

# Constructing the extended Haagerup planar algebra

by

STEPHEN BIGELOW

*University of California, Santa Barbara  
Santa Barbara, CA, U.S.A.*

SCOTT MORRISON

*Australian National University  
Acton, Australia*

EMILY PETERS

*Massachusetts Institute of Technology  
Cambridge, MA, U.S.A.*

NOAH SNYDER

*Indiana University, Bloomington  
Bloomington, IN, U.S.A.*

## 1. Introduction

A subfactor is an inclusion  $N \subset M$  of von Neumann algebras with trivial center. The theory of subfactors can be thought of as a non-abelian version of Galois theory, and has had many applications in operator algebras, quantum algebra and knot theory. For example, the construction of a new finite depth subfactor, as in this paper, also yields two new fusion categories (by taking the even parts) and a new 3-dimensional TQFT (via the Ocneanu–Turaev–Viro construction [48], [51], [62]).

A subfactor  $N \subset M$  has three key invariants. From strongest to weakest, they are: the standard invariant (which captures all information about “basic” bimodules over  $M$  and  $N$ ), the principal and dual principal graphs (which together describe the fusion rules for these basic bimodules) and the index (which is a real number measuring the “size” of the basic bimodules). We will use the axiomatization of the standard invariant as a subfactor planar algebra, which is due to Jones [31]. Other axiomatizations include Ocneanu’s paragroups [47] and Popa’s  $\lambda$ -lattices [56]. (For readers more familiar with tensor categories, these three approaches are analogous to the diagram calculus [35], [51], [58], basic  $6j$  symbols [61, Chapter 5], and towers of endomorphism algebras [65], respectively.) The standard invariant is a complete invariant of amenable subfactors of the hyperfinite  $\text{II}_1$  factor [53], [55].

The index of a subfactor  $N \subset M$  must lie in the set

$$\left\{ 4 \cos^2\left(\frac{\pi}{n}\right) : n \geq 3 \right\} \cup [4, \infty],$$

and all numbers in this set can be realized as the index of a subfactor [26]. Early work on classifying subfactors of “small index” concentrated on the case of index less than 4. The principal graphs of these subfactors are exactly the Dynkin diagrams  $A_n$ ,  $D_{2n}$ ,  $E_6$  and  $E_8$ . Furthermore there is exactly one subfactor planar algebra with principal graph  $A_n$  or  $D_{2n}$  and there is exactly one pair of complex conjugate subfactor planar algebras with principal graph  $E_6$  or  $E_8$ . (See [47] for the outline of this result, and [5], [22], [23] and [38] for more details.) The story of the corresponding classification for index equal to 4 is outlined in [55, p. 231]. In this case, the principal graph must be an affine Dynkin diagram. For some principal graphs there are multiple non-conjugate subfactors with the same principal graph, which are distinguished by homological data.

The classification of subfactors of “small index” greater than 4 was initiated by Haagerup [18]. His main result is a list of all possible pairs of principal graphs of irreducible subfactors of index larger than 4 but smaller than  $3 + \sqrt{3}$ . Here we begin to see subfactors whose principal graph is different from its dual principal graph. If  $\Gamma$  refers to a pair of principal graphs and we need to refer to one individually, we will use the notation  $\Gamma^p$  and  $\Gamma^d$ . Any subfactor  $N \subset M$  has a dual given by the basic construction  $M \subset M_1$ . Taking duals reverses the shading on the planar algebra, switches the principal and dual principal graphs and preserves index. Haagerup’s list is as follows (we list each pair once):

- $(A_\infty, A_\infty)$ ,
- the infinite family  $\{\mathcal{H}_n\}_{n \in \mathbb{N}}$ , where

$$\mathcal{H}_n = \left( \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right),$$

Diagram 1: A path of  $4n+3$  edges starting with a star, then a path of  $4n+3$  edges, and finally a forked path with two branches.

Diagram 2: A path of  $4n+3$  edges starting with a star, then a path of  $4n+3$  edges, and finally a forked path with two branches.

which has  $\text{index}(\mathcal{H}_0) = \frac{1}{2}(5 + \sqrt{13})$ ,  $\text{index}(\mathcal{H}_1)$  equal to the largest root of  $x^3 - 8x^2 + 17x - 5$  and  $\text{index}(\mathcal{H}_n)$  increasing with  $n$ , converging to the real root of  $x^3 - 6x^2 + 8x - 4$ , (and thus  $\text{index}(\mathcal{H}_0) \approx 4.30278$ ,  $\text{index}(\mathcal{H}_1) \approx 4.37720$ , and  $\lim_{n \rightarrow \infty} \text{index}(\mathcal{H}_n) \approx 4.38298$ );

- the infinite family  $\{\mathcal{B}_n\}_{n \in \mathbb{N}}$ , where

$$\mathcal{B}_n = \left( \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right),$$

Diagram 1: A path of  $6n+3$  edges starting with a star, then a path of  $6n+3$  edges, and finally a hexagonal loop.

Diagram 2: A path of  $6n+3$  edges starting with a star, then a path of  $6n+3$  edges, and finally a forked path with two branches.

which has  $\text{index}(\mathcal{B}_0) = \frac{1}{2}(7 + \sqrt{5})$  and  $\text{index}(\mathcal{B}_n)$  increasing with  $n$ , converging to the real root of  $x^3 - 8x^2 + 19x - 16$  (thus  $\text{index}(\mathcal{B}_0) \approx 4.61803$  and  $\lim_{n \rightarrow \infty} \text{index}(\mathcal{B}_n) \approx 4.65897$ );

- one more pair of graphs



which has index  $\frac{1}{2}(5+\sqrt{17})\approx 4.56155$ .

Haagerup’s paper announces this result up to index  $3+\sqrt{3}\approx 4.73205$ , but only proves it up to index  $3+\sqrt{2}\approx 4.41421$ ; this includes all of the graphs  $\mathcal{H}_n$ , but none of the graphs  $\mathcal{B}_n$  or  $\mathcal{AH}$ . Haagerup’s proof of the full result has not yet appeared. In work in progress, Jones, Morrison, Penneys, Peters and Snyder have independently confirmed his result (following Haagerup’s outline except at one point using a result from [32]), and have extended his techniques to give a partial result up to index 5 (see [25], [42], [45] and [50]). In this paper, we will only rely on the part of Haagerup’s classification that has appeared in print.

Haagerup’s original result did not specify which of the possible principal graphs are actually realized. Considerable progress has since been made in this direction. Asaeda and Haagerup [2] proved the existence and uniqueness of a subfactor planar algebra whose principal graphs are  $\mathcal{H}_0$  (called the *Haagerup subfactor*), and a subfactor planar algebra for  $\mathcal{AH}$  (called the *Asaeda–Haagerup subfactor*). Izumi [24] gave an alternative construction of the Haagerup subfactor. Bisch [8] showed that none of the graphs  $\mathcal{B}_n$  can be principal graphs because they give inconsistent fusion rules. Asaeda [1] and Asaeda–Yasuda [3] proved that  $\mathcal{H}_n$  is not a principal graph for  $n\geq 2$ . To do this, they showed that the index is not a cyclotomic integer, and then appealed to a result of Etingof, Nikshych and Ostrik [15], which in turn is proved by reduction to the case of modular categories, where it was proved in the context of rational conformal field theories by Coste–Gannon [13] using a result of de Boer–Goeree [11].

The following is the main result of this paper.

**THEOREM 3.10.** *There is a subfactor planar algebra with principal graphs  $\mathcal{H}_1$ .*

In addition, we prove in Theorem 3.9 that this planar algebra is the only one with these principal graphs. This result completes the classification of all subfactor planar algebras up to index  $3+\sqrt{3}$ .

**COROLLARY** ([2], [3], [8], [18] and Theorem 3.10) *The only irreducible subfactor planar algebras with index in the range  $(4, 3+\sqrt{3})$  are*

- *the non-amenable Temperley–Lieb planar algebra at every index in this range, with principal graphs  $(A_\infty, A_\infty)$ ,*

- *the Haagerup planar algebra with principal graphs  $\mathcal{H}_0$ , and its dual,*
- *the Haagerup–Asaeda planar algebra with principal graphs  $\mathcal{AH}$ , and its dual,*
- *the extended Haagerup planar algebra with principal graphs  $\mathcal{H}_1$ , and its dual.*

By Popa’s classification [53], the latter three pairs can each be realized uniquely as the standard invariant of a subfactor of the hyperfinite  $\text{II}_1$  factor. This gives a complete classification of amenable subfactors of the hyperfinite  $\text{II}_1$  factor with index between 4 and  $3+\sqrt{3}$ . The non-amenable case remains open because it is unknown for which indices the Temperley–Lieb planar algebra can be realized as the standard invariant of the hyperfinite  $\text{II}_1$  factor, nor in how many ways it can be realized (see [6] and [54] for some work in this direction). Furthermore, there remain many interesting questions about small-index subfactors of arbitrary factors.

It was already expected that the extended Haagerup subfactor should exist, due to approximate numerical evidence coming from computations by Ikeda [21]. We note that, although our construction relies on a computation of the traces of a few large matrices, this computation consists of exact arithmetic in a number field, and is a very different calculation from the one Ikeda did numerically.

The search for small-index subfactors has so far produced the three pairs of “sporadic” examples: the Haagerup, Asaeda–Haagerup and extended Haagerup subfactors. These are some of the very few known subfactors that do not seem to fit into the frameworks of groups, quantum groups, or conformal field theory [20]. (See also a generalization of the Haagerup subfactor due to Izumi [24, Example 7.2].) You might think of them as analogues of the exceptional simple Lie algebras, or of the sporadic finite simple groups. (Without a good extension theory, it is not yet clear what “simple” should mean in this context.)

In this paper, we study the extended Haagerup planar algebra. We construct the extended Haagerup planar algebra by locating it inside the graph planar algebra [28] of its principal graph. By a result of Jones–Penneys [46] (generalized in [33]) every subfactor planar algebra occurs in this way. We find the right planar subalgebra by following a recipe outlined by Jones [28], [32] and further developed by Peters [52], who applied it to the Haagerup planar algebra.

We also give a presentation of the extended Haagerup planar algebra using a single planar generator and explicit relations. We prove that the subalgebra of the graph planar algebra contains an element also satisfying these relations. This is convenient because different properties become more apparent in different descriptions of the planar algebra. For example, the subalgebra of the graph planar algebra is clearly non-trivial, which would be difficult to prove directly from the generators and relations. In the other direction, in §5 we prove that our relations result in a space of closed diagrams that is

at most 1-dimensional, which would be difficult to prove in the graph planar algebra setting.

In §2 we recall the definitions of planar algebras and graph planar algebras [28], [31]. We also set some notation for the graph planar algebra of  $\mathcal{H}_1^p$ . In §3 we prove our two main theorems, Theorems 3.9 and 3.10. Theorem 3.9, the uniqueness theorem, says that for each  $k$  there is at most one subfactor planar algebra with principal graphs  $\mathcal{H}_k$ . Furthermore we give a skein-theoretic description by generators and relations of the unique candidate planar algebra. Theorem 3.10, the existence theorem, constructs a subfactor planar algebra with principal graphs  $\mathcal{H}_1$  by realizing the skein-theoretic planar algebra as a subalgebra of the graph planar algebra. Proofs of several key results needed for the main existence and uniqueness arguments are deferred to §§4–6. In particular, §4 describes an evaluation algorithm that uses the skein theory to evaluate any closed diagram (Theorem 3.8). This is crucial to our proofs of both existence and uniqueness and may be of broader interest in quantum topology. This section can be read independently of the rest of the paper. §5 consists of calculations of inner products using generators and relations. §6 gives the description of the generator of our subfactor planar algebra inside the graph planar algebra and verifies its properties. Appendix A gives the tensor product rules for the two fusion categories associated with the extended Haagerup subfactor.

Part of this work was done while Stephen Bigelow and Emily Peters were visiting the University of Melbourne. Scott Morrison was at Microsoft Station Q and the Miller Institute for Basic Research during this work. Emily Peters was supported in part by NSF Grant DMS-0401734 and a fellowship from Soroptimist International, and Noah Snyder was supported in part by RTG grant DMS-0354321 and in part by an NSF postdoctoral fellowship. We would like to thank Vaughan Jones for many useful discussions, and Yossi Farjoun for lessons on Newton’s method.

## 2. Background

### 2.1. Planar algebras

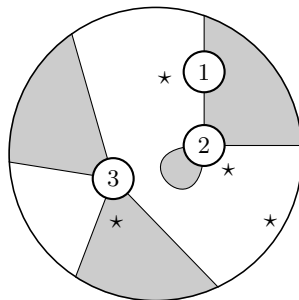
Planar algebras were defined in [28] and [31]. More general definitions have since appeared elsewhere, but we only need the original notion of a *shaded planar algebra*, which we sketch here. For further details see [28, §2], [31, §0] or [9].

*Definition 2.1.* A (*shaded*) *planar tangle* has an outer disk, a finite number of inner disks and a finite number of non-intersecting strings. A string can be either a closed loop or an edge with endpoints on boundary circles. We require that there be an even number of endpoints on each boundary circle, and a checkerboard shading of the regions in the

complement of the interior disks. We further require that there be a marked point on the boundary of each disk, and that the inner disks are ordered.

Two planar tangles are considered equal if they are isotopic (not necessarily relative to the boundary).

Here is an example of a planar tangle:



Planar tangles can be composed by placing one planar tangle inside an interior disk of another, lining up the marked points and connecting endpoints of strands. The numbers of endpoints and the shadings must match up appropriately. This composition turns the collection of planar tangles into a colored operad.

*Definition 2.2.* A (*shaded*) *planar algebra* consists of the following:

- A family of vector spaces  $\{V_{n,\pm}\}_{n \in \mathbb{N}}$ , called the positive and negative  $n$ -box spaces;
- For each planar tangle, a multilinear map  $V_{n_1,\pm_1} \otimes \dots \otimes V_{n_k,\pm_k} \rightarrow V_{n_0,\pm_0}$  where  $n_j$  is half the number of endpoints on the  $j$ th interior boundary circle,  $n_0$  is half the number of endpoints on the outer boundary circle, and the signs  $\pm$  are positive (resp. negative) when the marked point on the corresponding boundary circle is in an unshaded region (resp. shaded region).

For example, the planar tangle above gives a map

$$V_{1,+} \otimes V_{2,+} \otimes V_{2,-} \longrightarrow V_{3,+}.$$

The linear map associated with a ‘radial’ tangle (with one inner disk, radial strings and matching marked points) must be the identity. We require that the action of planar tangles be compatible with composition of planar tangles. In other words, composition of planar tangles must correspond to the obvious composition of multilinear maps. In operadic language, this says that a planar algebra is an algebra over the operad of planar tangles.

We will refer to an element of  $V_{n,\pm}$  (and specifically  $V_{n,+}$ , unless otherwise stated) as an “ $n$ -box.”

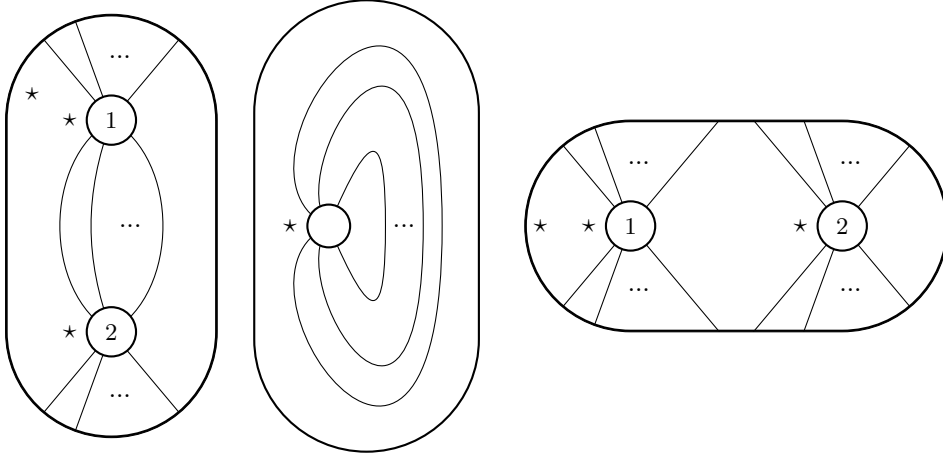


Figure 1. The multiplication, trace and tensor product tangles.

We make frequent use of three families of planar tangles called multiplication, trace and tensor product, which are shown in Figure 1. Multiplication gives an associative product  $V_{n,\pm} \otimes V_{n,\pm} \rightarrow V_{n,\pm}$ . Trace gives a map  $V_{n,\pm} \rightarrow V_{0,\pm}$ . Tensor product gives an associative product  $V_{m,\pm} \otimes V_{n,\pm} \rightarrow V_{m+n,\pm}$  if  $m$  is even, or  $V_{m,\pm} \otimes V_{n,\mp} \rightarrow V_{m+n,\pm}$  if  $m$  is odd.

The (shaded or unshaded) empty diagrams can be thought of as elements of  $V_{0,\pm}$ , since the ‘empty tangle’ induces a map from the empty tensor product  $\mathbb{C}$  to the space  $V_{0,\pm}$ . If the space  $V_{0,\pm}$  is 1-dimensional, then we can identify it with  $\mathbb{C}$  by sending the empty diagram to 1. In many other cases, we can make do with the following definition.

*Definition 2.3.* A *partition function* is a pair of linear maps

$$Z_{\pm}: V_{0,\pm} \longrightarrow \mathbb{C}$$

that send the empty diagrams to 1.

In a planar algebra with a partition function, let

$$\text{tr}: V_{n,\pm} \longrightarrow \mathbb{C}$$

denote the composition of the trace tangle with  $Z$ .

Sometimes we will need to refer simply to the action of the trace tangle, which we denote by  $\text{tr}_0: V_{n,\pm} \rightarrow V_{0,\pm}$ .

Notice that the above trace tangle is the ‘right trace’. There is also a ‘left trace’, where all the strands are connected around the left side.

*Definition 2.4.* A planar algebra with a partition function is

- *positive definite*, if there is an antilinear adjoint operation  $*$  on each  $V_{n,\pm}$ , compatible with the adjoint operation on planar tangles given by reflection; the sesquilinear form  $\langle x, y \rangle = \text{tr}(xy^*)$  is positive definite;
- *spherical*, if the left trace

$$\text{tr}_l: V_{1,\pm} \longrightarrow V_{0,\mp} \xrightarrow{Z_\mp} \mathbb{C}$$

and the right trace

$$\text{tr}_r: V_{1,\pm} \longrightarrow V_{0,\pm} \xrightarrow{Z_\pm} \mathbb{C}$$

are equal.

The spherical property implies that the left and right traces are equal on every  $V_{n,\pm}$ . Since every planar algebra we consider is spherical, we will usually ignore the distinction between left and right trace.

*Definition 2.5.* A *subfactor planar algebra* is a positive definite spherical planar algebra such that  $\dim V_{0,+} = \dim V_{0,-} = 1$  and  $\dim V_{n,\pm} < \infty$ .

As a consequence of being spherical and having 1-dimensional 0-box spaces, subfactor planar algebras always have a well-defined modulus, as described below.

*Definition 2.6.* We say that the planar algebra has *modulus*  $d$  if the following relations hold:

$$\begin{array}{c} \text{⊙} \\ \text{⊙} \end{array} = d \cdot \text{○} \quad \text{and} \quad \begin{array}{c} \text{⊙} \\ \text{⊙} \end{array} = d \cdot \text{⊙}.$$

The *principal graphs* of a subfactor encode the fusion rules for the basic bimodules  ${}_N M_M$  and  ${}_M M_N$ . The vertices of the principal graph are the isomorphism classes of simple  $N$ - $N$  and  $N$ - $M$  bimodules that occur in tensor products of the basic bimodules. The edges give the decompositions of tensor products of simple bimodules with the basic bimodule. The dual principal graph encodes similar information, but for  $M$ - $N$  and  $M$ - $M$  bimodules. This definition is due to Connes [12] and Ocneanu [47], together with later work of Jones [30] that lets you replace the original Hilbert space bimodules with algebraic bimodules, for example  ${}_M L^2(M)_N$  with  ${}_M M_N$ .

In the language of planar algebras, the basic bimodule is a single strand, and the isomorphism classes of simple bimodules are equivalence classes of irreducible projections in the box spaces. For a more detailed description, see [43, §4.1].

*Definition 2.7.* A subfactor planar algebra  $\mathcal{P}$  is *irreducible* if  $\dim \mathcal{P}_{1,+} = 1$ .

A subfactor planar algebra has *finite depth* if it has finitely many isomorphism classes of irreducible projections, that is, finitely many vertices in the principal graphs [47], [53].



The following is well known, and combines the results of [31] and [53].

**THEOREM 2.8.** *Finite-depth finite-index subfactors of the hyperfinite  $\text{II}_1$  factor are in one-to-one correspondence with finite-depth subfactor planar algebras. Irreducible subfactors (those for which  $M$  is irreducible as an  $N$ - $M$  bimodule) correspond to irreducible subfactor planar algebras.*

*Proof.* Suppose we are given a subfactor  $N \subset M$ . The corresponding planar algebra is constructed as follows. Let  $\mathcal{C}$  be the 2-category of all bimodules that appear in the decomposition of some tensor product of alternating copies of  $M$  as an  $N$ - $M$  bimodule and  $M$  as an  $M$ - $N$  bimodule. These are  $A$ - $B$  bimodules for  $A, B \in \{M, N\}$ , and form the 1-morphisms of  $\mathcal{C}$ . Composition of 1-morphisms is given by tensor product. The 2-morphisms of  $\mathcal{C}$  are the intertwiners.

We can define duals in  $\mathcal{C}$  by taking the contragredient bimodule, which interchanges  $M$  as an  $N$ - $M$  bimodule with  $M$  as an  $M$ - $N$  bimodule. Now define the associated planar algebra by

$$\mathcal{P}_{n,\pm} = \text{End}_{\mathcal{C}} \left( \widehat{\bigotimes}_n M^{\pm} \right).$$

Here  $M^{\pm}$  means  $M$  or  $M^*$ , and  $\widehat{\bigotimes}_n M$  means  $M \otimes M^* \otimes M \otimes \dots \otimes M^{\pm}$ . The action of tangles is via the usual interpretation of string diagrams as 2-morphisms in a 2-category [35], with critical points interpreted as evaluation and coevaluation maps.

The difficult direction is to recover a subfactor from a planar algebra. The proof of this result was given in [53]. However in that paper, Popa uses towers of commutants instead of tensor products of bimodules, and  $\lambda$ -lattices instead of planar algebras. See [31] to translate from  $\lambda$ -lattices into planar algebras. See [7] and [30] to translate from towers of commutants into tensor products of bimodules.  $\square$

*Remark.* The above theorem says that a certain kind of subfactor is completely characterized by its representation theory (that is, the bimodules). This can be thought of as a subfactor version of the Doplicher–Roberts theorem [14] or, more generally, of Tannaka–Krein type theorems [36].

In general, given any extremal finite-index subfactor of a  $\text{II}_1$  factor, the standard invariant is a subfactor planar algebra. Several other reconstruction results have been proved. Popa extended his results on finite-depth subfactors to amenable subfactors of the hyperfinite  $\text{II}_1$  factor in [55]. The general situation for non-amenable subfactors of the hyperfinite  $\text{II}_1$  factor is more complicated: some subfactor planar algebras cannot be realized at all (an unpublished result of Popa, see [54]), while others can be realized by a continuous family of different subfactors [10]. Furthermore, once you move beyond the hyperfinite  $\text{II}_1$  factor, there are many new questions. On the one hand, any subfactor

planar algebra comes from a (canonically constructed, but not necessarily unique) subfactor of the free group factor  $L(F_\infty)$  [17], [34], [39], [57], while, on the other hand, there exist factors for which only the trivial planar algebra can be realized as the standard invariant of a subfactor [63].

**2.2. The Temperley–Lieb planar algebra**

Everyone’s favorite example of a planar algebra is the Temperley–Lieb planar algebra. It was defined (as an algebra) in [60], applied to subfactor theory in [26], and formulated diagrammatically in [37]. The vector space  $TL_{n,\pm}$  is spanned by non-crossing pairings of  $2n$  points (where the  $\pm$  depends on whether the marked point is in a shaded or an unshaded region). These pairings are drawn as intervals in a disk, starting from a marked point on the boundary. For example,

$$TL_{3,+} = \text{span} \left\{ \begin{array}{c} \star \\ \text{Diagram 1} \end{array}, \begin{array}{c} \star \\ \text{Diagram 2} \end{array}, \begin{array}{c} \star \\ \text{Diagram 3} \end{array}, \begin{array}{c} \star \\ \text{Diagram 4} \end{array}, \begin{array}{c} \star \\ \text{Diagram 5} \end{array} \right\}.$$

Planar tangles act on Temperley–Lieb elements “diagrammatically”: the inputs are inserted into the inner disk, strings are smoothed out, and each loop is discarded in exchange for a factor of  $d \in \mathbb{C}$ . For example,

If  $d \in \mathbb{R}$  we can introduce an antilinear involution  $*$  by reflecting diagrams. If  $d \geq 2$  then the Temperley–Lieb planar algebra is a subfactor planar algebra. If  $d = 2 \cos(\pi/n)$  for  $n = 3, 4, 5, \dots$ , then we can take a certain quotient to obtain a subfactor planar algebra. The irreducible projections in the Temperley–Lieb planar algebra are the Jones–Wenzl idempotents [27], [64].

*Definition 2.9.* The Jones–Wenzl idempotent  $f^{(n)} \in TL_{n,\pm}$  is characterized by

$$\begin{aligned} f^{(n)} &\neq 0, \\ f^{(n)} f^{(n)} &= f^{(n)}, \\ e_j f^{(n)} &= f^{(n)} e_j = 0 \quad \text{for } j = 1, 2, \dots, n-1, \end{aligned}$$

where  $e_1, \dots, e_{n-1}$  are the Jones projections

$$e_1 = \frac{1}{d} \begin{array}{c} \cup \\ | \\ \cap \end{array} \dots \begin{array}{c} \cup \\ | \\ \cap \end{array}, \quad e_2 = \frac{1}{d} \begin{array}{c} \cup \\ | \\ \cap \end{array} \begin{array}{c} \cup \\ | \\ \cap \end{array} \dots \begin{array}{c} \cup \\ | \\ \cap \end{array}, \quad \dots, \quad e_{n-1} = \frac{1}{d} \begin{array}{c} \cup \\ | \\ \cap \end{array} \dots \begin{array}{c} \cup \\ | \\ \cap \end{array}.$$

The following gives a recursive definition of the Jones–Wenzl idempotents. We should mention that the following pictures are drawn using rectangles instead of disks, and the marked points are assumed to be on the left side of the rectangles (including the implicit bounding rectangles). The quantum integers  $[n] = (q^n - q^{-n}) / (q - q^{-1})$  which appear below are specialized at a value of  $q$  such that  $[2] = d$ .

LEMMA 2.10. ([16])

$$\begin{array}{c} \text{Diagram of } f^{(k)} \end{array} = \begin{array}{c} \text{Diagram of } f^{(k-1)} \end{array} + \frac{1}{[k]} \sum_{a=1}^{k-1} (-1)^{a+k} [a] \begin{array}{c} \text{Diagram of } f^{(k-1)} \text{ with } a \text{ strands on top} \end{array} .$$

*Proof.* It is straightforward to check that the right-hand side of this equation satisfies the characterizing relations of Definition 2.9.  $\square$

We will also use the following more symmetrical version of the lemma.

LEMMA 2.11.

$$\begin{array}{c} \text{Diagram of } f^{(k)} \end{array} = \begin{array}{c} \text{Diagram of } f^{(k-1)} \end{array} + \frac{1}{[k][k-1]} \sum_{a,b=1}^{k-1} (-1)^{a+b+1} [a][b] \begin{array}{c} \text{Diagram of } f^{(k-2)} \text{ with } a \text{ strands on top and } b \text{ strands on bottom} \end{array} .$$

*Proof.* First apply Lemma 2.10, and then apply the vertically reflected version of that lemma to all but the first term in the resulting expression.  $\square$

We sometimes consider the complete expansion of a Jones–Wenzl idempotent into a linear combination of Temperley–Lieb diagrams. Suppose  $\beta$  is a  $k$ -strand Temperley–Lieb diagram. Let  $\text{Coeff}_{f^{(k)}}(\beta)$  denote the coefficient of  $\beta$  in the expansion of  $f^{(k)}$ . Thus

$$f^{(k)} = \sum \text{Coeff}_{f^{(k)}}(\beta) \beta,$$

where the sum is over all  $k$ -strand Temperley–Lieb diagrams  $\beta$ .

We will frequently state values of  $\text{Coeff}_{f^{(k)}}(\beta)$  without giving the details of how they are computed. A convenient formula for these values is given by Frenkel and Khovanov in [16]. See also [41] for a detailed exposition, including a helpful example at the end of §4 of that paper. A related formula was announced by Ocneanu [49], and special cases of this were proved by Reznikoff [59].

### 2.3. The graph planar algebra

In this section we define the *graph planar algebra*  $\text{GPA}(G)$  of a bipartite graph  $G$  with a chosen base point, and recall some of its basic properties [28]. Except in degenerate cases, this fails to be a subfactor planar algebra because  $\dim \text{GPA}(G)_{0,+}$  and  $\dim \text{GPA}(G)_{0,-}$  are greater than 1. However, after specifying a certain partition function, all the other axioms for a subfactor planar algebra hold.

The box space  $\text{GPA}(G)_{n,\pm}$  is the space of functionals on the set of loops on  $G$  that have length  $2n$  and are based at an even vertex in the case of  $\text{GPA}(G)_{n,+}$ , or an odd vertex in the case of  $\text{GPA}(G)_{n,-}$ .

Suppose that  $T$  is a planar tangle with  $k$  inner disks, and  $f_1, \dots, f_k$  are functionals in the appropriate spaces  $\text{GPA}(G)_{n_j, \pm_j}$ . Then we will define  $T(f_1, \dots, f_k)$  as a certain “weighted state sum”.

A *state* on  $T$  is an assignment of vertices of  $G$  to regions of  $T$  and edges of  $G$  to strings of  $T$ , such that unshaded regions are assigned even vertices, shaded regions are assigned odd vertices, and the edge assigned to the string between two regions goes between the vertices assigned to those regions. In particular, a state for any graph is uniquely specified by giving only the assignment of edges, and a state for a simply laced graph is specified by giving only the assignment of vertices. Since all the graphs we consider are simply laced, we typically specify states by giving the assignment of vertices. The inner boundaries  $\partial_j(\sigma)$  and outer boundary  $\partial_0(\sigma)$  of a state are the loops obtained by reading the edges assigned to strings clockwise around the corresponding disk.

We define  $T(f_1, \dots, f_k)$  by describing its value on a loop  $\ell$ . This is given by the weighted state sum

$$T(f_1, \dots, f_k)(\ell) = \sum_{\sigma} c(T, \sigma) \prod_{j=1}^k f_j(\partial_j(\sigma)).$$

Here, the sum is over all states  $\sigma$  on  $G$  such that  $\partial_0(\sigma) = \ell$ , and the weight  $c(T, \sigma)$  is defined below.

To specify the weight  $c(T, \sigma)$ , it helps to draw  $T$  in a certain standard form. Each disk is drawn as a rectangle, with the same number of strands meeting the top and bottom edges, no strands meeting the side edges, and the starred region on the left side. The strands are drawn smoothly, with a finite number of local maxima and minima. Then,

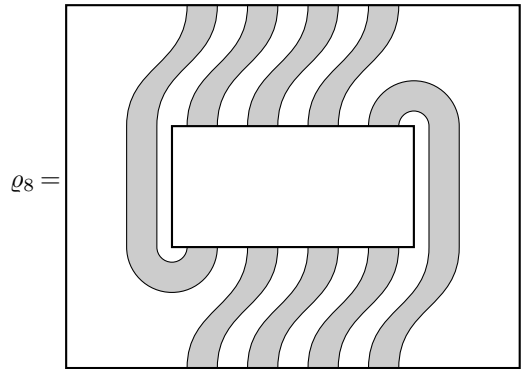
$$c(T, \sigma) = \prod_{t \in E(T)} \sqrt{\frac{d_{\sigma(t_{\text{convex}})}}{d_{\sigma(t_{\text{concave}})}}},$$

where  $E(T)$  is the set of local maxima and minima of the strands of  $T$ ,  $d_v$  is the Perron–Frobenius dimension of the vertex  $v$ , and  $t_{\text{convex}}$  and  $t_{\text{concave}}$  are, respectively, the regions

on the convex and concave sides of  $t$ . The Perron–Frobenius dimension of a vertex is the corresponding entry in the Perron–Frobenius eigenvector of the adjacency matrix. This is the largest-eigenvalue eigenvector, normalized so the Perron–Frobenius dimension of the base point is 1, and its entries are strictly positive.

It is now easy to check that this planar algebra has modulus  $d$ , the Perron–Frobenius dimension of  $G$ .

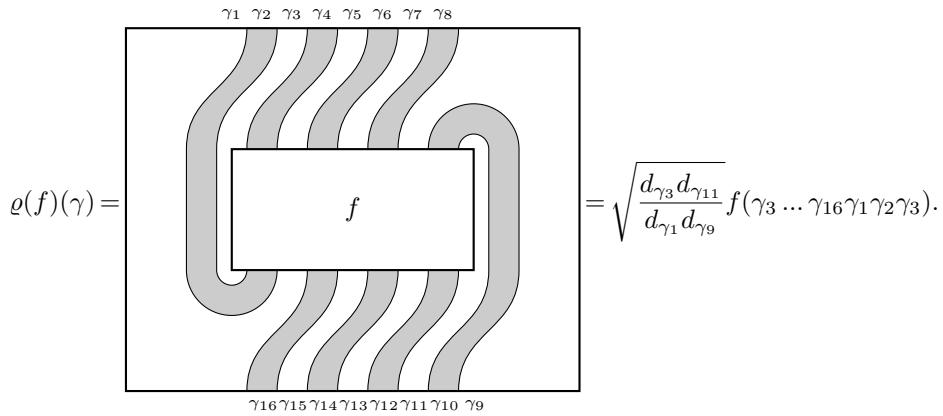
*Example 2.12.* Fix a simply laced graph  $G$ . Consider



the “2-click” rotation on 8-boxes, already drawn in standard form, and a loop

$$\gamma = \gamma_1 \gamma_2 \dots \gamma_{16} \gamma_1.$$

Then



It is a general fact about the Perron–Frobenius dimensions of bipartite graphs that

$$\sum_{\text{even vertices } v} d_v^2 = \sum_{\text{odd vertices } v} d_v^2.$$

Call this number  $\mathcal{I}$ , the *global index*. We use the partition function

$$Z: \text{GPA}_{0,\pm} \longrightarrow \mathbb{C},$$

$$f \longmapsto \sum_v f(v) \frac{d_v^2}{\mathcal{I}},$$

and the involution  $*$  given by reversing loops, that is

$$f^*(\gamma_1\gamma_2\gamma_3 \dots \gamma_n\gamma_1) := f(\gamma_1\gamma_n \dots \gamma_3\gamma_2\gamma_1).$$

PROPOSITION 2.13. *For any bipartite graph  $G$  with base point, the planar algebra with partition function and involution  $(\text{GPA}(G), Z, *)$  is a spherical positive definite planar algebra whose modulus is the Perron–Frobenius eigenvalue for  $G$ .*

*Proof.* This is due to [28], but we recall the easy details here. The inner product is positive definite, because the basis of Kronecker-delta functionals on loops  $\{\delta_\gamma\}_{\gamma \in \Gamma_{2k}}$  is an orthogonal basis and  $\langle \delta_\gamma, \delta_\gamma \rangle = d_{\gamma_1} d_{\gamma_{k+1}} / \mathcal{I} > 0$ .

Sphericity is a straightforward computation:

$$\text{tr}_l(X) = Z \left( \begin{array}{c} \text{Diagram: A circle labeled } X \text{ is inside a shaded vertical rectangle. A loop is formed by the top and bottom edges of the rectangle and the left and right sides of the circle.} \end{array} \right) = Z \left( \sum_{\substack{\text{edges } e \text{ from even} \\ \text{to odd vertices}}} X(e) \frac{d_{s(e)}}{d_{t(e)}} \delta_{t(e)} \right)$$

$$= \sum_{\substack{\text{edges } e \text{ from even} \\ \text{to odd vertices}}} X(e) d_{s(e)} \frac{d_{t(e)}}{\mathcal{I}}$$

and

$$\text{tr}_r(X) = Z \left( \begin{array}{c} \text{Diagram: A circle labeled } X \text{ is inside a shaded vertical rectangle. A loop is formed by the top and bottom edges of the rectangle and the left and right sides of the circle.} \end{array} \right) = Z \left( \sum_{\substack{\text{edges } e \text{ from even} \\ \text{to odd vertices}}} X(e) \frac{d_{t(e)}}{d_{s(e)}} \delta_{s(e)} \right)$$

$$= \sum_{\substack{\text{edges } e \text{ from even} \\ \text{to odd vertices}}} X(e) d_{t(e)} \frac{d_{s(e)}}{\mathcal{I}},$$

where  $s(e)$  and  $t(e)$  are, respectively, the even and odd vertices of the edge  $e$ .  $\square$

The main reason for interest in graph planar algebras is the following result from [33] and [46].

**THEOREM 2.14.** *Given a finite depth subfactor planar algebra  $\mathcal{P}$  with principal graph  $\Gamma$  there is an injective map of planar algebras  $\mathcal{P} \hookrightarrow \text{GPA}(\Gamma)$ .*

This theorem assures us that if we believe in the existence of the extended Haagerup subfactor, and have enough perseverance, we will inevitably find it as a subalgebra of the graph planar algebra. Indeed, this paper is the result of such perseverance. On the other hand, nothing in this paper logically depends on the above theorem.

#### 2.4. Notation for $\mathcal{H}_k$

Let  $d_k$  be the Perron–Frobenius dimension of the graphs  $\mathcal{H}_k$ . For the Haagerup subfactor, we have

$$d_0 = \sqrt{\frac{1}{2}(5 + \sqrt{13})} \approx 2.07431.$$

For the extended Haagerup subfactor,  $d_1$  is the largest root of the polynomial

$$x^6 - 8x^4 + 17x^2 - 5,$$

that is

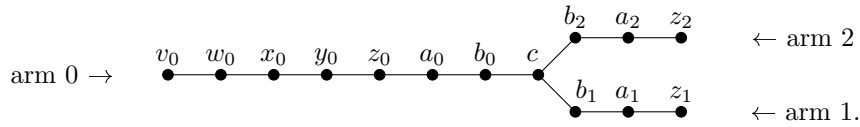
$$d_1 = \sqrt{\frac{8}{3} + \frac{1}{3} \sqrt[3]{\frac{13}{2}(-5 - 3i\sqrt{3})} + \frac{1}{3} \sqrt[3]{\frac{13}{2}(-5 + 3i\sqrt{3})}},$$

approximately 2.09218.

Throughout, if  $d$  is the modulus of a planar algebra, we let  $q$  be a solution to  $q + q^{-1} = d$ , and use the quantum integers

$$[n] = \frac{q^n - q^{-n}}{q - q^{-1}}.$$

By  $\mathcal{H}_k^p$  we mean the first graph in the pair of principal graphs  $\mathcal{H}_k$ . When we talk about loops or paths on  $\mathcal{H}_k^p$  it is useful to have names for the vertices and arms:



**LEMMA 2.15.** *If  $[2] = d_k$ , then  $[3][4k+4] = [4k+8]$ .*

*Proof.* The dimensions of the three vertices on an arm of  $\mathcal{H}_k^p$ , counting from the branch, are

$$\dim b_1 = \frac{[4k+5]}{2}, \quad \dim a_1 = \frac{[4k+6] - [4k+4]}{2} \quad \text{and} \quad \dim z_1 = \frac{[4k+7] - [4k+5] - [4k+3]}{2}.$$

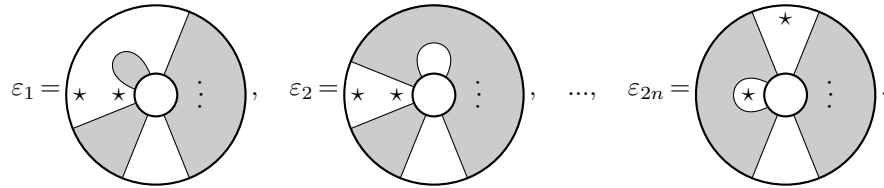
The condition  $[2] \dim z_1 = \dim a_1$  easily gives the desired formula.  $\square$

### 3. Uniqueness and existence

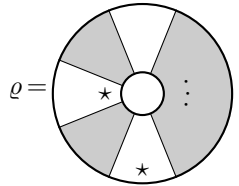
#### 3.1. Uniqueness

The goal of this section is to prove that there is at most one subfactor planar algebra with principal graphs  $\mathcal{H}_k$ . To prove this, we will give a skein-theoretic description of a planar algebra  $\mathcal{Q}^k/\mathcal{N}$  (which is not necessarily a subfactor planar algebra). We then prove in Theorem 3.9 that any subfactor planar algebra with principal graphs  $\mathcal{H}_k$  must be isomorphic to  $\mathcal{Q}^k/\mathcal{N}$ .

*Definition 3.1.* We say that an  $n$ -box  $S$  is *uncappable* if  $\varepsilon_j(S)=0$  for all  $j=1, \dots, 2n$ , where



We say that  $S$  is a *rotational eigenvector with eigenvalue  $\omega$*  if  $\varrho(S)=\omega S$ , where

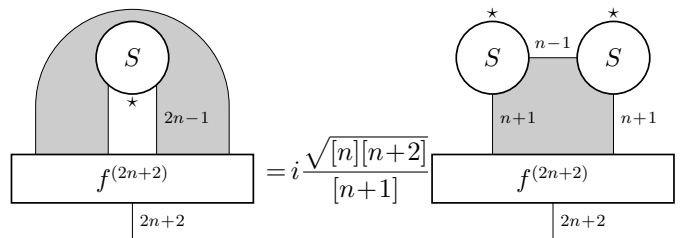


Note that  $\omega$  must be an  $n$ th root of unity.

As described in [29], every subfactor planar algebra is generated by uncappable rotational eigenvectors.

*Definition 3.2.* If  $S$  is an  $n$ -box, we use the following names and numbers for relations on  $S$ :

- (1)  $\varrho(S)=-S$ ;
- (2)  $S$  is uncappable;
- (3)  $S^2=f^{(n)}$ ;
- (4) 1-strand braiding substitute:





(5) *2-strand braiding substitute:*

$$\begin{array}{c} \text{Diagram with } S \text{ box and loop} \\ \hline f^{(2n+4)} \\ \hline 2n+4 \end{array} = \frac{[2][2n+4]}{[n+1][n+2]} \begin{array}{c} \text{Diagram with three } S \text{ boxes} \\ \hline f^{(2n+4)} \\ \hline 2n+4 \end{array} .$$

We call relations (4) and (5) “braiding substitutes” because we think of them as allowing us to move a generator “through” strands, rather like an identity

$$\begin{array}{c} \text{Diagram with } X \text{ box and larger box} \\ \hline \text{Diagram with } X \text{ box} \end{array} = \text{Diagram with } X \text{ box} \quad (3.1)$$

in a braided tensor category. The planar algebras we consider in this paper are not braided, and do not satisfy the equation (3.1). Nevertheless, we found it useful to look for relations that could play a similar role. In particular, the evaluation algorithm described in §4 was inspired by the evaluation algorithms in [4] and [43] for planar algebras of types  $D_{2n}$ ,  $E_6$  and  $E_8$ , where equation (3.1) holds.

*Definition 3.3.* Let  $\mathcal{Q}^k$  be the spherical planar algebra of modulus  $[2]=d_k$ , generated by a  $(4k+4)$ -box  $S$ , subject to relations (1)–(5) above.

*Definition 3.4.* A *negligible element* of a spherical planar algebra  $\mathcal{P}$  is an element  $x \in \mathcal{P}_{n,\pm}$  such that the diagrammatic trace  $\text{tr}_0(xy)$  is zero for all  $y \in \mathcal{P}_{n,\pm}$ .

The set  $\mathcal{N}$  of all negligible elements of a planar algebra  $\mathcal{P}$  forms a planar ideal of  $\mathcal{P}$ . In the presence of an antilinear involution  $*$ , we can replace  $\text{tr}_0(xy)$  in the definition with  $\text{tr}_0(xy^*)$  without changing the ideal. If the planar algebra is positive definite, then  $\mathcal{N}=0$ . The following is well known.

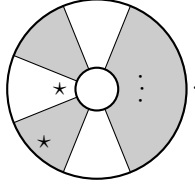
**PROPOSITION 3.5.** *Suppose that  $\mathcal{P}$  is a spherical planar algebra with non-zero modulus and  $\mathcal{N}$  is the ideal of negligible morphisms. If the spaces  $\mathcal{P}_{0,\pm}$  are 1-dimensional then every non-trivial planar ideal is contained in  $\mathcal{N}$ .*

*Proof.* Suppose that a planar ideal  $\mathcal{I}$  contains a non-negligible element  $x$  and assume, without loss of generality, that  $x \in \mathcal{P}_{n,+}$ . Then there is some element  $y \in \mathcal{P}_{n,+}$  such that  $\text{tr}_0(xy) \neq 0 \in \mathcal{P}_{0,+}$ . The element  $\text{tr}_0(xy)$  is itself in the planar ideal, and thus, since  $\mathcal{P}_{0,+}$  is

1-dimensional, it must be entirely contained in  $\mathcal{I}$ , and so the unshaded empty diagram is in the ideal. Drawing a circle around this empty diagram, and using the fact that the modulus is non-zero, shows that the shaded empty diagram is also in the ideal. Now, every box space  $\mathcal{P}_{m,\pm}$  is a module over  $\mathcal{P}_{0,\pm}$  under tensor product, with the empty diagram acting by the identity. Thus  $\mathcal{P}_{m,\pm} \subset \mathcal{I}$  for all  $m \in \mathbb{N}$ .  $\square$

The sesquilinear pairing descends to  $\mathcal{Q}^k/\mathcal{N}$  and is then non-degenerate.

Let  $\varrho^{1/2}$  denote the ‘‘one-click’’ rotation from  $\mathcal{P}_{n,+}$  to  $\mathcal{P}_{n,-}$  given by



*Definition 3.6.* Let the *Haagerup moments* be as follows:

- $\text{tr}(S^2) = [n+1]$ ;
- $\text{tr}(S^3) = 0$ ;
- $\text{tr}(S^4) = [n+1]$ ;
- $\text{tr}(\varrho^{1/2}(S)^3) = i[2n+2]/\sqrt{[n][n+2]}$ .

**PROPOSITION 3.7.** *Suppose that  $\mathcal{P}$  is a positive definite spherical planar algebra with modulus  $d_k$ , and let  $S \in \mathcal{P}_{n,+}$ , with  $n=4k+4$ . If  $S$  is uncappable and satisfies  $\varrho(S) = -S$  and the Haagerup moments given in Definition 3.6, then  $S$  satisfies the five relations given in Definition 3.2.*

We defer the proof until §5.

**THEOREM 3.8.** *If  $\mathcal{P}$  is a planar algebra that is singly generated by an  $n$ -box  $S$  satisfying the five relations of Definition 3.2, then any closed diagram in  $\mathcal{P}_{0,+}$  is a multiple of the empty diagram (so  $\dim \mathcal{P}_{0,+} = 1$ ).*

The proof of Theorem 3.8 is given in §4.

**THEOREM 3.9.** *If there exists a subfactor planar algebra  $\mathcal{P}$  with principal graphs  $\mathcal{H}_k$ , then  $\mathcal{P}$  is isomorphic to  $\mathcal{Q}^k/\mathcal{N}$ .*

*Proof.* The principal and dual principal graphs of  $\mathcal{P}$  both have their first trivalent vertex at depth  $4k+3$ . In the language of [32],  $\mathcal{P}$  has  $n$ -excess 1, where  $n=4k+4$ . We follow [32, §5.1]. There exists  $S \in \mathcal{P}_{n,+}$  such that  $\langle S, \text{TL}_{n,+} \rangle = 0$ , so

$$\mathcal{P}_{n,+} = \text{TL}_{n,+} \oplus \mathbb{C}S.$$

Let  $r$  be the ratio of the dimensions of the two vertices at depth  $4k+4$  on the principal graph, chosen so that  $r \geq 1$ . By [32], we can choose  $S$  to be self-adjoint, uncappable and a rotational eigenvector, such that

$$S^2 = (1-r)S + rf^{(n)}.$$

(Our  $S$  is  $-\tilde{R}$  in [32].)

The symmetry of  $\mathcal{H}_k^p$  implies that  $r=1$ , so  $S^2=f^{(n)}$ . We can use this to compute powers of  $S$  and their traces. These agree with the first three Haagerup moments, as given in Definition 3.6.

In a similar fashion, one defines  $\check{r} \geq 1$  and  $\check{S}$  from the dual principal graph and calculates the moments of  $\check{S}$ . Since the complement of  $\check{S}$  is 1-dimensional,  $\check{S}$  and  $\varrho^{1/2}(S)$  must be multiples of each other; that multiple can be calculated to be  $\check{S} = \varrho^{1/2}(S) \sqrt{\check{r}/\omega r}$ . (This can be done by comparing  $\langle \check{S}, \check{S} \rangle$  and  $\langle \varrho^{1/2}(S), \varrho^{1/2}(S) \rangle$ , as we learned from an earlier draft of [32].) Then it follows that

$$\mathrm{tr}(\varrho^{1/2}(S)^3) = \omega^{3/2} \sqrt{\frac{\check{r}}{r}} r(\check{r}-1)[n+1], \quad (3.2)$$

for some square root  $\omega^{1/2}$  of the rotational eigenvalue of  $S$ .

Although we will not use it here, we record the identity

$$\varrho^{1/2}(S)^2 = -\omega^{1/2} r^{1/2} (\check{r}^{1/2} - \check{r}^{-1/2}) \varrho^{1/2}(S) + \omega^{-1} r f^{(n)}, \quad (3.3)$$

which is equivalent to

$$\check{S}^2 = (1-\check{r})\check{S} + \check{r}f^{(n)}.$$

By [32, Theorem 5.1.11], whenever  $\mathcal{P}$  has  $n$ -excess 1, then  $\check{r} = [n+2]/[n]$  and

$$r + \frac{1}{r} = 2 + \frac{2 + \omega + \omega^{-1}}{[n][n+2]}.$$

Since  $r=1$ , this implies that  $\omega = -1$ . Note that we could also compute  $\check{r}$  directly from the dual principal graph. Jones' proof that  $\omega = -1$  uses the converse of a result along the lines of Lemma 5.14, since there must be some linear relation of the form given in that lemma.

In the case  $r=1$  we also have the freedom to replace  $S$  by  $-S$ , which we use to (arbitrarily) choose the square root  $\omega^{1/2} = -i$ . Substituting all these quantities into equation (3.2), and using the identity  $[n+1]([n+2]-[n]) = [2n+2]$ , we now see that  $S$  has all of the Haagerup moments, as given in Definition 3.6.

By Proposition 3.7,  $S$  satisfies the relations given in Definition 3.2. Thus there is a planar algebra morphism  $\mathcal{Q}^k \rightarrow \mathcal{P}$  given by sending  $S$  to  $S$ . Since  $\mathcal{P}$  is positive definite, this descends to the quotient to give a map

$$\Phi: \mathcal{Q}^k/\mathcal{N} \longrightarrow \mathcal{P}.$$

By Proposition 3.5,  $\mathcal{Q}^k/\mathcal{N}$  has no non-trivial proper ideals. Since  $\Phi$  is non-zero, it must be injective. The image of  $\Phi$  is the planar algebra in  $\mathcal{P}$  generated by  $S$ . This is a subfactor planar algebra with the same modulus as  $\mathcal{P}$ . Its principal graphs are not  $(A_\infty, A_\infty)$ , because the dimension of the  $n$ -box space is too large. Haagerup's classification shows that the principal graphs of the image of  $\Phi$  must be  $\mathcal{H}_k$ . However, since the principal graphs determine the dimensions of all box spaces, the image of  $\Phi$  must be all of  $\mathcal{P}$ . Thus  $\Phi$  is an isomorphism of planar algebras.  $\square$

### 3.2. Existence

The subfactor planar algebra with principal graphs  $\mathcal{H}_0$  is called the Haagerup planar algebra, and is isomorphic to  $\mathcal{Q}^0/\mathcal{N}$ . The corresponding subfactor was constructed in [2] and [24]. The subfactor planar algebra was directly constructed in [52]. There is no subfactor planar algebra with principal graphs  $\mathcal{H}_k$  for  $k > 1$ . In this case, by [3],  $\mathcal{Q}^k/\mathcal{N}$  cannot be a finite-depth planar algebra, let alone a subfactor planar algebra. The following theorem deals with the one remaining case.

**THEOREM 3.10.** *There is a subfactor planar algebra with principal graphs  $\mathcal{H}_1$ .*

We prove this by finding  $\mathcal{H}_1$  as a sub-planar algebra of the graph planar algebra of one of the extended Haagerup graphs. The following lemma simplifies the proof of irreducibility for subalgebras of graph planar algebras.

**LEMMA 3.11.** *If  $\mathcal{P} \subset \text{GPA}(G)$ ,  $\dim \mathcal{P}_{0,+} = 1$  and  $G$  has an even univalent vertex, then  $\mathcal{P}$  is an irreducible subfactor planar algebra.*

*Proof.* To show that  $\mathcal{P}$  is an irreducible subfactor planar algebra, we need to show that  $\mathcal{P}$  is spherical and positive definite, and that  $\dim \mathcal{P}_{0,\pm} = 1$  and  $\dim \mathcal{P}_{1,+} = 1$ . By Proposition 2.13, the graph planar algebra is spherical and positive definite. The subalgebra  $\mathcal{P}$  inherits both of these properties. We are given  $\dim \mathcal{P}_{0,+} = 1$ . Also,  $\mathcal{P}_{0,-}$  injects into  $\mathcal{P}_{1,+}$  (by tensoring with a strand on the left). It remains only to show that  $\dim \mathcal{P}_{1,+} = 1$ .

Let  $v$  be an even univalent vertex of  $G$ . Let  $w$  be the unique vertex connected to  $v$ . Suppose that  $X \in \mathcal{P}_{1,+}$  is some functional on paths of length 2 in  $G$ .

Now  $\text{tr}_0(X)$  is a closed diagram with unshaded exterior. (Note that here we use  $\text{tr}_0$ , the diagrammatic trace, without applying a partition function, even though  $\dim \mathcal{P}_{0,+} = 1$ .)

This is a functional defined on even vertices, via a state sum. Since  $v$  is univalent, the state sum for  $\text{tr}_0(X)(v)$  has only one term, giving

$$\text{tr}_0(X)(v) = X(vw) \frac{d_w}{d_v}.$$

Similarly,

$$\text{tr}_0(X^*X)(v) = X(vw)X^*(vw) \frac{d_w}{d_v}.$$

Thus, if  $\text{tr}_0(X)(v)$  is zero then  $\text{tr}_0(X^*X)(v)$  is zero also. Note that  $\text{tr}_0(X)$  and  $\text{tr}_0(X^*X)$  are both scalar multiples of the empty diagram, and so  $\text{tr}_0(X^*X)(v)=0$  implies that  $\text{tr}_0(X^*X)=0$ .

Therefore, if  $\text{tr}_0(X)$  is zero then  $\text{tr}_0(X^*X)$  is zero. Then, by positive definiteness, if  $\text{tr}_0(X^*X)$  is zero then  $X$  is zero.

We conclude that the diagrammatic trace function is injective on  $\mathcal{P}_{1,+}$  and thus  $\mathcal{P}_{1,+}$  is 1-dimensional.  $\square$

Recall the Haagerup moments from Definition 3.6. In the current setting,  $n=8$ ,  $[2]=d_1$  and the Haagerup moments are as follows:

- $\text{tr}(S^2)=[9] \approx 24.66097$ ;
- $\text{tr}(S^3)=0$ ;
- $\text{tr}(S^4)=[9]$ ;
- $\text{tr}(\varrho^{1/2}(S)^3)=i[18]/\sqrt{[8][10]} \approx 15.29004i$ .

**PROPOSITION 3.12.** *Suppose that  $S \in \text{GPA}(\mathcal{H}_1^p)_{8,+}$  is self-adjoint, uncappable, a rotational eigenvector with eigenvalue  $-1$ , and has the above Haagerup moments. Let  $\mathcal{PA}(S)$  be the subalgebra of  $\text{GPA}(\mathcal{H}_1^p)_{8,+}$  generated by  $S$ . Then  $\mathcal{PA}(S)$  is an irreducible subfactor planar algebra with principal graphs  $\mathcal{H}_1$ .*

*Proof.* By Proposition 3.7,  $S \in \text{GPA}(\mathcal{H}_1^p)$  satisfies all of the relations used to define  $\mathcal{Q}^1$ . Thus, by Theorem 3.9,  $\mathcal{PA}(S)$  is isomorphic to  $\mathcal{Q}^1/\mathcal{N}$ . By Theorem 3.8,  $(\mathcal{Q}^1/\mathcal{N})_{0,+}$  is 1-dimensional. By Lemma 3.11, it follows that  $\mathcal{Q}^1/\mathcal{N}$  is an irreducible subfactor planar algebra. By Haagerup's classification [18], it follows that the principal graphs of  $\mathcal{Q}^1/\mathcal{N}$  must be the unique possible graph pair with the correct graph norm, namely  $\mathcal{H}_1$ .  $\square$

To prove Theorem 3.10, it remains to find  $S \in \text{GPA}(\mathcal{H}_1^p)_{8,+}$  satisfying the requirements of the above proposition. We defer this to §6, where we give an explicit description of  $S$  and some long computations of the moments, assisted by computer algebra software.

### 4. The jellyfish algorithm

The aim of this section is to prove that the relations of Definition 3.2 enable us to reduce any closed diagram built from copies of  $S$  to a scalar multiple of the empty diagram.

Questions of whether you can evaluate an arbitrary closed diagram are ubiquitous in quantum topology. The simplest such algorithms (e.g., the Kauffman bracket algorithm for knots) decrease the number of generators (in this case, crossings) at each step. Slightly more complicated algorithms (e.g., HOMFLY evaluations) include steps that leave the number of generators constant while decreasing some other measure of complexity (such as the unknotting number). Another common technique is to apply Euler characteristic arguments to find a small “face” (with generators thought of as vertices) that can then be removed. Again, the simplest such algorithms decrease the number of faces at every step (e.g., Kuperberg’s rank-2 spiders [40]), while more difficult algorithms require steps that maintain the number of faces before removing a face (e.g., Peters’ approach to  $\mathcal{H}_0$  in [52]). In all of these algorithms, the number of generators is non-increasing as the algorithm proceeds. The algorithm we describe below is unusual in that it initially increases the number of generators in order to put them in a desirable configuration. We hope that this technique will be of wider interest in quantum topology (see [19] for a subsequent application of this technique). Therefore we have written this section to be independent of the rest of the paper, apart from references to Definitions 3.1 and 3.2.

The algorithm we will describe gives a proof of Theorem 3.8, which we repeat from above.

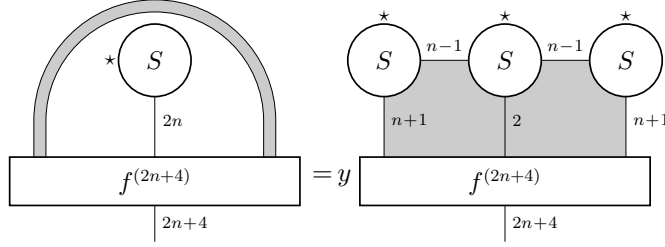
**THEOREM 3.8.** *If  $\mathcal{P}$  is a planar algebra that is singly generated by an  $n$ -box  $S$  satisfying the five relations of Definition 3.2, then any closed diagram in  $\mathcal{P}_{0,+}$  is a multiple of the empty diagram (so  $\dim \mathcal{P}_{0,+} = 1$ ).*

We do not actually need the full strength of the relations of Definition 3.2. The theorem is true for any planar algebra that is singly generated by an  $n$ -box  $S$  such that

- $S$  is a rotational eigenvector:  $\varrho(S) = \omega S$  for some  $\omega$ ;
- $S$  is uncappable (see Definition 3.1);
- $S^2 = aS + bf^{(n)}$  for some scalars  $a$  and  $b$  (multiplication was defined in Figure 1);
- $S$  satisfies 1- and 2-strand braiding substitutes of the form

$$\begin{array}{c}
 \text{Diagram 1: A box labeled } S \text{ with a star } \star \text{ above it. Two strands enter from the bottom, go up, loop around the box, and exit. The box is labeled } f^{(2n+2)} \text{ below it, with } 2n+2 \text{ strands indicated.} \\
 \\
 \text{Diagram 2: Two boxes labeled } S \text{ with stars } \star \text{ above them. Two strands enter from the bottom, go up, loop around the first } S \text{ box, then around the second } S \text{ box, and exit. The box is labeled } f^{(2n+2)} \text{ below it, with } 2n+2 \text{ strands indicated.} \\
 \\
 \text{Equation: Diagram 1} = x \text{ Diagram 2
 \end{array}
 \tag{4.1}$$

and



for some scalars  $x$  and  $y$  in  $\mathbb{C}$ .

Before going through the details, we briefly sketch the idea. First use the 1- and 2-strand braiding substitutes to pull all copies of  $S$  to the outside of the diagram. This will usually increase the number of copies of  $S$ . We can then guarantee that there is a pair of copies of  $S$  connected by at least  $n$  strands. This is a copy of  $S^2$ , which we can then express using fewer copies of  $S$ . All copies of  $S$  remain on the outside, and so we can again find a copy of  $S^2$ . Repeating this eventually gives an element of the Temperley–Lieb planar algebra, which is evaluated as usual. See Figure 2 for an example. We like to think of the copies of  $S$  as “jellyfish floating to the surface”, and hence the name for the algorithm.

*Definition 4.1.* Suppose  $D$  is a diagram in  $\mathcal{P}$ . Let  $S_0$  be a fixed copy of the generator inside  $D$ . Suppose  $\gamma$  is an embedded arc in  $D$  from a point on the boundary of  $S_0$  to a point on the top edge of  $D$ . Suppose  $\gamma$  is in general position, meaning that it intersects the strands of  $D$  transversely, and does not touch any generator except at its initial point on  $S_0$ . Let  $m$  be the number of points of intersection between  $\gamma$  and the strands of  $D$ . If  $m$  is minimal over all such arcs  $\gamma$  then we say that  $\gamma$  is a *geodesic* and  $m$  is the *distance* from  $S_0$  to the top of  $D$ .

*LEMMA 4.2.* Suppose  $X$  is a diagram consisting of one copy of  $S$  with all strands pointing down, and  $d$  parallel strands forming a “rainbow” over  $S$ , where  $d \geq 1$ . Then  $X$  is a linear combination of diagrams that contain at most three copies of  $S$ , each having distance less than  $d$  from the top of the diagram.

*Proof.* First consider the case  $d=1$ . Up to some number of applications of the rotation relation  $\varrho(S)=\omega S$ ,  $X$  is as shown in Figure 3.

Recall that we have the relation (4.1). Consider what happens to the left-hand side of that relation when we write  $f^{(2n+2)}$  as a linear combination of Temperley–Lieb diagrams  $\beta$ . The term in which  $\beta$  is the identity occurs with coefficient 1, and gives the diagram  $X$ . Suppose that  $\beta$  is not the identity. Then  $\beta$  contains a cup that connects two adjacent strands from  $X$ . If both ends of the cup are attached to  $S$ , then the resulting diagram is zero. If not, then the cup must be at the far left or the far right of  $\beta$ . Such

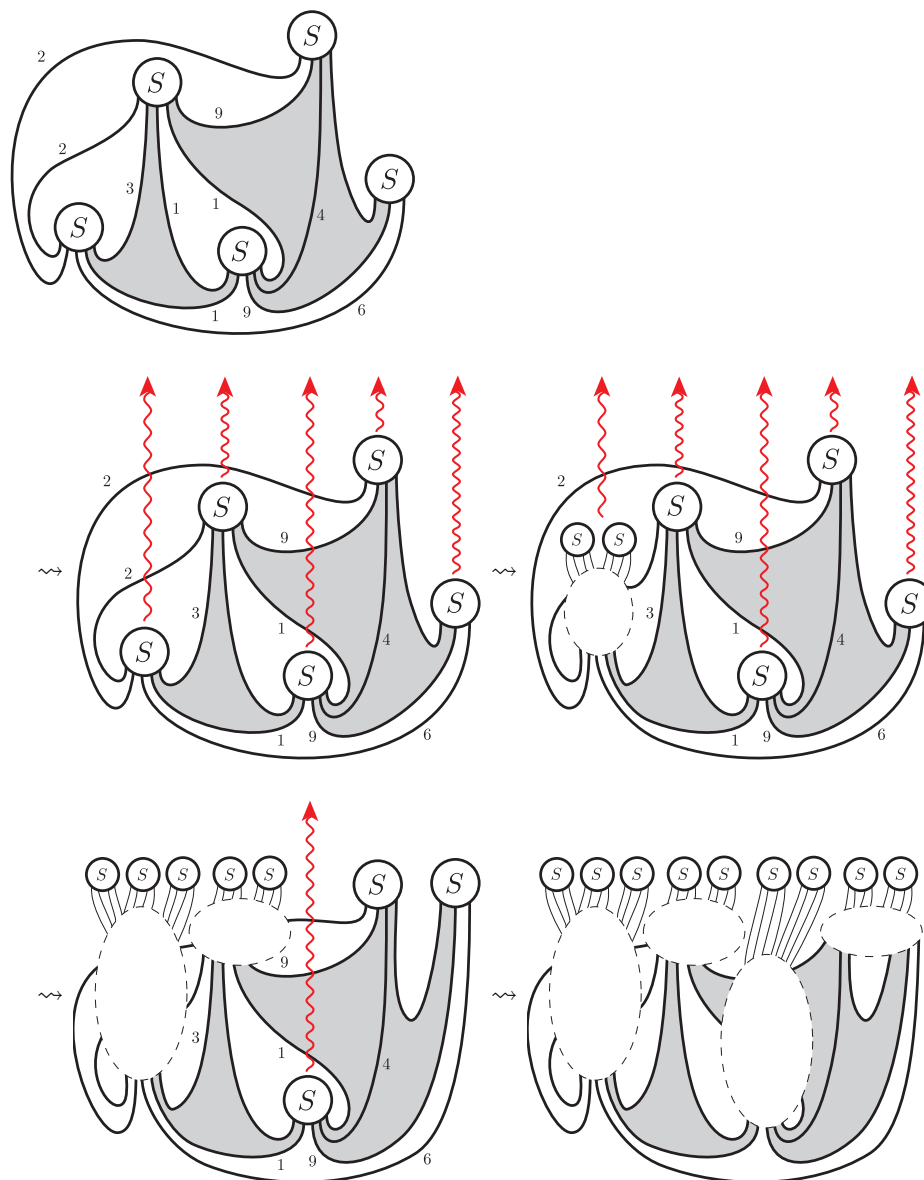


Figure 2. The initial steps of the jellyfish algorithm. The dotted ovals represent linear combinations of Temperley–Lieb diagrams. This is only a schematic illustration—to be precise, the result should be a linear combination of diagrams with various (sometimes large) numbers of copies of  $S$ .



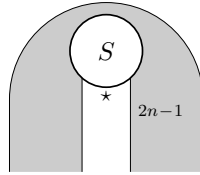


Figure 3.  $X$  in the case  $d=1$ .

a cup converts  $X$  to a rotation of  $S$ , and so gives distance zero from  $S$  to the top of the diagram.

Now consider what happens to the right-hand side of (4.1) when we write  $f^{(2n+2)}$  as a linear combination of Temperley–Lieb diagrams  $\beta$ . Every term in this expansion is a diagram with two copies of  $S$ , each having distance zero from the top.

By rearranging terms in the 1-strand braiding substitute, we can write  $X$  as a linear combination of diagrams that contain one or two copies of  $S$ , each having distance zero from the top of the diagram. This completes the case  $d=1$ .

The case  $d=2$  is similar, but we use the 2-strand braiding substitute.

Finally, suppose that  $d > 2$ . If  $d$  is odd then  $\gamma$  begins in a shaded region of  $X$ . Then  $X$  contains a copy of the diagram shown in Figure 3, up to the rotation relation  $\varrho(S) = \omega S$ . We can therefore use the 1-strand braiding substitute, as we did in the case  $d=1$ . Similarly, if  $d$  is even then we use the 2-strand braiding substitute.  $\square$

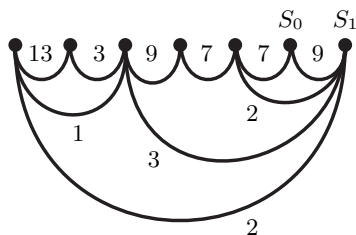
*Definition 4.3.* We say that a diagram  $D$  in  $\mathcal{P}$  is in *jellyfish form* if all occurrences of  $S$  lie in a row at the top of  $D$ , and all strands of  $D$  lie entirely below the height of the tops of the copies of  $S$ .

**LEMMA 4.4.** *Every diagram in  $\mathcal{P}$  is a linear combination of diagrams in jellyfish form.*

*Proof.* Let  $D$  be a diagram in  $\mathcal{P}$  (not necessarily closed), drawn in such a way that all endpoints lie on the bottom edge of  $D$ . If every copy of the generator in  $D$  is at distance zero from the top edge of  $D$ , then  $D$  is already in jellyfish form, up to isotopy. If not, we use Lemma 4.2 to pull each copy of  $S$  to the top  $D$ . It is convenient for our proof, but not necessary for the algorithm, to move copies of our generator  $S$  along geodesics.

Suppose that  $S_0$  is a copy of  $S$  that has distance  $d$  from the top of  $D$ , with  $d \geq 1$ . Let  $\gamma$  be a geodesic from  $S_0$  to the top edge of  $D$ . Let  $X$  be a small neighborhood of  $S_0 \cup \gamma$ . By applying an isotopy, we consider  $X$  to be a diagram in a rectangle, consisting of a copy of  $S_0$  with all strands pointing down, and a “rainbow” of  $d$  strands over it.

By Lemma 4.2,  $X$  is a linear combination of diagrams that contain at most three copies of  $S$ , each having distance less than  $d$  from the top of the diagram. Let  $X'$  be one

Figure 4. Jellyfish form, illustrating (with  $n=8$ ) the proof of Theorem 3.8.

of the terms in this expression for  $X$ . Let  $D'$  be the result of replacing  $X$  by  $X'$  in  $D$ .

Suppose that  $S_1$  is a copy of the generator in  $D'$ . If  $S_1$  lies in  $X'$  then the distance from  $S_1$  to the top of  $D'$  is at most  $d-1$ . Now suppose  $S_1$  does not lie in  $X'$ . By basic properties of geodesics, there is a geodesic in  $D$  from  $S_1$  to the top of  $D$  that does not intersect  $\gamma$ . This geodesic is still a path in general position in  $D'$ , and still intersects strands in the same number of points. Thus the distance from  $S_1$  to the top of  $D$  does not increase when we replace  $X$  by  $X'$ .

In summary, if we replace  $X$  by  $X'$ , then  $S_0$  will be replaced by one, two or three copies of  $S$  that are closer to the top of  $D$ , and no other copy of  $S$  will become farther from the top of  $D$ . Although the number of copies of  $S$  may increase, it is not hard to see that this process must terminate. In fact, if for each generator  $S_0$  we denote by  $d(S_0)$  the distance of  $S_0$  from the top of the diagram, following the above processes the quantity  $\sum_{S_0} 4^{d(S_0)}$  strictly decreases.  $\square$

We now prove Theorem 3.8, showing that  $\dim \mathcal{P}_{0,+} = 1$ .

*Proof of Theorem 3.8.* Let  $D$  be a closed diagram with unshaded exterior. We must show that  $D$  is a scalar multiple of the empty diagram. By the previous lemma, we may assume that  $D$  is in jellyfish form. We may also assume that there are no closed loops or cups attached to the generators, so that every strand must connect two different copies of the generator.

We argue that there is a copy of the generator whose strands only go to one or both of its immediate neighbors. This is a simple combinatorial fact about this kind of planar graph. Think of the copies of the generator as vertices, and consider all strands that do not connect adjacent vertices. Among these, find one that has the smallest (positive) number of vertices between its endpoints. Any vertex between the endpoints of this strand can connect only to its two neighbors.

Let  $S_0$  be a copy of the generator such that the strands of  $S_0$  only go to one or both of its immediate neighbors. Then  $S_0$  is connected to some neighbor, say  $S_1$ , by at least  $n$  parallel strands. See Figure 4 for an example. Recall that  $S^2 = aS + bf^{(n)}$ . Thus we may

replace  $S_0$  and  $S_1$  by  $aS + bf^{(n)}$ , giving a linear combination of diagrams that are still in jellyfish form, but contain fewer copies of the generator. By induction,  $D$  is a scalar multiple of the empty diagram.  $\square$

## 5. Relations from moments

In this section we prove Proposition 3.7, which says that certain conditions on an element  $S$  imply the five relations of Definition 3.2. We use this Proposition once in the proof of Theorem 3.9 and once in the proof of Theorem 3.10. These are the uniqueness and existence results. In the proof of uniqueness, we must show that a certain subfactor planar algebra  $\mathcal{P}$  is isomorphic to  $\mathcal{Q}^k/\mathcal{N}$ . We use Proposition 3.7 to show that an element  $S$  of  $\mathcal{P}$  satisfies the defining relations of  $\mathcal{Q}^k/\mathcal{N}$ . In the proof of existence, we must show that a certain subalgebra  $\mathcal{P}$  of a graph planar algebra has a 1-dimensional space of  $n$ -boxes. We use Proposition 3.7 to show that the generator  $S$  of  $\mathcal{P}$  satisfies relations, which we then use in the algorithm of §4.

Most of this section consists of computations of inner products between diagrams. Since the values of these inner products may be useful for studying other planar algebras, we strive to use weaker assumptions whenever possible.

*Assumption 5.1.*  $\mathcal{P}$  is a spherical planar algebra with modulus  $[2]=q+q^{-1}$ , where  $q$  is not a root of unity (so we can safely divide by quantum integers). Furthermore,  $S \in \mathcal{P}_{n,+}$  is uncappable and has rotational eigenvalue  $\omega$ .

Recall that the Haagerup moments are as follows:

- $\text{tr}(S^2)=[n+1]$ ;
- $\text{tr}(S^3)=0$ ;
- $\text{tr}(S^4)=[n+1]$ ;
- $\text{tr}(\varrho^{1/2}(S)^3)=i[2n+2]/\sqrt{[n][n+2]}$ .

*Assumption 5.2.*  $\mathcal{P}$  is positive definite and has modulus  $[2]=d_k$ , where  $n=4k+4$ . Furthermore,  $S \in \mathcal{P}_{n,+}$  has rotational eigenvalue  $\omega=-1$ , and has the Haagerup moments.

The following is a restatement of Proposition 3.7.

**PROPOSITION 5.3.** *Let a planar algebra  $\mathcal{P}$  and  $S \in \mathcal{P}_{n,+}$  be such that Assumptions 5.1 and 5.2 hold. Then  $S$  satisfies the five relations given in Definition 3.2.*

The proof involves some long and difficult computations, but the basic idea is very simple. We will define diagrams  $A$ ,  $B$ ,  $C$  and  $D$ . We must prove that certain linear relations hold between  $A$  and  $B$ , and between  $C$  and  $D$ . Since  $\mathcal{P}$  is positive definite, we

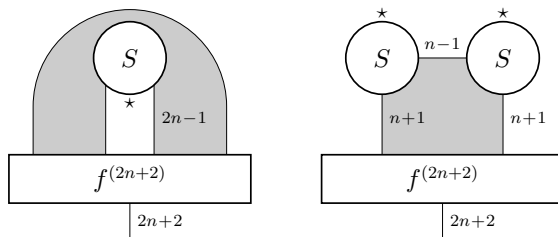


Figure 5. Diagrams *A* (left) and *B* (right).

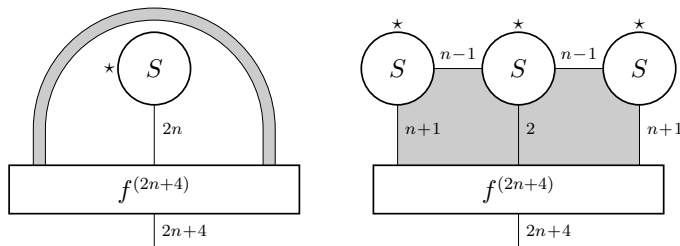


Figure 6. Diagrams *C* (left) and *D* (right).

can do this by computing certain inner products. In general, there is a linear relation between  $X$  and  $Y$  if and only if

$$\langle X, X \rangle \langle Y, Y \rangle = |\langle X, Y \rangle|^2.$$

In this case,

$$\langle Y, Y \rangle X - \langle X, Y \rangle Y = 0,$$

as can be seen by taking the inner product of this expression with itself.

To compute the necessary inner (ss)-1(ar)1(y)-3013innnss00-30.inss04s0S(ro)-28r00In

To comMo:

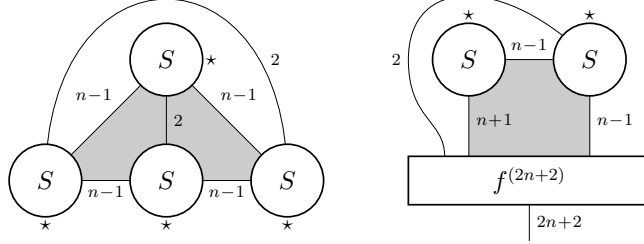


Figure 7. Diagrams  $\Gamma$  (left) and  $B'$  (right).

*Definition 5.4.* For  $m \geq 0$  let

$$W_m = q^m + q^{-m} - \omega - \omega^{-1},$$

as in [32, Definition 4.2.6].

The diagrams  $A$ ,  $B$ ,  $C$  and  $D$  in Figures 5 and 6 are the terms in the “braiding” relations we wish to prove.

Along the way, we will also use the diagrams  $\Gamma$  and  $B'$ , as shown in Figure 7.

### 5.2. Computing inner products

We now calculate the necessary inner products.

LEMMA 5.5. *If Assumption 5.1 holds, then*

$$\langle A, A \rangle = \frac{1}{[2n+2]} W_{2n+2} \text{tr}(S^2).$$

*The same holds with the reverse shading.*

*Proof.* We must evaluate the closed diagram

$$\langle A, A \rangle = Z \left( \begin{array}{c} \text{Diagram with two } S \text{ circles, arcs } 2n-1, \text{ and box } f^{(2n+2)} \end{array} \right).$$

The idea is to apply Lemma [2.11](#) to the copy of  $f$

$\beta$	Coeff $_{f^{(2n+2)}}(\beta)$	value of diagram
	1	$\text{tr}(\varrho^{1/2}(S)^3)$
	$(-1)^{n+1} \frac{[n+1]}{[2n+2]}$	$\text{tr}(S^3)$
	$(-1)^{n+1} \frac{[n+1]}{[2n+2]}$	$\omega^{-1} \text{tr}(S^3)$

Table 8. The terms of  $f^{(2n+2)}$  that contribute to  $\langle A, B \rangle$ .

Consider the complete expansion of  $f^{(2n+2)}$  into a linear combination of Temperley–Lieb diagrams  $\beta \in \text{TL}_{2n+2}$ . For most such  $\beta$ , the resulting diagram is zero because  $S$  is uncappable. There are only three values of  $\beta$  we need to consider. For each of these, we compute the corresponding coefficient, and easily evaluate the corresponding diagram. The results are shown in Table 8.

Now take the sum over all  $\beta$  in the table of the coefficient times the value of the diagram. Note that if  $S^2 = f^{(n)}$  then  $\text{tr}(S^3) = 0$ . Thus the two non-identity values of  $\beta$  either cancel or give zero. The term where  $\beta$  is the identity gives the desired result.  $\square$

LEMMA 5.7. *If Assumption 5.1 holds and  $S^2 = f^{(n)}$ , then*

$$\langle B, B \rangle = \frac{[n+1][2n+2]}{[n][n+2]}.$$

*Proof.* Consider the two diagrams

$$\langle B, B \rangle = Z \left( \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right) \quad \text{and} \quad \langle f^{(n+1)}, B \rangle = Z \left( \begin{array}{c} \text{Diagram 3} \\ \text{Diagram 4} \end{array} \right).$$

The second is clearly zero. We will compare what happens to each of these diagrams when we expand the copy of  $f^{(2n+2)}$  into a linear combination of Temperley–Lieb diagrams.

Let  $\beta$  be a Temperley–Lieb diagram in the expansion of  $f^{(2n+2)}$ . Suppose that  $\beta$  contains a cup that connects endpoints number  $j$  and  $j+1$  at the top for some  $j \neq n+1$ .

The corresponding diagram for  $\langle B, B \rangle$  is zero because the cup connects two strands from the same copy of  $S$ . Similarly, the corresponding diagram for  $\langle f^{(n+1)}, B \rangle$  is zero because the cup connects two strands from the same side of  $f^{(n+1)}$ . Thus both diagrams corresponding to  $\beta$  are zero.

Now suppose that  $\beta$  contains a cup in the middle, connecting endpoints number  $n+1$  and  $n+2$  at the top. In the corresponding diagram for  $\langle B, B \rangle$ , this cup produces a copy of  $S^2$ , which we can replace with  $f^{(n)}$ . For  $\langle f^{(n+1)}, B \rangle$ , this cup produces a partial trace of  $f^{(n+1)}$ , which we can replace with  $([n+2]/[n+1])f^{(n)}$ . Thus, the two diagrams corresponding to  $\beta$  differ only by a factor of  $[n+2]/[n+1]$ .

Finally, suppose that  $\beta$  is the identity diagram. The corresponding diagram for  $\langle B, B \rangle$  consists of four copies of  $S$  arranged in a rectangle. The left and right sides of this rectangle consist of  $n+1$  parallel strands. We can replace one of these sides with a partial trace of  $f^{(n)}$ . Thus the diagram is equal to  $([n+1]/[n])\text{tr}(S^2)$ . The corresponding diagram for  $\langle f^{(n+1)}, B \rangle$  is equal to  $\text{tr}(S^2)$ .

We can now evaluate

$$\langle B, B \rangle = \langle B, B \rangle - \frac{[n+1]}{[n+2]} \langle f^{(n+1)}, B \rangle.$$

For both terms on the right-hand side, we express  $f^{(2n+2)}$  as a linear combination of Temperley–Lieb diagrams  $\beta$ . For every  $\beta$  except the identity, these terms cancel. The identity term gives the following.

$$\langle B, B \rangle = \frac{[n+1]}{[n]} \text{tr}(S^2) - \frac{[n+1]}{[n+2]} \text{tr}(S^2).$$

As  $\text{tr}(S^2)=[n+1]$ , the result now follows from a quantum integer identity.  $\square$

LEMMA 5.8. *If Assumption 5.1 holds, then*

$$\langle C, C \rangle = \frac{[2][2n+2]}{[2n+3][2n+4]} W_{2n+4} \langle A, A \rangle.$$

*Proof.* We must evaluate the closed diagram

$$\langle C, C \rangle = Z \left( \begin{array}{c} \text{Diagram} \end{array} \right).$$



The proof is very similar to that of Lemma 5.5. Indeed, these are both special cases of a general recursive formula. The idea is to apply Lemma 2.11 to the copy of  $f^{(2n+4)}$ , and then evaluate each of the resulting diagrams.

Consider the first term. Here,  $f^{(2n+4)}$  is replaced by a copy of  $f^{(2n+3)}$  together with a single vertical strand on the right. We can use sphericity to drag this strand over to the left. This results in a partial trace of  $f^{(2n+3)}$ , which is

$$\frac{[2n+4]}{[2n+3]} f^{(2n+2)}.$$

Using Lemma 5.5, we obtain

$$\frac{[2n+4]}{[2n+3]} \langle A, A \rangle.$$

Now consider the terms in the sum over  $a$  and  $b$ . Here,  $f^{(2n+4)}$  is replaced by a copy of  $f^{(2n+2)}$  together with a ‘‘cup’’ and a ‘‘cap’’ in positions given by  $a$  and  $b$ . In most cases, the resulting diagram is zero because  $S$  is uncappable. A cup at the leftmost position also gives zero since it connects two strands coming from the top right of  $f^{(2n+2)}$ . Similarly, a cup in the rightmost position gives zero, as does a cap in the leftmost or rightmost position. The only cases that give a non-zero diagram are when  $a, b \in \{2, 2n+2\}$ . We obtain

$$\frac{1}{[2n+3][2n+4]} (-[2]^2 - [2n+2]^2 - [2][2n+2]\omega - [2][2n+2]\omega^{-1}) \langle A, A \rangle.$$

The result now follows by adding the above two expressions and expanding the quantum integers in terms of  $q$ .  $\square$

LEMMA 5.9. *If Assumption 5.1 holds and  $S^2 = f^{(n)}$ , then*

$$\langle D, D \rangle = \frac{[n+1]^2 [2n+2]}{[2][n]^2 [2n+3]} ([n+3] - [2][n]).$$

*Proof.* We must evaluate the closed diagram

$$\langle D, D \rangle = Z \left( \begin{array}{c} \left( \begin{array}{ccc} \overset{\star}{S} & \overset{\star}{S} & \overset{\star}{S} \\ \overset{n-1}{\text{---}} & \overset{n-1}{\text{---}} & \overset{n-1}{\text{---}} \\ \underset{n+1}{\text{---}} & \underset{2}{\text{---}} & \underset{n+1}{\text{---}} \\ \text{---} f^{(2n+4)} \text{---} \\ \underset{n+1}{\text{---}} & \underset{2}{\text{---}} & \underset{n+1}{\text{---}} \\ \underset{\star}{S} & \underset{\star}{S} & \underset{\star}{S} \\ \overset{n-1}{\text{---}} & \overset{n-1}{\text{---}} & \overset{n-1}{\text{---}} \\ \star & \star & \star \end{array} \right) \end{array} \right).$$

$\beta$	$\text{Coeff}_{f^{(2n+4)}}(\beta)$	value of diagram
	1	$\left(\frac{[n+1]}{[n]}\right)^2 \text{tr}(S^2)$
	$-\frac{[n+1][n+3]}{[2n+4]}$	$\frac{[n+1]}{[n]} \text{tr}(S^4)$
	$\frac{[n][n+1][n+2][n+3]}{[2][2n+3][2n+4]}$	$\left(\frac{[n+1]}{[n]}\right)^2 \text{tr}(S^2)$
	$\frac{[n]^2[n+1]^2}{[2][2n+3][2n+4]}$	$\left(\frac{[n+1]}{[n]}\right)^2 \text{tr}(S^2)$
	$-\frac{[n][n+1]^2[n+2]}{[2n+3][2n+4]}$	$\frac{[n+1]}{[n]} \text{tr}(S^4)$
	$\frac{[2][n+1]^2[n+2]^2}{[2n+3][2n+4]}$	$\text{tr}(S^6)$

Table 9. The terms of  $f^{(2n+4)}$  that contribute to  $\langle D, D \rangle$ .

Consider the expansion of  $f^{(2n+4)}$  into a linear combination of Temperley–Lieb diagrams  $\beta \in \text{TL}_{2n+4}$ . For each such  $\beta$ , we compute the coefficient and the value of the corresponding diagram. There are twelve values of  $\beta$  that give a non-zero diagram. Many of these are reflections or rotations of each other. They are shown in Table 9.

Now take the sum over all  $\beta$  in the table of the coefficient times the value of the diagram. Since  $S^2 = f^{(n)}$ , we have

$$\text{tr}(S^2) = \text{tr}(S^4) = \text{tr}(S^6). \quad \square$$

LEMMA 5.10. *If Assumption 5.1 holds,  $S^2 = f^{(n)}$  and  $\omega = -1$ , then*

$$\langle C, D \rangle = Z(\Gamma) + \frac{2}{[n]} + \frac{1}{[2n+3]} \langle A, A \rangle.$$

*Proof.* First we prove a formula for  $D$ . We have

$$D = \begin{array}{c} \begin{array}{ccc} \overset{\star}{S} & \overset{\star}{S} & \overset{\star}{S} \\ \downarrow^{n-1} & \downarrow^{n-1} & \downarrow^{n-1} \\ \downarrow^n & \downarrow^2 & \downarrow^{n+1} \end{array} \\ \boxed{f^{(2n+3)}} \\ \downarrow^{2n+3} \end{array} . \quad (5.1)$$

Apply a left-to-right reflection of Lemma 2.10 to the copy of  $f^{(2n+4)}$  in  $D$ . The first term gives the desired diagram. Now consider a term in the sum over  $a$ . This contains a cup in a position given by  $a$ . For all but two values of  $a$ , this cup connects two strands from the same copy of  $S$ , so the resulting diagram is zero. The remaining two values of  $a$  are  $n+1$  and  $n+3$ . For each of these, the cup connects two different copies of  $S$ , giving rise to a copy of  $S^2$ . We can replace this with  $f^{(n)}$ , which is a linear combination of Temperley–Lieb diagrams. But any such Temperley–Lieb diagram gives rise to a cup connected to the top edge of  $f^{(2n+3)}$ , and thus gives zero. This completes the derivation of equation (5.1).

Next, we prove that

$$D = \begin{array}{c} \begin{array}{ccc} \overset{\star}{S} & \overset{\star}{S} & \overset{\star}{S} \\ | & | & | \\ n & 2 & n \\ \hline f^{(2n+2)} \\ \hline 2n+2 \end{array} & + \frac{1}{[2n+3]} & \begin{array}{c} \overset{\star}{S} \\ | \\ 2n \\ \hline f^{(2n+2)} \\ \hline 2n+4 \end{array} \end{array} \quad (5.2)$$

To prove this, apply Lemma 2.10 to the copy of  $f^{(2n+3)}$  in equation (5.1). The first term in the expansion gives the first term in the desired expression for  $D$ .

It remains to show that the sum over  $a$  is equal to the second term in the desired expression. Consider a term for  $a \notin \{n, n+2\}$ . The cup connects two strands from the same copy of  $S$ , giving zero.

Consider the term corresponding to  $a=n+2$ . The position of the cup is such that the right two copies of  $S$  are connected by  $n$  strands. This is a copy of  $S^2$ , which is equal to  $f^{(n)}$ , which in turn is a linear combination of Temperley–Lieb diagrams. Any such Temperley–Lieb diagram results in a cap connected to the top edge of  $f^{(2n+2)}$ , giving zero.

Now consider the term corresponding to  $a=n$ . The coefficient of this term is

$$(-1)^{n+1} \frac{[n]}{[2n+3]}.$$

The left two copies of  $S$  form a copy of  $S^2$ , which is equal to a sideways copy of  $f^{(n)}$ , which in turn we express as a linear combination of Temperley–Lieb diagrams  $\beta$ . Every such  $\beta$  gives zero except

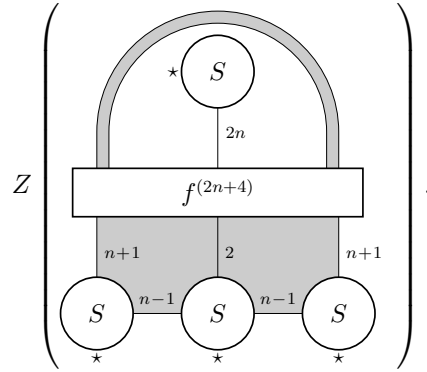
$$\beta = \begin{array}{c} \diagdown \dots \diagup \\ \diagup \dots \diagdown \end{array},$$

which has coefficient

$$(-1)^{n+1} \frac{1}{[n]}$$

and gives the second diagram in the desired expression for  $D$ . The total coefficient of this diagram is the product of the above coefficients for the term  $a$  and the diagram  $\beta$ . This completes the derivation of equation (5.2).

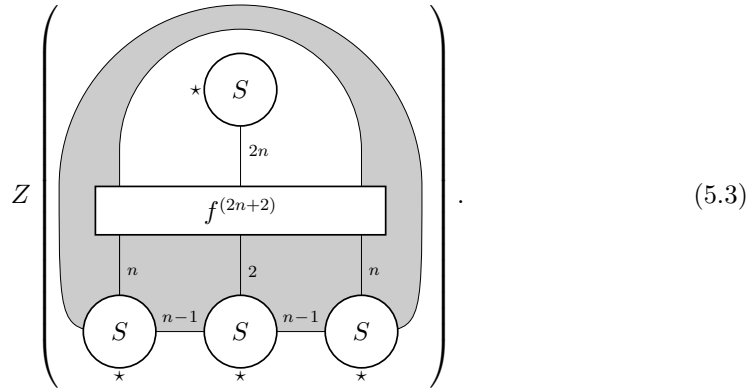
Now we return to our computation of  $\langle C, D \rangle$ . We must evaluate the expression



Apply equation (5.2), upside down, to the bottom half of this diagram. For the last term of this equation, apply sphericity and use Lemma 5.5 to reverse the shading. We obtain the term

$$\frac{1}{[2n+3]} \langle A, A \rangle.$$

The first term from the equation gives



We expand  $f^{(2n+2)}$  into a linear combination of Temperley–Lieb diagrams  $\beta$ . There are five values of  $\beta$  we need to consider. These are shown in Table 10.

Now take the sum over all  $\beta$  in the table of the coefficient times the value of the diagram. □

The following inner products involving  $B'$  will help us to evaluate  $Z(\Gamma)$ .





$\beta$	$\text{Coeff}_{f^{(2n+2)}}(\beta)$	value of diagram
	1	$Z(\Gamma)$
	$(-1)^n \frac{[n+2]}{[2n+2]}$	$(-1)^{n+1} \frac{1}{[n]} \omega \text{tr}(S^2)$
	$(-1)^n \frac{[n+2]}{[2n+2]}$	$(-1)^{n+1} \frac{1}{[n]} \omega^{-1} \text{tr}(S^2)$
	$(-1)^n \frac{[n]}{[2n+2]}$	$(-1)^{n+1} \frac{1}{[n]} \text{tr}(S^2)$

Table 10. The terms of  $f^{(2n+2)}$  that contribute to (5.3).



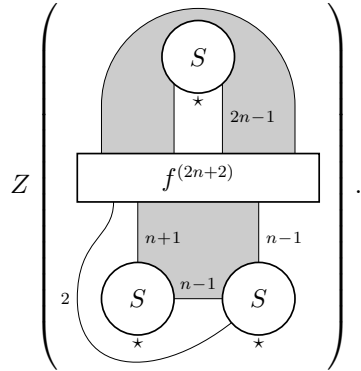
$\beta$	$\text{Coeff}_{f^{(2n+2)}}(\beta)$	value of diagram
	$\frac{[2n]}{[2n+2]}$	$\text{tr}(\varrho^{1/2}(S)^3)$
	$\frac{[2]}{[2n+2]}$	$\omega^{-1} \text{tr}(\varrho^{1/2}(S)^3)$

Table 11. The terms of  $f^{(2n+2)}$  that contribute to  $\langle A, B' \rangle$ .

LEMMA 5.11. *If Assumption 5.1 holds,  $S^2 = f^{(n)}$  and  $\omega = -1$ , then*

$$\langle A, B' \rangle = \frac{[n-1]}{[n+1]} \text{tr}(\varrho^{1/2}(S)^3).$$

*Proof.* We must evaluate the closed diagram

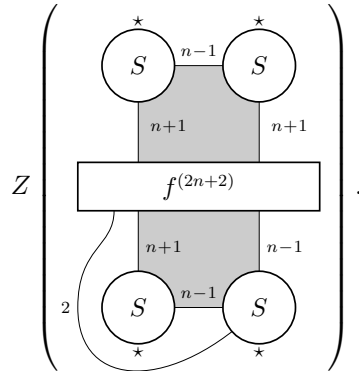


The proof is very similar to that of Lemma 5.6, so we will omit the details. The relevant information is shown in Table 11. □

LEMMA 5.12. *If Assumption 5.1 holds,  $S^2 = f^{(n)}$  and  $\omega = -1$ , then*

$$\langle B, B' \rangle = Z(\Gamma) + \frac{[2][n+1]}{[n][n+2]}.$$

*Proof.* We must evaluate the closed diagram



Inspired by the proof of Lemma 5.7, we observe that

$$\langle B, B' \rangle = \langle B, B' \rangle - \frac{[n+1]}{[n+2]} \langle f^{(n+1)}, B' \rangle.$$

We expand the copies of  $f^{(2n+2)}$  on the right-hand side. By the same argument as for Lemma 5.7, all terms will cancel except for those coming from the identity diagram.

If we replace  $f^{(2n+2)}$  by the identity in  $\langle B, B' \rangle$  then we obtain  $\Gamma$ . If we replace  $f^{(2n+2)}$  by the identity in  $\langle f^{(n+1)}, B' \rangle$  then we obtain a diagram containing two copies of  $S$  and one copy of  $f^{(n+1)}$ . We must now expand  $f^{(n+1)}$  as a linear combination of Temperley–Lieb diagrams  $\beta$ . For all but one such diagram  $\beta$ , the resulting diagram is zero because  $S$  is uncappable. The only diagram we need to consider is

$$\beta = \begin{array}{c} \diagup \dots \diagdown \\ \cup \quad \cup \end{array},$$

which has coefficient  $[2]/[n][n+1]$  and gives the diagram  $\omega^{-1} \text{tr}(S^2)$ . □

### 5.3. Proving relations

We now use our inner products, together with Assumptions 5.1 and 5.2, to prove that the required relations hold. Note that the assumption  $\omega = -1$  implies that

$$W_{2m} = \left( \frac{[2m]}{[m]} \right)^2.$$

LEMMA 5.13. *If Assumptions 5.1 and 5.2 hold, then  $S^2 = f^{(n)}$ .*

*Proof.* The relevant inner products are as follows:

- $\langle S^2, S^2 \rangle = \text{tr}(S^4) = [n+1]$ ;
- $\langle S^2, f^{(n)} \rangle = \text{tr}(S^2) = [n+1]$ ;
- $\langle f^{(n)}, f^{(n)} \rangle = \text{tr}(f^{(n)}) = [n+1]$ .

The inner product of  $S^2 - f^{(n)}$  with itself is zero, and the result follows from the assumption that  $\mathcal{P}$  is positive definite.  $\square$

LEMMA 5.14. *If Assumptions 5.1 and 5.2 hold, then*

$$A = i \frac{\sqrt{[n][n+2]}}{[n+1]} B.$$

*Proof.* By Lemmas 5.5–5.7, and our values for the moments, we have that

- $\langle A, A \rangle = [2n+2]/[n+1]$ ;
- $\langle A, B \rangle = i[2n+2]/\sqrt{[n][n+2]}$ ;
- $\langle B, B \rangle = [n+1][2n+2]/[n][n+2]$ .

Thus,

$$\langle A, A \rangle \langle B, B \rangle = |\langle A, B \rangle|^2,$$

and hence  $A$  and  $B$  are linearly dependent. The precise relation is then

$$A = \frac{\langle A, B \rangle}{\langle B, B \rangle} B. \quad \square$$

LEMMA 5.15. *If Assumptions 5.1 and 5.2 hold, then*

$$Z(\Gamma) = \frac{[n-1][2n+2] - [2][n+1]}{[n][n+2]}.$$

*Proof.* By Lemmas 5.11 and 5.12, we have

- $\langle A, B' \rangle = i[n-1][2n+2]/[n+1]\sqrt{[n][n+2]}$ ;
- $\langle B, B' \rangle = Z(\Gamma) + [2][n+1]/[n][n+2]$ .

By Lemma 5.14, we have

$$A = i \frac{\sqrt{[n][n+2]}}{[n+1]} B.$$

Thus

$$\langle A, B' \rangle = i \frac{\sqrt{[n][n+2]}}{[n+1]} \langle B, B' \rangle.$$

The result follows by solving for  $Z(\Gamma)$ .  $\square$

LEMMA 5.16. *If Assumptions 5.1 and 5.2 hold, then*

$$C = \frac{[2][2n+4]}{[n+1][n+2]}D.$$

*Proof.* By Lemmas 5.8–5.10, and our values for  $Z(\Gamma)$  and the moments, we have

- $\langle C, C \rangle = [2][2n+2]^2[2n+4]/[n+1][n+2]^2[2n+3]$ ;
- $\langle C, D \rangle = [2n+2]^2/[n+2][2n+3]$ ;
- $\langle D, D \rangle = [n+1]^2[2n+2]([n+3] - [2][n])/[2][n]^2[2n+3]$ .

Here, we have used quantum integer identities to simplify the expression for  $\langle C, D \rangle$ .

For arbitrary  $n$ ,  $m$  and  $q$ , we have

$$[n+m] = \frac{1}{[4]}([4-m][n] + [m][n+4])$$

and

$$[2m] = [m]([m+1] - [m-1]).$$

By Lemma 2.15 and the assumption  $[2] = d_k$ , we have

$$[n+4] = [3][n].$$

(This is the only time we use the assumption  $[2] = d_k$ .) We can now express each of our inner products in terms of  $[n]$ ,  $[2]$ ,  $[3]$  and  $[4]$ . After some computation, we find that

$$\langle C, C \rangle \langle D, D \rangle = |\langle C, D \rangle|^2.$$

Thus,  $C$  and  $D$  are linearly dependent. The precise relation is then

$$C = \frac{\langle C, C \rangle}{\langle C, D \rangle} D. \quad \square$$

## 6. Properties of the generator

In this section we construct an 8-box  $S \in \text{GPA}(\mathcal{H}_1^p)$  that satisfies the hypotheses of Proposition 3.12. The planar algebra generated by  $S$  is the desired extended Haagerup planar algebra, thus completing the proof of Theorem 3.10.

We start with a brief description of how we found  $S$ , since the definition of  $S$  is not very enlightening on its own. The goal was to find  $S \in \text{GPA}(\mathcal{H}_1^p)_8$  satisfying the first three relations of Definition 3.2, which say that  $\varrho(S) = -S$ ,  $S$  is uncappable and  $S^2 = f^{(8)}$ . The dimension of  $\text{GPA}(\mathcal{H}_1^p)_8$  is the number of loops of length 16 based at even vertices of  $\mathcal{H}_1^p$ , which is equal to 148375. We found the 19-dimensional space of solutions to the first



two relations, then tried to solve the equation  $S^2 = f^{(8)}$ . This one equation in the 8-box space is actually 148375 separate equations over  $\mathbb{C}$ . We expect of course that there are many redundancies among these equations.

At this point the problem sounds quite tractable, but we were still unable to solve it by general techniques. We then used various ad hoc methods. First, we searched for quadratics that are perfect squares and solved those. This reduced the problem from 19 variables to 9. We then chose a small collection of quadratics, corresponding to certain ‘extremal’ loops in the basis, and found numerical approximations to a solution of these, using Newton’s method. Approximating such a solution by algebraic numbers, we could then go back and check that all the quadratic equations are satisfied exactly.

*Remark.* Our solution  $S$  need not be unique. Although the subfactor planar algebra with principal graphs  $\mathcal{H}_1$  is unique, there may be more than one way to embed it in its graph planar algebra. Indeed,  $-\bar{S}$  is also a solution, which corresponds to applying the graph automorphism, by Lemma 6.4. Due to the approximate nature of our search for  $S$ , we cannot say whether there are any other solutions.

The above description may sound daunting, but we manage to give a definition of  $S$  that involves specifying only 21 arbitrary looking numbers, and we reduce all the conditions we need to check on this element to computing certain powers of two matrices. The definition of  $S$  is still somewhat overwhelming, and the verification of its properties is done by computer. Those intrepid readers who continue reading this section will have to read a short `Mathematica` program in order to fully verify some of the steps.

We will use the notation for vertices of  $\mathcal{H}_1^p$  given in §2.4. Let

$$\lambda = \sqrt{2-d^2} \quad \text{and} \quad C = -21516075\lambda^4 + 8115925\lambda^2 + 45255025.$$

For each  $w \in \{0, 1, 2\}^8$  we will define an element  $p_w \in \mathbb{Z}[\lambda]$  below.

*Definition 6.1.* Let  $\gamma$  be a loop of length 16 in  $\mathcal{H}_1^p$ . Let the *collapsed loop*  $\hat{\gamma}$  be the sequence in  $\{0, 1, 2\}^8$  such that  $\gamma_{2j-1}$  is in arm number  $\hat{\gamma}_j$  (in the notation of §2.4) of  $\mathcal{H}_1^p$ . Further, define  $\sigma(\gamma)$  to be  $-1$  raised to the number of times the vertices  $v_0, w_0, z_j$  and  $a_j$  appear in  $\gamma$ . Let

$$S(\gamma) = C\sigma(\gamma)p_{\hat{\gamma}} \frac{1}{\sqrt{d_{\gamma_1}d_{\gamma_9}}} \prod_{j=1}^{16} \frac{1}{\sqrt{d_{\gamma_j}}}, \tag{6.1}$$

where the  $p_{\hat{\gamma}}$  are defined below.

*Remark.* The main reason for which we write  $S$  in the above form is that the  $p_{\hat{\gamma}}$  have much better number theoretic properties than  $S(\gamma)$ . In particular, the  $p_{\hat{\gamma}}$  all live

in a degree-6 extension of  $\mathbb{Q}$ , while the  $S(\gamma)$  live in a much larger number field. As a consequence, it is easier to do exact arithmetic using the  $p_{\tilde{\gamma}}$ . There is a general reason for this phenomenon: the convention that subfactor planar algebras be spherical is not the best convention from the point of view of number theory. A much more convenient convention is the “lopsided” one, where shaded circles count for 1, while unshaded circles count for the index  $d^2$ . Furthermore, this convention is also well motivated from the perspective of subfactor theory where  ${}_N M_M$  has the index as its left von Neumann dimension, while its right von Neumann dimension is 1. These issues warrant further investigation (see [46] and [44]).

We make an apparently ad-hoc definition of 21 elements of  $\mathbb{Z}[\lambda]$ :

$$\begin{aligned}
p_{00000001} &= -2\lambda^4 - \lambda^2 + 9, & p_{00000011} &= -\lambda^5 - \lambda^3 + 3\lambda, \\
p_{00000101} &= 2\lambda^4 + \lambda^2 - 9, & p_{00000111} &= 1, \\
p_{00001001} &= \lambda^5 - \lambda^3 - 3\lambda, & p_{00001011} &= \lambda^3 - 1, \\
p_{00010001} &= 2\lambda^4 + \lambda^2 - 9, & p_{00010011} &= \lambda^5 - \lambda^4 + \lambda^2 - 3\lambda + 4, \\
p_{00010101} &= \lambda^4 - 2\lambda^2 + 1, & p_{00010111} &= -\lambda^4 + 1, \\
p_{00011011} &= \lambda^4 - \lambda^2 - 3, & p_{00100101} &= -2\lambda^4 + 5, \\
p_{00100111} &= \lambda^2 + 1, & p_{00101011} &= -\lambda^5 - \lambda^3 + \lambda + 1, \\
p_{00101101} &= \lambda^5 - \lambda, & p_{00110011} &= 2\lambda^5 + 5\lambda^3 + 4\lambda, \\
p_{00110111} &= -\lambda^5 - 2\lambda^3 - 4\lambda^2 - \lambda - 5, & p_{01010101} &= -4\lambda^4 + 3\lambda^2 + 7, \\
p_{01010111} &= \lambda^4 + \lambda^2, & p_{01011011} &= \lambda^4 - 2\lambda^2 - 4, \\
p_{01101111} &= \lambda^4 + 6\lambda^2 + 6.
\end{aligned}$$

These elements are also defined in a `Mathematica` notebook, available along with the sources for this article on the `arXiv` (as the file `extra/code/Generator.nb`), or at <http://tqft.net/EH/notebook>. A PDF printout of the notebook is available by following this URL, and then replacing `.nb` by `.pdf`. Everything that follows in this section is paralleled in the notebook, and in particular each of the statements below that requires checking some arithmetic has a corresponding test defined in the notebook.

DEFINITION-LEMMA 6.2. *We can consistently extend these definitions to every  $p_w$  for  $w \in \{0, 1\}^8$  by the rules*

$$p_{abcdefgh} = -p_{bcdefgha}, \tag{6.2}$$

$$p_{abcdefgh} = \bar{p}_{ahgfedcb}, \tag{6.3}$$

and

$$p_{00000000} = 0, \quad (6.4)$$

$$p_{abcd1111} = 0. \quad (6.5)$$

*Proof.* For example, one can get from  $p_{00110011}$  to  $p_{01100110}$  either by rotating, or by reversing; fortunately  $p_{00110011}$  is purely imaginary. Under the operations implicit in equations (6.2) and (6.3), each orbit in  $\{0, 1\}^8$  contains exactly one of the elements on which  $p$  is defined above or in equations (6.4) and (6.5). The `Mathematica` notebook provides functions `VerifyRotation` and `VerifyConjugation` to check that these rules hold uniformly.  $\square$

We further extend these definitions to every  $p_w$ , for  $w \in \{0, 1, 2\}^8$ , by the rules

$$p_{x0y} + p_{x1y} + p_{x2y} = 0. \quad (6.6)$$

LEMMA 6.3. *For every  $abcd \in \{0, 1, 2\}^4$  we have*

$$p_{abcd2222} = 0. \quad (6.7)$$

*Proof.* This is a direct computation of 16 cases for  $abcd \in \{0, 1\}^4$  using equation (6.6), after which the general case of  $abcd \in \{0, 1, 2\}^4$  follows, again from (6.6). The `Mathematica` notebook provides a function `Verify2sVanish` that checks this lemma.  $\square$

We point out a final interesting note on the  $p_w$ .

LEMMA 6.4. *If  $w'$  is obtained from  $w$  by exchanging all 1's and 2's, then  $p_w = -\bar{p}_{w'}$ .*

*Proof.* This is a direct computation which can be verified using the `Mathematica` function `VerifyGraphSymmetry`.  $\square$

This ends the definition of  $S$ . We now prepare to prove that it has the properties required to generate a subfactor planar algebra with principal graph  $\mathcal{H}_1$ .

LEMMA 6.5. *The generator  $S$  is self-adjoint, has rotational eigenvalue  $-1$  and is uncappable:*

$$S^* = S, \quad \varrho(S) = -S \quad \text{and} \quad \varepsilon_j(S) = 0 \quad \text{for } j = 1, \dots, 2k.$$

LEMMA 6.6. *The generator  $S$  and its "one-click" rotation  $\varrho^{1/2}(S)$  have the moments*

$$\mathrm{tr}_0(S^2) = [9], \quad \mathrm{tr}_0(S^3) = 0, \quad \mathrm{tr}_0(S^4) = [9] \quad \text{and} \quad \mathrm{tr}_0(\varrho^{1/2}(S)^3) = i \frac{[18]}{\sqrt{[8][10]}}.$$

*Note that the scalars on the right-hand sides of these equalities actually refer to scalar multiples of the empty diagram in  $\mathrm{GPA}(\mathcal{H}_1^p)_{0,\pm}$ . In particular, each of them is a constant function on the even (or odd in the last case) vertices of the graph  $\mathcal{H}_1^p$ .*

*Proof of Lemma 6.5.* Self-adjointness follows immediately from equation (6.3).

To show that  $\varrho(S(\gamma)) = -S(\gamma)$ , first note that  $\sigma(\gamma)$  and

$$\prod_{j=1}^{16} \frac{1}{\sqrt{d_{\gamma_j}}}$$

are independent of the order of the vertices appearing in  $\gamma = \gamma_1 \dots \gamma_{16} \gamma_1$ . Thus, recalling Example 2.12 from §2.3,

$$\begin{aligned} \varrho(S)(\gamma) &= \sqrt{\frac{d_{\gamma_3} d_{\gamma_{11}}}{d_{\gamma_9} d_{\gamma_1}}} S(\gamma_3 \dots \gamma_{16} \gamma_1 \gamma_2 \gamma_3) \\ &= \sqrt{\frac{d_{\gamma_3} d_{\gamma_{11}}}{d_{\gamma_9} d_{\gamma_1}}} C \sigma(\gamma) p_{\gamma_3 \dots \widehat{\gamma_{16} \gamma_1} \gamma_2 \gamma_3} \frac{1}{\sqrt{d_{\gamma_{11}} d_{\gamma_3}}} \prod_{j=1}^{16} \frac{1}{\sqrt{d_{\gamma_j}}} \\ &= C \sigma(\gamma) (-p_{\widehat{\gamma}}) \frac{1}{\sqrt{d_{\gamma_9} d_{\gamma_1}}} \prod_{j=1}^{16} \frac{1}{\sqrt{d_{\gamma_j}}} \\ &= -S(\gamma), \end{aligned}$$

where we used equation (6.2) in the third step.

Next consider  $\varepsilon_j(S)$ , the result of attaching a cap on strands  $j$  and  $j+1$ . Since we know that  $S$  is a rotational eigenvector, we only need to check that  $\varepsilon_1(S) = \varepsilon_2(S) = 0$ . In particular, we do not need to explicitly treat the more complicated cases of  $\varepsilon_8(S)$  and  $\varepsilon_{16}(S)$ , in which the cap is attached ‘‘around the side’’ of  $S$ , and the coefficients coming from critical points in the graph planar algebra are more complicated.

Let  $\Gamma_k$  be the set of length- $k$  loops on  $\mathcal{H}_1^p$ , and  $\gamma_j$  denote the  $j$ th vertex of  $\gamma \in \Gamma_k$ . The graph planar algebra formalism tells us that for  $\varphi \in \Gamma_{14}$ ,

$$\varepsilon_j(S)(\varphi) = \sum_{\substack{\gamma \in \Gamma_{16} \text{ with} \\ \gamma_l = \varphi_l \text{ for } l \leq j, \\ \gamma_l = \varphi_{l-2} \text{ for } l \geq j+2}} \sqrt{\frac{d_{\gamma_{j+1}}}{d_{\gamma_j}}} S(\gamma).$$

We consider three cases, depending on whether the valence of  $\varphi_j$  is 1, 2 or 3.

If  $\varphi_j$  has valence 1, that is, it is an endpoint, then there is just one term in the sum: if  $\gamma_j = v_0$  then  $\gamma_{j+1} = w_0$ , and if  $\gamma_j = z_l$  then  $\gamma_{j+1} = a_l$ . In the first case, the collapsed loop  $\widehat{\gamma}$  must be 00000000, so  $S(\gamma) = 0$  by equation (6.4). In the second case, if  $\gamma_j = z_1$  then  $\widehat{\gamma}$  must contain at least four consecutive 1’s, so  $S(\gamma) = 0$  by equation (6.5). If  $\gamma_j = z_2$ , then  $\widehat{\gamma}$  must contain at least four consecutive 2’s, so  $S(\gamma) = 0$  by Lemma 6.3.

If  $\varphi_j$  has valence 2, that is, it lies on one of the arms, then there are two terms in the sum, say  $\gamma^+$  and  $\gamma^-$ . Moreover, the collapsed loops for the two terms are the same,

and  $\sigma(\gamma^+) = -\sigma(\gamma^-)$ . Thus,

$$\begin{aligned} \varepsilon_j(S)(\varphi) &= Cp_{\widehat{\gamma}^\pm} \frac{1}{\sqrt{d_{\gamma_1^\pm} d_{\gamma_9^\pm}}} \sqrt{\prod_{l=1}^{14} \frac{1}{d_{\varphi_l}}} \left( \frac{\sigma(\gamma^+)}{\sqrt{d_{\gamma_{j+1}^+} d_{\gamma_{j+2}^+}}} \sqrt{\frac{d_{\gamma_{j+1}^+}}{d_{\gamma_j^+}}} + \frac{\sigma(\gamma^-)}{\sqrt{d_{\gamma_{j+1}^-} d_{\gamma_{j+2}^-}}} \sqrt{\frac{d_{\gamma_{j+1}^-}}{d_{\gamma_j^-}}} \right) \\ &= Cp_{\widehat{\gamma}^\pm} \frac{1}{\sqrt{d_{\gamma_1^\pm} d_{\gamma_9^\pm}}} \sqrt{\prod_{l=1}^{14} \frac{1}{d_{\varphi_l}}} \left( \frac{\sigma(\gamma^+)}{\sqrt{d_{\gamma_j^+} d_{\gamma_{j+2}^+}}} + \frac{\sigma(\gamma^-)}{\sqrt{d_{\gamma_j^-} d_{\gamma_{j+2}^-}}} \right) = 0. \end{aligned}$$

Since  $\gamma_j^+ = \gamma_j^- = \gamma_{j+2}^+ = \gamma_{j+2}^- = \varphi_j$ , the two terms in parentheses cancel exactly.

Finally, if  $\varphi_j$  has valence 3, then it must be the triple point,  $c$ . There are then three terms, say  $\gamma^0$ ,  $\gamma^1$  and  $\gamma^2$ , with  $\gamma_{j+1}^l = b_l$ . Now the collapsed paths differ;  $\widehat{\gamma}^l = w_1 l w_2$  for some fixed words  $w_1$  and  $w_2$ . On the other hand, the signs  $\sigma(\gamma^l)$  are all equal. Thus, we obtain

$$\varepsilon_j(S)(\varphi) = C\sigma(\gamma^l) \frac{1}{\sqrt{d_{\gamma_1^l} d_{\gamma_9^l}}} \sqrt{\prod_{l=1}^{14} \frac{1}{d_{\varphi_l}}} \left( \frac{p_{\widehat{\gamma}^0}}{\sqrt{d_{\gamma_j^0} d_{\gamma_{j+2}^0}}} + \frac{p_{\widehat{\gamma}^1}}{\sqrt{d_{\gamma_j^1} d_{\gamma_{j+2}^1}}} + \frac{p_{\widehat{\gamma}^2}}{\sqrt{d_{\gamma_j^2} d_{\gamma_{j+2}^2}}} \right).$$

Since  $\gamma_j^l = \gamma_{j+2}^l = \varphi_j$ , the three terms in parentheses cancel exactly by (6.6).  $\square$

We now verify that the moments of  $S$  are the Haagerup moments.

*Computer-assisted proof of Lemma 6.6.* We first treat the moments of  $S$ , and later describe the changes required to calculate the moments of  $\varrho^{1/2}(S)$ .

With multiplication given by the multiplication tangle from Figure 1, the vector space  $\text{GPA}(\mathcal{H}_1)_{8,+}$  becomes a finite-dimensional semisimple associative algebra, which of course must just be a multimatrix algebra. It is easy to see that the simple summands are indexed by pairs of even vertices, and that the minimal idempotents in the summand indexed by  $(s, t)$  are given by symmetric loops of length 16, which go from  $s$  to  $t$  in 8 steps, and then return the same way. Since there are 8 even vertices ( $v_0, x_0, z_0, b_0, b_1, b_2, z_1$  and  $z_2$ ), there are 64 simple summands  $\mathcal{A}_{s,t}$ , although four of these ( $\mathcal{A}_{v_0, z_1}$ ,  $\mathcal{A}_{z_1, v_0}$ ,  $\mathcal{A}_{v_0, z_2}$  and  $\mathcal{A}_{z_2, v_0}$ ) are trivial because  $s$  and  $t$  are more than 8 edges apart. Moreover, the trace tangle from Figure 1 composed with the partition function puts a trace on each of these matrix algebras. We write  $\mathcal{A}_{s,t} = (\mathcal{M}_{k \times k}, d_t/d_s)$  to indicate that there are  $k$  paths of length 8 from  $s$  to  $t$ , and that the trace of the identity in  $\mathcal{M}_{k \times k}$  is  $kd_t/d_s$ . We find that

$$(\text{GPA}(\mathcal{H}_1)_{8,+}, \text{multiplication tangle}) \cong \bigoplus_{\substack{s,t \\ \text{even vertices}}} \mathcal{A}_{s,t}.$$

Now, to compute the required moments, we just need to identify the image of  $S$  in this multimatrix algebra, compute the appropriate powers via matrix multiplication, and take weighted traces. It turns out that the necessary calculation, namely taking  $k$ th powers of the matrices for  $S$ ,  $k=2, 3, 4$ , is actually computationally difficult! First notice that some of the matrices are quite large, up to  $118 \times 118$ . Worse than this, the entries are quite complicated numbers, involving square roots of dimensions, and so the arithmetic step of simplifying matrix entries after multiplication turns out to be extremely slow. One can presumably do these calculations directly with the help of a computer, using exact arithmetic, but our implementation in `Mathematica` took more than a day attempting to simplify the matrix entries in  $S^4$  before we stopped it. Instead, we choose a matrix (really, a multimatrix)  $A$  so that all the entries of  $ASA^{-1}$  lie in the number field  $\mathbb{Q}(\lambda)$ ; this matrix certainly has the same moments as  $S$ , but once the computer can do its arithmetic inside a fixed number field, everything happens much faster. In particular, the moments required here take less than an hour to compute, using `Mathematica 7` on a 2.4GHz Intel Core 2 Duo processor. See the remark following Definition 6.1 for an explanation of why this trick works: we cooked up the matrix  $A$  with the desired property by comparing the usual definition of the graph planar algebra with an alternative definition that produces the corresponding “lopsided” planar algebra.

The matrix  $A$  is defined by

$$(A_{s,t})_{\pi,\varepsilon} = \delta_{\pi=\varepsilon} \prod_{j=1}^8 \sqrt{d_{\pi_j}}, \quad (6.8)$$

recalling that the matrix entries in  $A_{s,t}$  are indexed by pairs of paths  $\pi, \varepsilon$  from  $s$  to  $t$ , so  $\pi = \pi_1 \dots \pi_9$  and  $\varepsilon = \varepsilon_1 \dots \varepsilon_9$  with  $\pi_1 = \varepsilon_1 = s$  and  $\pi_9 = \varepsilon_9 = t$ . Notice that the index in the product ranges from 1 to 8, leaving out the endpoint  $t$ .

LEMMA 6.7. *The entries of  $ASA^{-1}$  lie in  $\mathbb{Q}(\lambda)$ .*

(The proof appears below.)

The second half of the `Mathematica` notebook referred to above produces the matrices for  $ASA^{-1}$  (these, and the corresponding matrices for  $\varrho^{1/2}(S)$  described below, are also available at <http://tqft.net/EH/matrices> in machine-readable form and as a PDF typeset for an enormous sheet of paper) and actually does the moment calculation. Any reader wanting to check the details should look there. Here, we will just indicate the schematic calculation:

$$\mathrm{tr}(S^2)(s) = \sum_t \frac{d_t}{d_s} \mathrm{tr}(S_{s,t}^2) = \sum_t \frac{d_t}{d_s} \mathrm{tr}((A_{s,t} S_{s,t} A_{s,t}^{-1})^2) = [9]$$

(the result took approximately 8 minutes),

$$\begin{aligned} \operatorname{tr}(S^3)(s) &= \sum_t \frac{d_t}{d_s} \operatorname{tr}(S_{s,t}^3) = \sum_t \frac{d_t}{d_s} \operatorname{tr}((A_{s,t} S_{s,t} A_{s,t}^{-1})^3) = 0 \\ &\text{(approximately 16 minutes)} \end{aligned}$$

and

$$\begin{aligned} \operatorname{tr}(S^4)(s) &= \sum_t \frac{d_t}{d_s} \operatorname{tr}(S_{s,t}^4) = \sum_t \frac{d_t}{d_s} \operatorname{tr}((A_{s,t} S_{s,t} A_{s,t}^{-1})^4) = [9] \\ &\text{(approximately 24 minutes).} \end{aligned}$$

Note that in each case above we are actually computing 8 potentially different numbers, as  $s$  ranges over the even vertices of the graph.

The moments of  $\varrho^{1/2}(S)$  can be calculated by a very similar approach. The other 8-box space  $\operatorname{GPA}(\mathcal{H}_1)_{8,-}$  becomes a multimatrix algebra with summands indexed by pairs of odd vertices on the graph  $\mathcal{H}_1$ .

LEMMA 6.8. *The entries of  $A_{s,t} \varrho^{1/2}(S)_{s,t} A_{s,t}^{-1}$  lie in  $d\mathbb{Q}(\lambda)$ .*

(Again, the proof appears below.)

We thus compute

$$\operatorname{tr}(\varrho^{1/2}(S)^3) = d^3 \operatorname{tr}((d^{-1} A_{s,t} \varrho^{1/2}(S)_{s,t} A_{s,t}^{-1})^3).$$

As before, this is implemented in `Mathematica`. The calculation takes slightly longer than in the first case. The details can be found in the notebook.  $\square$

*Proof of Lemma 6.7.* Let  $\sqcup$  denote concatenation of paths, and  $\bar{\varepsilon}$  be the reverse of the path  $\varepsilon$ . We readily calculate

$$\begin{aligned} (A_{s,t} S_{s,t} A_{s,t}^{-1})_{\pi, \varepsilon} &= C \sigma_{\pi \sqcup \bar{\varepsilon} p_{\pi \sqcup \bar{\varepsilon}}} \frac{1}{\sqrt{d_s d_t}} \left( \prod_{j=1}^8 \frac{1}{\sqrt{d_{\pi_j}}} \right) \left( \prod_{j=2}^9 \frac{1}{\sqrt{d_{\varepsilon_j}}} \right) \frac{\prod_{j=1}^8 \sqrt{d_{\pi_j}}}{\prod_{j=1}^8 \sqrt{d_{\varepsilon_j}}} \\ &= \frac{C \sigma_{\pi \sqcup \bar{\varepsilon} p_{\pi \sqcup \bar{\varepsilon}}}}{\prod_{j=1}^9 d_{\varepsilon_j}}. \end{aligned}$$

Most of the factors in this product are already in  $\mathbb{Q}(\lambda)$ ; the one in question is  $\prod_{j=1}^9 d_{\varepsilon_j}$ . All even dimensions are in  $\mathbb{Q}[d^2] = \mathbb{Q}[\lambda^2]$ , whereas all odd dimensions are in  $d\mathbb{Q}[\lambda^2]$ . Therefore  $\prod_{j=1}^9 d_{\varepsilon_j}$ , a product of five even and four odd dimensions, lies in  $d^4 \mathbb{Q}[d^2] \subset \mathbb{Q}(\lambda)$  and

$$(ASA^{-1})_{\gamma, \varepsilon} \in \mathbb{Q}(\lambda). \quad \square$$

*Proof of Lemma 6.8.* First, we have

$$\begin{aligned} \varrho^{1/2}(S)(\gamma_1\gamma_2 \dots \gamma_{16}\gamma_1) &= \sqrt{\frac{d_{\gamma_2}d_{\gamma_{10}}}{d_{\gamma_9}d_{\gamma_1}}} S(\gamma_2 \dots \gamma_{16}\gamma_1\gamma_2) \\ &= \sqrt{\frac{d_{\gamma_2}d_{\gamma_{10}}}{d_{\gamma_9}d_{\gamma_1}}} C\sigma(\gamma) p_{\gamma_2 \dots \widehat{\gamma_{16}\gamma_1}\gamma_2} \frac{1}{\sqrt{d_{\gamma_2}d_{\gamma_{10}}}} \prod_{j=1}^{16} \frac{1}{\sqrt{d_{\gamma_j}}} \\ &= C\sigma(\gamma) p_{\gamma_2 \dots \widehat{\gamma_{16}\gamma_1}\gamma_2} \frac{1}{\sqrt{d_{\gamma_1}d_{\gamma_9}}} \prod_{j=1}^{16} \frac{1}{\sqrt{d_{\gamma_j}}}. \end{aligned}$$

Be careful here: although this looks very similar to the formula in equation (6.1) for  $S$ , the path  $\gamma$  here starts at an odd vertex.

We now conjugate by a multimatrix  $A$  that has exactly the same formula for its definition as in equation (6.8), except again for the paths  $\gamma$  and  $\varepsilon$  that start and finish at odd vertices. We obtain

$$(A_{s,t}\varrho^{1/2}(S)_{s,t}A_{s,t}^{-1})_{\pi,\varepsilon} = \frac{r\sigma_{\pi\sqcup\varepsilon} p_{\varepsilon_2\pi_1 \dots \widehat{\pi_8\varepsilon_9} \dots \varepsilon_2}}{\prod_{j=1}^9 d_{\varepsilon_j}}.$$

One readily checks that these matrix entries are in  $d\mathbb{Q}(\lambda)$ . □

We have finally shown the existence and uniqueness of the extended Haagerup subfactor. Uniqueness is Theorem 3.9. By Lemmas 6.5 and 6.6,  $S$  satisfies the hypotheses of Proposition 3.12. Therefore  $\mathcal{PA}(S)$  is a subfactor planar algebra with principal graphs  $\mathcal{H}_1$ .

### Appendix A. Fusion categories coming from the extended Haagerup subfactor

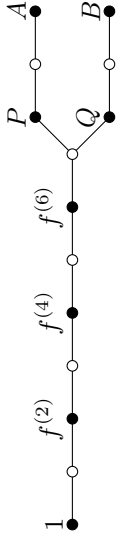
The even parts of a subfactor are the unitary tensor categories of  $N$ - $N$  and  $M$ - $M$  bimodules respectively. Hence every finite depth subfactor yields two unitary fusion categories. In terms of the planar algebra, the simple objects in these categories are the irreducible projections in the box spaces  $P_{2m,\pm}$  for some  $m$ .

In the case of the extended Haagerup subfactor, the global dimension of each of these fusion categories is the largest real root of

$$x^3 - 585x^2 + 8450x - 21125$$

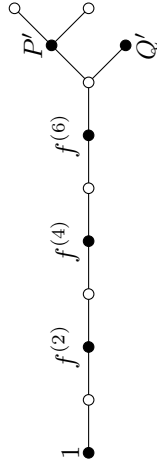
(approximately 570.247). The fusion tables are given in Tables 12 and 13.





$\otimes$	$f^{(2)}$	$f^{(4)}$	$f^{(6)}$	$P$	$Q$	$A$	$B$
$f^{(2)}$	$1+f^{(2)}+f^{(4)}$	$f^{(2)}+f^{(4)}+f^{(6)}$	$f^{(4)}+W$	$B+W$	$A+W$	$Q$	$P$
$f^{(4)}$	$f^{(2)}+f^{(4)}+f^{(6)}$	$1+f^{(2)}+f^{(4)}+W$	$f^{(2)}+f^{(4)}+A+B+2W$	$f^{(4)}+A+2W$	$f^{(4)}+B+2W$	$f^{(6)}+P$	$f^{(6)}+Q$
$f^{(6)}$	$f^{(4)}+W$	$f^{(2)}+f^{(4)}+A+B+2W$	$1+W+Z$	$f^{(6)}+Q+Z$	$f^{(6)}+P+Z$	$f^{(4)}+B+W$	$f^{(4)}+A+W$
$P$	$A+W$	$f^{(4)}+B+2W$	$f^{(6)}+Q+Z$	$1+P+Z$	$f^{(6)}+Z$	$f^{(2)}+A+W$	$f^{(4)}+W$
$Q$	$B+W$	$f^{(4)}+A+2W$	$f^{(6)}+P+Z$	$f^{(6)}+Z$	$1+Q+Z$	$f^{(4)}+W$	$f^{(2)}+B+W$
$A$	$P$	$f^{(6)}+Q$	$f^{(4)}+B+W$	$f^{(4)}+W$	$f^{(2)}+A+W$	$f^{(6)}$	$1+P$
$B$	$Q$	$f^{(6)}+P$	$f^{(4)}+A+W$	$f^{(2)}+B+W$	$f^{(4)}+W$	$1+Q$	$f^{(6)}$

Table 12. The simple objects and fusion rules for the  $N$ - $N$  fusion category coming from the extended Haagerup subfactor. We use the abbreviations  $W=f^{(6)}+P+Q$  and  $Z=A+B+f^{(2)}+2f^{(4)}+3f^{(6)}+3P+3Q$ .



$\otimes$	$f^{(2)}$	$f^{(4)}$	$f^{(6)}$	$P'$	$Q'$
$f^{(2)}$	$1 + f^{(2)} + f^{(4)}$	$f^{(2)} + f^{(4)} + f^{(6)}$	$f^{(4)} + f^{(6)} + P' + Q'$	$f^{(6)} + 2P' + Q'$	$f^{(6)} + P'$
$f^{(4)}$	$f^{(2)} + f^{(4)} + f^{(6)}$	$1 + f^{(2)} + f^{(4)} + f^{(6)} + P' + Q'$	$f^{(2)} + f^{(4)} + 2f^{(6)} + 3P' + Q'$	$f^{(4)} + 3f^{(6)} + 3P' + 2Q'$	$f^{(4)} + f^{(6)} + 2P' + Q'$
$f^{(6)}$	$f^{(4)} + f^{(6)} + P' + Q'$	$f^{(2)} + f^{(4)} + 2f^{(6)} + 3P' + Q'$	$1 + f^{(2)} + 2f^{(4)} + 4f^{(6)} + 5P' + 3Q'$	$f^{(2)} + 3f^{(4)} + 5f^{(6)} + 6P' + 3Q'$	$f^{(2)} + f^{(4)} + 3f^{(6)} + 3P' + 2Q'$
$P'$	$f^{(6)} + 2P' + Q'$	$f^{(4)} + 3f^{(6)} + 3P' + 2Q'$	$f^{(2)} + 3f^{(4)} + 5f^{(6)} + 6P' + 3Q'$	$1 + 2f^{(2)} + 3f^{(4)} + 6f^{(6)} + 7P' + 4Q'$	$f^{(2)} + 2f^{(4)} + 3f^{(6)} + 4P' + 2Q'$
$Q'$	$f^{(6)} + P'$	$f^{(4)} + f^{(6)} + 2P' + Q'$	$f^{(2)} + f^{(4)} + 3f^{(6)} + 3P' + 2Q'$	$f^{(2)} + 2f^{(4)} + 3f^{(6)} + 4P' + 2Q'$	$1 + f^{(4)} + 2f^{(6)} + 2P' + Q'$

Table 13. The simple objects and fusion rules for the  $M$ - $M$  fusion category coming from the extended Haagerup subfactor.

## References

- [1] ASAEDA, M., Galois groups and an obstruction to principal graphs of subfactors. *Internat. J. Math.*, 18 (2007), 191–202.
- [2] ASAEDA, M. & HAAGERUP, U., Exotic subfactors of finite depth with Jones indices  $(5+\sqrt{13})/2$  and  $(5+\sqrt{17})/2$ . *Comm. Math. Phys.*, 202 (1999), 1–63.
- [3] ASAEDA, M. & YASUDA, S., On Haagerup’s list of potential principal graphs of subfactors. *Comm. Math. Phys.*, 286 (2009), 1141–1157.
- [4] BIGELOW, S., Skein theory for the ADE planar algebras. *J. Pure Appl. Algebra*, 214 (2010), 658–666.
- [5] BION-NADAL, J., An example of a subfactor of the hyperfinite  $\text{II}_1$  factor whose principal graph invariant is the Coxeter graph  $E_6$ , in *Current Topics in Operator Algebras* (Nara, 1990), pp. 104–113. World Scientific, River Edge, NJ, 1991.
- [6] BISCH, D., An example of an irreducible subfactor of the hyperfinite  $\text{II}_1$  factor with rational, noninteger index. *J. Reine Angew. Math.*, 455 (1994), 21–34.
- [7] — Bimodules, higher relative commutants and the fusion algebra associated to a subfactor, in *Operator Algebras and their Applications* (Waterloo, ON, 1994/1995), Fields Inst. Commun., 13, pp. 13–63. Amer. Math. Soc., Providence, RI, 1997.
- [8] — Principal graphs of subfactors with small Jones index. *Math. Ann.*, 311 (1998), 223–231.
- [9] — Subfactors and planar algebras, in *Proceedings of the International Congress of Mathematicians*, Vol. II (Beijing, 2002), pp. 775–785. Higher Ed. Press, Beijing, 2002.
- [10] BISCH, D., NICOARA, R. & POPA, S. T., Continuous families of hyperfinite subfactors with the same standard invariant. *Internat. J. Math.*, 18 (2007), 255–267.
- [11] DE BOER, J. & GOEREE, J., Markov traces and  $\text{II}_1$  factors in conformal field theory. *Comm. Math. Phys.*, 139 (1991), 267–304.
- [12] CONNES, A., *Noncommutative Geometry*. Academic Press, San Diego, CA, 1994.
- [13] COSTE, A. & GANNON, T., Remarks on Galois symmetry in rational conformal field theories. *Phys. Lett. B*, 323 (1994), 316–321.
- [14] DOPLICHER, S. & ROBERTS, J. E., A new duality theory for compact groups. *Invent. Math.*, 98 (1989), 157–218.
- [15] ETINGOF, P., NIKSHYCH, D. & OSTRIK, V., On fusion categories. *Ann. of Math.*, 162 (2005), 581–642.
- [16] FRENKEL, I. B. & KHOVANOV, M. G., Canonical bases in tensor products and graphical calculus for  $U_q(\mathfrak{sl}_2)$ . *Duke Math. J.*, 87 (1997), 409–480.
- [17] GUIONNET, A., JONES, V. F. R. & SHLYAKHTENKO, D., Random matrices, free probability, planar algebras and subfactors, in *Quanta of Maths*, Clay Math. Proc., 11, pp. 201–239. Amer. Math. Soc., Providence, RI, 2010.
- [18] HAAGERUP, U., Principal graphs of subfactors in the index range  $4 < [M:N] < 3 + \sqrt{2}$ , in *Subfactors* (Kyuzeso, 1993), pp. 1–38. World Scientific, River Edge, NJ, 1994.
- [19] HAN, R., *A Construction of the “2221” Planar Algebra*. Ph.D. Thesis, University of California, Riverside, CA, 2010.
- [20] HONG, S.-M., ROWELL, E. & WANG, Z., On exotic modular tensor categories. *Commun. Contemp. Math.*, 10 (2008), 1049–1074.
- [21] IKEDA, K., Numerical evidence for flatness of Haagerup’s connections. *J. Math. Sci. Univ. Tokyo*, 5 (1998), 257–272.
- [22] IZUMI, M., Application of fusion rules to classification of subfactors. *Publ. Res. Inst. Math. Sci.*, 27 (1991), 953–994.
- [23] — On flatness of the Coxeter graph  $E_8$ . *Pacific J. Math.*, 166 (1994), 305–327.
- [24] — The structure of sectors associated with Longo–Rehren inclusions. II. Examples. *Rev. Math. Phys.*, 13 (2001), 603–674.

- [25] IZUMI, M., JONES, V. F. R., MORRISON, S. & SNYDER, N., Subfactors of index less than 5, part 3: quadruple points. To appear in *Comm. Math. Phys.*
- [26] JONES, V. F. R., Index for subfactors. *Invent. Math.*, 72 (1983), 1–25.
- [27] — Braid groups, Hecke algebras and type  $\text{II}_1$  factors, in *Geometric Methods in Operator Algebras* (Kyoto, 1983), Pitman Res. Notes Math. Ser., 123, pp. 242–273. Longman, Harlow, 1986.
- [28] — The planar algebra of a bipartite graph, in *Knots in Hellas '98* (Delphi), Ser. Knots Everything, 24, pp. 94–117. World Scientific, River Edge, NJ, 2000.
- [29] — The annular structure of subfactors, in *Essays on Geometry and Related Topics*, Vol. 2, Monogr. Enseign. Math., 38, pp. 401–463. Enseignement Math., Geneva, 2001.
- [30] — Two subfactors and the algebraic decomposition of bimodules over  $\text{II}_1$  factors. *Acta Math. Vietnam.*, 33 (2008), 209–218.
- [31] — Planar algebras, I. Preprint, 1999. [arXiv:math/9909027](https://arxiv.org/abs/math/9909027) [[math.QA](#)].
- [32] — Quadratic tangles in planar algebras. To appear in *Duke Math. J.*
- [33] JONES, V. F. R. & PENNEYS, D., The embedding theorem for finite depth subfactor planar algebras. *Quantum Topol.*, 2 (2011), 301–337.
- [34] JONES, V. F. R., SHLYAKHTENKO, D. & WALKER, K., An orthogonal approach to the subfactor of a planar algebra. *Pacific J. Math.*, 246 (2010), 187–197.
- [35] JOYAL, A. & STREET, R., The geometry of tensor calculus. I. *Adv. Math.*, 88 (1991), 55–112.
- [36] — An introduction to Tannaka duality and quantum groups, in *Category Theory* (Como, 1990), Lecture Notes in Math., 1488, pp. 413–492. Springer, Berlin, 1991.
- [37] KAUFFMAN, L. H., State models and the Jones polynomial. *Topology*, 26 (1987), 395–407.
- [38] KAWAHIGASHI, Y., On flatness of Ocneanu’s connections on the Dynkin diagrams and classification of subfactors. *J. Funct. Anal.*, 127 (1995), 63–107.
- [39] KODIYALAM, V. & SUNDER, V. S., From subfactor planar algebras to subfactors. *Internat. J. Math.*, 20 (2009), 1207–1231.
- [40] KUPERBERG, G., Spiders for rank 2 Lie algebras. *Comm. Math. Phys.*, 180 (1996), 109–151.
- [41] MORRISON, S., A formula for the Jones–Wenzl projections. Unpublished manuscript. Available at <http://tqft.net/math/JonesWenzlProjections.pdf>.
- [42] MORRISON, S., PENNEYS, D., PETERS, E. & SNYDER, N., Subfactors of index less than 5, part 2: triple points. *Internat. J. Math.*, 23 (2012), 1250016, 33 pp.
- [43] MORRISON, S., PETERS, E. & SNYDER, N., Skein theory for the  $D_{2n}$  planar algebras. *J. Pure Appl. Algebra*, 214 (2010), 117–139.
- [44] MORRISON, S. & SNYDER, N., Non-cyclotomic fusion categories. To appear in *Trans. Amer. Math. Soc.*
- [45] — Subfactors of index less than 5, part 1: the principal graph odometer. To appear in *Comm. Math. Phys.*
- [46] MORRISON, S. & WALKER, K., The graph planar algebra embedding theorem. Unpublished manuscript. Available at <http://tqft.net/papers/gpa.pdf>.
- [47] OCNEANU, A., Quantized groups, string algebras and Galois theory for algebras, in *Operator Algebras and Applications*, Vol. 2, London Math. Soc. Lecture Note Ser., 136, pp. 119–172. Cambridge Univ. Press, Cambridge, 1988.
- [48] — Chirality for operator algebras, in *Subfactors* (Kyuzeso, 1993), pp. 39–63. World Scientific, River Edge, NJ, 1994.
- [49] — The classification of subgroups of quantum  $\text{SU}(N)$ , in *Quantum Symmetries in Theoretical Physics and Mathematics* (Bariloche, 2000), Contemp. Math., 294, pp. 133–159. Amer. Math. Soc., Providence, RI, 2002.

- [50] PENNEYS, D. & TENER, J. E., Subfactors of index less than 5, part 4: vines. *Internat. J. Math.*, 23 (2012), 1250017, 18 pp.
- [51] PENROSE, R., Applications of negative dimensional tensors, in *Combinatorial Mathematics and its Applications* (Oxford, 1969), pp. 221–244. Academic Press, London, 1971.
- [52] PETERS, E., A planar algebra construction of the Haagerup subfactor. *Internat. J. Math.*, 21 (2010), 987–1045.
- [53] POPA, S. T., Classification of subfactors: the reduction to commuting squares. *Invent. Math.*, 101 (1990), 19–43.
- [54] — Subfactors and classification in von Neumann algebras, in *Proceedings of the International Congress of Mathematicians*, Vol. II (Kyoto, 1990), pp. 987–996. Math. Soc. Japan, Tokyo, 1991.
- [55] — Classification of amenable subfactors of type II. *Acta Math.*, 172 (1994), 163–255.
- [56] — An axiomatization of the lattice of higher relative commutants of a subfactor. *Invent. Math.*, 120 (1995), 427–445.
- [57] POPA, S. T. & SHLYAKHTENKO, D., Universal properties of  $L(\mathbf{F}_\infty)$  in subfactor theory. *Acta Math.*, 191 (2003), 225–257.
- [58] RESHETIKHIN, N. & TURAEV, V. G., Invariants of 3-manifolds via link polynomials and quantum groups. *Invent. Math.*, 103 (1991), 547–597.
- [59] REZNIKOFF, S. A., Coefficients of the one- and two-gap boxes in the Jones–Wenzl idempotent. *Indiana Univ. Math. J.*, 56 (2007), 3129–3150.
- [60] TEMPERLEY, H. N. V. & LIEB, E. H., Relations between the “percolation” and “colouring” problem and other graph-theoretical problems associated with regular planar lattices: some exact results for the “percolation” problem. *Proc. Roy. Soc. London Ser. A*, 322 (1971), 251–280.
- [61] TURAEV, V. G., *Quantum Invariants of Knots and 3-Manifolds*. de Gruyter Studies in Mathematics, 18. de Gruyter, Berlin, 1994.
- [62] TURAEV, V. G. & VIRO, O. Y., State sum invariants of 3-manifolds and quantum  $6j$ -symbols. *Topology*, 31 (1992), 865–902.
- [63] VAES, S., Explicit computations of all finite index bimodules for a family of  $\text{II}_1$  factors. *Ann. Sci. Éc. Norm. Supér.*, 41 (2008), 743–788.
- [64] WENZL, H., On sequences of projections. *C. R. Math. Rep. Acad. Sci. Canada*, 9 (1987), 5–9.
- [65] — On the structure of Brauer’s centralizer algebras. *Ann. of Math.*, 128 (1988), 173–193.

STEPHEN BIGELOW  
University of California, Santa Barbara  
Department of Mathematics  
South Hall Room 6607  
Santa Barbara, CA 93106  
U.S.A.  
[bigelow@math.ucsb.edu](mailto:bigelow@math.ucsb.edu)

EMILY PETERS  
Massachusetts Institute of Technology  
Department of Mathematics  
Building 2, Room 236  
77 Massachusetts Avenue  
Cambridge, MA 02139  
U.S.A.  
[eep@math.mit.edu](mailto:eep@math.mit.edu)

SCOTT MORRISON  
Australian National University  
Mathematical Sciences Institute  
John Dedman Building #27  
Acton ACT 2601  
Australia  
[scott@tqft.net](mailto:scott@tqft.net)

NOAH SNYDER  
Indiana University, Bloomington  
Department of Mathematics  
Rawles Hall, 831 E. 3rd St.  
Bloomington, IN 47405  
U.S.A.  
[nsnyder@gmail.com](mailto:nsnyder@gmail.com)

*Received January 31, 2010*