}) a_{85}^2 - 2\sqrt{2 + \sqrt{3}} \right) &= 5 + \sqrt{2} + \sqrt{3} + 2\sqrt{6} \\ 2a_{69}^4 + (5 + 2\sqrt{6}) a_{85}^4 &= (3 + \sqrt{2} + \sqrt{3} + \sqrt{6}) a_{85}^2 + 3\sqrt{6} + \sqrt{3} + 2\sqrt{2} + 7 \end{aligned}$$

Up to three choices of sign, the solution to this system is

$$\begin{aligned} a_8 &= \sqrt{2 + \sqrt{3} - \sqrt{2 + \sqrt{3}}} \\ a_{69} &= \sqrt{\frac{1}{2} \left(-1 + \sqrt{2} + \sqrt{3} \right)} \\ a_{85} &= \sqrt{2 + \sqrt{3} - \sqrt{2 + \sqrt{3}}} \end{aligned}$$




Similar equations containing a_{31} , a_{55} , and a_{63} appear as well. We may repeat this process and obtain the additional values

$$\begin{aligned} a_{31} &= \sqrt{2 + \sqrt{3} - \sqrt{2 + \sqrt{3}}} \\ a_{55} &= \sqrt{1 - \sqrt{\frac{3}{2}} + \frac{1}{\sqrt{2}}} \\ a_{63} &= \sqrt{2 + \sqrt{3} - \sqrt{2 + \sqrt{3}}} \end{aligned}$$

These six degree-8 algebraic numbers now begin a cascade of equation solving. They, along with the linear solution, reduce many of the original high-order equations to linear. We solve those, then repeat the process until we're forced to confront nonlinearity. The nonlinearity we encounter forces us to extract square roots, and ending up with degree-16 algebraic numbers. This lead to us concluding, for instance, that

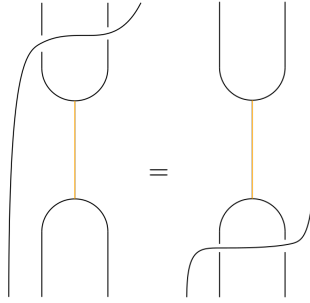
$$a_{10} = \frac{1}{2} \left(\sqrt{1 + \sqrt{6 - 3\sqrt{3}}} + \sqrt{\sqrt{2 + \sqrt{3}} - 1} \right).$$

In Section ?? we will discuss these numbers further.




4.2. Projection and its relations. The process of finding a GPA embedding of the projection  is similar to the process of finding the trivalent vertex described above. Now, however, we must use relations involving both  and . Call the coordinates of the projection b_i . Since the coordinates of the trivalent vertex are now known, the degree of the resulting equations now depends only on the number of projection strands appearing. Moreover, we do not necessarily assume the b_i are real; hence the resulting equations are polynomial in b_i and \bar{b}_i .

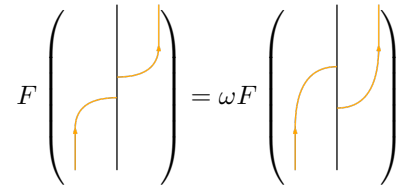
The relation (decStick) along with the one-strand relations of (Schur 0) and (Schur 1) give a system of linear equations, and the following Proposition [8, Lemma 2.4] provides an additional set of linear equations in the projection coefficients.

Proposition 7. *The following relation holds:*

(Half-braid) 

Remark 4. *The relation (Half-braid) is not used in the evaluation algorithm. It is merely a vehicle for obtaining a huge set of linear equations in the b_i and \bar{b}_i .*

In total, the linear system was enough to pin down the projection coefficients for both levels 3 and 4. It is at this point that the present work diverges from other similar published works on the topics of GPA embeddings [2] or presentations for conformal embeddings [8]. Previous investigations utilizing GPA embeddings have had a full set of relations on hand, and these relations were used to *find* the embeddings. On the other hand, recent progress on conformal embeddings have used theoretical means to uncover relations. At the present step in this work, we are standing before an unexplored category, with but an embedding of two of its generators,  and , in hand. We have a set of relations for  (i.e., the defining relations of $\mathcal{G}_2(q)$) sufficient to evaluate any undecorated closed diagram. However, we do not know what further relations we will find, nor exactly when we ought to stop looking. In order to uncover relations such as those of Definition 8, we use a process reminiscent of the scientific method. This process begins by considering a decorated trivalent diagram and searching for ways to decrease its complexity. We begin the process by assuming no more than a minimal collection of moves; i.e., (decStick), (Recouple), and (Product). Once we have applied all these minimal moves, we begin to barter. We look for the least egregious move we might make, and assume it comes at some cost. For example, being able to apply (Swap) might allow us to then apply (decStick); thus we eliminate a colored strand at the cost of a scalar ω . This is clearly a trade we should make. In order to find the exact price of this trade, we use our GPA-embedding $F : \mathcal{D}_3 \rightarrow \text{GPA}(\Gamma_3)$, assuming we know the form the cost will come in. We use the embedding coefficients we previously found to set up and solve the linear equation

$$F \left(\text{Diagram 1} \right) = \omega F \left(\text{Diagram 2} \right)$$


for ω . Another example of bartering appears in the proof of Lemma 2. During the proof, we apply (Swap) and (Change of Basis) with the goal of ridding ourselves of internal strands; this comes at the cost of external strands. The costs incurred in the (decTrigon), (decTetragon), and (decPentagon) relations are less straightforward to predict. The form the relations are presented in is the product of trial and error. As one will note when inspecting the coefficients of these relations in the attached Mathematica files, many of the (decTetragon) and (decPentagon) coefficients are zero. The obvious next question one asks is which of the numbers $u_{i,j}$, $v_{i,j}$, and $w_{i,j}$ one should expect to be nonzero. The examples we construct based on $\mathcal{G}_2(q)$ are too isolated to notice a pattern and drawn conclusions in general. However,

forthcoming work of the present author and Edie-Michell [7] constructing many examples of near-groups as Z_n -like extensions will work to shed light on the phenomenon as a whole.

Once we have a sufficient set of relations to recognize our quantum subgroups as Z_n -like extensions, we must ascend to a more theoretical plane to prove that we have really finished the job.

5. RESULTS: LEVEL 3

We begin at level $k = 3$, which makes $q = q_3 = e^{\frac{2\pi i}{42}}$. From the conformal embedding $\hat{\mathfrak{g}}_2 \subseteq \hat{\mathfrak{e}}_6$ given in [5] we obtain the algebra object $A = V_\emptyset \oplus V_{\Lambda_1 + \Lambda_2}$, as described in [3]. Also given in [3] is (the orbifold of) the module fusion graph Γ_3 with adjacency matrix

$$M_{\Gamma_3} = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}.$$

The graph Γ_3 itself is depicted on the left side of Figure ??.

It is known from [5] that

$$\overline{\text{Rep}(U_q(\mathfrak{g}_2))}_A^0 \cong \text{Vec}(\mathbb{Z}_3);$$

we deduce from the inclusion $\overline{\text{Rep}(U_q(\mathfrak{g}_2))}_A^0 \hookrightarrow \overline{\text{Rep}(U_q(\mathfrak{g}_2))}_A$ that $\overline{\text{Rep}(U_q(\mathfrak{g}_2))}_A$ contains two \mathbb{Z}_3 -like simple objects, denoted g and g^{-1} .

5.1. GPA Embedding and Relations. Here we give details of both the GPA-embedding of $\mathcal{D}(q_3)$ and its governing equations. Recall that the defining bases 3 for the spaces

$$\text{Hom}_{\text{GPA}(\Gamma)}(m \rightarrow n)$$

are given in terms of pairs of paths. The (undirected) graphs we are using have at most a single edge between any two vertices. Hence an edge is equivalent to a pair of vertices, and a path is equivalent to an ordered tuple of vertices. For example, the path

$$p = v_1 \longrightarrow v_2 \longrightarrow v_3$$

is equivalent to the ordered triple (v_1, v_2, v_3) . Which paths q pair validly with p to form a basis element of the $2 \rightarrow 1$ hom-space of a GPA? Well, by definition, q must be parallel to p ; i.e. the sources and targets of p and q must coincide. It follows that the only valid pairing for such p is

$$q = v_1 \longrightarrow v_3,$$

which may also be represented as (v_1, v_3) . So the only $2 \rightarrow 1$ basis element which p appears in is

$$((v_1, v_2, v_3), (v_1, v_3)).$$

But the parallel condition defining basis elements makes including (v_1, v_3) redundant; we might just as well have called the basis element by

$$(v_1, v_2, v_3).$$

This is how we refer to $2 \rightarrow 1$ GPA basis elements. Indeed, in Table 1, the first two columns combine to specify which basis elements are being specified, and the third column gives the approximate coordinate of the trivalent embedding on that basis element. For example, the first row of Table 1 tells us that the coordinate of the $(2, 2, 2)$ basis element is approximately 1.08393; the second row tells us that the coordinate of the $(4, 2, 3)$ basis element is approximately 0.619371.

Paths of the form (i, j, i) , (i, i, j) , or (i, j, j) for $i, j \neq 1$ require a bit more care to describe. There is nontrivial interplay with the graph symmetry swapping vertices 2 and 4. When these two vertices are swapped, a path whose coordinate has absolute value 0.155691 is sent to one whose coordinate has absolute value 1.69414. The nine paths whose coordinates have absolute value 0.155691 are:

$$(2, 3, 3), (3, 3, 2), (3, 2, 3), (2, 4, 2), (4, 3, 4), (2, 2, 4), (3, 4, 4), (4, 2, 2), (4, 4, 3)$$

One may use symmetry to find the rest of the coordinates.

Table 2 holds numerical approximations to the nonzero projection coordinates. There are blocks of nonzero coordinates of length 9 and 16. These sizes, and the location of the nonzero real coordinates follow naturally when one considers three facts:

- (1) The object g is \mathbb{Z}_3 and simple and therefore has fusion graph given in Figure ??.
- (2) There is a map $T_g \in \text{Hom}_{\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}}(Y^{\otimes 2} \rightarrow g)$ whose outer product $T_g^\dagger \circ T_g$ equals P_g , projection onto g .

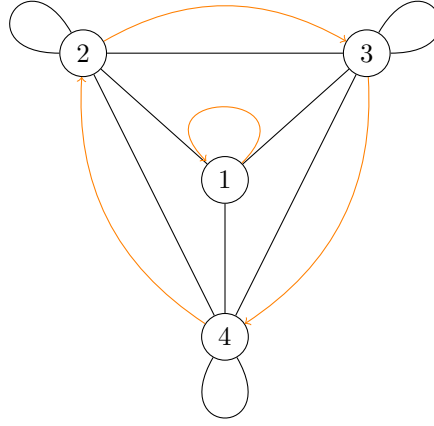


FIGURE 1. Fusion graphs at level 3 for Y (black) and g (orange).
See [3, Figure XXX]

- (3) The dagger of a simple projection is itself; i.e., $\left(\begin{array}{c} \diagup \\ | \\ \diagdown \end{array} \right)^\dagger = \begin{array}{c} \diagdown \\ | \\ \diagup \end{array}$.

The existence and behavior of T_g must be captured by the image of P_g in the GPA, which is all we have access to. This is indeed the case, as the only coordinates of the projection in the GPA which are nonzero are at those basis vectors

$$(i \rightarrow _ \rightarrow j, i \rightarrow _ \rightarrow j)$$

where $i \rightarrow j$ is a directed edge of the g -fusion graph. For $i = j = 1$ there are three possible values for $_$; pairing them gives 9 pairs. For $i, j \neq 1$ there are four possible values for $_$; pairing them gives 16 pairs. The columns of Table 2 give numerical approximations to the coordinates of the projection, with dictionary ordering on the pairs of $_$ values. That is, the column labeled by $1 \rightarrow _ \rightarrow 1$ shows the coordinates on the ordered basis

$$\begin{aligned} &(1 \rightarrow 2 \rightarrow 1, 1 \rightarrow 2 \rightarrow 1) \\ &(1 \rightarrow 2 \rightarrow 1, 1 \rightarrow 3 \rightarrow 1) \\ &(1 \rightarrow 2 \rightarrow 1, 1 \rightarrow 4 \rightarrow 1) \\ &(1 \rightarrow 3 \rightarrow 1, 1 \rightarrow 2 \rightarrow 1) \\ &(1 \rightarrow 3 \rightarrow 1, 1 \rightarrow 3 \rightarrow 1) \\ &(1 \rightarrow 3 \rightarrow 1, 1 \rightarrow 4 \rightarrow 1) \\ &(1 \rightarrow 4 \rightarrow 1, 1 \rightarrow 2 \rightarrow 1) \\ &(1 \rightarrow 4 \rightarrow 1, 1 \rightarrow 3 \rightarrow 1) \\ &(1 \rightarrow 4 \rightarrow 1, 1 \rightarrow 4 \rightarrow 1) \end{aligned}$$

With this ordering and fact (3) above in mind, and recalling that the GPA's dagger operation swaps paths, the real coordinates appear where one would expect them.

Finally we give explicit values for the coefficients of the equations of Proposition 6, excluding (decTetragon) and (decPentagon); the curious reader may find these in the attached Mathematica notebook. The structure constants for \mathcal{D}_3 are:

$$\omega = e^{2\pi i/3}$$

$$r_1 = \dots, \quad r_2 = \dots, \quad r_3 = \dots$$

$$s_1 = \dots, \quad s_2 = \dots, \quad s_3 = \dots$$

$$r_1 = \dots, \quad r_2 = \dots, \quad r_3 = \dots$$

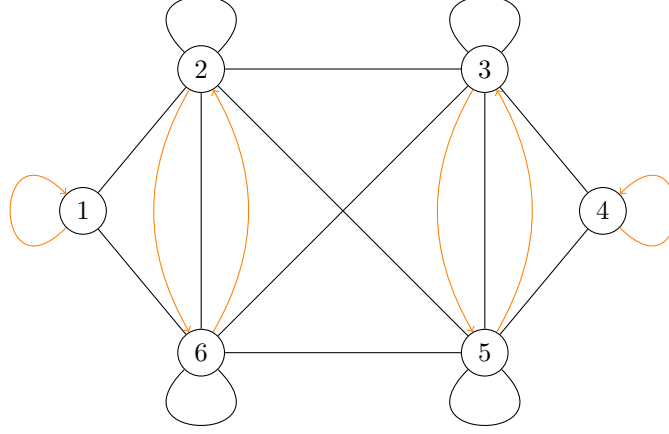


FIGURE 2. Fusion graphs at level 4 for Y (black) and g (orange).
See [3, Figure XXX]

Vertex Path	Conditions	Coefficient
(i, i, i)	$i \neq 1$	1.08393
(i, j, k)	$\{i, j, k\} = \{2, 3, 4\}$	0.619371
$(i, 1, k)$	$i, k \neq 1, i \neq k$	1.69414
$(i, 1, i)$	$i \neq 1$	0.861006
$(i, i, 1)$ or $(1, i, i)$	$i \neq 1$	0.967919

TABLE 1. Level 3 trivalent embedding coefficients.

$1 \rightarrow _ \rightarrow 1$	$2 \rightarrow _ \rightarrow 4$	$3 \rightarrow _ \rightarrow 2$	$4 \rightarrow _ \rightarrow 3$
1.26376	0.791288	0.791288	0.791288
$-0.631881 - 1.09445i$	$0.567622 - 0.684904i$	$0.876955 + 0.149123i$	$0.674406 + 0.580055i$
$-0.631881 + 1.09445i$	$0.674406 + 0.580055i$	$0.567622 - 0.684904i$	$0.876955 + 0.149123i$
$-0.631881 + 1.09445i$	$-0.876955 - 0.149123i$	$-0.674406 - 0.580055i$	$0.567622 - 0.684904i$
1.26376	$0.567622 + 0.684904i$	$0.876955 - 0.149123i$	$0.674406 - 0.580055i$
$-0.631881 - 1.09445i$	1	1	1
$-0.631881 - 1.09445i$	$-0.0182917 + 0.999833i$	$0.5 - 0.866025i$	$0.856735 - 0.515757i$
$-0.631881 + 1.09445i$	$-0.5 - 0.866025i$	$-0.856735 - 0.515757i$	$-0.0182917 - 0.999833i$
1.26376	$0.674406 - 0.580055i$	$0.567622 + 0.684904i$	$0.876955 - 0.149123i$
	$-0.0182917 - 0.999833i$	$0.5 + 0.866025i$	$0.856735 + 0.515757i$
	1	1	1
	$-0.856735 + 0.515757i$	$0.0182917 - 0.999833i$	$0.5 - 0.866025i$
	$-0.876955 + 0.149123i$	$-0.674406 + 0.580055i$	$0.567622 + 0.684904i$
	$-0.5 + 0.866025i$	$-0.856735 + 0.515757i$	$-0.0182917 + 0.999833i$
	$-0.856735 - 0.515757i$	$0.0182917 + 0.999833i$	$0.5 + 0.866025i$
	1	1	1

TABLE 2. Level 3 projection embedding coefficients.

$$t_1 = \dots, \quad t_2 = \dots, \quad t_3 = \dots$$

5.2. **Theorem and proof.** This subsection is devoted to proving the following theorem.

Theorem 1. *There is a monoidal equivalence*

$$\text{Ab}(\overline{\mathcal{D}_3}) \cong \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}.$$

Let $X = V_{\Lambda_1}$ be the object of $\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}$ by which we generate the planar algebra $\mathcal{P}_X \cong \mathcal{G}_2(q)$. Define $Y = \mathcal{F}_A(X)$ to be the image of X under the free functor. Now $\mathcal{F}_{A_3} : \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))} \rightarrow \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}$ restricts to an embedding $\mathcal{P}_{X; \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}} \hookrightarrow \mathcal{P}_{Y; \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}}$. Invertibility of the objects g and g^{-1} implies $g \otimes Y \cong Y$, with rigidity maps for g and g^{-1} building the mutually inverse isomorphisms.

We now compute some important dimensions.

Proposition 8. *The following are true:*

- (1) $\dim \text{Hom}_{\mathcal{C}_{A_3}}(Y^{\otimes 2} \rightarrow Y) = 3$
- (2) $\dim \text{Hom}_{\mathcal{C}_{A_3}}(Y^{\otimes 2} \rightarrow g^k) = 1$
- (3) $\dim \text{Hom}_{\mathcal{C}_{A_3}}(Y \rightarrow Y) = 1$ (i.e., Y is simple)

Proof. All three are proved using fusion graph calculations, so we prove only (1)³. The fusion graph tells us that

$$V_{\Lambda_1}^{\otimes 2} \cong V_{\emptyset} \oplus V_{\Lambda_1} \oplus V_{2\Lambda_1} \oplus V_{\Lambda_2}$$

and

$$V_{\Lambda_1} \otimes A \cong V_{\Lambda_1} \oplus V_{2\Lambda_1} \oplus V_{3\Lambda_1} \oplus V_{\Lambda_2} \oplus V_{\Lambda_2 + \Lambda_1} \oplus V_{\Lambda_2 + 2\Lambda_1}.$$

On the other hand, we compute

$$\begin{aligned} \text{Hom}_{\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}}(Y^{\otimes 2} \rightarrow Y) &= \text{Hom}_{\mathcal{C}_{A_3}}(\mathcal{F}_{A_3}(V_7)^{\otimes 2} \rightarrow \mathcal{F}_{A_3}(V_7)) \\ &\cong \text{Hom}_{\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}}(\mathcal{F}_{A_3}(V_7^{\otimes 2}) \rightarrow \mathcal{F}_{A_3}(V_7)) \\ &= \text{Hom}_{\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}}(\mathcal{F}_{A_3}(V_7^{\otimes 2}) \rightarrow V_7 \otimes A_3) \\ &\cong \text{Hom}_{\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}}(V_7^{\otimes 2} \rightarrow V_7 \otimes A_3). \end{aligned}$$

Counting common irreducible constituents of $V_{\Lambda_1}^{\otimes 2}$ and $V_{\Lambda_1} \otimes A_3$ gives the desired result. \square

We have an immediate consequence.

Corollary 1. *There is a dominant monoidal functor*

$$\Psi_3 : \mathcal{D}_3 \rightarrow \overline{\text{Rep}(U_q(\mathfrak{g}_2))}_{A_3}$$

which maps

$$\begin{array}{c} \text{Y-shape} \end{array} \mapsto \tau \in \text{Hom}_{\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}}(Y^{\otimes 2} \rightarrow Y), \quad \begin{array}{c} \text{X-shape} \end{array} \mapsto P_g \in \text{End}_{\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}}(Y^{\otimes 2})$$

Proof. Proposition 8, along with the defining relations of \mathcal{D}_3 tell us this assignment is functorial. Since Y is a \otimes -generator and Ψ_3 surjects onto objects of \mathcal{P}_Y , dominance also follows. \square

Lemma 4. *The induced map*

$$\overline{\Psi}_3 : \overline{\mathcal{D}_3} \rightarrow \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}$$

is faithful.

Proof. The evaluation algorithm for \mathcal{D}_3 implies that \mathcal{D}_3 has simple unit. Therefore every ideal is contained in the ideal of negligibles, which is killed when passing to the semisimplification $\overline{\mathcal{D}}$. Hence the map $\overline{\Psi}_3$ has no kernel. \square

Proof of Theorem 1. We now note that since $\mathcal{G}_2(q)$ and \mathcal{D}_3 are unitary, we know that $\mathcal{G}_2(q) \hookrightarrow \mathcal{D}_3$ induces a \dagger -embedding $\overline{\mathcal{G}_2(q)} \hookrightarrow \overline{\mathcal{D}_3}$. Thus, there is a chain

$$\overline{\mathcal{G}_2(q)} \hookrightarrow \overline{\mathcal{D}_3} \xrightarrow{\overline{\Psi}_3} \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}$$

³See, e.g., Figure 5 of [10] for the fusion graph.

of faithful dominant functors. Using the universal property of Karoubi completion, we arrive at the commutative diagram

$$\begin{array}{ccccc}
 \overline{\mathcal{G}_2(q_3)} & \hookrightarrow & \overline{\mathcal{D}_3} & \hookrightarrow & \\
 \downarrow & & \downarrow & \searrow \bar{\Psi} & \\
 \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))} & \xrightarrow{\mathcal{F}_1} & \text{Ab}(\overline{\mathcal{D}_3}) & \xrightarrow{\mathcal{F}_2} & \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}
 \end{array}$$

where \mathcal{F}_1 and \mathcal{F}_2 are the induced functors. At this point we shift our focus to the lower layer of the diagram.

By [[empty citation](#)], $(\mathcal{F}_2 \circ \mathcal{F}_1)|_{\overline{\mathcal{G}_2(q_3)}} = \mathcal{F}_{A_3}|_{\overline{\mathcal{G}_2(q_3)}}$ implies $\mathcal{F}_2 \circ \mathcal{F}_1 = \mathcal{F}_{A_3}$. Note that both $\overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}$ and $\text{Ab}(\overline{\mathcal{D}_3})$ are semisimple, and therefore \mathcal{F}_1 has a lax-monoidal right adjoint \mathcal{F}_1^\vee . Proposition 5 now allows us to conjecture K and B such that the following diagram commutes up to natural isomorphism:

$$\begin{array}{ccccc}
 \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))} & \xrightarrow{\mathcal{F}_1} & \text{Ab}(\overline{\mathcal{D}_3}) & \xrightarrow{\mathcal{F}_2} & \overline{\text{Rep}(U_q(\mathfrak{g}_2))}_A \\
 & \searrow \mathcal{F}_B & \downarrow K & \nearrow \mathcal{F}' & \\
 & & \overline{\text{Rep}(U_q(\mathfrak{g}_2))}_B & &
 \end{array}$$

Here, \mathcal{F}' is defined to complete the diagram. From here, apply \mathcal{F}_B^\vee to the containment $\mathbb{1} \subseteq \mathcal{F}'^\vee(\mathbb{1})$:

$$\begin{aligned}
 B &= \mathcal{F}_B^\vee(\mathbb{1}) \subseteq \mathcal{F}_B^\vee \circ \mathcal{F}'^\vee(\mathbb{1}) \\
 &\cong (\mathcal{F}_2 \circ \mathcal{F}_1)^\vee(\mathbb{1}) \\
 &= \mathcal{F}_{A_3}^\vee(\mathbb{1}) \\
 &= \mathcal{F}_A^\vee(A_3) = A_3.
 \end{aligned}$$

So $B \subseteq A_3$. Since A_3 has only two simple summands, we know A_3 has no nontrivial subalgebras: $B \cong \mathbb{1}$ or $B \cong A_3$. If $B \cong \mathbb{1}$ then

$$\text{Ab}(\overline{\mathcal{D}_3}) \cong \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{\mathbb{1}} \cong \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}$$

A quick dimension count falsifies this. Hence $\text{Ab}(\overline{\mathcal{D}_3}) \cong \overline{\text{Rep}(U_{q_3}(\mathfrak{g}_2))}_{A_3}$. \square

6. RESULTS: LEVEL 4

At level $k = 4$ we have $q = q_4 = e^{\frac{2\pi i}{48}}$ and $A_4 = V_\emptyset \oplus V_{3\Lambda_1}$. From [5] we have $\overline{\text{Rep}(U_{q_4}(\mathfrak{g}_2))}_{A_4}^0 \cong \text{Vec}(\mathbb{Z}_2)$, giving us one new \mathbb{Z}_2 -like simple object h . The module fusion graph for level 4 is shown in Figure 2. The details of the GPA embedding at level 4 are less instructive than the level 3 case, so we relegate the details to the attached Mathematica files. Much of the story remains the same. The trivalent coordinates are algebraically nicer than those at level 3; up to sign, we showed 5 of 9 in Subsection 4.1. The nonzero coordinates of the projection come in blocks of 4, and 9. There is also an analogue of Theorem 1 for level 4.

Theorem 2. *There is a monoidal equivalence*

$$\text{Ab}(\overline{\mathcal{D}(q_4)}) \cong \overline{\text{Rep}(U_{q_4}(\mathfrak{g}_2))}_{A_4}.$$

This theorem is proved by using analogues of Proposition 8, Corollary 1, Lemma 4. The same argument used in the proof of Theorem 1 except with, e.g., every q_3 switched out for a q_4 , may be applied.

Note that since $\overline{\text{Rep}(U_{q_4}(\mathfrak{g}_2))}_{A_4}^0$ contributes a \mathbb{Z}_2 -like simple object, there is only one decoration of a trivalent vertex; we represent this as an undirected colored strand. The structure constants for \mathcal{D}_4 are:

$$\omega = -1$$

$$r_1 = e^{-\frac{\pi i}{6}}, \quad r_2 = e^{-\frac{2\pi i}{3}}$$

$$s_1 = e^{-\frac{\pi i}{6}}, \quad s_2 = e^{-\frac{4\pi i}{3}}$$

$$t_1 = -1 \quad t_2 = -1$$

REFERENCES

- [1] Alain Bruguières and Sonia Natale. *Exact sequences of tensor categories*. 2010. arXiv: 1006.0569 [math.QA]. URL: <https://arxiv.org/abs/1006.0569>.
- [2] Daniel Copeland and Cain Edie-Michell. *Cell Systems for $\overline{\text{Rep}(U_q(\mathfrak{sl}_N))}$ Module Categories*. 2023. arXiv: 2301.13172 [math.QA].
- [3] R. Coquereaux, R. Rais, and E. H. Tahri. “Exceptional quantum subgroups for the rank two Lie algebras B2 and G2”. In: *Journal of Mathematical Physics* 51.9 (Sept. 2010). ISSN: 1089-7658. DOI: 10.1063/1.3476319. URL: <http://dx.doi.org/10.1063/1.3476319>.
- [4] Agustina Czenky. *Diagrammatics for cyclic pointed fusion categories*. 2024. arXiv: 2404.08084 [math.QA]. URL: <https://arxiv.org/abs/2404.08084>.
- [5] Alexei Davydov et al. *The Witt group of non-degenerate braided fusion categories*. 2011. arXiv: 1009.2117 [math.QA]. URL: <https://arxiv.org/abs/1009.2117>.
- [6] Cain Edie-Michell. *Auto-equivalences of the modular tensor categories of type A, B, C and G*. 2020. arXiv: 2002.03220 [math.QA]. URL: <https://arxiv.org/abs/2002.03220>.
- [7] Cain Edie-Michell and Caleb Kennedy Hill. “A graph planar algebra approach to near-group categories”. 2026.
- [8] Cain Edie-Michell, Noah Snyder, and Hans Wenzl. *Interpolation categories for conformal embeddings*. 2024.
- [9] David E. Evans and Terry Gannon. *Near-group fusion categories and their doubles*. 2012. arXiv: 1208.1500 [math.QA]. URL: <https://arxiv.org/abs/1208.1500>.
- [10] David E. Evans and Mathew Pugh. “Spectral Measures for G 2”. In: *Communications in Mathematical Physics* 337.3 (Feb. 2015), pp. 1161–1197. ISSN: 1432-0916. DOI: 10.1007/s00220-015-2293-0. URL: <http://dx.doi.org/10.1007/s00220-015-2293-0>.
- [11] Caleb Kennedy Hill. “sp4 stuff”. 2026.
- [12] Yigal Kamel. *Strong monoidal functors and modules*. 2023. URL: https://yigalkamel.web.illinois.edu/StrongFuncModules_Mar23.pdf.
- [13] David Kazhdan and Hans Wenzl. “Reconstructing monoidal categories”. In: (1993). URL: <https://api.semanticscholar.org/CorpusID:125218067>.
- [14] Greg Kuperberg. “Spiders for rank 2 Lie algebras”. In: *Communications in Mathematical Physics* 180.1 (Sept. 1996), pp. 109–151. ISSN: 1432-0916. DOI: 10.1007/bf02101184. URL: <http://dx.doi.org/10.1007/BF02101184>.
- [15] Scott Morrison, Emily Peters, and Noah Snyder. *Categories generated by a trivalent vertex*. 2016. arXiv: 1501.06869 [math.QA].
- [16] Viktor Ostrik. *Module categories, weak Hopf algebras and modular invariants*. 2001. arXiv: math/0111139 [math.QA]. URL: <https://arxiv.org/abs/math/0111139>.