Tetrahedral forms in monoidal categories and 3-manifold invariants

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Abstract. We introduce systems of objects and operators in linear monoidal categories called $\Psi$-systems. A $\Psi$-system satisfying several additional assumptions gives rise to a topological invariant of triples (a closed oriented 3-manifold $M$, a principal bundle over $M$, a link in $M$). This construction generalizes the quantum dilogarithmic invariant of links appearing in the original formulation of the volume conjecture. We conjecture that all quantum groups at odd roots of unity give rise to $\Psi$-systems and we verify this conjecture in the case of the Borel subalgebra of quantum $\mathfrak{sl}_2$. 

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Introduction

One of the fundamental achievements of quantum topology was a discovery of deep connections between monoidal categories and 3-dimensional manifolds. It was first observed by O. Viro and V. Turaev that the category of representations of the quantum group $U_q(\mathfrak{sl}_2)$ gives rise to a topological invariant of 3-manifolds. The invariant is obtained as a state sum on a triangulation of a 3-manifold; the key ingredients of the state sum are the 6$j$-symbols. This construction was generalized to other categories by several authors including J. Barrett, B. Westbury, A. Ocneanu, S. Gelfand, D. Kazhdan and others. Their results may be summarized by saying that every spherical fusion category gives rise to a state sum 3-manifold invariant. Similar methods apply to links in 3-manifolds and to 3-manifolds endowed with principal fiber bundles. A related but somewhat different line of development was initiated by Kashaev [7]. He defined a state sum invariant of links in 3-manifolds using “charged” versions of the 6$j$-symbols associated with certain representations of the Borel subalgebra of $U_q(\mathfrak{sl}_2)$. The work of Kashaev was further extended by S. Baseilhac and R. Benedetti, see [1], [2].
The aim of this paper is to analyze categorical foundations of the Kashaev–Baseilhac–Benedetti theory. The key new notions in our approach are the ones of $\Psi$-systems and $\Psi$-systems in linear monoidal categories. The $\Psi$-systems provide a general framework for 6j-symbols. Roughly speaking, a $\Psi$-system is a family of simple objects of the category $\{V_i\}_{i \in I}$ closed under duality and such that for “almost all” $i, j \in I$, the identity endomorphism of $V_i \otimes V_j$ splits as a sum of certain compositions $\{V_i \otimes V_j \rightarrow V_k \rightarrow V_l \otimes V_j\}_{k \in I}$ (see Section 1). Examples of $\Psi$-systems can be derived from quantum groups at roots of unity or, more generally, from Cayley–Hamilton Hopf algebras, see Section 11. Every fusion category has a $\Psi$-system formed by arbitrary representatives of the isomorphism classes of all simple objects. A $\Psi$-system in a linear monoidal category gives rise to a vector space $H$ (the space of multiplicities), a linear form $T$ on $H^{\otimes 4}$ (the tetrahedral evaluation form), and two automorphisms $A, B$ (obtained by taking adjoints of morphisms). The vector space $H$ has a natural symmetric bilinear form which allows us to consider the transposes $A^*, B^*$ of $A, B$. We use $T$ to define 6j-symbols and we use $A, B, A^*, B^*$ to formulate the tetrahedral symmetry of the 6j-symbols. We also develop a $T$-calculus for endomorphisms of $H$ which allows us to speak of equality/commutation of operators “up to composition with $T$”. These definitions and results occupy Sections 1–5.

To define 3-manifold invariants we need to fix square roots of the operators

$$L = A^* A, \quad R = B^* B, \quad C = (AB)^3 \in \text{End}(H).$$

A $\Psi$-system endowed with such square roots $L^\frac{1}{2}, R^\frac{1}{2}, C^\frac{1}{2}$ satisfying appropriate relations is said to be a $\Psi$-system. The $\Psi$-systems provide a general framework for so-called “charged” 6j-symbols depending on two additional integers of half-integer parameters. The advantage of the charged 6j-symbols lies in the simpler tetrahedral symmetry. This material occupies Sections 6–8.

We need two assumptions on a $\Psi$-system to produce a 3-manifold invariant. The first assumption says essentially that the operators $L^\frac{1}{2}$ and $R^\frac{1}{2}$ commute up to composition with $T$ and multiplication by a certain scalar $\bar{q}$. The second assumption introduces additional data: a group $G$ and a family of finite subsets $\{I_g\}_{g \in G}$ of $I$ satisfying certain conditions. We use this data to define a numerical topological invariant of any tuple (a closed connected oriented 3-manifold $M$, a non-empty link $L \subset M$, a conjugacy class of homomorphisms $\pi_1(M) \rightarrow G$, an element of $H^1(M; \mathbb{Z}/2\mathbb{Z})$), see Sections 9, 10. The invariant in question is defined as a state sum on a Hamiltonian triangulation of $(M, L)$. To encode the Hamiltonian path $L$ into the state sum, we use the charges on $H$-triangulations first introduced in [7]. The theory of charges subsequently has been developed in [2]. It is a natural extension of the theory of angle structures due to W. Neumann, see, for example, [13], [14]. The key ingredients of our state sum are the charged 6j-symbols. The resulting invariant is well-defined up to multiplication by integer powers of $\bar{q}$.

We conjecture that the $\Psi$-systems associated with quantum groups and their Borel subalgebras at odd roots of unity extend to $\Psi$-systems satisfying all our requirements. We verify this conjecture in the case of the Borel subalgebra of $U_q(sl_2)$, see Sections 11, 12. Geer and Patureau-Mirand [5] verify the conjecture for all quantum groups associated to simple Lie algebras and prove that the usual modular categories arising from quantum groups have $\Psi$-systems satisfying all our requirements. The conjecture is open for Borel subalgebras of quantum groups other than $U_q(sl_2)$. We expect that the associated invariants are closely related with the invariants constructed in [6], [11]. In the case of the example
of Section 12 with the trivial homomorphism \( \pi_1(M) \to G \), this construction coincides with the one of Kashaev [7]. The latter invariant enters the volume conjecture [8], and for links in \( S^3 \), it is a specialization of the colored Jones polynomial [12]. Precise relationships of our invariants with the Baseilhac–Benedetti 3-manifold invariants are yet unclear.

1. \( \Psi \)-systems in monoidal categories

1.1. Monoidal Ab-categories. A monoidal (tensor) category \( \mathcal{C} \) is a category equipped with a covariant bifunctor \( \boxtimes : \mathcal{C} \times \mathcal{C} \to \mathcal{C} \) called the tensor product, an associativity constraint, a unit object \( I \), and left and right unit constraints such that the Triangle and Pentagon Axioms hold. When the associativity constraint and the left and right unit constraints are all identities, the category \( \mathcal{C} \) is a strict monoidal (tensor) category. By MacLane’s coherence theorem, any monoidal category is equivalent to a strict monoidal category. To simplify the exposition, we formulate further definitions only for strict monoidal categories; the reader will easily extend them to arbitrary monoidal categories.

A monoidal category \( \mathcal{C} \) is said to be an Ab-category if for any objects \( V, W \) of \( \mathcal{C} \), the set of morphisms Hom\((V, W)\) is an additive abelian group and the composition and tensor product of morphisms are bilinear. Composition of morphisms induces a commutative ring structure on the abelian group \( k = \text{End}(I) \). The resulting ring is called the ground ring of \( \mathcal{C} \). For any objects \( V, W \) of \( \mathcal{C} \) the abelian group Hom\((V, W)\) becomes a left \( k \)-module via \( kf = k \otimes f \) for \( k \in k \) and \( f \in \text{Hom}(V, W) \). We assume that the tensor multiplication of morphisms in \( \mathcal{C} \) is \( k \)-bilinear.

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1.2. \( \Psi \)-systems. A \( \Psi \)-system\(^1\) in \( \mathcal{C} \) consists of

(i) a distinguished set of simple objects \( \{V_i\}_{i \in I} \) such that \( \text{Hom}(V_i, V_j) = 0 \) for all \( i \neq j \);

(ii) an involution \( I \to I, i \mapsto i^* \);

(iii) two families of morphisms \( \{b_i | \otimes V_i \to V_i \otimes V_{i^*}\}_{i \in I} \) and \( \{d_i | V_i \otimes V_{i^*} \to \otimes\}_{i \in I} \), such that for all \( i \in I \),

\[
(1) \quad (\text{Id}_{V_i} \boxtimes d_{i^*})(b_i \boxtimes \text{Id}_{V_i}) = \text{Id}_{V_i} \quad \text{and} \quad (d_i \boxtimes \text{Id}_{V_i})(\text{Id}_{V_i} \boxtimes b_{i^*}) = \text{Id}_{V_i}.
\]

To formulate the fourth (and the last) requirement on the \( \Psi \)-systems, set

\[
H^i_{ij} = \text{Hom}(V_i \boxtimes V_j) \quad \text{and} \quad H^k_{ij} = \text{Hom}(V_i \boxtimes V_j, V_k)
\]

for any \( i, j, k \in I \). We require that

\(^1\) This name is inspired by the logo of the Indiana University, where the definition has been finalized.
(iv) For any $i, j \in I$ such that $H_{ij}^{k} \neq 0$ for some $k \in I$, the identity morphism $\text{Id}_{V_{i} \boxtimes V_{j}}$ is in the image of the linear map

$$
\bigoplus_{k \in I} H_{ij}^{k} \otimes H_{ij}^{k} \rightarrow \text{End}(V_{i} \boxtimes V_{j}), \quad x \otimes y \mapsto x \circ y.
$$

We fix from now on a $\Psi$-system in $\mathcal{C}$ and keep the notation introduced above.

**Lemma 1.** For any $i, j, k \in I$, the linear spaces $H_{ij}^{k}$ and $H_{ij}^{k}$ are finite dimensional, and the bilinear pairing

$$(3) \quad H_{ij}^{k} \otimes H_{ij}^{k} \rightarrow \mathbb{k}, \quad x \otimes y \mapsto \langle x \circ y \rangle,$$

is non-degenerate. In particular, $\dim H_{ij}^{k} = \dim H_{ij}^{k}$.

**Lemma 2.** For any $i, j \in I$, there are only finitely many $k \in I$ such that $H_{ij}^{k} \neq 0$.

These lemmas will be proven in the next subsection after a little preparation.

### 1.3. The operators $A$ and $B$.

Consider the vector space $H = \hat{H} \oplus \check{H}$, where

$$\hat{H} = \bigoplus_{i,j,k \in I} H_{ij}^{k} \quad \text{and} \quad \check{H} = \bigoplus_{i,j,k \in I} H_{ij}^{k}.$$

Let

$$\pi_{ij}^{k} : H \rightarrow H_{ij}^{k}, \quad \pi_{ij}^{k} : H \rightarrow H_{ij}^{k}, \quad \hat{\pi} : H \rightarrow \hat{H}, \quad \check{\pi} : H \rightarrow \check{H}$$

be the obvious projections. We define linear maps $A, B : H \rightarrow H$ by

$$
A x = \sum_{i,j,k \in I} \left( (\text{Id}_{V_{i}} \boxtimes \pi_{ij}^{k} x) (b_{i} \boxtimes \text{Id}_{V_{i}}) + (d_{i} \boxtimes \text{Id}_{V_{i}}) (\pi_{ij}^{k} x \boxtimes \text{Id}_{V_{i}}) \right),
$$

$$
B x = \sum_{i,j,k \in I} \left( (\pi_{ij}^{k} x \boxtimes \text{Id}_{V_{i}}) (\text{Id}_{V_{i}} \boxtimes b_{j}) + (\text{Id}_{V_{i}} \boxtimes d_{j}) (\pi_{ij}^{k} x \boxtimes \text{Id}_{V_{j}}) \right).
$$

For each $x \in H$, there are only finitely many non-zero terms in these sums, since $x$ has only finitely many non-zero components $\pi_{ij}^{k} x$ and $\pi_{ij}^{k} x$. We can represent the definitions of $A$ and $B$ in the following graphical form:
where we use the graphical notation

\[ \pi_{ik}^j x = \begin{array}{c} \text{x}_i \\ k \end{array}, \quad \pi_{ij}^k x = \begin{array}{c} \text{x}_j \\ i \end{array}, \quad b_i = \begin{array}{c} i^* \\ i \end{array}, \quad d_i = \begin{array}{c} i^* \\ i \end{array}. \]

**Lemma 3.** The operators \( A \) and \( B \) are involutive and satisfy the "exchange" relations:

\[ (4) \quad \pi_{ik}^j A = A \pi_{ik}^j, \quad \pi_{ij}^k B = B \pi_{ij}^k, \quad \pi_{ij}^k A = A \pi_{ij}^k, \quad \pi_{ij}^k B = B \pi_{ij}^k. \]

**Proof.** The exchange relations easily follow from the inclusions

\[ (5) \quad A(H_{ij}^k) \subseteq H_{ij}^{i^*k}, \quad A(H_{ij}^{i^*k}) \subseteq H_{ij}^k, \quad B(H_{ij}^k) \subseteq H_{ij}^{kj^*}, \quad B(H_{ij}^{kj^*}) \subseteq H_{ij}^k. \]

For any \( x \in H \),

\[ \pi_{ik}^j A^2 x = \begin{array}{c} A^2 x \\ k \end{array} = i, \quad \pi_{ij}^k A x = \begin{array}{c} A x \\ i \end{array} = i, \quad \pi_{ij}^k x = \begin{array}{c} x \\ k \end{array} = k, \quad \pi_{ij}^k x = \begin{array}{c} x \\ k \end{array} = k. \]

and

\[ \pi_{ij}^k A^2 x = \begin{array}{c} A^2 x \\ i \end{array} = i, \quad \pi_{ij}^k x = \begin{array}{c} x \\ j \end{array} = j, \quad \pi_{ij}^k x = \begin{array}{c} x \\ k \end{array} = k, \quad \pi_{ij}^k x = \begin{array}{c} x \\ k \end{array} = k. \]

Thus, \( A^2 = 1 \). A similar calculation shows that \( B^2 = 1 \). \( \square \)

**Proof of Lemma 1.** Assume first that \( H_{ij}^{ij} \neq 0 \). By the basic condition,

\[ (6) \quad \text{Id}_{V_j} v_j = \sum_{l \in X} \sum_{x \in R_l} e_{l x} e^{l x}, \]

where \( X \) is a finite subset of \( I \) and for all \( l \in X \), we have a finite set of indices \( R_l \), linearly independent vectors \( \{ e_{l x} \}_{x \in R_l} \) in \( H_{ij}^{ij} \) and certain vectors \( e^{l x} \) in \( H_{ij}^{ij} \). For any \( x \in H_{ij}^{ij} \),

\[ (7) \quad x = \text{Id}_{V_j} v_j x = \sum_{l \in X} \sum_{x \in R_l} e_{l x} e^{l x} x = \sum_{l \in X} \sum_{x \in R_l} e_{l x} \langle e^{l x} x \rangle \delta_{k, l} = \sum_{x \in R_k} e_{k x} \langle e^{k x} x \rangle, \]

where \( \delta_{k, l} \) is the Kronecker delta. Thus, the vectors \( e_{k x} \) with \( x \in R_k \) generate \( H_{ij}^{ij} \). Since these vectors are linearly independent, they form a (finite) basis of \( H_{ij}^{ij} \). Similarly, for any \( y \in H_{ij}^{ij} \),

\[ (8) \quad y = y \text{Id}_{V_j} v_j = \sum_{x \in R_k} \langle y e_{k x} \rangle e^{k x}. \]
Therefore the vectors \( e^{k}\alpha \) with \( \alpha \in R_k \) generate \( H^k \). For all \( \alpha, \beta \in R_k \), formula (7) with \( x = e^{k}\alpha \) implies that \( \langle e^{k}\alpha e^{k}\beta \rangle = \delta_{\alpha, \beta} \). Hence \( \{e^{k}\alpha\}_{\alpha \in R_k} \) is a basis of \( H^k \) dual to the basis \( \{e^{k}\alpha\}_{\alpha \in R_k} \) of \( H^k \) with respect to the pairing (3). Therefore, this pairing is non-degenerate.

It remains to show that \( H^i \neq 0 \) implies \( H^j \neq 0 \). Indeed, if \( H^i \neq 0 \), then we have \( H^j A = (H^i)^* \neq 0 \). By the preceding argument, \( A(H^j) = H^i \neq 0 \). Hence \( H^j \neq 0 \).

Proof of Lemma 2. If \( H^i \neq 0 \), then by formula (7), \( k \) belongs to the finite set \( X \) appearing in (6).

1.4. Transposition of operators. We provide the vector space \( H = \mathcal{H} \oplus \mathcal{H} \) with the symmetric bilinear pairing \( \langle , \rangle \) by

\[
\langle x, y \rangle = \sum_{i,j,k \in I} \left( \langle \pi^k_{ij} x \pi^k_{ij} y \rangle + \langle \pi^k_{ij} y \pi^k_{ij} x \rangle \right) \in k
\]

for any \( x, y \in H \). Note that \( \langle \mathcal{H}, \mathcal{H} \rangle = \langle \mathcal{H}, \mathcal{H} \rangle = 0 \).

A transpose of \( f \in \text{End}(H) \) is a map \( f^* \in \text{End}(H) \) such that \( \langle fx, y \rangle = \langle x, f^*y \rangle \) for all \( x, y \in H \). Lemma 1 implies that if a transpose \( f^* \) of \( f \) exists, then it is unique and \( (f^*)^* = f \).

Lemma 4. The canonical projections have transposes computed as follows:

\[ \pi^* = \pi \quad \text{and} \quad (\pi^k_{ij})^* = \pi^k_{ij}. \]

Proof. \( \langle x, \pi y \rangle = \langle \pi x, \pi y \rangle = \langle \pi x, y \rangle, \)

\[ \langle x, \pi^k_{ij} y \rangle = \langle \pi^k_{ij} x, \pi^k_{ij} y \rangle = \langle \pi^k_{ij} x, y \rangle. \]

Lemma 5. The transposes of the operators \( A \) and \( B \) exist and

\[ A^* B^* A^* = BAB. \]

Proof. The existence of \( A^* \) and \( B^* \) follows from Lemma 1 and the inclusions (5). Note that

\[ A^*(H^i_{ij}) \subset H^i_{ij}, \quad A^*(H^k_{ij}) \subset H^k_{ij}, \quad B^*(H^i_{ij}) \subset H^i_{ij}, \quad B^*(H^k_{ij}) \subset H^k_{ij}. \]

To prove (10), observe that for any \( x \in \mathcal{H} \) and \( y \in \mathcal{H} \),

\[ \langle x, y \rangle = \langle BABy, ABAx \rangle. \]
Here is a graphical proof of this formula for \( x \in H_{jk}^i \) and \( y \in H_{ik}^j \) with \( i, j, k \in I \).

Now we can prove (10). Applying (12) to \( x = x_1 \) and \( y = BABx_2 \) with \( x_1, x_2 \in \hat{H} \), we obtain

\[
\langle x_1, BABx_2 \rangle = \langle (BAB)^2 x_2, ABAX_1 \rangle = \langle x_2, ABAX_1 \rangle = \langle ABAX_1, x_2 \rangle.
\]

Applying (12) to \( x = ABAy_1 \) and \( y = y_2 \) with \( y_1, y_2 \in \hat{H} \), we obtain

\[
\langle y_1, BABy_2 \rangle = \langle BABy_2, y_1 \rangle = \langle ABAy_1, y_2 \rangle.
\]

Hence \( BAB = (ABA)^* = A^*B^*A^* \). \qed

2. The tetrahedral forms

2.1. Operations on tensor powers. We recall the usual notation for operations on the tensor powers of a vector space. Given a \( k \)-vector space \( V \) and an integer \( n \geq 2 \), the symbol \( V^\otimes n \) denotes the tensor product of \( n \) copies of \( V \) over \( k \). Let \( \Sigma_n \) be the symmetric group on \( n \geq 2 \) letters. Recall the standard action \( \Sigma_n \to \text{Aut}(V^\otimes n) \), \( \sigma \mapsto P_\sigma \). By definition, for distinct \( i, j \in \{1, \ldots, n\} \), the flip \( P_{ij} \) permutes the \( i \)-th and the \( j \)-th tensor factors keeping the other tensor factors. For \( f \in \text{End}(V) \) and \( i = 1, \ldots, n \), set

\[
f_i = \text{id}^\otimes(i-1) \otimes f \otimes \text{id}^\otimes(n-i) \in \text{End}(V^\otimes n).
\]

Note the exchange relations \( P_{\sigma}f_i = f_{\sigma(i)}P_{\sigma} \) for any \( \sigma \in \Sigma_n \) and the commutativity relation \( f_ig_j = g_jf_i \) for any \( f, g \in \text{End}(V) \) and \( i \neq j \).

Given \( F \in \text{End}(V^\otimes_k V) \), we define for any \( i, j \in \{1, \ldots, n\} \) with \( i \neq j \) an endomorphism \( F_{ij} \) of \( V^\otimes n \) as follows. If \( i < j \), then \( F_{ij} \) acts as \( F \) on the \( i \)-th and the \( j \)-th tensor factors of \( V^\otimes n \) keeping the other tensor factors. If \( i > j \), then \( F_{ij} = P_{ij}F_{ji}P_{ij} \).

2.2. The forms \( T \) and \( \bar{T} \). Recall the vector space \( H = \hat{H} \oplus \bar{H} \) from Section 1.3. We define two linear forms \( T, \bar{T} : H^\otimes 4 \to k \) by the following diagrammatic formulae: for any \( u, v, x, y \in H \),
\[
T(u \otimes v \otimes x \otimes y) = \sum_{i, \ldots, n \in I} \langle v^i, j \rangle, \quad \bar{T}(u \otimes v \otimes x \otimes y) = \sum_{i, \ldots, n \in I} \langle j, x \rangle.
\]

The indices \(i, j, k, l, m, n\) in both formulas run over all elements of \(I\). For any given \(u, v, x, y \in H\), only a finite number of terms in these formulas may be non-zero.

**Lemma 6** (Fundamental lemma). We have

\[
TP_{(4321)} = TA_1^* A_3, \\
TP_{(23)} = TA_2 B_3, \\
TP_{(1234)} = \bar{T}B_2 B_4^*. 
\]

**Proof.** Since \(A^*\) is an involution, (13a) is equivalent to the identity

\[
T(u \otimes v \otimes x \otimes A^* y) = T(y \otimes u \otimes Av \otimes x), \quad u, v, x, y \in H,
\]

which is a direct consequence of the identity

\[
\langle \zeta, A^* y \rangle = \langle A \zeta, y \rangle = \langle y, A \zeta \rangle = \langle \zeta, y \rangle \in H_{in}^m.
\]

The other two identities are verified in a similar manner. □

The formulas

\[
P_{(12)} = P_{(4321)} P_{(23)} P_{(1234)}, \quad P_{(34)} = P_{(1234)} P_{(23)} P_{(4321)}
\]
allow us to compute the action of the permutations $P_{(12)}$ and $P_{(34)}$ on $T$:

\begin{align}
TP_{(12)} &= \overline{T}P_{(23)}P_{(1234)}A_4A_1 = TP_{(1234)}(BA)_1A_2A_4^* = \overline{T}(BA)_1(BA)_2(AB)_4^*, \\
TP_{(34)} &= \overline{T}P_{(23)}P_{(4321)}B_4B_1^* = TP_{(4321)}B_3(AB)_4B_1^* = \overline{T}(BA)_1(AB)_3(AB)_4^*.
\end{align}

The action of the permutations on $\overline{T}$ can be easily determined from the involutivity of $A, B, P_{(12)}, P_{(23)}, P_{(34)}$. The resulting formulae can be obtained from those for $T$ via the substitutions $T \leftrightarrow \overline{T}$ and $A \leftrightarrow B$.

The formulas computing the action of the permutations on $T$ and $\overline{T}$ may be re-written in a simpler form in terms of the equivalent tensors $S = TP_{(2134)} : H^{\otimes 4} \rightarrow k$ and $\overline{S} = \overline{T}P_{(1234)} : H^{\otimes 4} \rightarrow k$. For these tensors, equations (13a)–(13c) take the following form:

\begin{align}
SP_{(12)} &= \overline{S}A_4^*A_4, \\
SP_{(23)} &= \overline{S}A_1B_4, \\
SP_{(34)} &= \overline{S}B_1B_2^*.
\end{align}

Though these symmetry relations for $S, \overline{S}$ are simpler than the symmetry relations for $T, \overline{T}$, we shall mainly work with $T$ and $\overline{T}$. A geometric interpretation of these symmetry relations will be outlined in the appendix to the paper.

2.3. The adjoint operators. We define the operators $\tilde{H}^{\otimes 2} \rightarrow \tilde{H}^{\otimes 2}$ adjoint to $T$ and $\overline{T}$. For all $i, j, k \in I$ pick dual bases $(e^{ij}_k)_x$ and $(e^{kj}_i)_x$ in the multiplicity spaces $H^{ij}_k$ and $H^{kj}_i$, respectively. For the vectors of these bases, we shall use the graphical notation

$e^{ij}_{kx} = \begin{array}{c}
\alpha \\

\gamma \\
\delta \\
\epsilon
\end{array}$
and
$e^{kj}_{ix} = \begin{array}{c}
\alpha \\

\gamma \\
\delta \\
\epsilon
\end{array}$

Let $\tau, \overline{\tau} \in \text{End}(\tilde{H}^{\otimes 2})$ be the operators defined by the graphical formulae

$\tau(x \otimes y) = \sum_{i, \ldots, n \in I} \sum_{a \in a} j \begin{array}{c}
\alpha \\

\gamma \\
\delta \\
\epsilon
\end{array}$
and
$\overline{\tau}(x \otimes y) = \sum_{i, \ldots, n \in I} \sum_{a \in a} j \begin{array}{c}
\alpha \\

\gamma \\
\delta \\
\epsilon
\end{array}$

where $i, j, k, l, m, n$ run over all elements of $I$. By Lemma 2, for any $x, y \in \tilde{H}$, there are only finitely many terms in the expansions for $\tau(x \otimes y)$ and $\overline{\tau}(x \otimes y)$. 

\[ \tau(x \otimes y) = \sum_{i, \ldots, n \in I} \sum_{a \in a} j \begin{array}{c}
\alpha \\

\gamma \\
\delta \\
\epsilon
\end{array} \]
The operators $\tau$ and $\bar{\tau}$ do not depend on the choice of the bases in the multiplicity spaces. Indeed, these operators are adjoint to $T, \bar{T}$ in the sense that

$$\langle \langle u \otimes v, \tau(x \otimes y) \rangle \rangle = T(u \otimes v \otimes x \otimes y)$$

and

$$\langle \langle u \otimes v, \bar{\tau}(x \otimes y) \rangle \rangle = \bar{T}(u \otimes v \otimes x \otimes y)$$

for all $u, v \in \hat{H}, x, y \in \hat{H}$. Here the bilinear pairing

$$\langle \langle \cdot, \cdot \rangle \rangle : (\hat{H} \otimes \hat{H}) \times (\hat{H} \otimes \hat{H}) \to k$$

is defined by $\langle \langle u \otimes v, x \otimes y \rangle \rangle = \langle u, x \rangle \langle v, y \rangle$ where $\langle \cdot, \cdot \rangle$ is the symmetric bilinear form on $H = H \oplus \hat{H}$ introduced in Section 1.4.

2.4. The pentagon and inversion identities. To formulate the properties of $\tau$ and $\bar{\tau}$, we need further notation. For any $i, j \in I$ set

$$g_{i,j} = \begin{cases} 1 & \text{if there is } k \in I \text{ such that } H_{k}^{ij} \neq 0, \\ 0 & \text{otherwise.} \end{cases}$$

We define two endomorphisms $\pi^*$ and $\pi^*$ of $\hat{H}^{\otimes 2}$ by

$$\pi^* = \sum_{i,j,k,l,m \in I} g_{i,j} n_{m}^{ij} \otimes n_{l}^{jk} \quad \text{and} \quad \pi^* = \sum_{i,j,k,l,m \in I} g_{j,i} n_{k}^{ij} \otimes n_{m}^{kl}.$$

Clearly, $\pi^*$ and $\pi^*$ are commuting projectors onto certain subspaces of $\hat{H}^{\otimes 2}$.

Lemma 7. The operators $\tau$ and $\bar{\tau}$ satisfy

(i) the pentagon identity in $\text{End}(\hat{H}^{\otimes 3})$:

$$\tau_{23}\tau_{13}\tau_{12} = \tau_{12}\tau_{23}(\pi^*)_{21},$$

(ii) the inversion relations in $\text{End}(\hat{H}^{\otimes 2})$:

$$\tau_{21} \tau = \pi^* \quad \text{and} \quad \tau \tau_{21} = \pi^*,$$

where $\tau_{21} = P_{(12)} \tau P_{(12)}$ and $\tau_{21} = P_{(12)} \bar{\tau} P_{(12)}$.

Proof. (i) For $x, y, z \in \hat{H}$,
$$\tau_{23} \tau_{13} \tau_{12} (x \otimes y \otimes z)$$

$$= \sum_{i, \ldots, n} \tau_{23} \tau_{13} (x \otimes y \otimes z) = \sum_{i, \ldots, n} \tau_{23} (x \otimes y \otimes z)$$

$$= \sum_{i, \ldots, n} \tau_{12} \tau_{13} (x \otimes y \otimes z) = \sum_{i, \ldots, n} \tau_{12} (x \otimes y \otimes z)$$

$$= \sum_{i, \ldots, n} g_{i,j} \tau_{12} (x \otimes y \otimes z) = \sum_{i, \ldots, n} g_{i,j} \tau_{23} (x \otimes y \otimes z).$$
All these equalities follow directly from the definitions except the fifth equality. The sum on its left-hand side is preserved if we insert an additional factor $g_{o,k}$. Indeed, if the triangular block with the vertices labeled $\mu$, $\lambda$, $i$ contributes non-zero, then necessarily $g_{o,k} = 1$. This allows us to sum up over all $p$, $\kappa$ and then over all $k$, $i$ to obtain the fifth equality.

(ii) For $x, y \in \mathcal{H}$,

\[
\tau_{21}(x \otimes y) = \sum_{i,...,\mu,\lambda} \tau_{21}(x \otimes \lambda) \otimes \sum_{i,...,o,\mu} (i,j) = \sum_{i,...,o,\lambda,\mu} (i,j) \otimes \mu \otimes (i,j)
\]

\[
= \sum_{i,...,m,\mu} g_{j,l} \times \mu \otimes (i,j) = \sum_{i,...,m} g_{j,l} \times (i,j) \otimes \mu \otimes (i,j) = \pi^*(x \otimes y).
\]

The second inversion relation is proved similarly. \[\square\]

3. The 6j-symbols

3.1. Notation. For any $i, j, k \in I$, the non-degenerate pairing $H_{ij}^k \otimes H_{ij}^k \rightarrow k$ defined in Lemma 1 will be denoted $*_{ij}^k$. Composing this pairing with the flip $H_{ij}^k \otimes H_{ij}^k \rightarrow H_{ij}^k \otimes H_{ij}^k$, we obtain a non-degenerate pairing $H_{ij}^k \otimes H_{ij}^k \rightarrow k$ denoted $*_{ij}^k$. We shall use these pairings to identify the dual of $H_{ij}^k$ with $H_{ij}^k$ and the dual of $H_{ij}^k$ with $H_{ij}^k$. The pairings $*_{ij}^k$ and $*_{ij}^k$ induce the tensor contractions

\[
U \otimes H_{ij}^k \otimes V \otimes H_{ij}^k \otimes W \rightarrow U \otimes V \otimes W,
\]

\[
U \otimes H_{ij}^k \otimes V \otimes H_{ij}^k \otimes W \rightarrow U \otimes V \otimes W,
\]

where $U$, $V$, $W$ are arbitrary $k$-vector spaces. These tensor contractions will be denoted by the same symbols $*_{ij}^k$ and $*_{ij}^k$ respectively.
3.2. Definition of 6j-symbols. For any \( i, j, k, l, m, n \in I \), the restriction of
\[
T : \mathcal{H} \to \mathbb{C}
\]
to the tensor product
\[
H^m_{kl} \otimes H^k_{ij} \otimes H^j_{nl} \otimes H^m_{in} \subset \mathcal{H} \otimes \mathcal{H} \otimes \mathcal{H} \otimes \mathcal{H} \subset \mathcal{H}^\otimes 4
\]
gives a vector in the \( k \)-vector space
\[
(17) \quad \text{Hom}(H^m_{kl} \otimes H^k_{ij} \otimes H^j_{nl} \otimes H^m_{in}, \mathbb{C}) = H^m_{kl} \otimes H^k_{ij} \otimes H^j_{nl} \otimes H^m_{in}.
\]
This vector is denoted
\[
(18) \quad \{ i \quad j \quad k \}
\]
and called the positive 6j-symbol determined by the tuple \( i, j, k, l, m, n \). In graphical notation, the 6j-symbol (18) is the summand in the definition of \( T \) in Section 2.2 corresponding to the tuple \( i, j, k, l, m, n \in I \). Thus, for any \( u, v, x, y \in H \),
\[
T(u \otimes v \otimes x \otimes y) = \sum_{i,j,k,l,m,n \in I} *^m_{kl} *^k_{ij} *^k_{nl} *^m_{in}(\pi^m_{kl}(u) \otimes \pi^k_{ij}(v) \otimes \pi^j_{nl}(x) \otimes \pi^m_{in}(y) \otimes \{ i \quad j \quad k \})
\]
The adjoint operator \( \tau \in \text{End}(\mathcal{H}^\otimes 2) \) expands as follows: for any \( x, y \in \mathcal{H} \),
\[
\tau(x \otimes y) = \sum_{i,j,k,l,m,n \in I} *^k_{ij} *^m_{in} \left( \pi^k_{ij}(x) \otimes \pi^m_{in}(y) \otimes \{ i \quad j \quad k \} \right)
\]
Similarly restricting \( T \) to the tensor product \( H^m_{in} \otimes H^j_{nl} \otimes H^k_{ij} \otimes H^m_{kl} \), we obtain the negative 6j-symbol
\[
(19) \quad \{ i \quad j \quad k \}^- \in H^m_{in} \otimes H^j_{nl} \otimes H^k_{ij} \otimes H^m_{kl}.
\]
For any \( u, v, x, y \in H \),
\[
\bar{T}(u \otimes v \otimes x \otimes y) = \sum_{i,j,k,l,m,n \in I} *^m_{in} *^n_{ij} *^k_{kl} \left( \pi^m_{in}(u) \otimes \pi^n_{ij}(v) \otimes \pi^k_{kl}(x) \otimes \pi^m_{kl}(y) \otimes \{ i \quad j \quad k \}^- \right)
\]
The adjoint operator \( \bar{\tau} \in \text{End}(\mathcal{H}^\otimes 2) \) expands as follows: for any \( x, y \in \mathcal{H} \),
\[
\bar{\tau}(x \otimes y) = \sum_{i,j,k,l,m,n \in I} *^k_{ij} *^m_{kl} \left( \pi^k_{ij}(x) \otimes \pi^m_{kl}(y) \otimes \{ i \quad j \quad k \}^- \right)
\]
3.3. Identities. The properties of the forms $T$ and $\overline{T}$ established in Section 2 can be rewritten in terms of the $6j$-symbols. Formula (13a) yields

$$\begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} = P_{(4321)} A_1 A_3^{\ast} \left( \begin{pmatrix} i^* & k & j \\ l & n & m \end{pmatrix} \right)^{\ast},$$

where $A_1$ is induced by the restriction of $A$ to $H_i^{[i]}$ and $A_3^{\ast}$ is induced by the restriction of $A^*$ to $H_i^{[i]}$. Formula (13b) yields

$$\begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} = P_{(23)} A_2 B_3^{\ast} \left( \begin{pmatrix} k & j^* & i \\ n & m & l \end{pmatrix} \right)^{\ast},$$

where $A_2^{\ast}$ is induced by the restriction of $A^*$ to $H_i^{[i]}$ and $B_3^{\ast}$ is induced by the restriction of $B^*$ to $H_i^{[i]}$. Formula (13c) yields

$$\begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} = P_{(1234)} B_2 B_4^{\ast} \left( \begin{pmatrix} i & n & m \\ l^* & k & j \end{pmatrix} \right)^{\ast},$$

where $B_2^{\ast}$ is induced by the restriction of $B^*$ to $H_i^{[i]}$ and $B_4^{\ast}$ is induced by the restriction of $B_4$ to $H_i^{[i]}$.

Note for the record that formula (14) yields

$$\begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} = P_{(12)} (BA)^{\ast} (BA)^{\ast} (BA)_4 \left( \begin{pmatrix} j & l & n \\ m^* & i^* & k^* \end{pmatrix} \right)^{\ast},$$

where the operator $(BA)^{\ast}$ is induced by the restriction of $(BA)^{\ast} = A^* B^*$ to $H_i^{[i]}$; the operator $(BA)_2^{\ast}$ is induced by the restriction of $(BA)^{\ast}$ to $H_i^{[i]}$, and $(BA)_4$ is induced by the restriction of $AB$ to $H_i^{[i]}$. Formula (15) yields

$$\begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} = P_{(34)} (BA)^{\ast} (BA)^{\ast} (BA)_4 \left( \begin{pmatrix} m^* & i & n^* \\ j & l^* & k \end{pmatrix} \right)^{\ast},$$

where the operator $(BA)_4^{\ast}$ is induced by the restriction of $BA$ to $H_i^{[i]}$; the operator $(BA)_3^{\ast}$ is induced by the restriction of $(AB)^{\ast}$ to $H_i^{[i]}$, and $(BA)_4^{\ast}$ is induced by the restriction of $(AB)^{\ast}$ to $H_i^{[i]}$.

The pentagon identity yields that for any $j_0, j_1, \ldots, j_8 \in I$,

$$\sum_{j_0 \in I} *_{j_0} \left( \begin{pmatrix} j_1 & j_2 & j_3 \\ j_4 & j_5 & j_6 \end{pmatrix} \otimes \begin{pmatrix} j_1 & j_6 \\ j_3 & j_4 \end{pmatrix} \otimes \begin{pmatrix} j_2 & j_3 & j_5 \\ j_6 & j_7 & j_8 \end{pmatrix} \right) = g_{j_2, j_3} P_{(135642)} *_{j_0} \left( \begin{pmatrix} j_1 & j_2 & j_5 \\ j_3 & j_4 & j_6 \end{pmatrix} \otimes \begin{pmatrix} j_5 & j_3 & j_6 \\ j_8 & j_0 & j_7 \end{pmatrix} \otimes \begin{pmatrix} j_4 & j_7 & j_8 \end{pmatrix} \right).$$

Here both sides lie in the k-vector space

$$H_{j_0}^{[i]} \otimes H_{j_5}^{[i]} \otimes H_{j_0}^{[i]} \otimes H_{j_1}^{[i]} \otimes H_{j_6}^{[i]} \otimes H_{j_2}^{[i]} \otimes H_{j_7}^{[i]} \otimes H_{j_8}^{[i]}.$$
To rewrite the inversion relations in terms of the 6j-symbols, observe that the transpose of the pairing \( (*_{ij})^k_{ij} : H^k_{ij} \otimes H^j_{ik} \to k \) is a homomorphism \( k \to H^k_{ij} \otimes H^j_{ik} \). The image of the unit \( 1 \in k \) under this homomorphism is denoted by \( \delta^j_k \). In the notation of Section 2.3, we have \( \delta^j_k = \sum_x e^{x}_{ij} \otimes e^{x}_{jk} \). The relation \( \tau_{21} \tau = \pi^* \) may be rewritten as the identity

\[
\sum_{n \in I} 6j{ij}_{im} \begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} \otimes \begin{pmatrix} i & j & k' \\ l & m & n \end{pmatrix} = \delta^j_k, g_{ij}, P_{(432)}(\delta^j_k \otimes \delta^j_k)
\]

for all \( i, j, k, k', l, m \in I \). The relation \( \tau \tau_{21} = \pi^* \) may be rewritten as the identity

\[
\sum_{k \in I} 6j^{kl}_{ij} \begin{pmatrix} i & j & k \\ l & m & n' \end{pmatrix} \otimes \begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} = \delta^j_k, g_{ij}, P_{(432)}(\delta^j_k \otimes \delta^j_k)
\]

for all \( i, j, l, m, n, n' \in I \).

**Remark 8.** As an exercise, the reader may prove that \( \tau_{12} \tau_{23} (\pi^*)_{21} = (\pi^*)_{32} \tau_{12} \tau_{23} \). This formula does not give non-trivial identities between the 6j-symbols.

### 4. The T-calculus

#### 4.1. T-equalities

We say that two endomorphisms \( a, b \) of \( H \) are **T-equal** and write \( a \equiv_T b \) if \( Ta_i = Tb_i \) for all \( i = 1, 2, 3, 4 \). It is clear that the T-equality is an equivalence relation. If \( a \equiv_T b \), then \( ac \equiv_T bc \) for all \( c \in \text{End}(H) \).

Though the definition of the T-equality involves four conditions, two of them may be eliminated as is clear from the following lemma.

**Lemma 9.** For any \( a, b \in \text{End}(H) \), we have

\[
Ta_1 = Tb_1 \iff Ta_2 = Tb_2 \quad \text{and} \quad Ta_3 = Tb_3 \iff Ta_4 = Tb_4.
\]

**Proof.** Formulas (13) and the identity \( P_{(431)} = P_{(432)} P_{(23)} \) imply that

\[
TP_{(431)} = TA_1^*(BA)_2 A_3.
\]

Multiplying on the right by \( A_1^*(AB)_2 A_3 P_{(134)} = P_{(134)} A_1(AB)_2 A_4^* \), we obtain

\[
TP_{(134)} = TA_1(AB)_2 A_4^*.
\]

Similar arguments prove that

\[
TP_{(124)} = TB_2(AB)_3 B_4^*,
\]

\[
TP_{(421)} = TB_1^*(BA)_3 B_4.
\]
For each $i = 1, 2, 3, 4$ one of the equations (21)–(24) has the form

\[(25) \quad TP_\sigma = TX_kY_lZ_m,\]

where

\[\sigma \in \mathbb{S}_4, \quad X, Y, Z \in \{A, A^*, B, B^*, AB, BA\}, \quad \{k, l, m\} = \{1, 2, 3, 4\}\{i\},\]

and the set \{i, \sigma(i)\} is either \{1, 2\} or \{3, 4\}. Set $j = \sigma(i)$ and observe that

\[Ta_i = TP_\sigma(X_kY_lZ_m)^{-1}a_i = TP_\sigma a_i(X_kY_lZ_m)^{-1} = Ta_jP_\sigma(X_kY_lZ_m)^{-1}.\]

Also, $Tb_i = Tb_jP_\sigma(X_kY_lZ_m)^{-1}$. Hence, $Ta_i = Tb_i$ if and only if $Ta_j = Tb_j$. \qed

**Corollary 10.** The $T$-equality $a \mapsto b$ holds if and only if $Ta_i = Tb_i$ for some $i \in \{1, 2\}$ and for some $i \in \{3, 4\}$.

### 4.2. $T$-scalars.

An endomorphism $t$ of $H$ is a $T$-scalar if $t$ has a transpose $t^*$ and

\[(26) \quad Tt_1 = Tt_2 = Tt_3^* = Tt_4^* \quad \text{and} \quad Tt_1^* = Tt_2^* = Tt_3 = Tt_4.\]

For example, all scalar automorphisms of $H$ are $T$-scalars. A more interesting example of a $T$-scalar will be given in Lemma 14 below. If $t$ is a $T$-scalar, then the adjoint operator \(T: H^2 \to H^2\) introduced in Section 2.3 satisfies

\[(27) \quad t_1T = t_2T = Tt_1^* = Tt_2^* \quad \text{and} \quad t_1^*T = t_2^*T = Tt_1 = Tt_2.\]

If $t \in \text{End}(H)$ is a $T$-scalar, then so is $t^*$. If a $T$-scalar $t$ is invertible in $\text{End}(H)$, then \(t^{-1}\) is a $T$-scalar. Indeed, the equality $Tt_1 = Tt_2$ implies that $Tt_1^{-1} = Tt_2^{-1}$ and similarly for all the other required equalities.

The product of any two $T$-scalars $t, u \in \text{End}(H)$ is a $T$-scalar. Indeed, for any $r \in \{1, 2\}$ and $s \in \{3, 4\}$,

\[T(tu)_r = Tt_ru_r = Tt_r^*u_r = Tu_rT_r^* = Tu_r^*T_r^* = T(tu)^*_s\]

and similarly $T(tu)^*_r = T(tu)^*_s$. Thus, the $T$-scalars form a subalgebra of the $k$-algebra $\text{End}(H)$ invariant under the involution $a \mapsto a^*$.

If $t$ is a $T$-scalar, then $a \mapsto b \Rightarrow ta \mapsto tb$ for any $a, b \in \text{End}(H)$. Indeed,

\[T(ta)_1 = Tt_1a_1 = Tt_2a_1 = Ta_1t_2 = Tb_1t_2 = Tt_2b_1 = Tt_1b_1 = T(tb)_1\]

and similarly, $T(ta)_3 = T(tb)_3$.

We call an invertible endomorphism $t$ of $H$ unitary if $t^* = t^{-1}$. More generally, an invertible endomorphism $t$ of $H$ is $T$-unitary if $t^* \mapsto t^{-1}$. For a $T$-unitary $t \in \text{End}(H)$, equations (26) simplify to $Tt_rT_s = T$ for all $r \in \{1, 2\}$ and $s \in \{3, 4\}$. 
4.3. \textbf{T-commutation relations.} We now show that \( T \)-scalars \( T \)-commute with every product of an even number of operators \( A, B, A^*, B^* \). To give a more precise statement, we define a group \( F \) by the presentation

\begin{equation}
F = \langle a, b, a^*, b^* \mid a^2 = b^2 = (a^*)^2 = (b^*)^2 = 1 \rangle.
\end{equation}

Consider the group homomorphism \( F \to \mathbb{Z}/2\mathbb{Z} \) carrying the generators \( a, b, a^*, b^* \) to 1 (mod 2). Elements of \( F \) belonging to the kernel of this homomorphism are said to be \textit{even}; all other elements of \( F \) are said to be \textit{odd}. In other words, an element of \( F \) is even if it expands as a product of an even number of generators and odd otherwise. The \( T \)-group acts on some manifold invariants \( A \). To prove our claim, consider again equality (25). Pick any \( t \in \text{End}(H) \), then equality (25) proves that

\begin{equation}
\Delta^i = \{ g \in F \mid T(gt)_i = T(t^g i) \} \subset F.
\end{equation}

By the previous lemma, \( \Delta^1 = \Delta^2 = \Delta^4 = \Delta^3 \). We claim that for any generator \( c \in \{ a, b, a^*, b^* \} \), we have \( c\Delta^1 \subset \Delta^3 \) and \( c\Delta^3 \subset \Delta^1 \). This will imply that the set \( \Delta^1 \cap \Delta^3 \subset F \) is closed under left multiplication by the generators of \( F \). Since this set contains the neutral element of \( F \), we have \( \Delta^1 \cap \Delta^3 = F \). In other words, \( \Delta' = F \) for all \( i = 1, 2, 3, 4 \). This means that \( gt = t^g i \) for all \( g \in F \).

To prove our claim, consider again equality (25). Pick any \( g \in \Delta^{\sigma(k)} \). Then

\begin{align*}
T(Xgt)_k &= TP_\sigma(X_k Y_l Z_m)^{-1}(Xgt)_k = TP_\sigma(Y_l Z_m)^{-1}(gt)_k \\
&= T_(gt)_\sigma(k) P_\sigma(Y_l Z_m)^{-1} = T(t^g i)^\sigma(k) P_\sigma(Y_l Z_m)^{-1} \\
&= T_t^\sigma(k) g^\sigma(k) P_\sigma(Y_l Z_m)^{-1},
\end{align*}

where the fourth equality follows from the inclusion \( g \in \Delta^{\sigma(k)} \). Since \( t \in \text{End}(H) \) is a \( T \)-scalar, we have \( T_t^\sigma(k) = T_{t^k}^\sigma(i) \) for some \( t^k \in \{ t, t^* \} \). Then

\begin{align*}
T_t^\sigma(k) g^\sigma(k) P_\sigma(Y_l Z_m)^{-1} &= T_{t^k}^\sigma(i) g^\sigma(k) P_\sigma(Y_l Z_m)^{-1} = TP_\sigma(Y_l Z_m)^{-1} t^k g^k = T(t^g i)_k,
\end{align*}

where the last equality follows from (25). Since \( t \) is a \( T \)-scalar, \( T_t^i = T_{t^k}^i \) for some \( t^k \in \{ t, t^* \} \). Recall that \( X = x \) for some \( x \in \{ a, a^*, b, b^*, ab, ba \} \). A case by case analysis shows that \( t^\sigma = t^{a\sigma} \). Combining the formulas above, we obtain that

\begin{equation}
T(Xgt)_k = T(Xt^g)_k = T(t^g i Xg)_k,
\end{equation}

i.e., \( xg \in \Delta^k \). Thus, \( x\Delta^{\sigma(k)} \subset \Delta^k \). Applying this inclusion to all forms (21)–(24) of (25) and to all possible choices of \( k \), we obtain \( c\Delta^1 \subset \Delta^3 \) and \( c\Delta^3 \subset \Delta^1 \) for all \( c \in \{ a, b, a^*, b^* \} \). \( \square \)
5. Further properties of $T$

To study the form $T$ we introduce the operators

$$L = A^* A, \quad R = B^* B, \quad C = (AB)^3 \in \text{End}(H).$$

We shall study these operators and show that the commutator of $L$ and $R$ is a $T$-scalar. Though this fact will not be directly used in the sequel, the properties of the operators $L$, $R$, $C$ will lead us in the next section to a notion of a $\Psi$-system.

An operator $f \in \text{End}(H)$ such that $f^* = f$ is called symmetric. An operator $f \in \text{End}(H)$ such that $f(H^0_i) \subseteq H^0_i$ and $f(H^k_i) \subseteq H^k_i$ for all $i, j, k \in I$ is called grading-preserving.

**Lemma 12.** The operators $L, R, C$ are invertible, symmetric, and grading-preserving. They satisfy the following identities:

$$ACA = BCB = C^{-1},$$

$$LCL^{-1} = RCR^{-1} = C,$$

$$ALA = L^{-1}, \quad BRB = R^{-1},$$

$$ARA = L^{-1}RC^{-1}, \quad BLB = R^{-1}LC.$$

**Proof.** That $L$, $R$, $C$ are invertible follows from the fact that $A$ and $B$ are invertible. The inverses of these operators are computed by $L^{-1} = AA^*$, $R^{-1} = BB^*$, and $C^{-1} = (BA)^3$. The operators $L$ and $R$ are manifestly symmetric. We have

$$C = (AB)^3 = ABABAB = (ABA)(ABA)^*. $$

Therefore $C^* = C$. That $L$, $R$, $C$ are grading-preserving follows from (5) and (11).

The identities (29)–(32) are checked as follows:

$$ACA = A(AB)^3 A = A^2(BA)^3 = (BA)^3 = C^{-1},$$

and similarly for $BCB$;

$$LCL^{-1} = A^* ACA A^* = A^* C^{-1} A^* = (AC^{-1}A)^* = C^* = C,$$

and similarly for $RCR^{-1}$;

$$ALA = AA^* AA = AA^* = L^{-1},$$

and similarly for $BRB$;

$$L^{-1}RC^{-1} = AA^* B^* A(BA)^2 = AA^* B^* (BAB)^* BA = AB^* BA = ARA,$$

and similarly for $R^{-1}LC$. \(\square\)
Lemma 13. The following identities hold:

(33a) \( TC_1 C_2 = TC_3 C_4 \),
(33b) \( TR_1 L_2 = TR_3 L_4 \),
(33c) \( TR_1 R_2 = TC_3 R_4 \),
(33d) \( TL_1 = TC_2 L_3 L_4 \).

Proof. The proof is based on a study of the action of the standard generators of \( S_4 \) on \( T \) using the formulas of Section 2.2. We have

\[
TP_{(12)} P_{(23)} = \bar{TP}_{(23)} (BA)_1 (BA)_3 (AB)_4^* = T(BA)_1 B_2 (ABA)_3 (AB)_4^*.
\]

The Coxeter relation \( (P_{(12)} P_{(23)})^3 = 1 \) yields equation (33a):

\[
T = T(P_{(12)} P_{(23)})^3 = T(P_{(12)} P_{(23)})^2 (BA)_2 B_3 (ABA)_1 (AB)_4^* \\
= TP_{(12)} P_{(23)} (BAB)_3 (A(AB)_2^2) (BA)_1^2 (AB)_4^* \\
= T(BA)_1^3 (BA)_2^3 (AB)_4^3 (AB)_4^* = TC_1^{-1} C_2^{-1} C_3 C_4.
\]

The identity \( P_{(12)} P_{(23)} P_{(34)} P_{(4321)} = 1 \) implies that

\[
T = TP_{(12)} P_{(23)} P_{(34)} P_{(4321)} = \bar{TP}_{(23)} P_{(34)} P_{(4321)} (BA)_2 (BA)_1 (AB)_4^* \\
= TP_{(34)} P_{(4321)} B_3 (BA)_2 (ABA)_1 (AB)_4^* \\
= \bar{TP}_{(4321)} (A^* B^* BA)_2 B_3 ((AB)_2) (ABB^* A^*)_4 \\
= T(B^* (AB)_2) (A^* B^* BA)_2 (ABB^* A^*)_4 \\
= T(RC^{-1})_1 (RC^{-1})_2 (R^{-1} C)_4.
\]

This and (33a) yields (33c). The identity \( P_{(34)} P_{(23)} P_{(12)} P_{(1234)} = 1 \) implies that

\[
T = TP_{(34)} P_{(23)} P_{(12)} P_{(1234)} = TP_{(23)} P_{(12)} P_{(1234)} (BA)_1 (AB)_4 (AB)_3 \\
= TP_{(12)} P_{(1234)} A_2 (BA)_1^* (BAB)_4 (AB)_3 \\
= \bar{TP}_{(1234)} (BAA^* B^*)_1 A_2 ((BA)_2) (B^* A^* AB)_3 \\
= T(BAA^* B^*)_1 (B^* A^* AB)_3 (A^* (BA)_2^2 B)_4 \\
= T(L^{-1} C^{-1})_1 (LC)_3 (LC)_4.
\]

This and (33a) yields (33d). Finally,

\[
TP_{(12)} P_{(34)} = \bar{TP}_{(34)} (BA)_1 (BA)_2 (AB)_4^* \\
= T(B^* A^* BA)_1 (BA)_2 (BAB^* A^*)_3 (BA)_4.
\]
The relation \((P_{(12)}P_{(34)})^2 = 1\) gives
\[
T = T(P_{(12)}P_{(34)})^2 = TP_{(12)}P_{(34)}(B^*A^*BA)_{(2)(BA)}_1(BAB^*A^*)_4(BA)_3
\]
\[
= T(B^*A^*(BA)^2)(BABB^*A^*BA)_{(2)(BAB^*A^*BA)}_3((BA)^2B^*A^*)_4
\]
\[
= T(A^*A)_{(1)}(BAA^*B)_{(2)}(BAA^*B)_{(3)}(BB^*)_4
\]
\[
= TL_1(C^{-1}L^{-1}R)_{(2)}(C^{-1}L^{-1}R)_3R_4^{-1}.
\]
This formula can be rewritten in the following equivalent form:
\[
T(R^{-1}L)_2C_4 = TL_1C_2^{-1}(L^{-1}R)_3
\]
which reduces to (33b) after using (33c) on the left-hand side, and (33d) on the right-hand side. □

**Lemma 14.** \(Q = LRL^{-1}R^{-1} \in \text{End}(H)\) is a \(T\)-unitary \(T\)-scalar.

**Proof.** Applying consecutively (33d) and (33b) in alternating order, we obtain
\[
TQ_1 = T(RL^{-1}R^{-1})_1C_2L_3L_4 = T(L^{-1}R^{-1})_1(L^{-1}C)_2(RL)_3L_4^2
\]
\[
= TR_1^{-1}L_2^{-1}(L^{-1}RL)_3L_4 = TR_3^{-1}(L^{-1}RL)_3 = TQ_3^4.
\]
Similar transformations using (33d) and (33c) yield \(TQ_1 = TQ_4^4\). Analogously, using (33b)
and (33c), we obtain \(TQ_2 = TQ_4^4\). This verifies the first three equalities of (26). The other
three equalities are checked similarly.

Since \(Q\) is a \(T\)-scalar, so is \(Q^* = R^{-1}L^{-1}RL\). We have
\[
Q^{-1} = RLR^{-1}L^{-1} = LRQ^*R^{-1}L^{-1} = TLQ^*LRR^{-1}L^{-1} = Q^*,
\]
where the \(T\)-equality follows from Lemma 11 applied to the \(T\)-scalar \(Q^*\). □

**Remark 15.** It is clear that \(Q\) is grading-preserving. For any \(i, j, k, l, m, n \in I\), the
restrictions of \(Q\) to the corresponding multiplicity spaces induce the endomorphisms \(Q_1, Q_2, Q_3, Q_4\) of the vector space (17). Lemma 14 implies that for any \(r \in \{1, 2\}\) and
\(s \in \{3, 4\}\), the composition \(Q_rQ_s\) preserves the \(6\)-symbol (18).

### 6. \(Ψ\)-systems

#### 6.1. The operators \(C^1, R^1,\) and \(L^1\)

Recall the symmetric, grading-preserving, invertible operators \(C, R, L \in \text{End}(H)\). Suppose that we have symmetric, grading-preserving, invertible operators \(C^1, R^1, L^1 \in \text{End}(H)\) such that

\[
(C^1)^2 = C, \quad AC^1A = BC^1B = C^{-1},
\]
\[
(R^1)^2 = R, \quad BR^1B = R^{-1}, \quad R^1C^1 = C^1R^1.
\]
Consider the group homomorphism

\[
L^\frac{1}{2} = BAR^{-1}AB \in \text{End}(H) \quad \text{and} \quad L^{-\frac{1}{2}} = (L^\frac{1}{2})^{-1} = BAR^\frac{1}{2}AB \in \text{End}(H).
\]

The properties of \(L^\frac{1}{2}\) are summarized in the following lemma.

**Lemma 16.** The operator \(L^\frac{1}{2}\) is symmetric, grading-preserving, and

\[
(L^\frac{1}{2})^2 = L, \quad AL^\frac{1}{2}A = L^{-\frac{1}{2}}, \quad L^\frac{1}{2}C^\frac{1}{2} = C^\frac{1}{2}L^\frac{1}{2}.
\]

**Proof.** We have

\[
(L^\frac{1}{2})^2 = BAR^{-1}AB = BABB^*AB = A^*B^*A^*B^*AB = A^*ABAAB = A^*A = L,
\]

\[
AL^\frac{1}{2}A = ABAR^{-1}ABA = (AB)^2 R^\frac{1}{2}(BA)^2 = BACR^\frac{1}{2}C^{-1}AB = BAR^\frac{1}{2}AB = L^{-\frac{1}{2}},
\]

\[
(L^\frac{1}{2})^* = B^*A^*R^{-\frac{1}{2}}A^*B^* = B^*A^*B^*R^\frac{1}{2}B^*A^*B^* = ABAR^\frac{1}{2}ABA = AL^{-\frac{1}{2}}A = L^\frac{1}{2}.
\]

That \(L^\frac{1}{2}\) is grading-preserving and commutes with \(C^\frac{1}{2}\) follows from the definitions. \(\square\)

### 6.2. \(\Psi\)-systems in \(\mathcal{C}\).

A \(\Psi\)-system in \(\mathcal{C}\) is a \(\Psi\)-system in \(\mathcal{C}\) together with a choice of invertible, symmetric, grading-preserving operators \(C^\frac{1}{2}, R^\frac{1}{2} \in \text{End}(H)\) satisfying equalities (34) as well as the identities

\[
\begin{align*}
(37a) \quad & TC^\frac{1}{2}C^\frac{1}{2} = TC^\frac{1}{3}C^\frac{1}{4}, \\
(37b) \quad & TR^\frac{1}{2}L^\frac{1}{2} = TR^\frac{1}{3}L^\frac{1}{4}, \\
(37c) \quad & TR^\frac{1}{2}R^\frac{1}{2} = TC^\frac{1}{3}R^\frac{1}{4}, \\
(37d) \quad & TL^\frac{1}{2} = TC^\frac{1}{2}L^\frac{1}{3}L^\frac{1}{4},
\end{align*}
\]

where \(L^\frac{1}{2}\) is defined by (35). Generally speaking, a \(\Psi\)-system may not allow operators \(C^\frac{1}{2}, R^\frac{1}{2} \in \text{End}(H)\) as above.

Equations (37c) and (37d) above are not independent. In fact, any one of them may be omitted.

We suppose from now on that we do have a \(\hat{\Psi}\)-system.

### 6.3. Commutation relations.

We establish commutation relation analogous to those in Lemma 11. Consider the group

\[
\hat{F} = \langle a, b, a^*, b^*, c, r \mid a^2 = b^2 = (a^*)^2 = (b^*)^2 = 1 \rangle.
\]

Consider the group homomorphism \(\hat{F} \to \mathbb{Z}/2\mathbb{Z}\) carrying \(a, b, a^*\), \(b^*\) to 1 (mod 2) and carrying \(c, r\) to 0. Elements of \(\hat{F}\) belonging to the kernel of this homomorphism are said
to be even; all other elements of $\hat{F}$ are said to be odd. The group $\hat{F}$ acts on $H$ by
\[
a \mapsto A, \quad b \mapsto B, \quad a^* \mapsto A^*, \quad b^* \mapsto B^*, \quad c \mapsto C^2, \quad r \mapsto R^2.
\]

The endomorphism of $H$ determined by $g \in \hat{F}$ is denoted by $\dot{g}$.

**Lemma 17.** Let $t \in \text{End}(H)$ be a $T$-scalar that $T$-commutes with $C^2_i$ in the sense that $tC^2_i = C^2_i t$. For $g \in \hat{F}$, set $t^g = t$ if $g$ is even and $t^g = t^*$ if $g$ is odd. Then $gt^g = t^g g$ for all $g \in \hat{F}$.

**Proof.** Observe that $t$ also $T$-commutes with $C^{-1}_i$ and $t^* T$-commutes with both $C^2_i$ and $C^{-1}_i$. Indeed, let $\{i, j\}$ be the set $\{1, 2\}$ or the set $\{3, 4\}$. Set $\{k, l\} = \{1, 2, 3, 4\}\setminus\{i, j\}$.

Formula (37a) implies that
\[
T(tC^{-1}_i)_i = T(t)C^{-1}_i = T(t)C^{-1}_j = T(t)C^{-1}_j t_j = tC^{-1}_j C^{-1}_j t_j
\]
\[
= T(t)C^{-1}_j C^{-1}_j C^{-1}_j t_j = T(t)C^{-1}_j C^{-1}_j C^{-1}_j t_j t_i = (C^{-1}_i t)_i,
\]
\[
T(t^* C^2_j)_i = T(t^*)C^2_j = T(t^*)C^2_k = T(t^*)C^2_k t_k = T(t^*)C^2_k C^2_k t_k
\]
\[
= T(t^*)C^2_k C^2_k C^2_k t_i = T(t^*)C^2_k C^2_k C^2_k t_i = T(C^2_i t)_i.
\]

For $i \in \{1, 2, 3, 4\}$, set
\[
\hat{\Delta}_i = \{ g \in \hat{F} \mid T(gt)_i = T(t^g g)_i \} \subset \hat{F}.
\]

By Lemma 9, we have $\hat{\Delta}_1 = \hat{\Delta}_2$ and $\hat{\Delta}_3 = \hat{\Delta}_4$. Set $\hat{\Delta} = \hat{\Delta}_1 \cap \hat{\Delta}_3 \subset \hat{F}$. Clearly, $1 \in \hat{\Delta}$. It is enough to show that $\hat{\Delta} = \hat{F}$.

Pick any index $i \in \{1, 2, 3, 4\}$ and let $j, k, l \in \{1, 2, 3, 4\}$ be such that either $\{i, j\} = \{1, 2\}$ or $\{i, j\} = \{3, 4\}$, and $\{k, l\} = \{1, 2, 3, 4\}\setminus\{i, j\}$. For $X = \xi = C^2_i$ and any $g \in \hat{\Delta}$, formula (37a) implies that
\[
T(c_{gt})_i = T(X_{gt})_i = T(gt)_i X_j^{-1} X_k X_l = T(t^g g)_i X_j^{-1} X_k X_l = T(t^g g)_i X_j^{-1} X_k X_l g_i.
\]

(the last two equalities follow from the assumptions $g \in \hat{\Delta}$ and $t$ is a $T$-scalar, respectively). Since $t$, $t^*$ both $T$-commute with $C^{\pm 1}_i$, we similarly have
\[
T(t^g g)_i = T(t^g g)_i = T(t^g g)_i = T(t^g g)_i = T(t^g g)_i = T(t^g g)_i = T(t^g g)_i
\]

Thus, $T(c_{gt})_i = T(t^g cg)$, for all $i$ so that $cg \in \hat{\Delta}$. This shows the inclusion $c\hat{\Delta} \subset \hat{\Delta}$. The inclusion $c^{-1}\hat{\Delta} \subset \hat{\Delta}$ is proved similarly.

Next, pick indices $i, j, k$ such that $\{i, j, k\} = \{1, 2, 4\}$. Set $X = r = R^2_4$ and $Y = C^2_3$. For any $g \in \hat{\Delta}$, formula (37c) implies that for some $e = \pm 1$ and $X', X'' \in \{X, X^{-1}\}$,
\[
T(r_{gt})_i = TX_i(gt)_i = TY_3 X_j X_k'(gt)_i = T(t^g g)_i Y_3 X_j X_k'' = T(t^g g)_i Y_3 X_j X_k' X_k'',
\]

\[
T(r_{gt})_i = TX_i(gt)_i = TY_3 X_j X_k'(gt)_i = T(t^g g)_i Y_3 X_j X_k'' = T(t^g g)_i Y_3 X_j X_k' X_k'',
\]
where \( t' \in \{ t, t^* \} \) is such that \( \Theta t' = T \Theta t' \). Since \( t' Y = T Y t' \),
\[
\Theta t' \Theta t' \Theta t' = T Y \Theta t' \Theta t' \Theta t' = \Theta t' \Theta t' \Theta t'.
\]
Thus, \( r g \in \tilde{A} \) and so \( r \tilde{A} \subseteq \tilde{A} \). Similarly, \( r^{-1} \tilde{A} \subseteq \tilde{A} \). The rest of the proof is as in Lemma 11.

\[\square\]

### 6.4. Stable \( T \)-equivalence

We say that two operators \( a, b \in \text{End}(H) \) are **stably \( T \)-equal** and write \( a \overset{sT}{=} b \) if \( f a = T f b \) for all \( f \in \hat{F} \). Obviously, if \( a \overset{sT}{=} b \), then \( a = b \) and \( g a \overset{sT}{=} g b \) for all \( g \in \hat{F} \).

**Corollary 18.** For any \( g \in \hat{F} \) and any \( T \)-scalar \( t \) that \( T \)-commutes with \( C^1 \),
\[
(38) \quad gt \overset{sT}{=} t^g g.
\]
Indeed, by Lemma 17, for all \( f \in \hat{F} \),
\[
fgt = fgt = T f g = (t^g f) g = f t^g g.
\]

Corollary 18 and the evenness of the elements \( r \) and \( \bar{a} \bar{b}^{-1} \bar{a} \bar{b} \) of \( \hat{F} \) imply that if a \( T \)-scalar \( t \) commutes with \( C^1 \), then \( t \) stably \( T \)-commutes with \( R^1 \) and \( L^1 \) in the sense that \( R^1 t \overset{sT}{=} t R^1 \) and \( L^1 t \overset{sT}{=} t L^1 \).

### 6.5. The \( T \)-scalar \( q \)

The following \( T \)-scalar will play a key role in the sequel.

**Lemma 19.** The grading-preserving operator
\[
q = R^1 A R^{-1} A L^{-1} C^{-1} = R^1 B L^1 B L^{-1} C^{-1}
\]
is a unitary \( T \)-scalar commuting with \( C^1 \).

**Proof.** That \( q \) is grading-preserving is obvious because \( R^1 \), \( C^1 \), and \( L^1 \) are grading-preserving and \( A \) is involutive. Since \( R^1 \), \( L^1 \), and \( A R^{-1} A \) commute with \( C^1 \), the operator \( q \) also commutes with \( C^1 \). To prove the remaining claims, set
\[
(39) \quad D = A R^{-1} A = B L^1 B.
\]
It is clear that \( D C^1 = C^1 D \). Note also that
\[
(40a) \quad D^* = L D L^{-1},
\]
\[
(40b) \quad D^2 = R^{-1} L C = C R^{-1} L.
\]
Indeed,
\[
D^* = A^* R^{-1} A^* = A^* A B L^1 B A^* = L B L^1 B L^{-1} = L D L^{-1}
\]
and

\[ D^2 = BLB = BA^*AB = BB^*A^*A^*B^*A^*AB = BB^*A^*AABABAB = R^{-1}LC. \]

We claim that the operator \( D \) satisfies the following identities:

\begin{align*}
\text{(41a)} & \quad TD_1 = TR_2^1L_3^1L_4^iA^*_4(AB)_2(R^{-1}A)_1 = TL_4^1R_2^{1/2}L_3^{1/2}P_{(134)}A^*_4(BA)_2A_1 \\
\text{(41b)} & \quad TC_1^iD_2 = TR_3^iD_4^i, \\
\text{(41c)} & \quad TL_2^iD_3C_4^i = TD_1^i.
\end{align*}

Formula (41a) is proved as follows:

\[ TD_1 = TP_{(134)}A^*_4(BA)_2(R^{-1}A)_1 = TL_4^1R_2^{1/2}L_3^{1/2}P_{(134)}A^*_4(BA)_2A_1 = TR_2^1L_3^1L_4^iA^*_4(AB)_2A_1 = TR_2^1L_3^1L_4^iD_4^i, \]

where in the first, second, etc. equalities we use respectively: the definition of \( D \) and (22); the action of the permutation group \( S_4 \) and (37b); the action of \( S_4 \); the definitions of \( L^i, D \) and (22). The proof of (41b) is similar:

\[ TD_2 = TP_{(124)}B^*_4(BA)_3(L^iB)_2 = TL_1^1C_2^{-1}L_3^{-1}P_{(124)}B^*_4(BA)_3B_2 = TR_2^1L_3^{-1}B_4^i(BA)_3B_2 = TC_1^iR_3^iD_4^i, \]

where we use consecutively: the definition of \( D \) and (23); the action of \( S_4 \) and (37d); the action of \( S_4 \); the definitions of \( L^i, D \) and (23). Finally, we prove (41c):

\[ TD_3 = TP_{(431)}A^*_1(AB)_2(R^{-1}A)_3 = TR_2^1C_3^{-1}R_4^{1/2}P_{(431)}A^*_1(AB)_2A_3 = TR_2^1C_3^{-1}R_4^{1/2}A^*_1(AB)_2A_3 = TD_1^iL_2^{-1}C_4^{-1}. \]

Here we use: the definition of \( D \) and (21); the action of \( S_4 \) and (37c); the action of \( S_4 \); the definitions of \( L^i, D \) and (21).

The definition of \( q \) may be rewritten as

\[ q = R^iDL^{-1/2}C^{-1/2}. \]

We can now prove the unitarity of \( q \):

\[ q^* = C^{-1/2}L^{-1/2}D^*R^i = C^{-1/2}L^iDL^{-1}R^i = C^{-1/2}L^iD^{-1}D^2L^{-1}R^i = C^{-1/2}L^iD^{-1}C^{-1/2} = C^{-1/2}L^{-1}R^i = q^{-1}. \]
where we use the relations (40). Now,
\[
Tq_1 = TR_2^{-\frac{1}{2}}C_3^1R_4^1(DL^{-\frac{1}{2}}C^{-\frac{1}{2}})_1 = TL_3^1D_4^1C_3^1R_4^1(L^{-\frac{1}{2}}C^{-\frac{1}{2}})_1 = TC_2^{-\frac{1}{2}}L_4^1D_4^1C_3^1R_4^1C_1^{-\frac{1}{2}} = TC_1^{-\frac{1}{2}}C_2^{-\frac{1}{2}}C_3^1(qC_4^1)^* = Tq^*_4,
\]
where we use consecutively: formulas (42) and (37c); formula (41b); formula (37b); formula (42); formula (37a). Similarly,
\[
Tq_2 = TR_1^{-\frac{1}{2}}C_3^1R_4^1(DL^{-\frac{1}{2}}C^{-\frac{1}{2}})_2 = TC_1^{-\frac{1}{2}}R_3^1D_4^1R_4^{-\frac{1}{2}}C_3^1R_4^1(L^{-\frac{1}{2}}C^{-\frac{1}{2}})_2 = TC_1^{-\frac{1}{2}}C_2^{-\frac{1}{2}}C_3^1(qC_4^1)^* = Tq^*_4,
\]
where we use consecutively: formulas (42) and (37c); formula (41a); formula (37d); formula (42); formula (37a). Similarly,
\[
Tq_3 = TR_1^{-\frac{1}{2}}C_3^1R_4^1(DL^{-\frac{1}{2}}C^{-\frac{1}{2}})_3 = TD_4^1C_4^1R_4^{-\frac{1}{2}}L_4^1(L^{-\frac{1}{2}}C^{-\frac{1}{2}})_3 = TL_1^{-\frac{1}{2}}C_2^1D_4^1C_3^1R_3^1C_3^{-\frac{1}{2}} = T(qC_3^1)^*C_2^1C_3^{-\frac{1}{2}}C_4^3 = Tq^*_1,
\]
where we use: formulas (42) and (37b); formula (41b); formula (37b); formula (42); formula (37a). Together with the unitarity of \( q \) these identities imply that \( q \) is a \( T \)-scalar. 

**Lemma 20.** For all \( a, b \in \frac{1}{2} \mathbb{Z} \),
\[
L^a R^b \overset{sT}{=} q^{ab} R^b L^a.
\]
For all \( a, b \in \frac{1}{2} \mathbb{Z} \) and \( c \in \mathbb{Z} \),
\[
(L^a R^b)^c \overset{sT}{=} q^{abc(1-c)} L^{ac} R^{bc}.
\]

**Proof.** Formulas (42) and (40b) imply that
\[
qL^1 R^{-\frac{1}{2}} q = R^{-\frac{1}{2}} L^1.
\]
This and (38) yield (43) for \( a = b = \frac{1}{2} \):
\[
L^{-\frac{1}{2}} R^1 = R^1 R^{-\frac{1}{2}} L^{-\frac{1}{2}} R^1 = R^1 q L^1 R^{-\frac{1}{2}} q R^1 \overset{sT}{=} q^2 R^1 L^1 R^{-\frac{1}{2}} R^1 = q^2 R^1 L^1.
\]
Assuming (43) for some \( a \in \frac{1}{2} \mathbb{Z} \) and \( b = \frac{1}{2} \), we obtain
\[
L^{a+\frac{1}{2}} R^\frac{1}{2} = L^a L^1 R^\frac{1}{2} \overset{sT}{=} L^a q^2 R^1 L^\frac{1}{2} \overset{sT}{=} q^2 L^a R^\frac{1}{2} L^\frac{1}{2} \overset{sT}{=} q^2 q^{4a} R^a L^a L^\frac{1}{2} = q^{4(a+\frac{1}{2})} R^a L^a L^\frac{1}{2}.
\]
This proves (43) for all positive $a \in \frac{1}{2} \mathbb{Z}$ and $b = \frac{1}{2}$. Similarly, assuming (43) for some positive $a, b \in \frac{1}{2} \mathbb{Z}$, we obtain

$$L^a R^{b+\frac{1}{2}} = L^a R^b L^a R^{\frac{1}{2}} q^{4a} R^\frac{1}{2} L^a R^b = q^{4a} R^\frac{1}{2} q^{8ab} R^b L^a$$

This proves (43) for all positive $a, b \in \frac{1}{2} \mathbb{Z}$. Moreover, for such $a, b$, we have:

$$L^{-a} R^b = L^{-a} R^b L^{-a} = L^{-a} q^{-8ab} L^a R^b L^{-a} = q^{-8ab} R^b L^{-a},$$

$$L^a R^{-b} = R^{-b} L^a R^{-b} = R^{-b} q^{-8ab} L^a R^b R^{-b} = q^{-8ab} R^b L^{-a},$$

and

$$L^{-a} R^{-b} = R^{-b} L^{-a} R^{-b} = R^{-b} q^{-8ab} L^{-a} R^b R^{-b} = q^{-8ab} R^b L^{-a}.$$

This proves (43) for all non-zero $a, b$. For $a = 0$ or $b = 0$, formula (43) is obvious.

The case $c = 0$ of (44) is obvious. Assuming (44) for some $c \in \mathbb{Z}$, we obtain

$$(L^a R^b)^{c+1} = (L^a R^b)^c L^a R^b = q^{4abc(1-c)} L^{ac} R^{bc} L^a R^b = q^{4abc(1-c)} L^{ac} q^{-8abc} L^a R^{bc} R^b$$

This implies (44) for all $c \geq 0$. The proof for negative $c$ is similar.

**Remark 21.** If we apply formula (43) to $a = b = 1$, we obtain $q^8 \eqdef Q$, where $Q = LRL^{-1} R^{-1}$ is the operator studied in Lemma 14.

### 7. Charged $T$-forms

#### 7.1. Definition.

For any $a, c \in \frac{1}{2} \mathbb{Z}$, we define the “charged” $T$-forms

$$T(a, c) = T q^{4ac} R^c_1 R^{-a}_2 L^{-a}_3 R^{-c}_3 : H^{\otimes 4} \to k$$

and

$$T(a, c) = T q^{-4ac} L^{a}_1 R^{-a}_2 R^{-c}_3 R^{c}_3 : H^{\otimes 4} \to k.$$

**Lemma 22.** Set $A = AL^{-1}, B = BR^{-1} \in \text{End}(H)$. Then $A, B$ are symmetric involutions and for any $a, b, c \in \frac{1}{2} \mathbb{Z}$ such that $a + b + c = \frac{1}{2}$ we have
(45a) \[ T(a, c)P_{(4321)} = \bar{T}(a, b)q_1^{2a}A_1A_3, \]
(45b) \[ T(a, c)P_{(23)} = T(b, c)q_1^{2a}A_2B_3, \]
(45c) \[ T(a, c)P_{(1234)} = \bar{T}(a, b)q_1^{-2a}B_2B_4. \]

Proof. The equalities \( A^2 = B^2 = 1 \) directly follow from the involutivity of the operators \( A, B \) and the formulas \( AL^\frac{1}{2}A = L^{-\frac{1}{2}} \) and \( BR^\frac{1}{2}B = R^{-\frac{1}{2}} \). We have

\[
A^* = (L^{-\frac{1}{2}})^*A^* = L^{-\frac{1}{2}}A^* = AL^\frac{1}{2}A^* = AL^\frac{1}{2}L^{-1} = AL^{-\frac{1}{2}} = A.
\]
Similarly, \( B^* = B \). To prove (45), observe that

\[
AL^{-b}R^{-c}A = AL^\frac{1}{2-b}R^{-c}A = L^bL^{-\frac{1}{2}}AR^{-c}A = L^bL^{-\frac{1}{2}}(AR^{-c}A)^{2c}
\]
\[= L^bL^{-\frac{1}{2}}L^\frac{1}{2}R^{-\frac{1}{2}}C^2q)^{2c} = q^{2c}C^cL^bL^{-\frac{1}{2}}(L^\frac{1}{2}R^{-\frac{1}{2}})^{2c}
\]
\[= q^{2c}C^cL^bL^{-\frac{1}{2}}q^{2c(1-2c)}L^cR^{-c} = q^{4c^2}C^cL^bh-c-b^{-\frac{1}{2}}R^{-c}.
\]

Here the first, second, etc. equalities follow respectively from: the definition of \( A \); the formula \( AL^\frac{1}{2} = L^{-\frac{1}{2}}A \); the involutivity of \( A \); the definition of \( q \); the fact that \( R^\frac{1}{2} \) and \( L^\frac{1}{2} \) commute with \( C^\frac{1}{2} \) and stably \( T \)-commute with \( q \); the formula (44); the fact that \( L^\frac{1}{2} \) stably \( T \)-commutes with \( q \). A similar computation shows that

\[ (46) \quad BL^{-a}R^{-b}B = q^{4a^2-4a}C^{-a}L^{-a}R^{a+b-\frac{1}{2}}.
\]

Formula (45b) is equivalent to the formula \( \bar{T}(b, c)q_1^{2c}A_2B_3P_{(23)} = T(a, c) \) which we now prove:

\[
\bar{T}(b, c)q_1^{2c}A_2B_3P_{(23)} = \bar{T}q_1^{2c(1-2b)}L_2^{-b}R_2^{-c}R_3^{-b}R_4^{-c}A_2B_3P_{(23)}
\]
\[= TP_{(23)}A_2B_3q_1^{2c(1-2b)}L_2^{-b}R_2^{-c}R_3^{-b}R_4^{-c}A_2B_3P_{(23)}
\]
\[= Tq_1^{2c(1-2b)}(BR^{-b}B)(AL^{-b}R^{-c}A)^3R_4^{-c}
\]
\[= Tq_1^{2c(1-2b)}q_3^{4c^2}R_2^{-b-\frac{1}{2}}(C^cL^{-a}R^{-c})^3R_4^{-c}
\]
\[= Tq_1^{4ac}R_2^{-b-\frac{1}{2}}(C^cL^{-a}R^{-c})^3R_4^{-c}
\]
\[= T(R^cq_1^{4ac})R_2^{-a}(L^{-a}R^{-c})^3 = T(a, c).
\]

Here we use consecutively: the definition of \( \bar{T}(b, c) \); formula (13b); the action of \( S_4 \); the equalities \( BR^{-b}B = R^{b-\frac{1}{2}} \) and \( AL^{-b}R^{-c}A = q^{4c^2}C^cL^{-a}R^{-c} \) established above; the equality \( Tq_3 = Tq_1^{-1} \); formula (37c); the fact that \( R \) stably \( T \)-commutes (and therefore \( T \)-commutes) with \( q \); the definition of \( T(a, c) \).

The proof of (45c) is similar:
Here we use consecutively: the definition of $\tilde{T}(a, b)$ and formula (13c); the action of $S_4$; formula $B^aR^bB = R^{1-b}$ which follows from the definitions of $R, B$ and the equality $BR^bB = R^{-b}$; formula (46) and the equality $Tq_3 = Tq_2^{-1}$; formula (37c); the formulas $Rq = qR, Tq_2 = Tq_1$ and the definition of $T(a, c)$.

Finally, we prove (45a):

$$
\tilde{T}(a, b)q_1^{-2a}B_1A_1A_2P_{(134)} = TP_{(134)}A_1^*A_3q_1^{-2a(2b+1)}L^{-a}R_2^{-b}R_3^{-a}R_4^{-b}A_1A_3P_{(134)}
$$

where we use (among others) formulas (13a), (37d), (37b), and (43). 

\textbf{Remark 23.} Though we shall not need it in the sequel, note that the involutions $A, B : H \rightarrow H$ introduced in Lemma 22 satisfy the relations $(BA)^3 = q^2$ and

$$(AC^2)^2 = (BC^2)^2 = (Aq)^2 = (Bq)^2 = (AL^2)^2 = (BR^2)^2 = 1.$$ 

\textbf{7.2. The charged pentagon and inversion identities.} For any $a, c \in \frac{1}{2} \mathbb{Z}$, we define the "charged" operators $\tau(a, c), \tilde{\tau}(a, c) : \hat{H}^\odot 2 \rightarrow \hat{H}^\odot 2$ by

$$
\tau(a, c) = q_1^{-4ac}R_1^aR_2^{-a}R_3^{-a}R_4^{-a} \text{ and } \tilde{\tau}(a, c) = q_1^{4ac}R_2^{-c}L^{-a}R_1^{-a}R_2^{-a},
$$

where $\tau$ and $\tilde{\tau}$ are the endomorphisms of $\hat{H}^\odot 2$ introduced in Section 2.3. The operator $\tau(a, c)$ is adjoint to $T(a, c)$: for any $u, v \in \hat{H}, x, y \in \hat{H},$

$$
\langle\langle u \otimes v, \tau(a, c)(x \otimes y) \rangle\rangle = \langle\langle u \otimes v, (q^{-4ac}R^c \otimes R^{-a})\tau(L^{-a}R^{-c}(x \otimes y)) \rangle\rangle
$$

$$
= \langle\langle q^{4ac}R^c(u) \otimes R^{-a}(v), \tau(L^{-a}R^{-c}(x \otimes y)) \rangle\rangle
$$

$$
= T\left(q^{4ac}R^c(u) \otimes R^{-a}(v) \otimes L^{-a}R^{-c}(x \otimes y)\right)
$$

$$
= T(a, c)(u \otimes v \otimes x \otimes y),
$$
where we use the pairing $\langle \cdot , \cdot \rangle$ introduced in Section 2.3, the unitarity of $q$, and the symmetry of $L^{\frac{1}{2}}, R^{\frac{1}{2}}$. Similarly, $\bar{\tau}(a, c)$ is adjoint to $\bar{T}(a, c)$.

**Lemma 24.** The charged operators $\tau$, $\bar{\tau}$ satisfy the following identities.

(i) The charged pentagon identity:

$\tau_{23}(a_0, c_0) \tau_{13}(a_2, c_2) \tau_{12}(a_4, c_4) = \tau_{12}(a_3, c_3) \tau_{23}(a_1, c_1)(^*\pi)_{21}$

for any $a_0, a_1, a_2, a_3, a_4, c_0, c_1, c_2, c_3, c_4 \in \frac{1}{2} \mathbb{Z}$ such that

$$a_1 = a_0 + a_2, \quad a_3 = a_2 + a_4, \quad c_1 = c_0 + a_4, \quad c_3 = a_0 + c_4, \quad c_2 = c_1 + c_3.$$  

(ii) The charged inversion identities: for any $a, c \in \frac{1}{2} \mathbb{Z}$,

$$\tau_{21}(a, c) \tau(-a, -c) = ^*\pi \quad \text{and} \quad \tau(-a, -c) \tau_{21}(a, c) = ^*\pi.$$

**Proof.** We first rewrite formulas (37) in terms of $\tau$ and $\bar{\tau}$:

$$C_1^1 C_2^1 \tau = \tau C_1^1 C_2^1, \quad R_1^1 L_2^1 \tau = \tau R_1^1 L_2^1, \quad R_1^1 R_2^1 \tau = \tau C_1^1 R_2^1, \quad L_1^1 C_2^1 \tau = \tau L_1^1 L_2^1.$$

In the following computations, the underlined expressions are transformed via one of these four equalities. We have

$$q_1^{4(a_1 c_1 + a_2 c_2)} \tau_{12}(a_3, c_3) \tau_{23}(a_1, c_1)(^*\pi)_{21}$$

where the last equality follows from the definition of $^*\pi$ and the fact that $R_2^\frac{1}{2}, L_2^\frac{1}{2}, C_2^\frac{1}{2}$ are grading-preserving operators. We also have

$$q_1^{4(a_0 c_0 + a_2 c_2 + a_4 c_4)} \tau_{23}(a_0, c_0) \tau_{13}(a_2, c_2) \tau_{12}(a_4, c_4)$$

where the last equality follows from the definition of $^*\pi$ and the fact that $R_2^\frac{1}{2}, L_2^\frac{1}{2}, C_2^\frac{1}{2}$ are grading-preserving operators.
Comparing the obtained expressions and using that
\[ t_{12} t_{23} (\pi_{12}^{\ast})_{21} = t_{23} t_{13} t_{12}, \]
we conclude that the charged pentagon equality follows from the formula
\[ a_0 c_0 + a_2 c_2 + a_4 c_4 + 2a_0 a_4 = a_1 c_1 + a_3 c_3. \]
This formula is verified as follows:
\[
a_0 c_0 + a_2 c_2 + a_4 c_4 + 2a_0 a_4 = a_0 (c_0 + a_4) + a_2 c_2 + a_4 (a_0 + c_4) \\
= a_0 c_1 + a_2 (c_1 + c_3) + a_4 c_3 \\
= (a_0 + a_2) c_1 + (a_2 + a_4) c_3 = a_1 c_1 + a_3 c_3. 
\]
We now prove the first inversion identity:
\[
\tau_{21}(a,c) \tau(-a,-c) = q_1^{-a c} R_1^c R_1^{-a} \tau_{21} L_2^{-a} R_2^{-c} q_1^{a c} R_2^c L_2^{-a} R_1^{-c} \\
= R_2^c R_1^{-a} \tau_{21} \tau R_1^{-c} R_2^{-c} = R_2^c R_1^{-a} \pi^* R_1^{-a} R_2^{-c} = \pi^*,
\]
where the second equality follows from (27) since \( q \) is a \( T \)-scalar. The equality
\[ R_2^c R_1^{-a} \pi^* R_1^{-a} R_2^{-c} = \pi^* \]
follows from the fact that \( \pi^* \) is the projector on a direct sum of multiplicity spaces. The second inversion identity is proved similarly. □

8. Charged 6j-symbols

Let \( i, j, k, l, m, n \in I \) and \( a, c \in \frac{1}{2} \mathbb{Z} \). Replacing \( T \) by \( T(a,c) \) in the definition of the positive 6j-symbol in Section 3.2, we obtain the charged positive 6j-symbol
\[
(48) \quad \left\{ \begin{array}{ccc} i & j & k \\ l & m & n \end{array} \right\}^{+}(a,c) \in H_{m}^{k l} \otimes H_{k}^{m} \otimes H_{l}^{j n} \otimes H_{n}^{j} \otimes H_{m}. 
\]
Replacing \( T \) by \( T(a,c) \) in the definition of the negative 6j-symbol in Section 3.2, we obtain the charged negative 6j-symbol
\[
(49) \quad \left\{ \begin{array}{ccc} i & j & k \\ l & m & n \end{array} \right\}^{-}(a,c) \in H_{m}^{n} \otimes H_{n}^{l} \otimes H_{l}^{j k} \otimes H_{k}^{i} \otimes H_{n}. 
\]
The formulas of Section 3.2 computing \( T, \bar{T}, \tau, \bar{\tau} \) in terms of the 6j-symbols extend to the present setting by inserting \( (a,c) \) after each occurrence of \( T, \bar{T}, \tau, \bar{\tau} \) and after each 6j-symbol.

The properties of the charged \( T \)-forms established in Section 7 can be rewritten in terms of the charged 6j-symbols. For any \( a, b, c \in \frac{1}{2} \mathbb{Z} \) such that \( a + b + c = \frac{1}{2} \), formula (45a)
yields
\[
(50) \quad \{i \atop j \atop k}^{l \atop m \atop n}_{a,c} = P_{(4321)}q_1^{2a}A_1A_3\left(\{i \atop j \atop k}^{l \atop m \atop n}_{a,b}\right),
\]
where $A_1$ is induced by the restriction of $A$ to $H_i^{l,m}$ and $A_3$ is induced by the restriction of $A$ to $H_{i,k}$. Formula (45b) yields
\[
(51) \quad \{i \atop j \atop k}^{l \atop m \atop n}_{a,c} = P_{(23)}q_1^{2c}A_2B_3\left(\{k \atop i \atop j}^{l \atop m \atop n}_{b,c}\right),
\]
where $A_2$ is induced by the restriction of $A$ to $H_i^{l,m}$ and $B_3$ is induced by the restriction of $B$ to $H_{l,m}$. Finally, formula (45c) yields
\[
(52) \quad \{i \atop j \atop k}^{l \atop m \atop n}_{a,c} = P_{(1345)}q_1^{2d}B_2B_4\left(\{i \atop n \atop m}^{l \atop k \atop j}_{a,b}\right),
\]
where $B_2$ is induced by the restriction of $B$ to $H_i^{l,m}$ and $B_4$ is induced by the restriction of $B$ to $H_{l,m}$. The charged pentagon identity yields that for any $a_0, a_1, a_2, a_3, a_4, c_0, c_1, c_2, c_3, c_4 \in \frac{1}{2}Z$ satisfying (47),
\[
(53) \quad \sum_{j \in I} \sum_{j \in I} \sum_{j \in I} \sum_{j \in I} \left(\{j_0 \atop j_1 \atop j_2 \atop j_3}^{j_4 \atop j_5 \atop j_6 \atop j_7}_{a_0 \atop a_1 \atop a_2 \atop a_3} \otimes \{j_1 \atop j_2 \atop j_3 \atop j_4}^{j_5 \atop j_6 \atop j_7 \atop j_8}_{c_0 \atop c_1 \atop c_2 \atop c_3}\right).
\]
Here both sides lie in the k-vector space (20).

The first inversion relation gives that for all $i, j, k, k', l, m \in I$ and $a, c \in \frac{1}{2}Z$,
\[
\sum_{n \in I} \sum_{n \in I} \left(\{i \atop j \atop k}^{l \atop m \atop n}_{a,c} \otimes \{i \atop j \atop k'}^{l \atop m \atop n}_{-a,-c}\right) = \delta_{kk'}^{-1}g_{j_1 \atop j_2 \atop j_3}^{j_4 \atop j_5 \atop j_6}P_{(4321)}(\delta_{jj}^{m} \otimes \delta_{jj}^{n}).
\]
The second inversion relation gives that for all $i, j, l, m, n, n' \in I$ and $a, c \in \frac{1}{2}Z$,
\[
\sum_{n \in I} \sum_{n' \in I} \left(\{i \atop j \atop k}^{l \atop m \atop n}_{a,c} \otimes \{i \atop j \atop k}^{l \atop m \atop n'}_{-a,-c}\right) = \delta_{nn'}^{-1}g_{i_1 \atop i_2 \atop i_3}^{i_4 \atop i_5 \atop i_6}P_{(4321)}(\delta_{ii}^{m} \otimes \delta_{ii}^{n}).
\]

9. Three-manifold invariants

In this section, following the ideas of the paper [7], we associate to a $\Psi$-system an invariant of an oriented compact three-manifold together with a non-empty link.
### 9.1. Topological preliminaries

Throughout this subsection, the symbol $M$ denotes a closed connected orientable 3-manifold. Following [2], by a *quasi-regular triangulation* of $M$ we mean a decomposition of $M$ as a union of embedded tetrahedra such that the intersection of any two tetrahedra is a union (possibly, empty) of several of their vertices, edges, and (2-dimensional) faces. Quasi-regular triangulations differ from the usual triangulations in that they may have tetrahedra meeting along several vertices, edges, and faces. Note that each edge of a quasi-regular triangulation has two distinct endpoints.

A *Hamiltonian link* in a quasi-regular triangulation $\mathcal{T}$ of $M$ is a set $\mathcal{L}$ of unoriented edges of $\mathcal{T}$ such that every vertex of $\mathcal{T}$ belongs to exactly two elements of $\mathcal{L}$. Then the union of the edges of $\mathcal{T}$ belonging to $\mathcal{L}$ is a link $L$ in $M$. We call the pair $(\mathcal{T}, \mathcal{L})$ an *H-triangulation* of $(M, L)$.

**Proposition 25** ([2], Proposition 4.20). For any non-empty link $L$ in $M$, the pair $(M, L)$ admits an H-triangulation.

$H$-triangulations of $(M, L)$ can be related by elementary moves of two types, the $H$-bubble moves and the $H$-Pachner $2 \leftrightarrow 3$ moves. The *positive H-bubble move* on an $H$-triangulation $(\mathcal{T}, \mathcal{L})$ starts with a choice of a face $F = v_1v_2v_3$ of $\mathcal{T}$ such that at least one of its edges, say $v_1v_3$, is in $\mathcal{L}$. Consider two tetrahedra of $\mathcal{T}$ meeting along $F$. We unglue these tetrahedra along $F$ and insert a 3-ball between the resulting two copies of $F$. We triangulate this 3-ball by adding a vertex $v_4$ at its center and three edges connecting $v_4$ to $v_1$, $v_2$, and $v_3$. The edge $v_1v_3$ is removed from $\mathcal{L}$ and replaced by the edges $v_1v_4$ and $v_3v_4$. This move can be visualized as the transformation

![H-bubble move](image)

where the bold (green) edges belong to $\mathcal{L}$. The inverse move is the *negative H-bubble move*. The *positive H-Pachner $2 \leftrightarrow 3$ move* can be visualized as the transformation

![H-Pachner move](image)

This move preserves the set $\mathcal{L}$. The inverse move is the *negative H-Pachner move*; it is allowed only when the edge common to the three tetrahedra on the right is not in $\mathcal{L}$.

**Proposition 26** ([2], Proposition 4.23). Let $L$ be a non-empty link in $M$. Any two $H$-triangulations of $(M, L)$ can be related by a finite sequence of $H$-bubble moves and $H$-Pachner moves in the class of $H$-triangulations of $(M, L)$.

Charges on $H$-triangulations first have been introduced in [7] and the corresponding theory subsequently has been developed in [2]. This theory is a natural extension of the theory of angle structures, see for example [13], [14], into the framework of arbitrary triangulated three-manifolds.
By a *charge* on a tetrahedron $T$, we mean a $\frac{1}{2}\mathbb{Z}$-valued function $c$ on the set of edges of $T$ such that $c(e) = c(e')$ for any opposite edges $e, e'$ and $c(e_1) + c(e_2) + c(e_3) = 1/2$ for any edges $e_1, e_2, e_3$ of $T$ forming the boundary of a face. Consider now an $H$-triangulation $(\mathcal{T}, \mathcal{L})$ of $(M, L)$ as above. Let $E(\mathcal{T})$ be the set of edges of $\mathcal{T}$ and let $\hat{E}(\mathcal{T})$ be the set of pairs (a tetrahedron $T$ of $\mathcal{T}$, an edge of $T$). Let $\epsilon_\mathcal{T} : \hat{E}(\mathcal{T}) \rightarrow E(\mathcal{T})$ be the obvious projection. For any edge $e$ of $\mathcal{T}$, the set $\epsilon_\mathcal{T}^{-1}(e)$ has $n$ elements, where $n$ is the number of tetrahedra of $\mathcal{T}$ adjacent to $e$.

**Definition 27.** A *charge* on $(\mathcal{T}, \mathcal{L})$ is a map $c : \hat{E}(\mathcal{T}) \rightarrow \frac{1}{2}\mathbb{Z}$ such that

(i) the restriction of $c$ to any tetrahedron $T$ of $\mathcal{T}$ is a charge on $T$,

(ii) for each edge $e$ of $\mathcal{T}$ not belonging to $\mathcal{L}$ we have $\sum_{e' \in \epsilon_\mathcal{T}^{-1}(e)} c(e') = 1$,

(iii) for each edge $e$ of $\mathcal{T}$ belonging to $\mathcal{L}$ we have $\sum_{e' \in \epsilon_\mathcal{T}^{-1}(e)} c(e') = 0$.

Each charge $c$ on $(\mathcal{T}, \mathcal{L})$ determines a cohomology class $[c] \in H^1(M; \mathbb{Z}/2\mathbb{Z})$ as follows. Let $s$ be a simple closed curve in $M$ which lies in general position with respect to $\mathcal{T}$ and such that $s$ never leaves a tetrahedron $T$ of $\mathcal{T}$ through the same 2-face by which it entered. Thus each time $s$ passes through $T$, it determines a unique edge $e$ belonging to both the entering and departing faces. The sum of the residues $2c|_T(e) \pmod{2} \in \mathbb{Z}/2\mathbb{Z}$ over all passages of $s$ through tetrahedra of $\mathcal{T}$ depends only on the homology class of $s$ and is the value of $[c]$ on $s$.

It is known that each $H$-triangulation $(\mathcal{T}, \mathcal{L})$ of $(M, L)$ has a charge representing any given element of $H^1(M; \mathbb{Z}/2\mathbb{Z})$. We briefly outline a proof of this claim following [13], [1] and referring to these papers for the exact definitions and the details. In this argument (and only here) we shall use “integral charges” that are equal to two times our charges and take only integer values. Let $\mathcal{J}$ be the abelian group generated by pairs (a tetrahedron $\Delta$ of $\mathcal{T}$, an edge of $\Delta$) modulo the relations $(\Delta, e) = (\Delta, \hat{e})$ where $\hat{e}$ is the edge opposite to $e$ in $\Delta$. An integral charge on $\mathcal{T}$ may be seen as an element of $\mathcal{J}$ satisfying certain additional properties. Recall the Neumann chain complex associated with $\mathcal{T}$:

$$
\tau = (C_0 \xrightarrow{\alpha} C_1 \xrightarrow{\beta} J \xrightarrow{\beta^*} C_1 \xrightarrow{\alpha^*} C_0 \rightarrow 0).
$$

Here $C_i$ with $i = 0, 1$ is the free abelian group freely generated by the $i$-dimensional (unoriented) simplices of $\mathcal{T}$ and $J$ is the quotient of $\mathcal{J}$ by the relations

$$(\Delta, e_1) + (\Delta, e_2) + (\Delta, e_3) = 0$$

where $e_1, e_2, e_3$ are edges of a tetrahedron $\Delta \in \mathcal{T}$ forming a triangle. The homomorphisms $\alpha, \beta$ are defined by Neumann and the homomorphisms $\alpha^*, \beta^*$ are their transposes with respect to the obvious bases of $C_0, C_1$ and a canonical non-degenerate bilinear form on $J$.

The relationship to the charges comes from the fact that $\beta^* : J \rightarrow C_1$ splits canonically as a composition of certain homomorphisms $\beta_1 : J \rightarrow J$ and $\beta_2 : J \rightarrow C_1$. The rest of the argument is a homological chase. One starts with any $x \in \mathcal{J}$ such that for every tetrahe-
dron $\Delta$ of $\mathcal{T}$, the coefficients of the edges of $\Delta$ in $x$ total to 1. One shows that then $\beta_2(x) - 2\sigma \in \text{Ker}(\alpha^*)$ where $\sigma \in C_1$ is the formal sum of the edges of $\mathcal{T}$ not belonging to $\mathcal{L}$. Using Neumann’s computation of $H_2(\tau)$, one deduces that $\beta_2(x) - 2\sigma = \beta^*(a)$ for some $a \in J$. Then $x' = x - \beta_1(a)$ is an integral charge on $\mathcal{T}$. Next, using Neumann’s formula $H_3(\tau) = H^1(M; \mathbb{Z}/2\mathbb{Z})$, one picks a cycle $b \in J$ of the chain complex $\tau$ such that $x' - \beta_1(b)$ is an integral charge on $\mathcal{T}$ representing the given element of $H^1(M; \mathbb{Z}/2\mathbb{Z})$.

**Lemma 28.** Let $(\mathcal{T}, \mathcal{L})$ and $(\mathcal{T}', \mathcal{L}')$ be $H$-triangulations of $(M, L)$ such that $(\mathcal{T}', \mathcal{L}')$ is obtained from $(\mathcal{T}, \mathcal{L})$ by an $H$-Pachner move or an $H$-bubble move. Let $c$ be a charge on $(\mathcal{T}, \mathcal{L})$. Then there exists a charge $c'$ on $(\mathcal{T}', \mathcal{L}')$ such that $c'$ equals $c$ on all pairs (a tetrahedron $T$ of $\mathcal{T}$ not involved in the move, an edge of $T$) and for any common edge $e$ of $\mathcal{T}$ and $\mathcal{T}'$,

$$
\sum_{a \in \epsilon_{\mathcal{T}'}(e)} c'(a') = \sum_{a' \in \epsilon_{\mathcal{T}'}(e)} c'(a').
$$

Moreover, $[c] = [c']$.

**Proof.** A straightforward calculation, cf. [2], Lemma 4.10. $\Box$

The charge $c'$ in this lemma is unique if the move $(\mathcal{T}, \mathcal{L}) \mapsto (\mathcal{T}', \mathcal{L}')$ is negative. In this case we say that $c'$ is induced by $c$. If the move $(\mathcal{T}, \mathcal{L}) \mapsto (\mathcal{T}', \mathcal{L}')$ is positive, then $c'$ is not unique, see [2], Lemma 4.12.

### 9.2. The algebraic data.

We describe the algebraic data needed to define our 3-manifold invariant. Let $\mathcal{C}$ be a monoidal Ab-category whose ground ring $k$ is a field. Fix a $\Psi$-system in $\mathcal{C}$ with distinguished simple objects $\{V_i\}_{i \in I}$. Fix a family $\{I_g\}_{g \in G}$ of finite subsets of the set $I$ numerated by elements of a group $G$ and satisfying the following conditions:

(i) For any $g \in G$, if $i \in I_g$, then $i^* \in I_{g^{-1}}$.

(ii) For any $i_1 \in I_{g_1}, i_2 \in I_{g_2}, k \in I \setminus I_{g_1 g_2}$ with $g_1, g_2 \in G$, we have $H_k^{i_1 i_2} = 0$.

(iii) If $i_1 \in I_{g_1}, i_2 \in I_{g_2}$ with $g_1, g_2 \in G$, then either $I_{g_1 g_2} = \emptyset$ or there is $k \in I_{g_1 g_2}$ such that $H_k^{i_1 i_2} \neq 0$.

(iv) For any finite family $\{g_r \in G\}_r$, there is $g \in G$ such that $I_{g g_r} = \emptyset$ for all $r$.

(v) We are given a map $b : I \to k$ such that $b(i) = b(i^*)$ for all $i \in I$, and for any $g_1, g_2 \in G, k \in I_{g_1 g_2}$ such that $I_{g_1} = \emptyset$ and $I_{g_2} = \emptyset$,

$$\sum_{i_1 \in I_{g_1}, i_2 \in I_{g_2}} b(i_1) b(i_2) \dim(H_k^{i_1 i_2}) = b(k).$$


We fix algebraic data as in Section 9.2. Let $M$ be a closed connected orientable 3-manifold and $\mathcal{T}$ a quasi-regular triangulation of $M$ as in Section 9.1. A $G$-coloring of $\mathcal{T}$ is a map $\Phi$ from the set of oriented edges of $\mathcal{T}$ to $G$ such that
(i) $\Phi(-e) = \Phi(e)^{-1}$ for any oriented edge $e$ of $\mathcal{T}$, where $-e$ is $e$ with opposite orientation;

(ii) if $e_1, e_2, e_3$ are ordered edges of a face of $\mathcal{T}$ endowed with orientation induced by the order, then $\Phi(e_1)\Phi(e_2)\Phi(e_3) = 1$.

A $G$-gauge of $\mathcal{T}$ is a map from the set of vertices of $\mathcal{T}$ to $G$. The $G$-gauges of $\mathcal{T}$ form a multiplicative group which acts on the set of $G$-colorings of $\mathcal{T}$ as follows. If $\delta$ is a $G$-gauge of $\mathcal{T}$ and $\Phi$ is a $G$-coloring of $\mathcal{T}$, then the $G$-coloring $\delta\Phi$ is given by

$$(\delta\Phi)(e) = \delta(v^-_e)\Phi(e)\delta(v^+_e)^{-1},$$

where $v^-_e$ (resp. $v^+_e$) is the initial (resp. terminal) vertex of an oriented edge $e$.

Let $\mathcal{M}(M, G)$ be the set of conjugacy classes of group homomorphisms from the fundamental group of $M$ to $G$. The elements of $\mathcal{M}(M, G)$ bijectively correspond to the $G$-colorings of $\mathcal{T}$ considered up to gauge transformations. Indeed, for a vertex $x_0$ of $\mathcal{T}$, each $G$-coloring $\Phi$ of $\mathcal{T}$ determines a homomorphism $\pi_1(M, x_0) \to G$. To compute this homomorphism on an element of $\pi_1(M, x_0)$, one represents this element by a loop based at $x_0$ and formed by a sequence of oriented edges of $\mathcal{T}$; then one takes the product of the values of $\Phi$ on these edges. Let $[\Phi] \in \mathcal{M}(M, G)$ be the conjugacy class of this homomorphism. We say that $\Phi$ represents $[\Phi]$. The assignment $\Phi \mapsto [\Phi]$ establishes the bijective correspondence mentioned above.

A state of a $G$-coloring $\Phi$ of $\mathcal{T}$ is a map $\varphi$ assigning to every oriented edge $e$ of $\mathcal{T}$ an element $\varphi(e)$ of $I_\Phi(e)$ such that $\varphi(-e) = \varphi(e)^*$ for all $e$. The set of all states of $\Phi$ is denoted $\text{St}(\Phi)$. The identity $b(\varphi(e)) = b(\varphi(-e))$ allows us to use the notation $b(\varphi(e))$ for non-oriented edges. It is easy to see that $\text{St}(\Phi) \neq \emptyset$ if and only if $I_\Phi(e) \neq \emptyset$ for all oriented edges $e$ of $\mathcal{T}$. In this case we say that $\Phi$ is admissible.

Let now $L$ be a non-empty link in $M$ and $(\mathcal{T}, \mathcal{L})$ be an $H$-triangulation of $(M, L)$ with charge $c$. From this data, we derive a certain partition function (state sum) as follows. Fix a total order on the set of vertices of $\mathcal{T}$. Consider a tetrahedron $T$ of $\mathcal{T}$ with vertices $v_1, v_2, v_3, v_4$ in increasing order. We say that $T$ is right oriented if the tangent vectors $v_1v_2$, $v_1v_3$, $v_1v_4$ form a positive basis in the tangent space of $M$; otherwise $T$ is left oriented. For an admissible $G$-coloring $\Phi$ of $\mathcal{T}$ and a state $\varphi \in \text{St}(\Phi)$, set

$$i = \varphi(v_1v_2), \quad j = \varphi(v_2v_3), \quad k = \varphi(v_1v_3),$$

$$l = \varphi(v_3v_4), \quad m = \varphi(v_1v_4), \quad n = \varphi(v_2v_4),$$

where $v_iv_j$ is the oriented edge of $T$ going from $v_i$ to $v_j$. Set

$$|T|_\varphi = \begin{cases} \{ i & j & k \} (c(v_1v_2), c(v_2v_3)) & \text{if } T \text{ is right oriented}, \\ \{ i & j & k \}^* (c(v_1v_2), c(v_2v_3)) & \text{if } T \text{ is left oriented}, \\ \{ l & m & n \} (c(v_1v_2), c(v_2v_3)) & \end{cases}$$

for all $i, j, k, l, m, n$. The product

$$\prod |T|_\varphi$$

is a well-defined function of $\varphi$.
The $6j$-symbol $|T|_\varphi$ belongs to the tensor product of four multiplicity modules associated to the faces of $T$. Specifically,

$$|T|_\varphi \in \begin{cases} H_{m_1}^{k_1} \otimes H_{j_1}^{i_1} \otimes H_{j_2}^{i_2} \otimes H_{m_2}^{k_2} & \text{if } T \text{ is right oriented}, \\ H_{m_1}^{k_1} \otimes H_{j_1}^{i_1} \otimes H_{k_2}^{j_2} \otimes H_{m_2}^{i_2} & \text{if } T \text{ is left oriented}. \end{cases}$$

Note that any face of $\mathcal{F}$ belongs to exactly two tetrahedra of $\mathcal{F}$, and the associated multiplicity modules are dual to each other, see Lemma 1. These dualities allow us to contract $\bigotimes_T |T|_\varphi$ into a scalar. Denote by $\text{cntr}$ the tensor product of all these tensor contractions determined by the faces of $\mathcal{F}$. Set

$$K(\mathcal{F}, \mathcal{L}, \Phi, c) = \sum_{\varphi \in \text{St}(\Phi)} \left( \prod_{e \in \mathcal{E}} b(\varphi(e)) \right) \text{cntr} \left( \bigotimes_T |T|_\varphi \right) \in k,$$

where $T$ runs over all tetrahedra of $\mathcal{F}$. To compute $K(\mathcal{F}, \mathcal{L}, \Phi, c)$ we may need to order the faces of $\mathcal{F}$, but the result does not depend on this order.

**Theorem 29.** Suppose that there exists a scalar $q \in k$ such that $q$ is $T$-equal to the operator

$$\tilde{q} \text{Id}_H \oplus \tilde{q}^{-1} \text{Id}_H \in \text{End}(H).$$

Then, up to multiplication by integer powers of $\tilde{q}$, the state sum $K(\mathcal{F}, \mathcal{L}, \Phi, c)$ depends only on the isotopy class of $L$ in $M$, the conjugacy class $[\Phi] \in \mathcal{M}(M, G)$, and the cohomology class $[c] \in H^1(M; \mathbb{Z}/2\mathbb{Z})$ (and does not depend on the choice of $c$ in its cohomology class, the admissible representative $\Phi$ of $[\Phi]$, the $H$-triangulation $\mathcal{F}$ of $(M, L)$, and the ordering of the vertices of $\mathcal{F}$).

A proof of this theorem will be given in Section 10.

**Lemma 30.** Any element of the set $\mathcal{M}(M, G)$ can be represented by an admissible $G$-coloring on an arbitrary quasi-regular triangulation $\mathcal{F}$ of $M$.

**Proof.** Take any $G$-coloring $\Phi$ of $\mathcal{F}$ representing the given element of $\mathcal{M}(M, G)$. We say that a vertex of $\mathcal{F}$ is bad for $\Phi$ if there is an oriented edge $e$ in $\mathcal{F}$ incident to this vertex and such that $I_{\Phi(e)} = \emptyset$. It is clear that $\Phi$ is admissible if and only if $\Phi$ has no bad vertices. We show how to modify $\Phi$ in the class $[\Phi]$ to reduce the number of bad vertices. Observe first that each pair (a vertex $v$ of $\mathcal{F}$, an element $g$ of $G$) determines a $G$-gauge $\delta^{v,g}$ whose value on any vertex $u$ of $\mathcal{F}$ is defined by

$$\delta^{v,g}(u) = \begin{cases} g & \text{if } u = v, \\ 1 & \text{else}. \end{cases}$$

Let $v$ be a bad vertex for $\Phi$. Pick any $g \in G$ such that $I_{\Phi(e)} \neq \emptyset$ for all edges $e$ of $\mathcal{F}$ adjacent to $v$ and oriented away from $v$. The $G$-coloring $\delta^{v,g}\Phi$ takes values in the set $\{h \in G \mid I_h \neq \emptyset\}$ on all edges of $\mathcal{F}$ incident to $v$ and takes the same values as $\Phi$ on all edges of $\mathcal{F}$ not incident to $v$. Here we use the fact that the edges of $\mathcal{F}$ are not loops which is ensured by the quasi-regularity of $\mathcal{F}$. The transformation $\Phi \mapsto \delta^{v,g}\Phi$ decreases the number
of bad vertices. Repeating this argument, we find a $G$-coloring without bad vertices in the class $[\Phi]$. \qed

We represent any $h \in \mathcal{M}(M, G)$ by an admissible $G$-coloring $\Phi$ of $\mathcal{T}$ and any $\zeta \in H^1(M; \mathbb{Z}/2\mathbb{Z})$ by a charge $c$, and set

$$K(M, L, h, \zeta) = K(\mathcal{T}, \mathcal{L}, \Phi, c) \in \mathbb{k}.$$ 

By Theorem 29, $K(M, L, h, \zeta)$ is a topological invariant of the tuple $(M, L, h, c)$.

### 10. Proof of Theorem 29

Throughout this section we keep the assumptions of Theorem 29.

**Lemma 31.** Up to multiplication by integer powers of $\tilde{q}$, $K(\mathcal{T}, \mathcal{L}, \Phi, c)$ does not depend on the ordering of the vertices of $\mathcal{T}$.

**Proof.** Consider the natural action of the symmetric group on the orderings of the vertices of $\mathcal{T}$. As the symmetric group is generated by simple transpositions $(r, r + 1)$, it is enough to consider the action of one such transposition on an ordering. If the vertices labeled by $r$ and $r + 1$ do not span an edge of $\mathcal{T}$, then the new state sum is identical to the old one. Suppose that an edge, $e$, of $\mathcal{T}$ connects the vertices labeled by $r$ and $r + 1$. Let $P$ be the set of all labels $p$ such that the vertices labeled by $r$, $r + 1$, and $p$ form a face of $\mathcal{T}$. This face, denoted $f_p$, belongs to two adjacent tetrahedra of $\mathcal{T}$ containing $e$ and determines two dual multiplicity spaces.

For a tetrahedron $T$ of $\mathcal{T}$, consider the transformation of the $6j$-symbol $|T|_\phi$ under the permutation $(r, r + 1)$. If $T$ does not contain $e$, then $|T|_\phi$ does not change. We claim that for $T \ni e$, the $6j$-symbol $|T|_\phi$ is multiplied by an integer power of $\tilde{q}$ independent of $\phi$ and composed with the tensor product of operators acting on the multiplicity spaces corresponding to $f_p$, where $p$ runs over the 2-element set $\{p \in P | f_p \subset T\}$. Here the operator corresponding to $p$ in this set is $A$ if $p > r$ and $B$ if $p < r$. Since $A$ and $B$ are involutive and self-dual, the effect of this transformation after the tensor contraction $\text{cntr}$ will be multiplication by an integer power of $\tilde{q}$ independent of $\phi$. This will imply the lemma.

The claim above follows from equations (50)–(52). Indeed, let $r, r + 1, p, p'$ be the labels of the vertices of $T$. Suppose for concreteness that $p < r$ and $r + 1 < p'$ (the other cases are similar). Then the left- (resp. right-) hand side of formula (51) with $a = c(T, v_p v_r)$, $b = c(T, v_p v_{r+1})$, $c = c(T, v_r v_{r+1})$ computes $|T|_\phi$ before (resp. after) the permutation of $r$ and $r + 1$. The operators $A_2$ and $B_3$ in (51) act on the multiplicity spaces corresponding to the faces $f_{p'}$ and $f_p$, respectively. Therefore formula (51) implies our claim. \qed

**Lemma 32.** Let $(\mathcal{T}, \mathcal{L})$, $(\mathcal{T}', \mathcal{L}')$ be H-triangulations of $(M, L)$ such that $(\mathcal{T}', \mathcal{L}')$ is obtained from $(\mathcal{T}, \mathcal{L})$ by a negative $H$-Pachner move or a negative $H$-bubble move. Then any admissible $G$-coloring $\Phi$ on $\mathcal{T}$ restricts to an admissible $G$-coloring $\Phi'$ of $\mathcal{T}'$. For any charge $c$ on $(\mathcal{T}, \mathcal{L})$, we have (up to multiplication by powers of $\tilde{q}$)

$$K(\mathcal{T}, \mathcal{L}, \Phi, c) = K(\mathcal{T}', \mathcal{L}', \Phi', c'),$$

where $c'$ is the charge on $(\mathcal{T}', \mathcal{L}')$ induced by $c$. 


Proof. The values of $\Phi'$ form a subset of the set of values of $\Phi$; therefore the admissibility of $\Phi$ implies the admissibility of $\Phi'$.

The rest of the proof follows the lines of [15], Section VII.2.3, via translating the geometric moves into algebraic identities. First, we prove (56) for a negative $H$-bubble move. Let $v_1, v_2, v_3, v_4$ be the vertices of $\mathcal{T}$ and $F = v_1v_2v_3$ the face of $\mathcal{T}'$ as in the description of the bubble move in Section 9.1 (see Figure 1). Since our state sums do not depend on the order of the vertices of $\mathcal{T}$ and the order of the vertices of $\mathcal{T}'$ is induced by the order of the vertices of $\mathcal{T}$. We can also assume that $v_4$ is the last in the order of the vertices of $\mathcal{T}$ and $v_1v_4, v_3v_4 \in \mathcal{L}$ and $v_1v_3 \in \mathcal{L'}$. Let $T_r$ (resp. $T_l$) be the right oriented (resp. left oriented) tetrahedron of $\mathcal{T}$ disappearing under the move. Let $a, b \in \frac{1}{2}\mathbb{Z}$ be the $c$-charges of the edges $v_1v_2, v_2v_3$ of $T_r$ respectively. The properties of a charge imply that the charges of the edges $v_1v_2, v_2v_3$ of $T_l$ are $-a$ and $-b$, respectively.

Figure 1. $T_l \cup T_r$ colored by $\varphi \in S$.

Fix a state $\varphi' \in \text{St}(\Phi')$ and let $S \subseteq \text{St}(\Phi)$ be the set of all states of $\Phi$ extending $\varphi'$. It is enough to show that the term $K_{\varphi'}$ of $K(\mathcal{T}', \mathcal{L}', \Phi', c')$ associated to $\varphi'$ is equal to the sum $\sum_{\varphi \in S} K_{\varphi}$ of the terms of $K(\mathcal{T}, \mathcal{L}, \Phi, c)$ associated to all $\varphi \in S$. Set $i = \varphi'(v_1v_2), j = \varphi'(v_2v_3)$, and $k = \varphi'(v_1v_3)$. For any distinct indices $p, q \in \{1,2,3,4\}$, set $I_{pq} = I_{\Phi'(v_pv_q)} \subset I$. The admissibility of $\Phi$ implies that $I_{pq} \neq \emptyset$ for all $p, q$. Clearly, $i \in I_{12}, j \in I_{23}, k \in I_{13}$. A state $\varphi \in S$ is determined by the labels

$$l = \varphi(v_3v_4) \in I_{34}, \quad m = \varphi(v_1v_4) \in I_{14}, \quad n = \varphi(v_2v_4) \in I_{24}.$$  

We have

$$|T_r|_{\varphi} = \begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} (a, b) \quad \text{and} \quad |T_l|_{\varphi} = \begin{pmatrix} i & j & k \\ l & m & n \end{pmatrix} (-a, -b).$$

It is convenient to write $|T_r|^{ijk}_{lmn}$ for $|T_r|_{\varphi}$ and $|T_l|^{ijk}_{lmn}$ for $|T_l|_{\varphi}$.

Denote by $*_{f}$ the tensor contraction determined by a face $f$. We have $K_{\varphi'} = *_{f}(b(k)X)$, where $X$ is the term of the state sum determined by $\varphi'$ before contraction $*_{F}$ and multiplication by $b(k)$. Let $F_r$ and $F_l$ be the faces of $T_r$ and $T_l$, respectively, with vertices $v_1, v_2, v_3$. We have

$K_{\varphi'} = *_{f}(b(k)X)$,
where the third equality follows from the first inversion relation and condition (ii) in Section 9.2. The existence of the admissible coloring \( \Phi \) and condition (iii) of Section 9.2 imply that in the latter expression \( g_j,l = 1 \) for all \( l \in I_{34} \). Therefore this expression is equal to

\[
* F_\varphi * F_I \left( X \otimes \sum_{l \in I_{34}, m \in I_{14}} b(l) b(m) *_{m}^{k l} *_{l}^{n} \left( |T_{ij}^{ijk} \otimes |T_{lj}^{ijkl}| \right) \right)
\]

\[
= * F_\varphi * F_I \left( X \otimes \sum_{l \in I_{34}, m \in I_{14}} b(l) b(m) *_{m}^{k l} \left( \sum_{n \in I_{24}} *_{l}^{m} |T_{ij}^{ijk} \otimes |T_{lj}^{ijkl}| \right) \right)
\]

\[
= * F_\varphi * F_I \left( X \otimes \sum_{l \in I_{34}, m \in I_{14}} b(l) b(m) *_{m}^{k l} (g_j,l (\delta_{m}^{k l} \otimes \delta_{k}^{ij})) \right)
\]

\[
= * F_\varphi * F_I \left( X \otimes \sum_{l \in I_{34}, m \in I_{14}} b(l) b(m) g_j,l \dim(H_k^{ij}) \right),
\]

where the second equality is ensured by condition (v) in Section 9.2. This proves the lemma for the \( H \)-bubble moves. Similarly, the \( H \)-Pachner move translates into the charged pentagon identity (53), see Figure 2. \( \square \)

**Figure 2.** Labeling for \( H \)-Pachner move.

**Lemma 33.** Let \( v \) be a vertex of \( T \) and let \( g \in G \) be such that \( I_g \neq \emptyset \). If \( \Phi \) and \( \delta^{v-g} \Phi \) are admissible \( G \)-colorings of \( T \), then \( K(T, L, \Phi, c) = K(T, L, \delta^{v-g} \Phi, c) \), where \( \delta^{v-g} \) is the \( G \)-gauge of \( T \) defined in (55).

**Proof.** A similar claim in a simpler setting (no charges and \( G \) is abelian) was established in [6], Lemma 27. The proof there relies on Lemma 26 of the same paper. Replacing
Lemma 26 by Lemma 32 above and making the appropriate adjustments, we easily adapt the argument in [6] to the present setting. □

**Lemma 34.** If admissible $G$-colorings $\Phi$ and $\Phi'$ of $\mathcal{T}$ represent the same element of $\mathcal{M}(M, G)$, then $K(\mathcal{T}, \mathcal{L}, \Phi, c) = K(\mathcal{T}, \mathcal{L}, \Phi', c)$ for any charge $c$.

**Proof.** Since $[\Phi] = [\Phi']$, there are pairs $(v_i, g_i) \in \{\text{vertices of } \mathcal{T}\} \times G$ such that

$$\Phi' = \delta_{v_n, g_n} \delta_{v_{n-1}, g_{n-1}} \cdots \delta_{v_1, g_1} \Phi.$$ 

Note that the gauges $\delta^{v, g}$ and $\delta^{v', g'}$ commute for all $g, g' \in G$ provided the vertices $v, v'$ are distinct. Using this property and the identity $\delta^{v, g} \delta^{v', g'} = \delta^{v, gg'}$, we can ensure that all the vertices $v_i$ in the expansion of $\Phi'$ are pairwise distinct.

We prove the lemma by induction on $n$. If $n = 0$, then $\Phi' = \Phi$ and there is nothing to prove. For $n \geq 1$, pick any $g \in G$ such that the sets $I_g, I_{gg_1^{-1}}, I_{g\Phi(e)},$ and $I_{gg_1^{-1}\Phi'(e)}$ are non-empty for all oriented edges $e$ of $\mathcal{T}$ outgoing from $v_1$. Then the colorings $\delta^{v_1, g} \Phi$ and $\delta^{v_1, gg_1^{-1}} \Phi'$ are admissible. Clearly,

$$\delta^{v_1, gg_1^{-1}} \Phi' = \delta_{v_n, g_n} \delta_{v_{n-1}, g_{n-1}} \cdots \delta_{v_2, g_2} \delta_{v_1, g_1} \Phi.$$ 

Lemma 33 and the induction assumption imply that

$$K(\mathcal{T}, \mathcal{L}, \Phi, c) = K(\mathcal{T}, \mathcal{L}, \delta^{v_1, g} \Phi, c) = K(\mathcal{T}, \mathcal{L}, \delta^{v_1, gg_1^{-1}} \Phi', c) = K(\mathcal{T}, \mathcal{L}, \Phi', c). \, □$$

Lemma 34 implies that $K(\mathcal{T}, \mathcal{L}, \Phi, c)$ depends only on the element of $\mathcal{M}(M, G)$ represented by $\Phi$. We represent any $h \in \mathcal{M}(M, G)$ by an admissible $G$-coloring $\Phi$ of $\mathcal{T}$ and set $K(\mathcal{T}, \mathcal{L}, h, c) = K(\mathcal{T}, \mathcal{L}, \Phi, c)$. The scalar $K(\mathcal{T}, \mathcal{L}, h, c)$ is invariant under negative $H$-Pachner/$H$-bubble moves. More precisely, Lemma 32 implies that under the assumptions of this lemma, for any $h \in \mathcal{M}(M, G)$, we have (up to multiplication by powers of $q$)

$$K(\mathcal{T}, \mathcal{L}, h, c) = K(\mathcal{T}', \mathcal{L}', h, c'). \tag{57}$$

**Lemma 35.** For any $h \in \mathcal{M}(M, G)$, the scalar $K(\mathcal{T}, \mathcal{L}, h, c)$ does not depend on the choice of the charge $c$ in its cohomology class.

**Proof.** The lemma is proved in two steps: first, any two charges are connected by a finite sequence of local modifications and second, the state sum is shown to be preserved under these modifications. Recall from Section 9.1 the set $\hat{E}(\mathcal{T})$ of pairs (a tetrahedron $T$ of $\mathcal{T}$, an edge of $T$). Let $*$ be the involution on $\hat{E}(\mathcal{T})$ carrying a pair $(T, e)$ to the pair $*(T, e) = (T, *e)$ where $*e$ is the edge of $T$ opposite to $e$. Fix from now on an order on the set of vertices of $\mathcal{T}$.

For each edge $e$ of $\mathcal{T}$ we define a map $d(e) : \hat{E}(\mathcal{T}) \to \{-1/2, 0, 1/2\}$ as follows. Let $v$ be the vertex of $e$ which is largest in the ordering of vertices. Let $T_0, T_1, T_2, \ldots, T_n = T_0$ be the vertex of $e$.
be the cyclically ordered tetrahedra of $\mathcal{T}$ adjacent to $e$. We choose the cyclic order so that the induced orientation in the plane transversal to $e$ followed by the orientation of $e$ towards $v$ determines the given orientation of $M$. For $i = 1, \ldots, n$, denote by $e_i$ the only edge of the 2-face $T_{i-1} \cap T_i$ which is distinct from $e$ and incident to $v$. For any $a \in E(\mathcal{T})$, set

$$d(e)(a) = \begin{cases} 1/2 & \text{if } a = (T_{i-1}, e_i) \text{ or } a = *(T_{i-1}, e_i) \text{ for some } i \in \{1, \ldots, n\}, \\ -1/2 & \text{if } a = (T_i, e_i) \text{ or } a = *(T_i, e_i) \text{ for some } i \in \{1, \ldots, n\}, \\ 0 & \text{otherwise.} \end{cases}$$

It is easy to see that for any family of integers $\{\lambda_e\}_e$ numered by the edges $e$ of $\mathcal{T}$ the sum $c + \sum e \lambda_e d(e)$ is a charge of $(\mathcal{T}, \mathcal{L})$ and \[ c + \sum e \lambda_e d(e) = [c]. \] The following is due to Baseilhac [1], see also Neumann [13] and [2], Proposition 4.8:

**Fact.** For any pair of charges $c, c'$ of $(\mathcal{T}, \mathcal{L})$ with $[c] = [c']$, there is a family of integers $\{\lambda_e\}_e$ numered by the edges $e$ of $\mathcal{T}$ such that $c' = c + \sum e \lambda_e d(e)$.

Therefore to prove the lemma, it is enough to show that for any edge $e$ of $\mathcal{T}$,

$$\text{K}(\mathcal{T}, \mathcal{L}, h, c) = \text{K}(\mathcal{T}, \mathcal{L}, h, c + d(e)). \quad (58)$$

We show how to reduce the case $e \in \mathcal{L}$ to the case $e \notin \mathcal{L}$. Suppose that $e \in \mathcal{L}$. Pick a face $F$ of $\mathcal{T}$ containing $e$. We apply the $H$-bubble move to $F$ producing a new $H$-triangulation $(\mathcal{T}_b, \mathcal{L}_b)$ such that $e$ viewed as an edge of $\mathcal{T}_b$ does not belong to $\mathcal{L}_b$. Pick a charge $c_b$ on $\mathcal{T}_b$ inducing the charge $c$ on $\mathcal{T}$. A direct calculation shows that the charge $c_b + d(e)$ on $\mathcal{T}_b$ induces the charge $c + d(e)$ on $\mathcal{T}$. By (57), we have

$$\text{K}(\mathcal{T}, \mathcal{L}, h, c) = \text{K}(\mathcal{T}_b, \mathcal{L}_b, h, c_b) \quad \text{and} \quad \text{K}(\mathcal{T}, \mathcal{L}, h, c + d(e)) = \text{K}(\mathcal{T}_b, \mathcal{L}_b, h, c_b + d(e)).$$

Therefore, it is enough to prove (58) in the case $e \notin \mathcal{L}$.

Suppose from now on that $e \notin \mathcal{L}$. We first reduce the proof of (58) to the case where $e$ is contained in at least three tetrahedra of $\mathcal{T}$ and $\mathcal{T}$ has a vertex such that there is precisely one face of $\mathcal{T}$ containing $e$ and this vertex. Let $V$ be the set of vertices of $\mathcal{T}$. Pick a face of $\mathcal{T}$ not containing $e$ and having at least one side in $\mathcal{L}$. We apply to this face the $H$-bubble move producing a new $H$-triangulation $(\mathcal{T}', \mathcal{L}')$ whose set of vertices is the union of $V$ with a 1-point set $\{v_0\}$. Pick a charge $c'$ on $\mathcal{T}'$ inducing the charge $c$ on $\mathcal{T}$. We can find a sequence $T_0, T_1, \ldots, T_m$ of distinct tetrahedra of $\mathcal{T}'$ with $m \geq 1$ such that: $v_0 \in T_0$ and $T_0 \cap T_1$ is the face of $T_0$ opposite to $v_0$; $T_i \cap T_{i+1}$ contains a common face of $T_i$ and $T_{i+1}$ for all $i$; $T_i$ does not contain $e$ for all $i < n$ and $e \subset T_m$. Generally speaking, the intersection $T_i \cap T_{i+1}$ may contain more than one face; we pick any face in this intersection and denote it $T_i \cap T_{i+1}$. We apply to $\mathcal{T}'$ a sequence of $m$ positive $H$-Pachner moves. The first move replaces the pair $T_0, T_1$ by three tetrahedra and adds an edge connecting $v_0$ to the vertex of $T_1$ opposite to $T_0 \cap T_1 = T_0 \cap T_1$. One of these new three tetrahedra, $t$, contains the face $T_1 \cap T_2$. The second move replaces the pair $t, T_2$ by three tetrahedra and adds an edge connecting $v_0$ to the vertex of $T_2$ opposite to $T_1 \cap T_2$. Continuing in this way $m$ times, we transform $(\mathcal{T}', \mathcal{L}')$ into a new $H$-triangulation $(\mathcal{T}''', \mathcal{L}''')$ having a (unique) face that
contains both \( v_0 \) and \( e \). The triangulation \( \mathcal{T}'' \) and all the intermediate triangulations are quasi-regular because the newly added edges always connect \( v_0 \) to another vertex (belonging to \( V \)). Our transformations preserve the set \( V \cup \{v_0\} \) of the vertices of the triangulation and lift to the charges (though non-uniquely). If the charge \( c' \) of \( \mathcal{T}' \) is transformed into a charge \( c_k \) at the \( k \)-th step, then \( c_k + d(e) \) is a transformation of \( c' + d(e) \) (this is obvious for \( k < m \) and is verified by a direct computation for \( k = m \)). Set \( c'' = c_m \) and observe that as above,

\[
K(\mathcal{T}, \mathcal{L}, h, c) = K(\mathcal{T}', \mathcal{L}', h, c') = K(\mathcal{T}'', \mathcal{L}'', h, c'')
\]

and

\[
K(\mathcal{T}, \mathcal{L}, h, c + d(e)) = K(\mathcal{T}', \mathcal{L}', h, c' + d(e)) = K(\mathcal{T}'', \mathcal{L}'', h, c'' + d(e)),
\]

where on the right-hand side we view \( e \) as an edge of \( \mathcal{T}'' \). Note that \( e \) is contained in at least three tetrahedra of \( \mathcal{T}'' \) because at the \((m - 1)\)-st step the edge \( e \) is contained in \( T_m \) and in at least one other tetrahedron of the triangulation, and the \( m \)-th move above creates three tetrahedra of which two contain \( e \). Moreover, there is precisely one face of \( \mathcal{T}'' \) containing \( e \) and the vertex \( v_0 \).

Let \( A_1, A_2 \) be the vertices of \( e \) and \( t_1, t_2, \ldots, t_n \) with \( n \geq 3 \) be the cyclically ordered tetrahedra of \( \mathcal{T}'' \) adjacent to \( e \). Let \( B_1 = v_0, B_2, \ldots, B_n \) be the vertices of \( \mathcal{T}'' \) (possibly with repetitions) such that \( A_1, A_2, B_i, B_{i+1} \) are the vertices of \( t_i \) for all \( i \) (here \( B_{n+1} = B_1 \)). Clearly, \( B_i \neq B_1 \) for all \( i \neq 1 \). If \( n > 3 \), then we apply to \( \mathcal{T}'' \) a positive \( H \)-Pachner move replacing \( t_1, t_2 \) by three tetrahedra and adding an edge connecting \( B_1 = v_0 \) to \( B_3 \). This produces a quasi-regular triangulation (\( \mathcal{T}''', \mathcal{L}''' \)) of \((M, L)\) with the same properties as \( \mathcal{T}'' \) but having \( n - 1 \) tetrahedra adjacent to \( e \). As above,

\[
K(\mathcal{T}'', \mathcal{L}'', h, c'') = K(\mathcal{T'''}, \mathcal{L''''}, h, c''')
\]

and

\[
K(\mathcal{T}'', \mathcal{L}'', h, c'' + d(e)) = K(\mathcal{T'''}, \mathcal{L''''}, h, c''' + d(e))
\]

for a certain charge \( c''' \) on \( \mathcal{T}''' \). Proceeding by induction, we reduce ourselves to the case \( n = 3 \). In this case, the edge \( e \) may be eliminated by a negative \( H \)-Pachner move so that the equality (58) follows from (57).

**Proof of Theorem 29.** Theorem 29 follows from the results of this section and Proposition 26.

**11. Cayley–Hamilton Hopf algebras**

In this section, we recall some of the results of [4] and use them to construct \( \Psi \)-systems in categories. We assume that the ground field \( k \) is algebraically closed and is of characteristic 0.

**Definition 36.** An algebra with trace is an (associative) algebra $\mathcal{R}$ over $k$ with a $k$-linear map $t : \mathcal{R} \to \mathcal{R}$ such that for all $a, b \in \mathcal{R}$,

$$t(a)b = bt(a), \quad t(ab) = t(ba), \quad t(a)t(b) = t(t(a)b).$$

The image $t(\mathcal{R})$ of $t$ is a subalgebra of $\mathcal{R}$ called the trace subalgebra. Note that $t(\mathcal{R})$ is contained in the center $Z$ of $\mathcal{R}$. In the polynomial algebra $k[x_1, \ldots, x_n]$ we define the elementary symmetric functions $e_i(x_1, \ldots, x_n)$,

$$\prod_{i=1}^n (x - x_i) = x^n + \sum_{i=1}^n e_i(x_1, \ldots, x_n)x^{n-i},$$

and the Newton functions

$$\psi_k(x_1, \ldots, x_n) = \sum_{i=1}^n x_i^k, \quad 1 \leq k \leq n,$$

which are well known to be related for certain uniquely defined polynomials $P_i(y_1, \ldots, y_i)$:

$$e_i(x_1, \ldots, x_n) = P_i(\psi_1(x_1, \ldots, x_n), \ldots, \psi_i(x_1, \ldots, x_n)).$$

**Definition 37.** An algebra with trace $(\mathcal{R}, t)$ is an $n$-th Cayley–Hamilton algebra, if $t(1) = n$ and

$$a^n + \sum_{i=1}^n P_i(t(a), t(a^2), \ldots, t(a^i))a^{n-i} = 0$$

for any $a \in \mathcal{R}$.

A prototypical example of an $n$-th Cayley–Hamilton algebra is the matrix algebra $M_n(k)$ of $n \times n$ matrices over $k$ with the usual trace (with values in $k = k \text{Id} \subset M_n(k)$).

Let $(\mathcal{R}, t)$ be a finitely generated $n$-th Cayley–Hamilton algebra with trace subalgebra $A = t(\mathcal{R})$. In the rest of this section we assume that:

(i) $\mathcal{R}$ is prime (that is the product of any two non-zero ideals is non-zero),

(ii) $\mathcal{R}$ is a finite $A$-module,

(iii) the center $Z$ of $\mathcal{R}$ is integrally closed,

(iv) $A$ is a finitely generated algebra over $k$.

The reduced trace of $\mathcal{R}$ is defined by the formula $t_{\mathcal{R}/A} = \frac{m}{n} t$, where $m \geq 1$ is the minimal divisor of $n$ such that $\mathcal{R}$ is an $m$-th Cayley–Hamilton algebra with trace $\frac{m}{n} t$. Then

$$m = [\mathcal{R} : A] = \dim_A \mathcal{R}.$$
and there exists a reduced trace \( t_{R/Z} : R \to Z \) such that \( t_{R/A} = t_{Z/A} \circ t_{R/Z} \). Note that \([R : A] = [R : Z][Z : A]\).

By an \( n \)-dimensional representation of \((R, t)\) we mean an algebra homomorphism \( \phi : R \to M_n(k) \) which is compatible with traces in the sense that \( t(a) = \text{Tr}(\phi(a)) \) for all \( a \in R \), where \( \text{Tr} \) is the standard trace on \( M_n(k) \). Let \( V(A) \) be the affine algebraic variety associated to \( A \), which can be identified with the maximal spectrum of \( A \) or with the set of homomorphisms \( A \to k \). By \([4], \text{Theorem 3.1}\), the (closed) points of \( V(A) \) parametrize semi-simple representations of \((R, t_{R/A})\) of dimension \( m = [R : A] \). We can similarly use the points of \( V(A) \) to parametrize semi-simple representations of \((Z, t_{Z/A})\) of dimension \( p = [Z : A] \). Since \( R \) is a finite \( A \)-module, \( Z \) also is a finite \( A \)-module. Then \( Z \) is a finitely generated algebra over \( k \) and its associated affine variety \( V(Z) \) parametrizes semi-simple representations of \((R, t_{R/Z})\) of dimension \([R : Z]\). Observe finally that the inclusion \( A \subset Z \) defines a morphism of algebraic varieties \( \pi : V(Z) \to V(A) \) of degree \( p \).

Given a point \( x \in V(A) \), denote by \( N_x \) the corresponding \( m \)-dimensional semi-simple representation of \( R \). Given a point \( P \in V(Z) \), denote by \( M_p \) the corresponding \([R : Z]\)-dimensional semi-simple representation of \( R \). For \( x \in V(A) \), the fiber \( \pi^{-1}(x) \) (with multiplicities) is a cycle \( \sum h_i P_i \) of degree \( \sum h_i = p \), where \( P_i \in V(Z) \) and \( h_i \geq 1 \). One has the following equality of \( R \)-modules:

\[
N_x = \bigoplus_i h_i M_{P_i}.
\]

The Zariski open subset of \( V(A) \) consisting of the points \( x \) such that \( \pi^{-1}(x) \) consists of \( p \) distinct points is called the unramified locus of \( R \). For \( x \) in the unramified locus, any \( P_i \in \pi^{-1}(x) \) corresponds to an irreducible representation \( M_{P_i} \).

### 11.2. Cayley–Hamilton Hopf algebras.

**Definition 38.** An \( n \)-th Cayley–Hamilton Hopf algebra is a Hopf algebra which is also an \( n \)-th Cayley–Hamilton algebra such that the trace subalgebra is a Hopf subalgebra.

Assume now that \( R \) is a Cayley–Hamilton Hopf algebra satisfying the assumptions (i)–(iv) of the last subsection. The co-multiplication on \( A \) defines an associative binary operation on the variety \( G = V(A) \) while the antipode defines the inverse operation, so \( G \) becomes an algebraic group. One has the following decomposition formula for \( x, y \in G \) ([4], Proposition 5.15):

\[
N_x \otimes N_y = mN_{xy}, \quad \text{where} \quad m = [R : A].
\]

A pair \( x, y \in G \) is generic if \( x, y \) and \( xy \) lie in the unramified locus. Then for each point \( P \in V(Z) \) lying in the fiber of \( x, y \) or \( xy \) the corresponding representation \( M_P \) is irreducible. For \( P \in \pi^{-1}(x) \) and \( Q \in \pi^{-1}(y) \), one has the following Clebsch–Gordan decomposition ([4], Theorem 5.16):

\[
M_P \otimes M_Q \simeq \bigoplus_{O \in \pi^{-1}(xy)} M_O^{\otimes h_P^O} \quad \text{and} \quad \sum h_P^O = [R : Z]
\]
for some non-negative integers $h^P_Q$. Also $\sum_{P,Q} h^P_Q = m$ for all $O \in \pi^{-1}(xy)$. Note that generic pairs $(x, y)$ form a Zariski open subvariety in $G \times G$.

For $x \in G$ we define a set $I_x$ as follows: if $x$ is in the unramified locus, then $I_x = \pi^{-1}(x)$, otherwise $I_x = \emptyset$. Set $I = \bigcup_{x \in G} I_x$ and consider the family $\{M_P\}_{P \in I}$ of irreducible representations discussed above.

**Theorem 39.** Let $\mathcal{C}$ be the monoidal Ab-category of $\mathcal{R}$-modules of finite dimension over $k$. Then $\mathcal{C}$ has a $\Psi$-system with distinguished simple objects $\{M_P\}_{P \in I}$.

**Proof.** Any $P \in I$ belongs to $I_x$ for a unique point $x$ of the unramified locus. Using the antipode $S : \mathcal{R} \to \mathcal{R}$, we associate to the irreducible representation $M_P$ the dual representation $M^*_P$ together with the evaluation morphism of $\mathcal{R}$-modules $M^*_P \otimes M_P \to k$ and the coevaluation morphism $k \to M^*_P \otimes M^*_P$ determined by $1 \mapsto \sum v_i \otimes v^*_i$ where $\{v_i\}$ is a basis of $M_P$ and $\{v^*_i\}$ is the dual basis of $M^*_P$. The representation $M^*_P$ is isomorphic to $M_{P^*}$ where $P^* = P \circ S \in \pi^{-1}(x^{-1})$ and $x^{-1} = x \circ S$. Thus, we obtain an involution $I \to I$, $P \mapsto P^*$ and $\mathcal{R}$-module morphisms $d_P : M^*_P \otimes M_P \to k$, $b_P : k \to M_P \otimes M^*_P$ satisfying equation (1). Equation (2) follows from (59). Thus, $\{M_P\}_{P \in I}$ is a $\Psi$-system. □

**Theorem 41.** Let $b : I \to k$ be the constant function taking the value $1/m$. The triple $(G, I, b)$ satisfies conditions (i)–(v) of Subsection 9.2 (where instead of $\Psi$-systems we should speak of $\Psi$-systems).

**Proof.** Condition (i) follows from the fact that if $x$ is in the unramified locus then so is $x^{-1} = x \circ S$. Conditions (ii) and (iii) follow from (59). Moreover, (59) implies that if $x_1, x_2, x_1x_2$ are in the unramified locus and $P \in I_{x_1x_2}$, then

$$\sum_{P_1 \in I_{x_1}, P_2 \in I_{x_2}} b(P_1)b(P_2) \dim(H^P_{P_1P_2}) = \frac{1}{m^2} \sum_{P_1 \in I_{x_1}, P_2 \in I_{x_2}} \dim(H^P_{P_1P_2}) = \frac{m}{m^2} = b(P).$$

This implies condition (v). Condition (iv) holds since the unramified locus is a Zariski open subset of $G = V(A)$. □

**Remark 41.** A Cayley–Hamilton Hopf algebra $\mathcal{R}$ is sovereign if $\mathcal{R}$ contains a group-like element $\phi$ such that $S^2(x) = \phi^{-1}x\phi$ for all $x \in \mathcal{R}$. If $\mathcal{R}$ is sovereign then the results of [3] imply that the category $\mathcal{C}$ of Theorem 39 is sovereign (also known as pivotal). In this case, the right duality comes from the sovereign structure on $\mathcal{C}$. Then the general theory of sovereign categories implies that the operator $C = (AB)^3 \in \text{End}(H)$ is the identity.

**11.3. Examples from quantum groups at roots of unity.** Let $g$ be a simple Lie algebra of rank $n$ over $k = \mathbb{C}$ with the root system $\Delta$. Fix simple roots $\alpha_1, \ldots, \alpha_n \in \Delta^+$ and denote by $(a_{ij})_{i,j=1}^n$ the corresponding Cartan matrix. Denote by $d_i$ the length of the $i$-th simple root.

For an odd positive integer $N$ denote by $\zeta$ a primitive complex root of $1$ of order $N$ (in the case of type $G_2$ we require that $N \notin 3\mathbb{Z}$).
Consider the quantized universal enveloping algebra $\mathcal{U}_\varpi = U_\varpi(\mathfrak{g})$. It is an associative unital algebra over $\mathbb{C}$ generated by $K_\mu$, where $\mu$ runs over the weight lattice of $\mathfrak{g}$ and $E_i, F_i$, $i = 1, \ldots, n$ with the defining relations

$$K_\mu K_\nu = K_{\mu + \nu}, \quad K_0 = 1,$$

$$K_\mu E_i = \varpi^{\alpha_i(\mu)} E_i K_\mu, \quad K_\mu F_i = \varpi^{-\alpha_i(\mu)} F_i K_\mu,$$

$$E_i F_j - F_j E_i = \delta_{ij} \frac{K_{\alpha_i} - K_{-\alpha_i}}{\varpi_i - \varpi_{-i}},$$

$$\sum_{k=0}^{1-a_{ij}} (-1)^k \binom{1-a_{ij}}{k} \varpi_i^{1-a_{ij}-k} E_i^{1-a_{ij}-k} E_j^k = 0, \quad i \neq j,$$

$$\sum_{k=0}^{1-a_{ij}} (-1)^k \binom{1-a_{ij}}{k} \varpi_i^{1-a_{ij}-k} F_i^{1-a_{ij}-k} F_j^k = 0, \quad i \neq j,$$

where $\varpi_i = \varpi^{a_i}$ and

$$\binom{m}{k}_{\varpi} = \frac{[m]_{\varpi}!}{[m-k]_{\varpi}![k]_{\varpi}!}, \quad [m]_{\varpi}! = [m]_{\varpi}[m-1]_{\varpi} \cdots [2]_{\varpi}[1]_{\varpi}, \quad [m]_{\varpi} = \varpi_m - \varpi^{-m}.$$

The formulas

$$\Delta(K_\mu) = K_\mu \otimes K_\mu,$$

$$\Delta(E_i) = E_i \otimes 1 + K_{\alpha_i} \otimes E_i,$$

$$\Delta(F_i) = 1 \otimes F_i + F_i \otimes K_{-\alpha_i},$$

define a homomorphism of algebras $\Delta : \mathcal{U}_\varpi \to \mathcal{U}_\varpi \otimes \mathcal{U}_\varpi$. There are unique counit and antipode turning $\mathcal{U}_\varpi$ into a Hopf algebra with comultiplication $\Delta$. We denote by $\mathcal{U}_{\varpi}^{\pm}$ the subalgebras of $\mathcal{U}_\varpi$ generated by $\{E_i\}_i$ and $\{F_i\}_i$ respectively. The subalgebra generated by $\{K_\mu\}_\mu$ will be denoted by $\mathcal{U}_\varpi^0$. We also consider Hopf subalgebras $\mathcal{B}_\varpi = \mathcal{U}_{\varpi}^0 \otimes \mathcal{U}_{\varpi}^0$. It is known that the subalgebras $Z^+_0 \subset \mathcal{B}_\varpi$ generated by $E_x^N, K_{a_i}$ (respectively $F_x^N, K_{a_i}$) and the subalgebra $Z_0 \subset \mathcal{B}_\varpi$ generated by $E_x^N, F_x^N, K_{a_i}$ are central Hopf subalgebras. Moreover, $\mathcal{B}_\varpi^{\pm}$ and $\mathcal{U}_\varpi$ are Cayley–Hamilton Hopf algebras with trace subalgebras $Z^+_0$ and $Z_0$ respectively, see [4]. In all these three situations, Theorem 39 produces a monoidal Ab-category $\mathcal{C}$ with a $\Psi$-system.

**Conjecture 42.** This $\Psi$-system can be extended to a $\Psi$-system in $\mathcal{C}$ such that there exists a scalar $\tilde{q} \in \mathbb{C}$ for which the operator $q \in \text{End}(H)$ of Lemma 19 is $T$-equal to $\tilde{q} \text{Id}_H \oplus \tilde{q}^{-1} \text{Id}_H$.

If this conjecture is true, then Theorem 29 implies that the state sum arising from $\mathcal{C}$ with this $\Psi$-system and the algebraic data of Theorem 40 is a topological invariant of the triple (a closed connected oriented 3-manifold $M$, a non-empty link in $M$, a conjugacy class of homomorphisms $\pi_1(M) \to G$). In the next section, we verify Conjecture 42 for the Borel subalgebra of $U_\varpi(\mathfrak{sl}_2)$ for any primitive complex root of unity $\varpi$ of odd order $N$. The corresponding topological invariant generalizes the one constructed in [7] which in the case of links in the 3-sphere coincides with the $N$-colored Jones polynomial evaluated at $\varpi$. 
12. The Borel subalgebra of $U_{\infty}(\mathfrak{sl}_2)$

12.1. The $\Psi$-system. As above, fix a positive integer $N$ and a primitive $N$-th root of unity $\varpi$. In what follows, $\mathbb{Z}_N = \mathbb{Z}/N\mathbb{Z}$. Consider the Hopf algebra $B_{\varpi}$ defined by the following presentation:

$$\mathbb{C}\langle a^{\pm 1}, b \mid ab = \varpi ba, \Delta(a) = a \otimes a, \Delta(b) = a \otimes b + b \otimes 1 \rangle.$$ 

Following [7], [9], we consider the cyclic representations of $B_{\varpi}$, i.e. the representations carrying $b$ to an invertible operator.

Let $G = \mathbb{R} \times \mathbb{R}_{>0}$ be the upper half plane with the group structure given by

$$(x, y)(u, v) = (x + yu, yv).$$

As a topological space, the set $I_1 = G \setminus \{(0, 1) \times \mathbb{R}_{>0}\}$ has two connected components

$$I_{\pm} = \{(x, y) \in G \mid \pm x > 0\}.$$ 

We fix $\epsilon \in \mathbb{C}$ such that $\epsilon^N = -1$. In particular, in the case of odd $N$, we assume that $\epsilon = -1$. We define the $N$-th root function $\sqrt[N]{x}$ on real numbers $x$ by the condition that it is positive real for positive real $x$ and $\sqrt[N]{x} = \epsilon \sqrt[N]{-x}$ for negative $x$. Define two maps

$$u : G \rightarrow \mathbb{R}_{>0}, \quad v : G \rightarrow \mathbb{R}_{>0} \cup \epsilon \mathbb{R}_{>0},$$

$$u(g) = u_g = \sqrt[N]{y}, \quad v(g) = v_g = \sqrt[N]{x}, \quad g = (x, y) \in G.$$ 

We have the following properties:

$$u_{gh} = u_g u_h, \quad u_{g^{-1}} = \frac{1}{u_g},$$

and

$$v_{g^{-1}} = \epsilon_g v_g, \quad \epsilon_g = \epsilon^{\pm 1}, \quad g \in I_{\pm}.$$ 

To any $g \in I$, we associate a $B_{\varpi}$-module $V_g$ which is an $N$-dimensional vector space with a distinguished basis $\{w_i\}_{i \in \mathbb{Z}_N}$, and the (left) $B_{\varpi}$-module structure is given by the formulae

$$aw_i = u_g \varpi^i w_i, \quad bw_i = v_g w_{i+1}, \quad i \in \mathbb{Z}_N.$$ 

Note that the distinguished basis permits to identify $V_g$ with $\mathbb{C}^N$.

In what follows, we need the following function:

$$\Phi_{g, m} = (-\epsilon_g)^m \varpi^{m(m-1)/2}, \quad \Phi_{g, m} = \frac{1}{\Phi_{g, m}}, \quad m \in \mathbb{Z}_N.$$
Proposition 43. In the category of $B_\omega$-modules, the set of objects $\{V_g\}_{g \in I}$ with the involution $g^* = g^{-1}$ is a $\Psi$-system, where the duality morphisms

$$d_g : V_g \otimes V_g^* \to \mathbb{C}, \quad b_g : \mathbb{C} \to V_g \otimes V_g^*$$

are given by the formulae

$$d_g(w_i \otimes w_j) = \begin{cases} \Phi_{g,i} & \text{if } i + j = 0, \\ 0 & \text{otherwise}, \end{cases} \quad b_g(1) = \sum_{i \in \mathbb{Z}_N} \Phi_{g^*,-i} w_i \otimes w_{-i},$$

and the multiplicity spaces $H_{fg}^{f,g}$ are such that $\dim(H_{fg}^{f,g})$ is $N$ if $h = fg$ and zero otherwise.

Proof. It is straightforward to verify that $d_g$ and $b_g$ are morphisms of the category of $B_\omega$-modules. The dimensions of the multiplicity spaces were calculated in [7], [9]. \qed

12.2. Calculation of the operators $A$, $B$, $L$, and $R$. Let us call a pair of elements $g, h \in I$ admissible if $gh \in I$. For an operator $E$ satisfying the equation $E^N = -1$ and an admissible pair $(g, h)$, we associate an operator valued function $\Psi_{g,h}(E)$ as a solution of the functional equation

$$\frac{\Psi_{g,h}(\varpi E)}{\Psi_{g,h}(E)} = \frac{v_g - u_g v_h E}{v_{gh}}.$$

More precisely, we choose numerical coefficients $\psi_{g,h,m}$, $m \in \mathbb{Z}_N$, such that

$$\Psi_{g,h}(E) = \sum_{m \in \mathbb{Z}_N} \psi_{g,h,m}(\epsilon E)^m.$$

The above functional equation translates to the following difference equation:

$$\frac{\psi_{g,h,m}}{\psi_{g,h,m-1}} = \frac{\epsilon^{-1} u_g v_h}{v_g - v_{gh} \varpi^m}.$$

We fix a unique solution of the latter equation normalized so that $\psi_{g,h,0} = 1$. Using the notation of [10], we have

$$\psi_{g,h,m} = w(v_{gh}, u_g v_h/\epsilon, v_g | m), \quad \Psi_{g,h}(E) = f(v_{gh}/v_g, 0 | Eu_g v_h/v_g),$$

where

$$w(x, y, z | m) = \frac{(y/z)^m}{(\varpi x/z; \varpi)_m}, \quad x^N + y^N = z^N,$$

$$f(x, y | z) = \sum_{m \in \mathbb{Z}_N} \frac{\varpi^m y | \varpi^m}{(\varpi x; \varpi)_m} z^m, \quad 1 - x^N = (1 - y^N) z^N,$$

and

$$(x; \varpi)_m = \prod_{j=0}^{m-1} (1 - x \varpi^j).$$
For two operators \( U \) and \( V \) satisfying the conditions \( U^N = V^N = 1, \) \( UV = VU, \) we also define

\[
L(U, V) = \frac{1}{N} \sum_{i,j \in \mathbb{Z}_N} \omega^{ij} U^i V^j.
\]

In what follows, the standard basis \( \{ e_i \} \) of \( \mathbb{C}^N \) will be indexed by elements of \( \mathbb{Z}_N. \) Define operators \( X, Y \in \text{Aut}(\mathbb{C}^N), \)

\[
X e_i = \omega^i e_i, \quad Y e_i = e_{i+1}, \quad i \in \mathbb{Z}_N.
\]

For \( g \in I, \) let \( \pi_g : B_\omega \rightarrow \text{End}(V_g) \) be the algebra homomorphism corresponding to the \( B_\omega \)-module structure of \( V_g. \)

**Lemma 44.** For any admissible pair \((g, h)\), the operator valued function

\[
S_{g,h} = \Psi_{g,h}(-Y^{-1}X \otimes Y)L(Y \otimes 1, 1 \otimes X)
\]

takes its values in the set of invertible matrices and satisfies the equation

\[
(\pi_g \otimes \pi_h)(\Delta(x)) = S_{g,h}(\pi_{gh}(x) \otimes \text{id}_{\mathbb{C}^N}) S_{g,h}^{-1}, \quad \forall x \in B_\omega.
\]

**Proof.** A straightforward computation. \( \square \)

The operator \( S_{g,h}, \) considered as a linear map \( S_{g,h} : V_{gh} \otimes \mathbb{C}^N \rightarrow V_g \otimes V_h, \) permits to identify the multiplicity spaces \( H_{gh}^{g,h} \) and \( H_{g,h}^{gh} \) with \( \mathbb{C}^N \) and \( (\mathbb{C}^N)^* \), respectively, through the formulæ

\[
fv = S_{g,h}(v \otimes f), \quad f \in H_{gh}^{g,h}, \quad v \in V_{gh},
\]

\[
f(v \otimes w) = (\text{id}_{V_{gh}} \otimes f) (S_{g,h}^{-1}(v \otimes w)), \quad v \in V_g, \quad w \in V_h, \quad f \in H_{g,h}^{gh}.
\]

In what follows, we shall use the notation \( e_i \) and \( e_i^* \) for the dual bases in \( H_{gh}^{g,h} \) and \( H_{g,h}^{gh} \) respectively, which correspond to the standard dual bases in \( \mathbb{C}^N \) and \( (\mathbb{C}^N)^* \).

**Lemma 45.** The action of the operators \( A, A^*, B, \) and \( B^* \) is given by

\[
A e_i = \Psi_{g^*,gh}(\epsilon g \omega) \sum_{j \in \mathbb{Z}_N} \Phi_{g^*,i-j} e_j^*, \quad A^* e_i = \Psi_{g,h}(\omega/\epsilon g) \sum_{j \in \mathbb{Z}_N} \Phi_{g,j-i} e_j^*,
\]

\[
e_i \in H_{g,h}^{g,h}, \quad e_j^* \in H_{g^*,gh}^h.
\]

\[
A e_i^* = \frac{1}{N \Psi_{g,h}(\omega/\epsilon g)} \sum_{j \in \mathbb{Z}_N} \Phi_{g,j-i} e_j, \quad A^* e_i^* = \frac{1}{N \Psi_{g,h}(\epsilon g \omega)} \sum_{j \in \mathbb{Z}_N} \Phi_{g^*,i-j} e_j^*,
\]

\[
e_i^* \in H_{gh}^{g,h}, \quad e_j \in H_{h^*,gh}^g.
\]

\[
B e_i = \frac{1}{v(\epsilon gh/\epsilon g)} \Phi_{h,i} e_{i^*}, \quad B^* e_i = \frac{1}{v(\epsilon g/\epsilon gh)} \Phi_{h^*,i} e_{-i^*}, \quad e_i \in H_{gh}^{g,h}, \quad e_{i^*} \in H_{gh}^{g,h},
\]

\[
B e_i^* = v(\epsilon gh/\epsilon g) \Phi_{h^*,i} e_{-i}, \quad B^* e_i^* = v(\epsilon g/\epsilon gh) \Phi_{h,i} e_{-i^*}, \quad e_i^* \in H_{gh}^{g,h}, \quad e_{i^*} \in H_{gh}^{g,h}.
\]
where
\[ v(x) = \frac{1 - x^N}{N(1 - x)}. \]

**Proof.** From Lemma 44 it follows that for any \( x \in V_h, y \in H^{g^*, h}, z \in H^{g, h} \) we have
\[ (d_{g^*} \otimes \text{id}_{V_h})(\text{id}_{V_{g^*}} \otimes S_{g, h})(S_{g^*, gh} \otimes \text{id}_{H^{g, h}})(x \otimes y \otimes z) = x \langle y, Az \rangle. \]

Starting from this identity, and using the results of [10], Appendices A and C, a straightforward calculation yields the formulas above for the action of \( A \).

Similarly, for any \( x \in V_g, y \in H^{g, h^*}, z \in H^{g, h} \) the identity
\[ (\text{id}_{V_g} \otimes d_{h})(S_{g, h} P \otimes \text{id}_{V_{h^*}})(\text{id}_{H^{g, h}} \otimes S_{gh, h^*})(z \otimes x \otimes y) = x \langle y, Bz \rangle \]
gives rise to the action of the operator \( B \). \( \square \)

**Lemma 46.** The action of the operators \( L = A^* A \) and \( R = B^* B \) is given by
\[
\begin{align*}
Le_i &= \left( \frac{u_g v_h}{v_{gh}} \right)^{N-1} e_{i-1}, \quad e_i \in H^{g, h}, \\
Le_i^* &= \left( \frac{u_g v_h}{v_{gh}} \right)^{N-1} e_{i+1}, \quad e_i^* \in H^{g, h^*}, \\
Re_i &= \varpi^{-i} \left( \frac{v_g}{v_{gh}} \right)^{N-1} e_i, \quad e_i \in H^{g, h}, \\
Re_i^* &= \varpi^{-i} \left( \frac{v_g}{v_{gh}} \right)^{N-1} e_i^*, \quad e_i^* \in H^{g, h^*}.
\end{align*}
\]

**Proof.** The case of \( R \) is straightforward. In the case of \( L \) we use the equality
\[ z^{N-1}f(x, 0 \mid z \varpi) = x^{N-1}f(z, 0 \mid x \varpi) \]
for the function \( f(x, y \mid z) \) of [10]. \( \square \)

12.3. The \( \Psi \)-system for odd \( N \). Assume from now on that \( N \) is odd.

**Proposition 47.** The \( \Psi \)-system of Proposition 43 extends to a \( \Psi \)-system where \( C_1 = \text{id}_H \) and \( R_1 \) is given by
\[
\begin{align*}
R_1 e_i &= \varpi^{-\frac{N+1}{2}} \left( \frac{v_g}{v_{gh}} \right)^{\frac{N-1}{2}} e_i, \quad e_i \in H^{g, h}, \\
R_1 e_i^* &= \varpi^{-\frac{N+1}{2}} \left( \frac{v_g}{v_{gh}} \right)^{\frac{N-1}{2}} e_i^*, \quad e_i^* \in H^{g, h^*}.
\end{align*}
\]
Proof. Since \( N \) is odd, we can set \( \epsilon = -1 \), and for any \( g \in I \), the coordinates \( u_g \) and \( v_g \) are real numbers. In particular, as the operator \( r = R^N \) has a positive spectrum, we define \( \sqrt{r} \) as the unique positive operator such that \((\sqrt{r})^2 = r\). Define

\[
R^\frac{1}{2} = (\sqrt{r})^{-1} R^{\frac{N+1}{2}}.
\]

Let us calculate \( R^\frac{1}{2} e_i \) for \( e_i \in H_{g,h}^\epsilon \). Write \( R = R_0 R_1 \) as the product of commuting operators \( R_0 \) and \( R_1 \) where \( R_0 = (v_g/v_{gh})^{N-1} \) and \( R_1 e_j = \varpi^{-j} e_j \) for \( e_j \in H_{g,h}^{\epsilon} \). Then we have \( R_1^N = \text{Id}_H \) and \( R = R^N = R_0^N R_1^N = R_0^N \), so

\[
(\sqrt{r})^{-1} R^{\frac{N+1}{2}} e_i = (R_0^N)^{-1/2} R_0^{(N+1)/2} R_1^{(N+1)/2} e_i = (v_g/v_{gh})^{N-1} \varpi^{-\frac{(N+1)}{2}} e_i.
\]

The computation of \( R^\frac{1}{2} e_i^* \) is similar.

Next consider the operator

\[
C = (AB)^3 = A(BAB)AB = AA^* B^* A^* AB = L^{-1} B^* LB.
\]

From Lemmas 45 and 46 it is easy to see that \( L^{-1} B^* LB = \text{Id}_H \). Thus, we can define \( C^\frac{1}{2} = \text{Id}_H \). Then it is easy to see that \( C^\frac{1}{2}, R^\frac{1}{2} \) satisfy equations (34) and (37) since \( C \) and \( R \) satisfy analogous formulas without square roots. \( \square \)

Lemma 48. The operator \( L^\frac{1}{2} = BAR^{-\frac{1}{2}} AB \) is given by

\[
L^\frac{1}{2} e_i = \left(\frac{u_g v_h}{v_{gh}}\right)^{\frac{N-1}{2}} \epsilon_{i-(N+1)/2}, \quad e_i \in H_{g,h}^\epsilon,
\]

\[
L^\frac{1}{2} e_i^* = \left(\frac{u_g v_h}{v_{gh}}\right)^{\frac{N-1}{2}} \epsilon_{i+(N+1)/2}, \quad e_i^* \in H_{g,h}^\epsilon.
\]

Proof. Write \( L = L_0 L_1 \) as the product of commuting operators \( L_0 \) and \( L_1 \) where

\[
L_0|_{H_{gh}^{\epsilon} \oplus H_{gh}^{\epsilon}} = \left(\frac{u_g v_h}{v_{gh}}\right)^{N-1}
\]

and \( L_1 \) is a translation operator such that \( L_1^N = \text{Id}_H \). We will show that \( L^\frac{1}{2} = L_0^{1/2} L_1^{(N+1)/2} \). Let \( r' = L^N = BAR^{-1} AB \) where \( r = R^N \). Then

\[
L^\frac{1}{2} = BA \sqrt{r} R^{\frac{N+1}{2}} AB = (\sqrt{r'})^{-1} BAR^{\frac{N+1}{2}} AB = (\sqrt{r'})^{-1} L_1^{\frac{N+1}{2}}.
\]

Since \( r' = L^N = L_0^N \) we have

\[
L^\frac{1}{2} = \sqrt{r'}^{-1} L_1^{\frac{N+1}{2}} = (L_0^{-1})^{\frac{1}{N-1}} L_0^{-\frac{1}{2}} L_1^{\frac{N+1}{2}} = L_0^{-\frac{1}{2}} L_1^{\frac{N+1}{2}}
\]

and the formulas of the lemma follow. \( \square \)
Lemma 49. The operator \( q = R_1^1 BL_1^1 BL_1^2 C^{-1} \) has the form

\[
q = (-1)^{(N-1)/2}(\omega^{-a} \text{Id}_H \oplus \omega^a \text{Id}_H) \in \text{End}(H),
\]

where \( a = \frac{N^2 - 1}{8} \).

Proof. A direct computation using Proposition 47 and Lemma 48 shows that

\[
qe_i = (-1)^{(N-1)/2} \omega^{\left(\frac{N^2 - 1}{8}\right)} i e_i
\]

for \( e_i \in H_{gh}^{g,h} \). Similarly, \( qe_i^* = (-1)^{(N-1)/2} \omega^{-\left(\frac{N^2 - 1}{8}\right)} i e_i^* \) for \( e_i^* \in H_{gh}^{g,h} \). \( \square \)

For \( g \in G \) set \( I_g = \{g\} \subseteq I \), if \( g \in I \) and \( I_g = \emptyset \), otherwise. Let \( b : I \to \mathbb{C} \) be the constant function taking the value \( \frac{1}{N} \). Then the triple \( (G, I, b) \) satisfies conditions (i)–(v) of Subsection 9.2. We summarize the results of this section in the following theorem.

Theorem 50. For any odd \( N \), the category of \( B_\omega \)-modules has a \( \Psi \)-system such that the algebraic data \( (G, I, b) \) satisfies conditions (i)–(v) of Subsection 9.2 and

\[
q = (-1)^{(N-1)/2}(\omega^{-a} \text{Id}_H \oplus \omega^a \text{Id}_H),
\]

where \( a = \frac{N^2 - 1}{8} \).

Thus, the category of \( B_\omega \)-modules gives rise to a topological invariant as in Theorem 29. As mentioned above, this invariant generalizes that of [7].

Appendix

The relations in the fundamental lemma (Lemma 6) express the action of the standard generators of the symmetric group \( S_4 \) on the tensors \( T, \bar{T} \) or equivalently on the tensors \( S, \bar{S} \) defined at the end of Section 2.2. We give a geometric interpretation of this action in the case where the operators \( A \) and \( B \) are symmetric, i.e., \( A = A^* \), \( B = B^* \). This interpretation involves a combinatorial 3-dimensional TQFT which we now define.

Consider a compact oriented surface (possibly with boundary) endowed with oriented cellular structure \( \Sigma \) such that all 2-cells are either bigons or triangles. For example, for any \( e, \mu \in \{-1, +1\} \), the unit disk \( D \) in \( \mathbb{C} \) has such a structure consisting of a single bigon with two 0-cells \( \{\pm 1\} \) and two 1-cells \( e^1_\pm : [0, 1] \to D \) given by \( e^1_+(t) = ve^{\mu it} \) and \( e^1_-(t) = \mu e^{-\mu it} \) where \( t \in [0, 1] \).

A bigon of \( \Sigma \) is inessential if its edges are co-oriented. In the example above, the cellular structures with \( e = \mu \) are inessential. A triangular 2-cell of \( \Sigma \) is positive (resp. negative) if the orientation of precisely two (resp. one) of its edges is compatible with that of the cell itself. We shall consider only cellular structures \( \Sigma \) without inessential bigons and such that all the triangular cells are either positive or negative. We associate the 1-dimensional vector space \( \mathbb{C} \) to all bigons, the vector space \( \bar{H} \) to all positive triangles and \( H \) to all negative
triangles. Finally, we associate with $\Sigma$ the tensor product over $\mathbb{C}$ of these vector spaces numerated by the 2-cells of $\Sigma$. It is isomorphic to $H^{\otimes m_+} \otimes \bar{H}^{\otimes m_-}$, where $m_+$ (resp. $m_-$) is the number of positive (resp. negative) triangles of $\Sigma$.

Next, we define elementary 3-cobordisms. An oriented tetrahedron in $\mathbb{R}^3$ with ordered vertices has a natural cell structure, where the orientation on the edges is induced from the order. Such a tetrahedron is *positive* if the oriented edges $(12,13,14)$ form a positive basis in $\mathbb{R}^3$ and *negative* otherwise. We associate with a positive (resp. negative) tetrahedron the tensor $S \in \bar{H} \otimes H \otimes \bar{H} \otimes H$ (resp. $\bar{S} \in \bar{H} \otimes H \otimes H \otimes \bar{H}$). Here the face opposite to the $i$-vertex corresponds to the $i$-th tensor factor for $i \in \{1,2,3,4\}$.

Next, we consider cones over essential bigons with induced cellular structure. The orientation condition on the triangular cells leaves four isotopy classes of such cones. We describe them for the cone over the unit disk $D \subset \mathbb{C}$ with the cone point $(0,1) \in \mathbb{C} \times \mathbb{R}$. The four possible cellular structures have three 0-cells $\{\pm 1, 0, (0,1)\}$ and four 1-cells

\[
\{e_{0+}^1(t) = \pm e^{i\theta}, e_{1+}^1(t) = (\pm(1-t), t)\}
\]

or

\[
\{e_{0-}^1(t) = \mp e^{-i\theta}, e_{1-}^1(t) = (\pm(1-t), t)\}
\]

or

\[
\{e_{0+}^1(t) = \pm e^{i\theta}, e_{1-}^1(t) = (\pm t, 1-t)\}
\]

or else

\[
\{e_{0-}^1(t) = \mp e^{-i\theta}, e_{1+}^1(t) = (\pm t, 1-t)\}
\]

Let us call them cones of type $a_+, a_-, b_+$, and $b_-$, respectively. We associate to these cones respectively the operators $A|_{H}$, $A|_{\bar{H}}$, $B|_{H}$, and $B|_{\bar{H}}$ viewed as vectors in $H^{\otimes 2}$ or $\bar{H}^{\otimes 2}$. Note that our cones are invariant under rotation by the angle $\pi$ around the vertical coordinate axis, and this invariance leads here to the condition $A = A^*$, $B = B^*$.

Now we give a TQFT interpretation of the formulae (16a)–(16c). Let us take, for example the right-hand side of (16a). The form $\bar{S}$ corresponds to a negative tetrahedron. The edge joining the first and the second vertices is incident to two faces opposite to the third and the forth vertices. We can glue two cones, one of type $a_+$ and another one of type $a_-$, to these two faces in the way that one of the edges of the base bigons are glued to the initial edge 12 and of course by respecting all orientations. Namely, we glue the cone of type $a_+$ to the face opposite to the third vertex of the tetrahedron so that the tip of the cone is glued to the forth vertex, and we glue the cone of type $a_-$ to the face opposite to the forth vertex of the tetrahedron so that the tip of the cone is glued to the third vertex. Finally, we can glue naturally the two bigons with each other by pushing continuously the initial edge inside the ball and eventually closing the gap like a book. The result of all these operations is that we obtain a positive tetrahedron, where the only difference with respect to the initial tetrahedron is that the orientation of the initial edge 12 has changed and this corresponds to changing the order of its vertices. Notice that as these vertices are neighbors, their
exchange does not affect the orientation of all other edges. On the other hand, as the order of the tensor components in our TQFT rules for tetrahedra is matched with the order of vertices, we have to exchange also the first two tensor components. This explains the left-hand side of (16a). The other two relations are interpreted in a similar manner.

References


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