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Virtual an arrow Temperley–Lieb algebras, Markov traces, and virtual link invariants

LUIS PARIS
LOIČ RABENDA

Abstract Let $R^f = \mathbb{Z}[A^{\pm 1}]$ be the algebra of Laurent polynomials in the variable A and let $R^a = \mathbb{Z}[A^{\pm 1}, z_1, z_2, \dots]$ be the algebra of Laurent polynomials in the variable A and standard polynomials in the variables z_1, z_2, \dots . For $n \geq 1$ we denote by VB_n the virtual braid group on n strands. We define two towers of algebras $\{\text{VTL}_n(R^f)\}_{n=1}^{\infty}$ and $\{\text{ATL}_n(R^a)\}_{n=1}^{\infty}$ in terms of diagrams. For each $n \geq 1$ we determine presentations for both, $\text{VTL}_n(R^f)$ and $\text{ATL}_n(R^a)$. We determine sequences of homomorphisms $\{\rho_n^f : R^f[\text{VB}_n] \rightarrow \text{VTL}_n(R^f)\}_{n=1}^{\infty}$ and $\{\rho_n^a : R^a[\text{VB}_n] \rightarrow \text{ATL}_n(R^a)\}_{n=1}^{\infty}$, we determine Markov traces $\{T_n^f : \text{VTL}_n(R^f) \rightarrow R^f\}_{n=1}^{\infty}$ and $\{T_n^a : \text{ATL}_n(R^a) \rightarrow R^a\}_{n=1}^{\infty}$, and we show that the invariants for virtual links obtained from these Markov traces are the f -polynomial for the first trace and the arrow polynomial for the second trace. We show that, for each $n \geq 1$, the standard Temperley–Lieb algebra TL_n embeds into both, $\text{VTL}_n(R^f)$ and $\text{ATL}_n(R^a)$, and that the restrictions to $\{\text{TL}_n\}_{n=1}^{\infty}$ of the two Markov traces coincide.

AMS Subject Classification 57K12, 57K14, 20F36

1 Introduction

Let S_1, \dots, S_ℓ be a collection of ℓ oriented circles smoothly immersed in the plane and having only normal double crossings. We assign to each crossing a value “positive”, “negative”, or “virtual”, that we indicate on the graphical representation of $S_1 \cup \dots \cup S_\ell$ as in Figure 1.1. Such a figure is called a *virtual link diagram*. We consider the equivalence relation on the set of virtual link diagrams generated by isotopy and the so-called *Reidemeister virtual moves*, as described in Kauffman [6, 7]. An equivalence class of virtual link diagrams is called a *virtual link*.

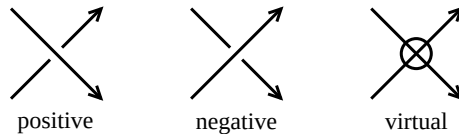


Figure 1.1: Crossings in a virtual link diagram

Let $b = (b_1, \dots, b_n)$ be a collection of n smooth paths in the plane \mathbb{R}^2 satisfying the following properties.

- $b_i(0) = (0, i)$ for all $i \in \{1, \dots, n\}$, and there exists a permutation $w \in \mathfrak{S}_n$ such that $b_i(1) = (1, w(i))$ for all $i \in \{1, \dots, n\}$.
- Let $p_1 : \mathbb{R}^2 \rightarrow \mathbb{R}$ be the projection on the first coordinate. Then $p_1(b_i(t)) = t$ for all $i \in \{1, \dots, n\}$ and all $t \in [0, 1]$.

(c) The union of the images of the b_i 's has only normal double crossings.

As with virtual link diagrams, we assign to each crossing a value “positive”, “negative”, or “virtual”, that we indicate on the graphical representation as in Figure 1.1. Such a figure is called a *virtual braid diagram* on n strands. We consider the equivalence relation on the set of virtual braid diagrams on n strands generated by isotopy and some *Reidemeister virtual moves*, as described in Kauffman [6]. An equivalence class of virtual braid diagrams on n strands is called a *virtual braid* on n strands. The virtual braids on n strands form a group, denoted VB_n , called *virtual braid group* on n strands. The group operation is induced by the concatenation.

We know from Kamada [4] and Vershinin [12] that VB_n admits a presentation with generators $\sigma_1, \dots, \sigma_{n-1}, \tau_1, \dots, \tau_{n-1}$ and relations

$$\begin{aligned} \tau_i^2 &= 1 \quad \text{for } 1 \leq i \leq n-1, \\ \sigma_i \sigma_j &= \sigma_j \sigma_i, \tau_i \tau_j = \tau_j \tau_i, \tau_i \sigma_j = \sigma_j \tau_i \quad \text{for } |i-j| \geq 2, \\ \sigma_i \sigma_j \sigma_i &= \sigma_j \sigma_i \sigma_j, \tau_i \tau_j \tau_i = \tau_j \tau_i \tau_j, \tau_i \tau_j \sigma_i = \sigma_j \tau_i \tau_j \quad \text{for } |i-j| = 1. \end{aligned}$$

The generators σ_i and τ_i are illustrated in Figure 1.2.

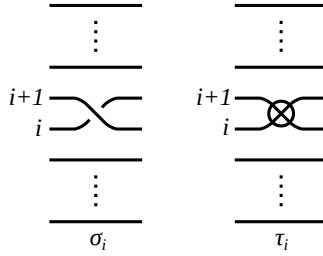


Figure 1.2: Generators of VB_n

Note that the subgroup of VB_n generated by $\sigma_1, \dots, \sigma_{n-1}$ is the braid group B_n on n strands. On the other hand, VB_n may be viewed as a subgroup of VB_{n+1} via the monomorphism $\text{VB}_n \hookrightarrow \text{VB}_{n+1}$ which sends σ_i to σ_i and τ_i to τ_i for all $i \in \{1, \dots, n-1\}$.

Using the same procedure as for classic braids, we can close a virtual braid β and obtain a virtual link, $\hat{\beta}$, called the *closure* of β . We know that each virtual link is the closure of a virtual braid, and we can say when two closed virtual braids are equivalent in terms of virtual Markov moves, as follows.

We denote by $\text{VB} = \bigsqcup_{n=1}^{\infty} \text{VB}_n$ the disjoint union of all virtual braid groups. Let $\beta_1, \beta_2 \in \text{VB}$. We say that β_1 and β_2 are connected by a *virtual Markov move* if we are in one of the following four cases.

- There exist $n \geq 1$ and $\alpha \in \text{VB}_n$ such that $\beta_1, \beta_2 \in \text{VB}_n$ and $\beta_2 = \alpha \beta_1 \alpha^{-1}$.
- There exist $n \geq 1$ and $u \in \{\sigma_n, \sigma_n^{-1}, \tau_n\}$ such that $\beta_1 \in \text{VB}_n$, $\beta_2 \in \text{VB}_{n+1}$ and $\beta_2 = \beta_1 u$, or vice versa.
- There exists $n \geq 2$ such that $\beta_1 \in \text{VB}_n$, $\beta_2 \in \text{VB}_{n+1}$, and $\beta_2 = \beta_1 \sigma_n^{-1} \tau_{n-1} \sigma_n$, or vice versa.
- There exists $n \geq 2$ such that $\beta_1 \in \text{VB}_n$, $\beta_2 \in \text{VB}_{n+1}$, and $\beta_2 = \beta_1 \tau_n \tau_{n-1} \sigma_{n-1} \tau_n \sigma_{n-1}^{-1} \tau_{n-1} \tau_n$, or vice versa.

Theorem 1.1 (Kamada [4], Kauffman–Lambropoulou [9]) *Let $\beta_1, \beta_2 \in \text{VB}$. Then $\hat{\beta}_1 = \hat{\beta}_2$ if and only if β_1 and β_2 are connected by a finite sequence of virtual Markov moves.*

Let R be a ring. For $n \geq 1$ we denote by $R[\text{VB}_n]$ the group R -algebra of VB_n . Notice that, since VB_n is a subgroup of VB_{n+1} , $R[\text{VB}_n]$ is a subalgebra of $R[\text{VB}_{n+1}]$. A sequence $\{T_n : R[\text{VB}_n] \rightarrow R\}_{n=1}^{\infty}$ of R -linear forms is called a *Markov trace* if it satisfies the following properties.

- (a) $T_n(xy) = T_n(yx)$ for all $n \geq 1$ and all $x, y \in R[\text{VB}_n]$.
- (b) $T_n(x) = T_{n+1}(x\sigma_n) = T_{n+1}(x\sigma_n^{-1}) = T_{n+1}(x\tau_n)$ for all $n \geq 1$ and all $x \in R[\text{VB}_n]$.
- (c) $T_n(x) = T_{n+1}(x\sigma_n^{-1}\tau_{n-1}\sigma_n)$ for all $n \geq 2$ and all $x \in R[\text{VB}_n]$.
- (d) $T_n(x) = T_{n+1}(x\tau_n\tau_{n-1}\sigma_{n-1}\tau_n\sigma_{n-1}^{-1}\tau_{n-1}\tau_n)$ for all $n \geq 2$ and all $x \in R[\text{VB}_n]$.

Note that our definition of “Markov trace” is not the one that can be usually found in the literature (see Kauffman–Lambropoulou [9], for example), but all known definitions, including this one, are equivalent up to renormalization.

Let \mathcal{VL} be the set of virtual links. Thanks to Theorem 1.1, from a Markov trace $\{T_n : R[\text{VB}_n] \rightarrow R\}_{n=1}^{\infty}$ we can define an invariant $I : \mathcal{VL} \rightarrow R$ by setting $I(\hat{\beta}) = T_n(\beta)$ for all $n \geq 1$ and all $\beta \in \text{VB}_n$. Conversely, any invariant of virtual links with coefficients in R can be obtained in this way.

A *tower of algebras* is a sequence $\{A_n\}_{n=1}^{\infty}$ of algebras such that A_n is a subalgebra of A_{n+1} for all $n \geq 1$. A sequence $\{\rho_n : R[\text{VB}_n] \rightarrow A_n\}_{n=1}^{\infty}$ of homomorphisms is said to be *compatible* if the restriction of ρ_{n+1} to $R[\text{VB}_n]$ is equal to ρ_n for all n . Let $\{A_n\}_{n=1}^{\infty}$ be a tower of algebras and let $\{\rho_n : R[\text{VB}_n] \rightarrow A_n\}_{n=1}^{\infty}$ be a compatible sequence of homomorphisms. Set $S_i = \rho_n(\sigma_i)$ and $v_i = \rho_n(\tau_i)$ for all $i \in \{1, \dots, n-1\}$. A sequence $\{T'_n : A_n \rightarrow R\}_{n=1}^{\infty}$ of linear forms is a *Markov trace* if it satisfies the following properties.

- (a) $T'_n(xy) = T'_n(yx)$ for all $n \geq 1$ and all $x, y \in A_n$.
- (b) $T'_n(x) = T'_{n+1}(xS_n) = T'_{n+1}(xS_n^{-1}) = T'_{n+1}(xv_n)$ for all $n \geq 1$ and all $x \in A_n$.
- (c) $T'_n(x) = T'_{n+1}(xS_n^{-1}v_{n-1}S_n)$ for all $n \geq 2$ and all $x \in A_n$.
- (d) $T'_n(x) = T'_{n+1}(xv_nv_{n-1}S_{n-1}v_nS_{n-1}^{-1}v_{n-1}v_n)$ for all $n \geq 2$ and all $x \in A_n$.

Clearly, in that case, the sequence $\{T_n = T'_n \circ \rho_n : R[\text{VB}_n] \rightarrow R\}_{n=1}^{\infty}$ is a Markov trace, and therefore it determines an invariant for virtual links.

A “natural” strategy to build Markov traces on $\{K[\text{VB}_n]\}_{n=1}^{\infty}$, and therefore invariants for virtual links, would be to transit through Markov traces on compatible towers of algebras, as defined above. This strategy won its spurs in the classical theory of knots and links, in particular thanks to Jones’ definitions of the Jones polynomial [2] and of the HOMFLY-PT polynomial [3]. As far as we know, this strategy is poorly used in the theory of virtual knots and links. Actually, the only reference we found is Li–Lei–Li [10], where the authors define a tower of algebras in terms of diagrams, claim (with no proof) that their algebras are the same as the virtual Temperley–Lieb algebras of Zhang–Kauffman–Ge [13], and show that the f -polynomial can be obtained from a Markov trace on this tower of algebras. By the way, one of their main results, [10, Proposition 4.1], is wrong (see Proposition 2.3).

Our aim in the present paper is to describe two invariants for virtual links in terms of Markov traces: the f -polynomial, also known as the Jones–Kauffman polynomial, and the arrow polynomial. The

f -polynomial is a version of the Jones polynomial for virtual links defined from the Kauffman bracket. This was introduced by Kauffman [6] in his seminal paper on virtual knots and links, and its construction closely follows Kauffman’s construction [5] of the Jones polynomial for classical links. The arrow polynomial is a refinement of the f -polynomial. It coincides with the Jones polynomial on classical links, but it is much more powerful for (non-classical) virtual links. In particular, it provides a lower bound for the number of virtual crossings. It was constructed by Miyazawa [11] and Dye–Kauffman [1] (see also Kauffman [8]).

Section 2 is dedicated to the construction of a Markov trace associated with the f -polynomial. Our approach is close to that of Li–Lei–Li [10], but, on the one hand, our study of the f -polynomial is needed in our study of the arrow polynomial, and, on the other hand, we complete the study of Li–Lei–Li [10] with correct presentations for virtual Temperley–Lieb algebras and other results. For each $n \geq 1$ we define an algebra $\text{VTL}_n(R^f)$ in terms of diagrams, so that the sequence $\{\text{VTL}_n(R^f)\}_{n=1}^\infty$ is a tower of algebras. In Proposition 2.2 we determine a presentation for $\text{VTL}_n(R^f)$ and in Proposition 2.3 we show that the presentation for $\text{VTL}_n(R^f)$ given in Li–Lei–Li [10] is wrong. Actually, the relation $E_i E_j E_i = E_i$ for $|i - j| = 1$, which is standard in Temperley–Lieb algebras, must be replaced by a “virtual relation” of the form $E_i v_j E_i = E_i$. Then we determine a compatible sequence of homomorphisms $\{\rho_n^f : R^f[\text{VB}_n] \rightarrow \text{VTL}_n(R^f)\}_{n=1}^\infty$ (Theorem 2.5), we determine a Markov trace on the tower of algebras $\{\text{VTL}_n(R^f)\}_{n=1}^\infty$ (Theorem 2.6), and we show that this construction leads to the f -polynomial (Theorem 2.8).

Section 3 is dedicated to the arrow polynomial. Our construction can be viewed as a labeled version of the construction of Section 2. For each $n \geq 1$ we define an algebra $\text{ATL}_n(R^a)$ in terms of labeled diagrams, so that $\{\text{ATL}_n(R^a)\}_{n=1}^\infty$ is a tower of algebras. Intuitively speaking, a label represents the number of cusps in Kauffman sense that can be found on an arc. In Proposition 3.2 we determine a presentation for $\text{ATL}_n(R^a)$. This is a sort of labeled version of the presentation for $\text{VTL}_n(R^f)$ given in Proposition 2.2. Then we proceed as in Section 2: we determine a compatible sequence of homomorphisms $\{\rho_n^a : R^a[\text{VB}_n] \rightarrow \text{ATL}_n(R^a)\}_{n=1}^\infty$ (Theorem 3.4), we determine a Markov trace on the tower of algebras $\{\text{ATL}_n(R^a)\}_{n=1}^\infty$ (Theorem 3.5), and we show that this construction leads to the arrow polynomial (Theorem 3.9).

It is known that the arrow polynomial coincides with the f -polynomial on classical links (see Miyazawa [11] and Dye–Kauffman [1]). We show that this fact has an interpretation in terms of Markov traces on Temperley–Lieb algebras. For $n \geq 1$ we denote by TL_n the n -th standard Temperley–Lieb algebra. We show that TL_n embeds into both, $\text{VTL}_n(R^f)$ (Proposition 2.4) and $\text{ATL}_n(R^a)$ (Proposition 3.3), and that the restriction to $\{\text{TL}_n\}_{n=1}^\infty$ of the Markov trace on $\{\text{VTL}_n(R^f)\}_{n=1}^\infty$ coincides with the restriction to $\{\text{TL}_n\}_{n=1}^\infty$ of the Markov trace on $\{\text{ATL}_n(R^a)\}_{n=1}^\infty$ (Proposition 3.7).

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2 Virtual Temperley–Lieb algebras and f -polynomial

Two rings are involved in this section. The first is the ring $R_0^f = \mathbb{Z}[z]$ of polynomials in the variable z with integer coefficients. The second is the ring $R^f = \mathbb{Z}[A^{\pm 1}]$ of Laurent polynomials in the

variable A with integer coefficients. We assume that R_0^f is embedded into R^f via the identification $z = -A^2 - A^{-2}$. Notice that the superscript f over R_0 and R in this notation is to underline the fact that all the constructions in the present section concern the f -polynomial. In contrast, the rings in the next section, which concerns the arrow polynomial, will be denoted R_0^a and R^a .

We start recalling the definition of the f -polynomial, as it will help the reader to understand the constructions and definitions that follow after.

Define the *Kauffman bracket* $\langle L \rangle \in R^f$ of a (non-oriented) virtual link diagram L as follows. If L has only virtual crossings, then $\langle L \rangle = z^\ell = (-A^2 - A^{-2})^\ell$, where ℓ is the number of components of L . Suppose that L has at least one non-virtual crossing p . Then $\langle L \rangle = A \langle L_1 \rangle + A^{-1} \langle L_2 \rangle$, where L_1 and L_2 are identical to L except in a neighborhood of p where there are as shown in Figure 2.1. The *writhe* of an (oriented) virtual link diagram L , denoted $w(L)$, is the number of positive crossings minus the number of negative crossings. Then the f -polynomial of an (oriented) virtual link diagram L is $f(L) = f(L)(A) = (-A^3)^{-w(L)} \langle L \rangle$.

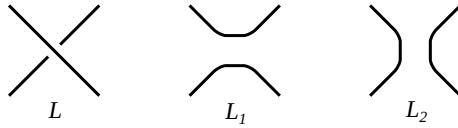


Figure 2.1: Relation in the Kauffman bracket

Theorem 2.1 (Kauffman [6]) *If two virtual link diagrams L and L' are equivalent, then $f(L) = f(L')$.*

The f -polynomial of a virtual link L , denoted $f(L)$, is the f -polynomial of any of its diagrams. This is a well-defined invariant thanks to Theorem 2.1.

Our goal now is to define a Markov trace whose associated invariant is the f -polynomial. We proceed as indicated in the introduction: we pass through a tower of algebras, the tower of virtual Temperley–Lieb algebras.

Let $n \geq 1$ be an integer. A *flat virtual n -tangle* is a collection of n disjoint pairs in $\{0, 1\} \times \{1, \dots, n\}$, that is, a partition of $\{0, 1\} \times \{1, \dots, n\}$ into pairs. Let $E = \{\alpha_1, \dots, \alpha_n\}$ be a flat virtual n -tangle. Then we graphically represent E on the plane by connecting the two ends of each α_i with an arc. For example, Figure 2.2 represents the flat virtual 3-tangle $\{\alpha_1, \alpha_2, \alpha_3\}$, where $\alpha_1 = \{(0, 1), (0, 2)\}$, $\alpha_2 = \{(0, 3), (1, 2)\}$ and $\alpha_3 = \{(1, 3), (1, 1)\}$.

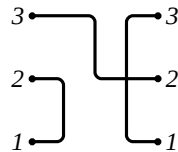


Figure 2.2: Flat virtual tangle

We denote by \mathcal{E}_n the set of flat virtual n -tangles, and by VTL_n the free R_0^f -module freely generated by \mathcal{E}_n . We define a multiplication in VTL_n as follows. Let E and E' be two flat virtual n -tangles. By

concatenating the diagrams of E and E' we get a family of closed curves and n arcs. These n arcs determine a partition of $\{0, 1\} \times \{1, \dots, n\}$ into pairs, that is, a flat virtual n -tangle that we denote by $E * E'$. Let m be the number of obtained closed curves. Then we set $E E' = z^m (E * E')$. It is easily checked that VTL_n endowed with this multiplication is an (unitary and associative) algebra that we call the n -th *virtual Temperley–Lieb algebra*.

Example On the left hand side of Figure 2.3 are illustrated the diagrams of two flat virtual 4-tangles, E and E' , and on the right hand side a diagram of $E * E'$. In this example, by concatenating the diagrams of E and E' we get only one closed curve, hence $m = 1$ and $E E' = z(E * E')$.

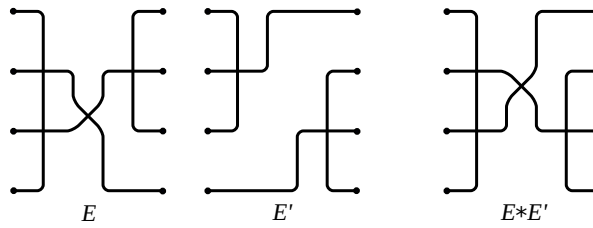


Figure 2.3: Multiplication in VTL_n

Remark It is easily seen that the embedding $\mathcal{E}_n \rightarrow \mathcal{E}_{n+1}$ which sends each $E \in \mathcal{E}_n$ to $E \cup \{(0, n+1), (1, n+1)\}$ induces an injective homomorphism $\text{VTL}_n \hookrightarrow \text{VTL}_{n+1}$, for all $n \geq 1$. So, we have a tower of algebras $\{\text{VTL}_n\}_{n=1}^\infty$.

Proposition 2.2 Let $n \geq 2$. Then VTL_n has a presentation with generators $E_1, \dots, E_{n-1}, v_1, \dots, v_{n-1}$ and relations

$$\begin{aligned} E_i^2 &= zE_i, \quad v_i^2 = 1, \quad E_i v_i = v_i E_i = E_i, \quad \text{for } 1 \leq i \leq n-1, \\ E_i E_j &= E_j E_i, \quad v_i v_j = v_j v_i, \quad v_i E_j = E_j v_i, \quad \text{for } |i-j| \geq 2, \\ E_i v_j E_i &= E_i, \quad v_i v_j v_i = v_j v_i v_j, \quad v_i v_j E_i = E_j v_i v_j, \quad \text{for } |i-j| = 1. \end{aligned}$$

The generators E_i and v_i are illustrated in Figure 2.4.

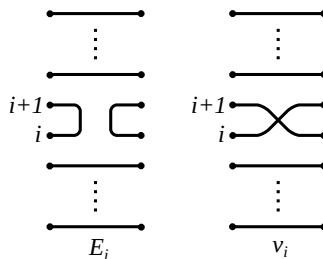


Figure 2.4: Generators of VTL_n

Proof Let A_n be the algebra over R_0^f defined by the presentation with generators $X_1, \dots, X_{n-1}, y_1, \dots, y_{n-1}$ and relations

$$\begin{aligned} X_i^2 &= zX_i, \quad y_i^2 = 1, \quad X_i y_i = y_i X_i = X_i, \quad \text{for } 1 \leq i \leq n-1, \\ X_i X_j &= X_j X_i, \quad y_i y_j = y_j y_i, \quad y_i X_j = X_j y_i, \quad \text{for } |i-j| \geq 2, \\ X_i y_j X_i &= X_i, \quad y_i y_j y_i = y_j y_i y_j, \quad y_i y_j X_i = X_j y_i y_j, \quad \text{for } |i-j| = 1. \end{aligned}$$

It is easily checked using diagrammatic calculation that there is a homomorphism $\varphi : A_n \rightarrow \text{VTL}_n$ which sends X_i to E_i and y_i to v_i for all $i \in \{1, \dots, n-1\}$. We need to prove that φ is an isomorphism.

Claim 1. The following relations hold in A_n .

$$\begin{aligned} X_i X_j y_i y_j &= X_i \quad \text{for } |i-j| = 1, \\ X_i X_j X_i &= X_i \quad \text{for } |i-j| = 1, \\ X_i X_j &= y_j y_i X_j \quad \text{for } |i-j| = 1, \\ y_{i+1} y_{i+2} y_i y_{i+1} X_i X_{i+2} &= X_i X_{i+2} \quad \text{for } 1 \leq i \leq n-3. \end{aligned}$$

Proof of Claim 1. Let $i, j \in \{1, \dots, n-1\}$ such that $|i-j| = 1$. Then

$$\begin{aligned} X_i X_j y_i y_j &= X_i y_i y_j X_i = X_i y_j X_i = X_i, \\ X_i X_j X_i &= X_i X_j y_i y_j y_i X_i = X_i y_j y_i X_i = X_i y_j X_i = X_i, \\ X_i X_j &= y_j y_i y_i y_j X_i X_j = y_j y_i X_j y_i y_j X_j = y_j y_i X_j y_i X_j = y_j y_i X_j. \end{aligned}$$

Let $i \in \{1, \dots, n-3\}$. Then

$$\begin{aligned} y_{i+1} y_{i+2} y_i y_{i+1} X_i X_{i+2} &= y_{i+1} y_{i+2} X_{i+1} X_i X_{i+2} = X_{i+2} X_{i+1} X_i X_{i+2} = \\ &X_{i+2} X_{i+1} X_{i+2} X_i = X_{i+2} X_i = X_i X_{i+2}. \end{aligned}$$

This concludes the proof of Claim 1.

We denote by $\mathcal{U}(A_n)$ the group of units of A_n and by \mathfrak{S}_n the n -th symmetric group. We have a homomorphism $\iota : \mathfrak{S}_n \rightarrow \mathcal{U}(A_n)$ which sends s_i to y_i for all $i \in \{1, \dots, n-1\}$, where $s_i = (i, i+1)$. Let n_0 be the integer part of $\frac{n}{2}$. Let $p \in \{0, 1, \dots, n_0\}$. We set $B_p = X_1 X_3 \cdots X_{2p-1}$ if $p \neq 0$, and $B_p = B_0 = 1$ if $p = 0$. We denote by $U_{1,p}$ the set of $w \in \mathfrak{S}_n$ satisfying

$$\begin{aligned} w(1) &< w(3) < \cdots < w(2p-1), \\ w(2i-1) &< w(2i) \quad \text{for } 1 \leq i \leq p, \\ w(2p+1) &< w(2p+2) < \cdots < w(n), \end{aligned}$$

and we denote by $U_{2,p}$ the set of $w \in \mathfrak{S}_n$ satisfying

$$\begin{aligned} w(1) &< w(3) < \cdots < w(2p-1), \\ w(2i-1) &< w(2i) \quad \text{for } 1 \leq i \leq p. \end{aligned}$$

Then we set

$$\mathcal{B}_p = \{\iota(w_1) B_p \iota(w_2^{-1}) \mid w_1 \in U_{1,p}, w_2 \in U_{2,p}\},$$

for $0 \leq p \leq n_0$, and

$$\mathcal{B} = \bigcup_{p=0}^{n_0} \mathcal{B}_p.$$

Let $E \in \mathcal{E}_n$. We can write E in the form $E = \{\alpha_1, \dots, \alpha_p, \alpha'_1, \dots, \alpha'_p, \beta_1, \dots, \beta_q\}$, where

- each α_i is of the form $\alpha_i = \{(0, a_i), (0, b_i)\}$, with $1 \leq a_1 < a_2 < \dots < a_p \leq n$, and $a_i < b_i$ for all $i \in \{1, \dots, p\}$;
- each α'_i is of the form $\alpha'_i = \{(1, a'_i), (1, b'_i)\}$, with $1 \leq a'_1 < a'_2 < \dots < a'_p \leq n$, and $a'_i < b'_i$ for all $i \in \{1, \dots, p\}$;
- each β_j is of the form $\beta_j = \{(0, c_j), (1, d_j)\}$, with $1 \leq c_1 < c_2 < \dots < c_q \leq n$, and $2p + q = n$.

We define $w_1 \in \mathfrak{S}_n$ by $w_1(2i - 1) = a_i$ and $w_1(2i) = b_i$ for all $i \in \{1, \dots, p\}$, and $w_1(2p + j) = c_j$ for all $j \in \{1, \dots, q\}$. Similarly, we define $w_2 \in \mathfrak{S}_n$ by $w_2(2i - 1) = a'_i$ and $w_2(2i) = b'_i$ for all $i \in \{1, \dots, p\}$, and $w_2(2p + j) = d_j$ for all $j \in \{1, \dots, q\}$. We see that $w_1 \in U_{1,p}$, $w_2 \in U_{2,p}$, and $E = \varphi(\iota(w_1)B_p \iota(w_2^{-1}))$. Moreover, such a form is unique for each $E \in \mathcal{E}_n$, and we have $\varphi(Y) \in \mathcal{E}_n$ for all $Y \in \mathcal{B}$, hence φ restricts to a bijection from \mathcal{B} to \mathcal{E}_n .

So, in order to prove Proposition 2.2, it suffices to show that \mathcal{B} spans A_n as a R_0^f -module. We denote by \mathcal{M} the submonoid of A_n generated by $X_1, \dots, X_{n-1}, y_1, \dots, y_{n-1}$, that is, the set of finite products of elements in $\{X_1, \dots, X_{n-1}, y_1, \dots, y_{n-1}\}$. By definition \mathcal{M} spans A_n as a R_0^f -module, hence we only need to show that \mathcal{M} is contained in the R_0^f -submodule $\text{Span}_{R_0^f}(\mathcal{B})$ of A_n spanned by \mathcal{B} .

Claim 2. Let $w_1, w_2 \in \mathfrak{S}_n$ and $p \in \{0, 1, \dots, n_0\}$. Then $\iota(w_1)B_p \iota(w_2^{-1}) \in \mathcal{B}$.

Proof of Claim 2. Let $i \in \{1, \dots, p\}$ such that $w_1(2i - 1) = b_i > w_1(2i) = a_i$. By applying the relation $y_{2i-1}X_{2i-1} = X_{2i-1}$ we can replace w_1 with w_1s_{2i-1} , and then $w_1(2i - 1) = a_i < w_1(2i) = b_i$. So, we can assume that $w_1(2i - 1) < w_1(2i)$ for all $i \in \{1, \dots, p\}$. Let $i \in \{1, \dots, p - 1\}$ such that $w_1(2i - 1) = a_{i+1} > w_1(2i + 1) = a_i$. By applying the relation $y_{2i}y_{2i-1}y_{2i+1}y_{2i}X_{2i-1}X_{2i+1} = X_{2i-1}X_{2i+1}$ we can replace w_1 with $w_1s_{2i}s_{2i-1}s_{2i+1}s_{2i}$, and then we have $w_1(2i - 1) = a_i < w_1(2i + 1) = a_{i+1}$ while keeping the inequalities $w_1(2i - 1) < w_1(2i)$ and $w_1(2i + 1) < w_1(2i + 2)$. So, we can also assume that $w_1(1) < w_1(3) < \dots < w_1(2p - 1)$. Set $q = n - 2p$. Let $j \in \{1, \dots, q - 1\}$ such that $w_1(2p + j) = c_{j+1} > w_1(2p + j + 1) = c_j$. By applying the relations $y_{2p+j}X_{2i-1} = X_{2i-1}y_{2p+j}$ for $i \in \{1, \dots, p\}$ we can replace w_1 with w_1s_{2p+j} and w_2 with w_2s_{2p+j} , and then $w_1(2p + j) = c_j < w_1(2p + j + 1) = c_{j+1}$. So, we can also assume that $w_1(2p + 1) < w_1(2p + 2) < \dots < w_1(n)$, that is, $w_1 \in U_{1,p}$. We use the same argument to show that w_2 can be replaced with some $w'_2 \in U_{2,p}$. So, $\iota(w_1)B_p \iota(w_2^{-1}) \in \mathcal{B}$. This concludes the proof of Claim 2.

Claim 3. Let $a, b \in \{1, \dots, n - 1\}$, $a \leq b$, and $p \in \{0, 1, \dots, n_0\}$. Then $X_a y_{a+1} \dots y_b B_p \in \text{Span}_{R_0^f}(\mathcal{B})$.

Proof of Claim 3. Suppose $a \geq 2p + 1$ (which is always true if $p = 0$). Then

$$\begin{aligned} X_a y_{a+1} \dots y_b B_p &= X_a B_p y_{a+1} \dots y_b = \\ X_a (y_{a-1} y_a) (y_{a-2} y_{a-1}) \dots (y_{2p+1} y_{2p+2}) (y_{2p+2} y_{2p+1}) \dots (y_{a-1} y_{a-2}) (y_a y_{a-1}) B_p y_{a+1} \dots y_b &= \\ (y_{a-1} y_a) (y_{a-2} y_{a-1}) \dots (y_{2p+1} y_{2p+2}) X_{2p+1} B_p (y_{2p+2} y_{2p+1}) \dots (y_{a-1} y_{a-2}) (y_a y_{a-1}) y_{a+1} \dots y_b &= \\ (y_{a-1} y_a) (y_{a-2} y_{a-1}) \dots (y_{2p+1} y_{2p+2}) B_{p+1} (y_{2p+2} y_{2p+1}) \dots (y_{a-1} y_{a-2}) (y_a y_{a-1}) y_{a+1} \dots y_b &= \\ \iota(w_1) B_{p+1} \iota(w_2^{-1}) &\in \mathcal{B}, \end{aligned}$$

where $w_1 = (s_{a-1}s_a) \cdots (s_{2p+1}s_{2p+2})$ and $w_2 = s_b \cdots s_{a+1}(s_{a-1}s_a) \cdots (s_{2p+1}s_{2p+2})$. Suppose $a \leq 2p$, a is odd, and $a = b$. Let $c \in \{1, \dots, p\}$ such that $a = 2c - 1$. Then

$$\begin{aligned} X_a y_{a+1} \cdots y_b B_p &= X_{2c-1}^2 X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ z X_{2c-1} X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} &= z B_p \in \text{Span}_{R_0^f}(\mathcal{B}). \end{aligned}$$

Suppose $a \leq 2p$, a is odd, and $a < b$. Let $c \in \{1, \dots, p\}$ such that $a = 2c - 1$. Then

$$\begin{aligned} X_a y_{a+1} \cdots y_b B_p &= X_{2c-1} y_{2c} \cdots y_b X_{2c-1} X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ X_{2c-1} y_{2c} X_{2c-1} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} &= \\ X_{2c-1} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} &= \\ y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c-1} X_{2c+1} \cdots X_{2p-1} &= \iota(s_{2c+1} \cdots s_b) B_p \in \mathcal{B}. \end{aligned}$$

Suppose $a \leq 2p$ and a is even. Let $c \in \{1, \dots, p\}$ such that $a = 2c$. Then

$$\begin{aligned} X_a y_{a+1} \cdots y_b B_p &= X_{2c} y_{2c+1} \cdots y_b X_{2c-1} X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ X_{2c} X_{2c-1} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} &= \\ y_{2c-1} y_{2c} X_{2c-1} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} &= \\ y_{2c-1} y_{2c} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c-1} X_{2c+1} \cdots X_{2p-1} &= \iota(s_{2c-1} s_{2c} s_{2c+1} \cdots s_b) B_p \in \mathcal{B}. \end{aligned}$$

This concludes the proof of Claim 3.

Claim 4. Let $p \in \{0, 1, \dots, n_0\}$ and $w \in \mathfrak{S}_n$. Then $X_1 \iota(w) B_p \in \text{Span}_{R_0^f}(\mathcal{B})$.

Proof of Claim 4. There exist $a \in \{1, \dots, n-1\}$, $b \in \{0, 1, \dots, n-1\}$ and $w_1 \in \langle s_3, \dots, s_{n-1} \rangle$ such that $w = w_1 s_2 s_3 \cdots s_a s_1 s_2 \cdots s_b$. Suppose $a \leq b$. Then

$$\begin{aligned} X_1 \iota(w) B_p &= \iota(w_1) X_1 y_2 \cdots y_a y_1 \cdots y_{a-1} y_a y_{a+1} \cdots y_b B_p = \\ \iota(w_1) X_1 (y_2 y_1) (y_3 y_2) \cdots (y_a y_{a-1}) y_a y_{a+1} \cdots y_b B_p &= \\ \iota(w_1) (y_2 y_1) (y_3 y_2) \cdots (y_a y_{a-1}) X_a y_a y_{a+1} \cdots y_b B_p &= \\ \iota(w_1 (s_2 s_1) (s_3 s_2) \cdots (s_a s_{a-1})) X_a y_{a+1} \cdots y_b B_p. \end{aligned}$$

We know by Claim 3 that $X_a y_{a+1} \cdots y_b B_p \in \text{Span}_{R_0^f}(\mathcal{B})$, hence, by Claim 2, $X_1 \iota(w) B_p \in \text{Span}_{R_0^f}(\mathcal{B})$.

Suppose $a > b$. Then

$$\begin{aligned} X_1 \iota(w) B_p &= \iota(w_1) X_1 y_2 \cdots y_b y_{b+1} \cdots y_a y_1 \cdots y_b B_p = \\ \iota(w_1) X_1 (y_2 y_1) (y_3 y_2) \cdots (y_{b+1} y_b) y_{b+2} \cdots y_a B_p &= \\ \iota(w_1) (y_2 y_1) (y_3 y_2) \cdots (y_{b+1} y_b) X_{b+1} y_{b+2} \cdots y_a B_p &= \\ \iota(w_1 (s_2 s_1) (s_3 s_2) \cdots (s_{b+1} s_b)) X_{b+1} y_{b+2} \cdots y_a B_p. \end{aligned}$$

We know by Claim 3 that $X_{b+1} y_{b+2} \cdots y_a B_p \in \text{Span}_{R_0^f}(\mathcal{B})$, hence, by Claim 2, $X_1 \iota(w) B_p \in \text{Span}_{R_0^f}(\mathcal{B})$.

This concludes the proof of Claim 4.

As pointed out above, the following claim ends the proof of Proposition 2.2.

Claim 5. The monoid \mathcal{M} is contained in $\text{Span}_{R_0^f}(\mathcal{B})$.

Proof of Claim 5. Let $Y \in \mathcal{M}$. By using the relations $y_i y_j X_i = X_j y_i y_j$ for $|i-j| = 1$, we see that Y can be written in the form $Y = \iota(w_0) X_1 \iota(w_1) X_1 \cdots X_1 \iota(w_k)$ where $k \geq 0$ and $w_0, w_1, \dots, w_k \in \mathfrak{S}_n$. We prove

that $Y \in \text{Span}_{R_0^f}(\mathcal{B})$ by induction on k . The case $k = 0$ is trivial and the case $k = 1$ follows from Claim 2. So, we can assume that $k \geq 2$ and that the inductive hypothesis holds. By the inductive hypothesis $\iota(w_1)X_1 \cdots X_1 \iota(w_k) \in \text{Span}_{R_0^f}(\mathcal{B})$, thus we just need to prove that $\iota(w_0)X_1 \iota(w'_1)B_p \iota(w_2'^{-1}) \in \text{Span}_{R_0^f}(\mathcal{B})$ for all $p \in \{0, 1, \dots, n_0\}$ and all $w'_1, w'_2 \in \mathfrak{S}_n$. We know by Claim 4 that $X_1 \iota(w'_1)B_p \in \text{Span}_{R_0^f}(\mathcal{B})$, hence, by Claim 2, $\iota(w_0)X_1 \iota(w'_1)B_p \iota(w_2'^{-1}) \in \text{Span}_{R_0^f}(\mathcal{B})$. This concludes the proof of Claim 5. \square

We have seen that the relation $E_i E_j E_i = E_i$ holds for $|i - j| = 1$ in VTL_n (see Claim 1 in the proof of Proposition 2.2). However, contrary to what some people may believe, we cannot replace the relation $E_i v_j E_i = E_i$ with the relation $E_i E_j E_i = E_i$ in the presentation of VTL_n . Indeed:

Proposition 2.3 *Let $n \geq 3$ and let VTL'_n be the algebra over R_0^f defined by the presentation with generators $E'_1, \dots, E'_{n-1}, v'_1, \dots, v'_{n-1}$ and relations*

$$\begin{aligned} E_i'^2 &= zE'_i, \quad v_i'^2 = 1, \quad E'_i v'_i = v'_i E'_i = E'_i, \quad \text{for } 1 \leq i \leq n-1, \\ E'_i E'_j &= E'_j E'_i, \quad v'_i v'_j = v'_j v'_i, \quad v'_i E'_j = E'_j v'_i, \quad \text{for } |i - j| \geq 2, \\ E'_i E'_j E'_i &= E'_i, \quad v'_i v'_j v'_i = v'_j v'_i v'_j, \quad v'_i v'_j E'_i = E'_j v'_i v'_j, \quad \text{for } |i - j| = 1. \end{aligned}$$

Let $\varphi : \text{VTL}'_n \rightarrow \text{VTL}_n$ be the homomorphism that sends E'_i to E_i and v'_i to v_i for all $i \in \{1, \dots, n-1\}$. Then φ is surjective but not injective.

Proof By definition $E_1, \dots, E_{n-1}, v_1, \dots, v_{n-1}$ belong to the image of φ . Since these elements generate VTL_n , the homomorphism φ is surjective. Let $C_2 = \{\pm 1\}$ be the cyclic group of order 2 and let $\mathbb{Z}[C_2]$ be the group algebra of C_2 . It is easily checked with the presentation of VTL'_n that there is a ring homomorphism $\theta : \text{VTL}'_n \rightarrow \mathbb{Z}[C_2]$ satisfying $\theta(E'_i) = -1$ for all $i \in \{1, \dots, n-1\}$, $\theta(v'_i) = 1$ for all $i \in \{1, \dots, n-1\}$, and $\theta(z) = -1$. Let $i, j \in \{1, \dots, n-1\}$ such that $|i - j| = 1$. Then $\theta(E'_i v'_j E'_i) = 1$ and $\theta(E'_i) = -1$, hence the relation $E'_i v'_j E'_i = E'_i$ does not hold in VTL'_n . So, φ is not injective. \square

Let $n \geq 1$. Recall that $V_n = \{0, 1\} \times \{1, \dots, n\}$ is ordered by $(0, 1) < (0, 2) < \cdots < (0, n) < (1, n) < \cdots < (1, 2) < (1, 1)$. Let E be a flat virtual n -tangle. Let $\gamma_1 = \{x_1, y_1\}, \gamma_2 = \{x_2, y_2\} \in E$ such that $x_1 < y_1, x_2 < y_2$, and $x_1 < x_2$. We say that γ_1 *crosses* γ_2 if $x_1 < x_2 < y_1 < y_2$. We say that E is *non-crossing* if there are no two elements in E that cross. Equivalently, a flat n -tangle is non-crossing if and only if it has a graphical representation with n disjoint arcs. We denote by \mathcal{E}_n^0 the set of non-crossing flat virtual n -tangles.

Let $n \geq 2$. Recall that the *Temperley–Lieb algebra* TL_n is the algebra over R_0^f defined by the presentation with generators E_1, \dots, E_{n-1} and relations

$$\begin{aligned} E_i^2 &= zE_i \text{ for } 1 \leq i \leq n-1, \quad E_i E_j = E_j E_i \text{ for } |i - j| \geq 2, \\ E_i E_j E_i &= E_i \text{ for } |i - j| = 1. \end{aligned}$$

The following is proved in Kauffman [5].

Proposition 2.4 (Kauffman [5]) *Let $n \geq 2$. The homomorphism $\text{TL}_n \rightarrow \text{VTL}_n$ which sends E_i to E_i for all $i \in \{1, \dots, n-1\}$ is injective and its image is the R_0^f -submodule of VTL_n freely generated by \mathcal{E}_n^0 .*

Recall that $R^f = \mathbb{Z}[A^{\pm 1}]$ denotes the algebra of Laurent polynomials in the variable A , and that $R_0^f = \mathbb{Z}[z]$ is a subalgebra of R^f via the identification $z = -A^2 - A^{-2}$. For each $n \geq 1$ we set $\text{VTL}_n(R^f) = R^f \otimes \text{VTL}_n$. This is a R^f -algebra and it is a free R^f -module freely generated by \mathcal{E}_n .

Theorem 2.5 *Let $n \geq 1$. There exists a homomorphism $\rho_n^f : R^f[\text{VB}_n] \rightarrow \text{VTL}_n(R^f)$ which sends σ_i to $-A^{-2}1 - A^{-4}E_i$ and τ_i to v_i for all $i \in \{1, \dots, n-1\}$.*

Proof We set $S_i = -A^{-2}1 - A^{-4}E_i$. We have

$$\begin{aligned} (-A^{-2}1 - A^{-4}E_i)(-A^21 - A^4E_i) &= 1 + (A^2 + A^{-2})E_i + E_i^2 = \\ &= 1 + (A^2 + A^{-2})E_i + (-A^2 - A^{-2})E_i = 1. \end{aligned}$$

So, S_i is invertible and its inverse is $-A^21 - A^4E_i$. The element v_i is also invertible since $v_i^2 = 1$. It remains to verify that the following relations hold.

$$\begin{aligned} v_i^2 &= 1, \quad \text{for } 1 \leq i \leq n-1, \\ S_i S_j &= S_j S_i, \quad v_i v_j = v_j v_i, \quad v_i S_j = S_j v_i, \quad \text{for } |i-j| \geq 2, \\ S_i S_j S_i &= S_j S_i S_j, \quad v_i v_j v_i = v_j v_i v_j, \quad v_i v_j S_i = S_j v_i v_j, \quad \text{for } |i-j| = 1. \end{aligned}$$

The only of these relations which is not trivial is $S_i S_j S_i = S_j S_i S_j$ for $|i-j| = 1$. Suppose $|i-j| = 1$. Then

$$\begin{aligned} S_i S_j S_i &= (-A^{-2}1 - A^{-4}E_i)(-A^{-2}1 - A^{-4}E_j)(-A^{-2}1 - A^{-4}E_i) = \\ &= -A^{-6}1 - A^{-8}E_i - A^{-8}E_j - A^{-10}E_i E_j - A^{-8}E_i - A^{-10}E_i^2 - A^{-10}E_j E_i - A^{-12}E_i E_j E_i = \\ &= -A^{-6}1 - 2A^{-8}E_i - A^{-8}E_j - A^{-10}E_i E_j - A^{-10}(-A^2 - A^{-2})E_i - A^{-10}E_j E_i - A^{-12}E_i = \\ &= -A^{-6}1 - A^{-8}E_i - A^{-8}E_j - A^{-10}E_i E_j - A^{-10}E_j E_i. \end{aligned}$$

By symmetry we also have $S_j S_i S_j = -A^{-6}1 - A^{-8}E_i - A^{-8}E_j - A^{-10}E_i E_j - A^{-10}E_j E_i$, hence $S_i S_j S_i = S_j S_i S_j$. \square

Remark (1) Recall that B_n denotes the braid group on n strands and TL_n denotes the n -th Temperley–Lieb algebra. Then $\rho_n^f(\beta) \in \text{TL}_n(R^f)$ for all $\beta \in B_n$, where $\text{TL}_n(R^f) = R^f \otimes \text{TL}_n \subset \text{VTL}_n(R^f)$.

- (2) The sequence of homomorphisms $\{\rho_n^f : R^f[\text{VB}_n] \rightarrow \text{VTL}_n(R^f)\}_{n=1}^{\infty}$ is compatible with the tower of algebras $\{\text{VTL}_n(R^f)\}_{n=1}^{\infty}$.
- (3) Setting $\rho_n^f(\sigma_i) = -A^{-2}1 - A^{-4}E_i$ instead of $\rho_n^f(\sigma_i) = A1 + A^{-1}E_i$, as an informed reader may expect, allows to include in ρ_n^f the corrective with the writhe and to define directly the f -polynomial without passing through the Kauffman bracket.

Let E be a flat virtual n -tangle. By connecting with an arc the point $(0, i)$ with the point $(1, i)$ for all $i \in \{1, \dots, n\}$ in a diagram of E we obtain a family of closed curves that we call the *closure of the diagram* of E . We denote by $t_n(E)$ the number of closed curves in this family, and we set $T_n^f(E) = z^{t_n(E)} = (-A^2 - A^{-2})^{t_n(E)}$. Then we define $T_n^f : \text{VTL}_n(R^f) \rightarrow R^f$ by extending linearly the map $T_n^f : \mathcal{E}_n \rightarrow R^f$.

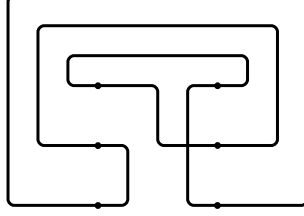


Figure 2.5: Closure of a flat virtual tangle

Example In Figure 2.5 is illustrated the closure of the flat virtual tangle E of Figure 2.2. In this case we have $t_n(E) = 1$, and therefore $T_n^{ff}(E) = z = -A^2 - A^{-2}$.

Theorem 2.6 The sequence $\{T_n^{ff} : \text{VTL}_n(\mathcal{R}^f) \rightarrow \mathcal{R}^f\}_{n=1}^\infty$ is a Markov trace.

Proof For each $n \geq 2$ and each $i \in \{1, \dots, n-1\}$ we set $S_i = -A^{-2}1 - A^{-4}E_i$. We have to show that the following equalities hold.

- (1) $T_n^{ff}(xy) = T_n^{ff}(yx)$ for all $n \geq 1$ and all $x, y \in \text{VTL}_n(\mathcal{R}^f)$.
- (2) $T_n^{ff}(x) = T_{n+1}^{ff}(xS_n) = T_{n+1}^{ff}(xS_n^{-1}) = T_{n+1}^{ff}(xv_n)$ for all $n \geq 1$ and all $x \in \text{VTL}_n(\mathcal{R}^f)$.
- (3) $T_n^{ff}(x) = T_{n+1}^{ff}(xS_n^{-1}v_{n-1}S_n)$ for all $n \geq 2$ and all $x \in \text{VTL}_n(\mathcal{R}^f)$.
- (4) $T_n^{ff}(x) = T_{n+1}^{ff}(xv_nv_{n-1}S_{n-1}v_nS_{n-1}^{-1}v_{n-1}v_n)$ for all $n \geq 2$ and all $x \in \text{VTL}_n(\mathcal{R}^f)$.

Proof of (1). We can assume that $x = E$ and $y = E'$ are flat virtual n -tangles. By concatenating E and E' and connecting with an arc the point $(0, i)$ of E to the point $(1, i)$ of E' for all $i \in \{1, \dots, n\}$ we obtain a family of closed curves. If m is the number of closed curves in this family, then $T_n^{ff}(EE') = z^m$. We observe that, by concatenating E' and E and connecting with an arc the point $(0, i)$ of E' to the point $(1, i)$ of E for all $i \in \{1, \dots, n\}$, we also obtain a family of m closed curves, hence $T_n^{ff}(E'E) = z^m = T_n^{ff}(EE')$.

Proof of (2). We can assume that $x = E$ is a flat virtual n -tangle. We see in Figure 2.6 that the following equalities hold

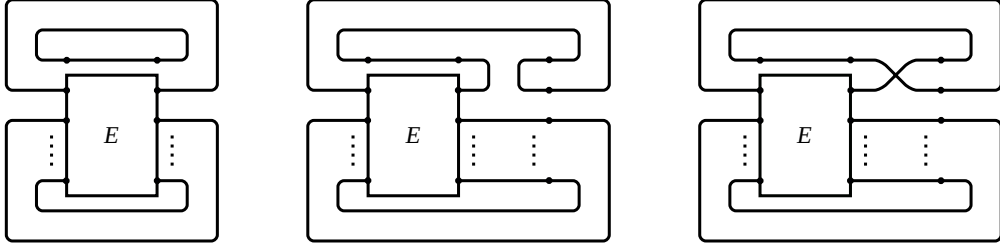
$$T_{n+1}^{ff}(E) = zT_n^{ff}(E), \quad T_{n+1}^{ff}(EE_n) = T_n^{ff}(E), \quad T_{n+1}^{ff}(Ev_n) = T_n^{ff}(E).$$

Recall that $S_n^{-1} = -A^21 - A^4E_n$ (see the proof of Theorem 2.5). We saw in Figure 2.6 that $T_{n+1}^{ff}(Ev_n) = T_n^{ff}(E)$. On the other hand,

$$\begin{aligned} T_{n+1}^{ff}(ES_n) &= -A^{-2}T_{n+1}^{ff}(E) - A^{-4}T_{n+1}^{ff}(EE_n) = (-A^{-2}z - A^{-4})T_n^{ff}(E) = T_n^{ff}(E), \\ T_{n+1}^{ff}(ES_n^{-1}) &= -A^2T_{n+1}^{ff}(E) - A^4T_{n+1}^{ff}(EE_n) = (-A^2z - A^4)T_n^{ff}(E) = T_n^{ff}(E). \end{aligned}$$

Proof of (3). We can again assume that $x = E$ is a flat virtual n -tangle. We have

$$\begin{aligned} ES_n^{-1}v_{n-1}S_n &= E(-A^21 - A^4E_n)v_{n-1}(-A^{-2}1 - A^{-4}E_n) = \\ &= Ev_{n-1} + A^2EE_nv_{n-1} + A^{-2}Ev_{n-1}E_n + EE_nv_{n-1}E_n = \\ &= Ev_{n-1} + A^2EE_nv_{n-1} + A^{-2}Ev_{n-1}E_n + EE_n. \end{aligned}$$

Figure 2.6: $n + 1$ -closures of E , EE_n and Ev_n

Hence, by the above

$$\begin{aligned}
& T_{n+1}^{ff}(ES_n^{-1}v_{n-1}S_n) = \\
& T_{n+1}^{ff}(Ev_{n-1}) + A^{-2}T_{n+1}^{ff}(Ev_{n-1}E_n) + A^2T_{n+1}^{ff}(EE_nv_{n-1}) + T_{n+1}^{ff}(EE_n) = \\
& zT_n^{ff}(Ev_{n-1}) + A^{-2}T_n^{ff}(Ev_{n-1}) + A^2T_{n+1}^{ff}(v_{n-1}EE_n) + T_n^{ff}(E) = \\
& (-A^2 - A^{-2})T_n^{ff}(Ev_{n-1}) + A^{-2}T_n^{ff}(Ev_{n-1}) + A^2T_n^{ff}(v_{n-1}E) + T_n^{ff}(E) = \\
& (-A^2 - A^{-2})T_n^{ff}(Ev_{n-1}) + A^{-2}T_n^{ff}(Ev_{n-1}) + A^2T_n^{ff}(Ev_{n-1}) + T_n^{ff}(E) = T_n^{ff}(E).
\end{aligned}$$

Proof of (4). Again, we can assume that $x = E$ is a flat virtual n -tangle. We have

$$\begin{aligned}
& Ev_nv_{n-1}S_{n-1}v_nS_{n-1}^{-1}v_{n-1}v_n = Ev_nv_{n-1}(-A^{-2}1 - A^{-4}E_{n-1})v_n(-A^21 - A^4E_{n-1})v_{n-1}v_n = \\
& (Ev_nv_{n-1}v_nv_{n-1}v_n) + A^2(Ev_nv_{n-1}v_nE_{n-1}v_{n-1}v_n) + \\
& A^{-2}(Ev_nv_{n-1}E_{n-1}v_nv_{n-1}v_n) + (Ev_nv_{n-1}E_{n-1}v_nE_{n-1}v_{n-1}v_n) = \\
& (Ev_{n-1}v_nv_{n-1}v_{n-1}v_n) + A^2(Ev_nv_{n-1}v_nE_{n-1}v_n) + \\
& A^{-2}(Ev_nE_{n-1}v_nv_{n-1}v_n) + (Ev_nE_{n-1}v_nE_{n-1}v_n) = \\
& (Ev_{n-1}) + A^2(Ev_nv_{n-1}v_{n-1}E_nv_{n-1}) + A^{-2}(Ev_{n-1}E_nv_{n-1}v_{n-1}v_n) + (Ev_nE_{n-1}v_n) = \\
& (Ev_{n-1}) + A^2(EE_nv_{n-1}) + A^{-2}(Ev_{n-1}E_n) + (Ev_{n-1}E_nv_{n-1}).
\end{aligned}$$

Hence, by the above

$$\begin{aligned}
& T_{n+1}^{ff}(Ev_nv_{n-1}S_{n-1}v_nS_{n-1}^{-1}v_{n-1}v_n) = \\
& T_{n+1}^{ff}(Ev_{n-1}) + A^2T_{n+1}^{ff}(EE_nv_{n-1}) + A^{-2}T_{n+1}^{ff}(Ev_{n-1}E_n) + T_{n+1}^{ff}(Ev_{n-1}E_nv_{n-1}) = \\
& zT_n^{ff}(Ev_{n-1}) + A^2T_{n+1}^{ff}(v_{n-1}EE_n) + A^{-2}T_n^{ff}(Ev_{n-1}) + T_{n+1}^{ff}(v_{n-1}Ev_{n-1}E_n) = \\
& (-A^2 - A^{-2})T_n^{ff}(Ev_{n-1}) + A^2T_n^{ff}(v_{n-1}E) + A^{-2}T_n^{ff}(Ev_{n-1}) + T_n^{ff}(v_{n-1}Ev_{n-1}) = \\
& (-A^2 - A^{-2})T_n^{ff}(Ev_{n-1}) + A^2T_n^{ff}(Ev_{n-1}) + A^{-2}T_n^{ff}(Ev_{n-1}) + T_n^{ff}(Ev_{n-1}v_{n-1}) = T_n^{ff}(E). \quad \square
\end{aligned}$$

Corollary 2.7 For each $n \geq 1$ we set $T_n^f = T_n^{ff} \circ \rho_n^f : R^f[\mathbf{VB}_n] \rightarrow R^f$. Then $\{T_n^f : R^f[\mathbf{VB}_n] \rightarrow R^f\}_{n=1}^\infty$ is a Markov trace.

Recall that \mathcal{VL} denotes the set of virtual links. To complete the study of this section it remains to prove the following.

Theorem 2.8 *Let $f^f : \mathcal{V}\mathcal{L} \rightarrow \mathcal{R}^f$ be the invariant defined from the Markov trace of Corollary 2.7. Then f^f coincides with the f -polynomial.*

Proof Let β be a virtual braid on n strands and let $\hat{\beta}$ be its closure. Observe that the relation $\langle L \rangle = A \langle L_1 \rangle + A^{-1} \langle L_2 \rangle$ in the definition of the Kauffman bracket corresponds in terms of closed virtual braids to replacing each σ_i with $A 1 + A^{-1} E_i$ and each σ_i^{-1} with $A^{-1} 1 + A E_i$. Once we have replaced each σ_i with $A 1 + A^{-1} E_i$ and each σ_i^{-1} with $A^{-1} 1 + A E_i$, we get a linear combination $\sum_{i=1}^{\ell} a_i E^{(i)}$, where $E^{(i)} \in \mathcal{E}_n$ and $a_i \in \mathcal{R}^f$. For each $i \in \{1, \dots, \ell\}$ we denote by $m_i = t_n(E^{(i)})$ the number of closed curves in the closure of $E^{(i)}$. We see that

$$\langle \hat{\beta} \rangle = \sum_{i=1}^{\ell} a_i z^{m_i}.$$

Recall that $w : \mathcal{V}\mathcal{L} \rightarrow \mathbb{Z}$ denotes the writhe. Let $\omega : \text{VB}_n \rightarrow \mathbb{Z}$ be the homomorphism which sends σ_i to 1 and τ_i to 0 for all $i \in \{1, \dots, n-1\}$. Then $w(\hat{\beta}) = \omega(\beta)$ and therefore $f(\hat{\beta}) = (-A^3)^{-\omega(\beta)} \langle \hat{\beta} \rangle$. So, in the above procedure, if we replace each σ_i with $(-A^3)^{-1}(A 1 + A^{-1} E_i) = -A^{-2} 1 - A^{-4} E_i$ and each σ_i^{-1} with $(-A^3)(A^{-1} 1 + A E_i) = -A^2 1 - A^4 E_i$, then we get directly $f(\hat{\beta})$. It is clear that this procedure also leads to $T_n^f(\beta)$. \square

3 Arrow Temperley–Lieb algebras and arrow polynomial

Throughout the section we consider the infinite families of variables $\mathcal{Z} = \{z_k\}_{k=0}^{\infty}$ and $\mathcal{Z}^* = \{z_k\}_{k=1}^{\infty} = \mathcal{Z} \setminus \{z_0\}$, and we consider the algebra $R_0^a = \mathbb{Z}[\mathcal{Z}]$ of polynomials in the variables in \mathcal{Z} , and the algebra $R^a = \mathbb{Z}[A^{\pm 1}, \mathcal{Z}^*]$ of Laurent polynomials in the variable A and standard polynomials in the variables in \mathcal{Z}^* . We also assume that the algebra R_0^a is embedded into R^a via the identification $z_0 = -A^2 - A^{-2}$. Following the same strategy as in Section 2, we start by recalling the definition of the arrow polynomial, so that the reader will understand easier the constructions that will follow after.

Let S_1, \dots, S_{ℓ} be a collection of ℓ circles smoothly immersed in the plane and having only a finite number of normal double crossings. We assume that each circle S_i has an even number m_i of marked points outside the crossings that we call *cusps*. We assume also that each segment between two successive cusps is oriented so that the orientations of the two segments adjacent to a given cusp are opposite. So, each cusp is either a *sink* or a *source*, according to the orientations of the segments adjacent to it (see Figure 3.1). If $m_i = 0$, then S_i is assumed to have a (unique) orientation. In addition, each cusp has a privileged side that we indicate with a small segment like in Figure 3.1. Finally, as for the virtual link diagrams, we assign a value “positive”, “negative”, or “virtual” to each crossing, that we indicate in its graphical representation as in Figure 1.1. Such a figure is called an *arrow virtual link diagram* with ℓ components. Note that the virtual link diagrams are the arrow virtual link diagrams with no cusps.



Figure 3.1: Sink and source in an arrow virtual link diagram

Example Figure 3.2 shows an arrow virtual link diagram with two components. One component has two cusps and the other has no cusp.

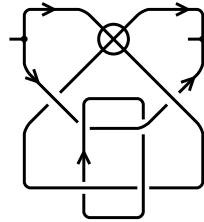


Figure 3.2: Arrow virtual link diagram

Let L be an arrow virtual link diagram with only virtual crossings. Let S be a component of L . If S has two consecutive cusps p and q having the same privileged side, then we remove the two cusps and orient the new arc with the same orientation as that of the arc adjacent to p different from $[p, q]$. In the particular case where p and q are the only cusps of S , then we can choose any of the orientations of S . This operation is called a *reduction* of S and is illustrated in Figure 3.3. We apply such a reduction as many times as needed to get an *irreducible component*, S' . If $2c$ is the number of cusp of S' , then c is called the *number of zigzags* of S and is denoted by $\zeta(S) = c$. If S_1, \dots, S_ℓ are the components of L , then we set

$$\langle\langle L \rangle\rangle = \prod_{i=1}^{\ell} z_{\zeta(S_i)}.$$

This is a monomial of R_0^a .

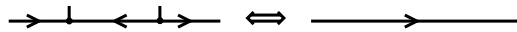


Figure 3.3: Reduction

We define the *arrow Kauffman bracket* $\langle\langle L \rangle\rangle \in R^a$ of any arrow virtual link diagram L as follows. If L has only virtual crossings, then $\langle\langle L \rangle\rangle$ is the monomial $\prod_{i=1}^{\ell} z_{\zeta(S_i)}$ defined above. Suppose that L has at least one non-virtual crossing at a point p . If the crossing is positive, then we set $\langle\langle L \rangle\rangle = A\langle\langle L_1 \rangle\rangle + A^{-1}\langle\langle L_2 \rangle\rangle$, and, if the crossing is negative, then we set $\langle\langle L \rangle\rangle = A^{-1}\langle\langle L_1 \rangle\rangle + A\langle\langle L_2 \rangle\rangle$, where L_1 and L_2 are identical to L except in a small neighborhood of p where there are as shown in Figure 3.4. As for the virtual link diagrams, the *writhe* of an arrow virtual link diagram L , denoted $w(L)$, is the number of positive crossings minus the number of negative crossings. Then the *arrow polynomial* of an arrow virtual link diagram L is defined by $\vec{f}(L) = (-A^3)^{-w(L)}\langle\langle L \rangle\rangle$.

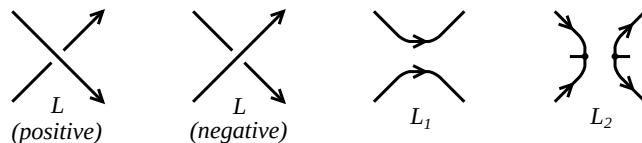


Figure 3.4: Relation in the arrow Kauffman bracket

Theorem 3.1 (Miyazawa [11], Dye–Kauffman [1]) (1) If two virtual link diagrams L and L' are equivalent, then $\vec{f}(L) = \vec{f}(L')$.

(2) If L is a diagram of a classical link, then $\vec{f}(L) = f(L) \in R^f = \mathbb{Z}[A^{\pm 1}]$.

Remark There is a notion of “equivalence” between arrow virtual link diagrams and Theorem 3.1 holds in this framework (see Miyazawa [11]), but the topic of the present paper are the virtual links, hence we state the theorem only for virtual link diagrams.

The *arrow polynomial* of a virtual link L , denoted $\vec{f}(L)$, is defined to be the arrow polynomial of any of its diagrams. This is a well-defined invariant thanks to Theorem 3.1.

Our aim now is to construct a Markov trace whose associated invariant is the arrow polynomial. We proceed with the same strategy as in Section 2 for the f -polynomial: we pass through a tower of algebras, $\{\text{ATL}_n\}_{n=1}^{\infty}$, that we will call arrow Temperley–Lieb algebras. We will also give a new proof/interpretation of Theorem 3.1 (2) in terms of Markov traces.

For the remainder of the section we need a more combinatorial definition of the multiplication in VTL_n . Recall that $V_n = \{0, 1\} \times \{1, \dots, n\}$ is ordered by $(0, 1) < (0, 2) < \dots < (0, n) < (1, n) < \dots < (1, 2) < (1, 1)$. Let $E, E' \in \mathcal{E}_n$. An *arc* of length ℓ in $E \sqcup E'$ is a ℓ -tuple $\hat{\alpha} = (\alpha_1, \dots, \alpha_\ell)$ in $E \sqcup E'$, where $\alpha_i = \{(a_i, b_{i-1}), (c_i, b_i)\}$, satisfying the following properties.

- (a) If $\alpha_i \in E$ and $i < \ell$, then $c_i = 1$, $\alpha_{i+1} \in E'$ and $a_{i+1} = 0$.
- (b) If $\alpha_i \in E'$ and $i < \ell$, then $c_i = 0$, $\alpha_{i+1} \in E$ and $a_{i+1} = 1$.
- (c) $a_0 = 0$ if $\alpha_1 \in E$, $a_0 = 1$ if $\alpha_1 \in E'$, $c_\ell = 0$ if $\alpha_\ell \in E$, $c_\ell = 1$ if $\alpha_\ell \in E'$, and $(a_1, b_0) < (c_\ell, b_\ell)$.

The *boundary* of $\hat{\alpha}$ is $\partial\hat{\alpha} = \{(a_1, b_0), (c_\ell, b_\ell)\}$. There are n arcs in $E \sqcup E'$ and their boundaries form a flat virtual n -tangle, denoted $E * E'$.

Let $E, E' \in \mathcal{E}_n$. A *cycle* of length $2p \geq 2$ in $E \sqcup E'$ is a $2p$ -tuple $\hat{\gamma} = (\gamma_1, \dots, \gamma_{2p})$ in $E \sqcup E'$, where $\gamma_i = \{(a_i, b_{i-1}), (c_i, b_i)\}$, satisfying the following properties.

- (a) $\gamma_i \in E$ and $a_i = c_i = 1$, if i is odd.
- (b) $\gamma_i \in E'$ and $a_i = c_i = 0$, if i is even.
- (c) $b_0 = b_{2p} < b_i$ for all $i \in \{1, \dots, 2p - 1\}$.

Let m be the number of cycles in $E \sqcup E'$. Then $EE' = z^m(E * E')$.

We can now define our algebra ATL_n . Let $n \geq 1$. An *arrow flat n -tangle* is a flat virtual n -tangle E endowed with a labeling $f : E \rightarrow \mathbb{Z}$ such that, for $\alpha = \{(a, b), (c, d)\} \in E$, $f(\alpha)$ is odd if $a = c$, and $f(\alpha)$ is even if $a \neq c$. Recall that $\mathcal{Z} = \{z_k\}_{k=0}^{\infty}$ and $R_0^a = \mathbb{Z}[\mathcal{Z}]$. We denote by \mathcal{F}_n the set of arrow flat n -tangles and by ATL_n the free R_0^a -module freely generated by \mathcal{F}_n .

Interpretation Instead of labeling the arcs we could endow each arc with marked points (cusps) and each cusp with a privileged side that we indicate with a small segment, like for arrow virtual link diagrams, so that two consecutive cusps have different privileged sides. The number of cusps on an arc α would be equal to $|f(\alpha)|$. Consider the order of V_n defined above. If we travel on the arc from its

smallest extremity to its largest one, we set $f(\alpha) > 0$ if the privileged side of the first encountered cusp is on the left hand side, and we set $f(\alpha) < 0$ otherwise. An arrow flat tangle and its version with cusps are illustrated in Figure 3.5.

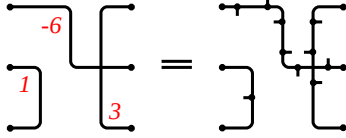


Figure 3.5: Arrow flat tangle

We now define the multiplication in ATL_n . Let $F = (E, f)$ and $F' = (E', f')$ be two arrow flat n -tangles. To simplify our notation we set $f^*(\alpha) = f(\alpha)$ if $\alpha \in E$ and $f^*(\alpha) = f'(\alpha)$ if $\alpha \in E'$. The *parity* of an element $\alpha = \{(a, b), (c, d)\} \in E \sqcup E'$ is $\varpi(\alpha) = -1$ if $a = c$, and $\varpi(\alpha) = 1$ if $a \neq c$. Let $\hat{\alpha} = (\alpha_1, \dots, \alpha_\ell)$ be an arc of $E \sqcup E'$. Let $i \in \{1, \dots, \ell\}$. As in the above definition of arc, we set $\alpha_i = \{(a_i, b_{i-1}), (c_i, b_i)\}$ for all i . We define the *cumulated parity* of α_i relative to $\hat{\alpha}$ by $\varpi^c(\alpha_i) = \prod_{j=1}^{i-1} \varpi(\alpha_j)$ if $(a_i, b_{i-1}) < (c_i, b_i)$, and $\varpi^c(\alpha_i) = \prod_{j=1}^i \varpi(\alpha_j)$ if $(c_i, b_i) < (a_i, b_{i-1})$. Then we set

$$g(\partial\hat{\alpha}) = g(\hat{\alpha}) = \sum_{i=1}^{\ell} \varpi^c(\alpha_i) f^*(\alpha_i).$$

At this stage we have an arrow flat n -tangle $F * F' = (E * E', g)$. Let $\hat{\gamma} = (\gamma_1, \dots, \gamma_\ell)$ be a cycle of $E \sqcup E'$. Again, we write $\gamma_i = \{(a_i, b_{i-1}), (c_i, b_i)\}$ for all i . As for an arc, we define the *cumulated parity* of γ_i relative to $\hat{\gamma}$ by $\varpi^c(\gamma_i) = \prod_{j=1}^{i-1} \varpi(\gamma_j)$ if $(a_i, b_{i-1}) < (c_i, b_i)$, and by $\varpi^c(\gamma_i) = \prod_{j=1}^i \varpi(\gamma_j)$ if $(c_i, b_i) < (a_i, b_{i-1})$. We set

$$h(\hat{\gamma}) = \sum_{i=1}^{\ell} \varpi^c(\gamma_i) f^*(\gamma_i).$$

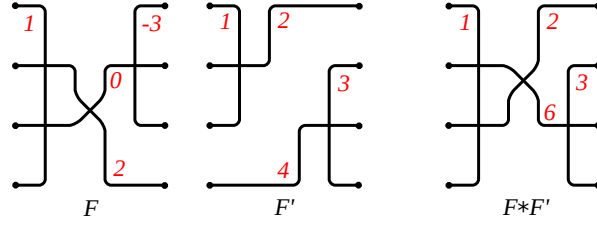
Observe that $h(\hat{\gamma})$ is an even number. The *number of zigzags* of $\hat{\gamma}$ is defined by $\zeta(\hat{\gamma}) = \frac{|h(\hat{\gamma})|}{2}$. Let $\hat{\gamma}_1, \dots, \hat{\gamma}_m$ be the cycles of $E \sqcup E'$. Then the product of F and F' is

$$F F' = z_{\zeta(\hat{\gamma}_1)} \cdots z_{\zeta(\hat{\gamma}_m)} (F * F').$$

It is easily checked that ATL_n endowed with this multiplication is an (associative and unitary) algebra. We call it the n -th *arrow Temperley–Lieb algebra*.

Example On the left hand side of Figure 3.6 are illustrated two arrow flat tangles F and F' , and $F * F'$ is illustrated on the right hand side. Here we have a unique cycle in $E \sqcup E'$, $\hat{\gamma}_1$, and $h(\hat{\gamma}_1) = 4$, hence $\zeta(\hat{\gamma}_1) = 2$ and $F F' = z_2(F * F')$.

Remark Let $n \geq 1$. For $F = (E, f) \in \mathcal{F}_n$ we define $F^\sharp = (E^\sharp, f^\sharp) \in \mathcal{F}_{n+1}$ by setting $E^\sharp = E \cup \{(0, n+1), (1, n+1)\}$, $f^\sharp(\alpha) = f(\alpha)$ for all $\alpha \in E$, and $f^\sharp(\{(0, n+1), (1, n+1)\}) = 0$. Then the map $\mathcal{F}_n \rightarrow \mathcal{F}_{n+1}$, $F \mapsto F^\sharp$, is an embedding which induces an injective homomorphism $ATL_n \hookrightarrow ATL_{n+1}$. So, we have a tower of algebras $\{ATL_n\}_{n=1}^\infty$.

Figure 3.6: Multiplication in ATL_n

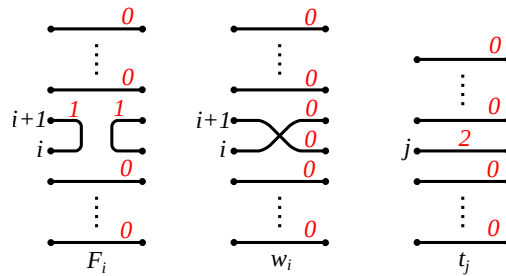
Proposition 3.2 *Let $n \geq 2$. Then ATL_n has a presentation with generators*

$$F_1, \dots, F_{n-1}, w_1, \dots, w_{n-1}, t_1, \dots, t_n, t_1^{-1}, \dots, t_n^{-1},$$

and relations

$$\begin{aligned} t_i t_i^{-1} &= t_i^{-1} t_i = 1 \text{ for } 1 \leq i \leq n, & t_i t_j &= t_j t_i \text{ for } 1 \leq i < j \leq n, \\ w_i^2 &= 1 \text{ for } 1 \leq i \leq n-1, & w_i w_j &= w_j w_i \text{ for } |i-j| \geq 2, \\ w_i w_j w_i &= w_j w_i w_j \text{ for } |i-j| = 1, & w_i t_i &= t_{i+1} w_i \text{ for } 1 \leq i \leq n-1, \\ w_i t_{i+1} &= t_i w_i \text{ for } 1 \leq i \leq n-1, & w_i t_j &= t_j w_i \text{ for } j \neq i, i+1, \\ F_i t_i^m F_i &= z_{|m|} F_i \text{ for } 1 \leq i \leq n-1 \text{ and } m \in \mathbb{Z}, & F_i w_i &= F_i t_i = F_i t_{i+1}^{-1} \text{ for } 1 \leq i \leq n-1, \\ w_i F_i &= t_i^{-1} F_i = t_{i+1} F_i \text{ for } 1 \leq i \leq n-1, & F_i F_j &= F_j F_i \text{ for } |i-j| \geq 2, \\ F_i w_j &= w_j F_i \text{ for } |i-j| \geq 2, & F_i t_j &= t_j F_i \text{ for } j \neq i, i+1, \\ F_i w_j F_i &= F_i \text{ for } |i-j| = 1, & w_i w_j F_i &= F_j w_i w_j \text{ for } |i-j| = 1. \end{aligned}$$

The generators F_i , w_i and t_j are illustrated in Figure 3.7.

Figure 3.7: Generators of ATL_n

Proof Let A_n be the R_0^a -algebra defined by a presentation with generators

$$X_1, \dots, X_{n-1}, y_1, \dots, y_{n-1}, u_1, \dots, u_n, u_1^{-1}, \dots, u_n^{-1},$$

and relations

$$\begin{aligned}
u_i u_i^{-1} &= u_i^{-1} u_i = 1 \text{ for } 1 \leq i \leq n, & u_i u_j &= u_j u_i \text{ for } 1 \leq i < j \leq n, \\
y_i^2 &= 1 \text{ for } 1 \leq i \leq n-1, & y_i y_j &= y_j y_i \text{ for } |i-j| \geq 2, \\
y_i y_j y_i &= y_j y_i y_j \text{ for } |i-j| = 1, & y_i u_i &= u_{i+1} y_i \text{ for } 1 \leq i \leq n-1, \\
y_i u_{i+1} &= u_i y_i \text{ for } 1 \leq i \leq n-1, & y_i u_j &= u_j y_i \text{ for } j \neq i, i+1, \\
X_i u_i^m X_i &= z_{|m|} X_i \text{ for } 1 \leq i \leq n-1 \text{ and } m \in \mathbb{Z}, & X_i y_i &= X_i u_i = X_i u_{i+1}^{-1} \text{ for } 1 \leq i \leq n-1, \\
y_i X_i &= u_i^{-1} X_i = u_{i+1} X_i \text{ for } 1 \leq i \leq n-1, & X_i X_j &= X_j X_i \text{ for } |i-j| \geq 2, \\
X_i y_j &= y_j X_i \text{ for } |i-j| \geq 2, & X_i u_j &= u_j X_i \text{ for } j \neq i, i+1, \\
X_i y_j X_i &= X_i \text{ for } |i-j| = 1, & y_i y_j X_i &= X_j y_i y_j \text{ for } |i-j| = 1.
\end{aligned}$$

It is easily checked using diagrammatic calculation that there is a homomorphism $\varphi : A_n \rightarrow \text{ATL}_n$ which sends X_i to F_i for $i \in \{1, \dots, n-1\}$, y_i to w_i for $i \in \{1, \dots, n-1\}$, and $u_i^{\pm 1}$ to $t_i^{\pm 1}$ for $i \in \{1, \dots, n\}$. It remains to prove that φ is an isomorphism.

Claim 1. The following equalities hold in A_n .

$$\begin{aligned}
X_i X_{i+1} y_i y_{i+1} &= X_i u_{i+2}^{-1} = u_{i+2}^{-1} X_i \text{ for } 1 \leq i \leq n-2, \\
y_{i+1} y_i X_{i+1} X_i &= u_{i+2} X_i = X_i u_{i+2} \text{ for } 1 \leq i \leq n-2, \\
X_i X_{i-1} y_i y_{i-1} &= X_i u_{i-1} = u_{i-1} X_i \text{ for } 2 \leq i \leq n-1, \\
y_{i-1} y_i X_{i-1} X_i &= u_{i-1}^{-1} X_i = X_i u_{i-1}^{-1} \text{ for } 2 \leq i \leq n-1.
\end{aligned}$$

Proof of Claim 1. We prove the first equality. The other three can be proved in the same way. Let $i \in \{1, \dots, n-2\}$. Then

$$\begin{aligned}
X_i X_{i+1} y_i y_{i+1} &= X_i y_i y_{i+1} X_i = X_i u_{i+1}^{-1} y_{i+1} X_i = X_i y_{i+1} u_{i+2}^{-1} X_i = X_i y_{i+1} X_i u_{i+2}^{-1} = \\
&X_i u_{i+2}^{-1} = u_{i+2}^{-1} X_i.
\end{aligned}$$

Claim 2. Let $i, j \in \{1, \dots, n-1\}$ such that $|i-j| = 1$. Then $X_i X_j X_i = X_i$.

Proof of Claim 2. We suppose that $j = i+1$. The case $j = i-1$ can be proved in the same way.

$$\begin{aligned}
X_i X_{i+1} X_i &= X_i X_{i+1} y_i y_{i+1} y_i y_{i+1} X_i = X_i u_{i+2}^{-1} y_{i+1} u_{i+1} X_i = X_i u_{i+2}^{-1} u_{i+2} y_{i+1} X_i = \\
&X_i y_{i+1} X_i = X_i.
\end{aligned}$$

Claim 3. Let $i \in \{1, \dots, n-3\}$. Then $y_{i+1} y_{i+2} y_i y_{i+1} X_i X_{i+2} = X_i X_{i+2}$.

Proof of Claim 3.

$$\begin{aligned}
y_{i+1} y_{i+2} y_i y_{i+1} X_i X_{i+2} &= y_{i+1} y_{i+2} y_i y_{i+1} X_i u_{i+2} u_{i+2}^{-1} X_{i+2} = \\
y_{i+1} y_{i+2} y_i y_{i+1} y_{i+1} y_i X_{i+1} X_i u_{i+2}^{-1} X_{i+2} &= y_{i+1} y_{i+2} X_{i+1} X_i u_{i+2}^{-1} X_{i+2} = \\
y_{i+1} y_{i+2} X_{i+1} u_{i+3} u_{i+3}^{-1} X_i u_{i+3} X_{i+2} &= y_{i+1} y_{i+2} y_{i+2} y_{i+1} X_{i+2} X_{i+1} X_i X_{i+2} = \\
X_{i+2} X_{i+1} X_{i+2} X_i &= X_{i+2} X_i = X_i X_{i+2}.
\end{aligned}$$

Consider the action of the symmetric group \mathfrak{S}_n on \mathbb{Z}^n by permutations of the coordinates, and set $G = \mathfrak{S}_n \times \mathbb{Z}^n$. Let $\{e_1, \dots, e_n\}$ be the standard basis of \mathbb{Z}^n and let $\{s_1, \dots, s_{n-1}\}$ be the standard set of generators of \mathfrak{S}_n . Recall that s_i is the transposition $(i, i+1)$ for $i \in \{1, \dots, n-1\}$. We use multiplicative notation for the operation in \mathbb{Z}^n and we denote by $1_{\mathbb{Z}^n}$ its neutral element. Let $\mathcal{U}(A_n)$ be the group of units of A_n . We have a homomorphism $\iota : G \rightarrow \mathcal{U}(A_n)$ which sends s_i to y_i for all $i \in \{1, \dots, n-1\}$ and e_j to u_j for all $j \in \{1, \dots, n\}$.

Let n_0 be the integer part of $\frac{n}{2}$. For $p \in \{1, \dots, n_0\}$ we set $B_p = X_1 X_3 \cdots X_{2p-1}$, and for $p = 0$ we set $B_p = B_0 = 1$. We denote by $U_{1,p}$ the subset of G formed by the elements of the form $g = wh$ where $w \in \mathfrak{S}_n$ satisfies

$$w(1) < w(3) < \cdots < w(2p-1), \quad w(2i-1) < w(2i) \text{ for } 1 \leq i \leq p, \\ w(2p+1) < w(2p+2) < \cdots < w(n),$$

and $h = e_1^{\nu_1} e_2^{\nu_2} \cdots e_n^{\nu_n} \in \mathbb{Z}^n$ satisfies

$$\nu_i = 0 \text{ for } i \in \{2, 4, \dots, 2p, 2p+1, 2p+2, \dots, n\}.$$

On the other hand, we denote by $U_{2,p}$ the subset of G formed by the elements of the form $g = wh$ where $w \in \mathfrak{S}_n$ satisfies

$$w(1) < w(3) < \cdots < w(2p-1), \quad w(2i-1) < w(2i) \text{ for } 1 \leq i \leq p,$$

and $h = e_1^{\nu_1} e_2^{\nu_2} \cdots e_n^{\nu_n} \in \mathbb{Z}^n$ satisfies

$$\nu_i = 0 \text{ for } i \in \{2, 4, \dots, 2p\}.$$

Then we set

$$\mathcal{B}_p = \{\iota(g_1) B_p \iota(g_2^{-1}) \mid g_1 \in U_{1,p}, g_2 \in U_{2,p}\},$$

for $0 \leq p \leq n_0$, and

$$\mathcal{B} = \bigcup_{p=0}^{n_0} \mathcal{B}_p.$$

Let $F = (E, f) \in \mathcal{F}_n$. We can write E in the form $E = \{\alpha_1, \dots, \alpha_p, \alpha'_1, \dots, \alpha'_p, \beta_1, \dots, \beta_q\}$, where

- each α_i is of the form $\alpha_i = \{(0, a_i), (0, b_i)\}$, with $a_1 < a_2 < \cdots < a_p$, and $a_i < b_i$ for all $i \in \{1, \dots, p\}$;
- each α'_i is of the form $\alpha'_i = \{(1, a'_i), (1, b'_i)\}$, with $a'_1 < a'_2 < \cdots < a'_p$, and $a'_i < b'_i$ for all $i \in \{1, \dots, p\}$;
- each β_j is of the form $\beta_j = \{(0, c_j), (1, d_j)\}$, with $c_1 < c_2 < \cdots < c_q$, and $2p + q = n$.

We define $w_1 \in \mathfrak{S}_n$ by $w_1(2i-1) = a_i$ and $w_1(2i) = b_i$ for all $i \in \{1, \dots, p\}$, and $w_1(2p+j) = c_j$ for all $j \in \{1, \dots, q\}$. We define $w_2 \in \mathfrak{S}_n$ by $w_2(2i-1) = a'_i$ and $w_2(2i) = b'_i$ for all $i \in \{1, \dots, p\}$, and $w_2(2p+j) = d_j$ for all $j \in \{1, \dots, q\}$. We define $h_1 = e_1^{\nu_{1,1}} e_2^{\nu_{1,2}} \cdots e_n^{\nu_{1,n}} \in \mathbb{Z}^n$ by $\nu_{1,2i-1} = \frac{f(\alpha_i)-1}{2}$ and $\nu_{1,2i} = 0$ for $i \in \{1, \dots, p\}$, and $\nu_{1,2p+j} = 0$ for $j \in \{1, \dots, q\}$. We define $h_2 = e_1^{\nu_{2,1}} e_2^{\nu_{2,2}} \cdots e_n^{\nu_{2,n}} \in \mathbb{Z}^n$ by $\nu_{2,2i-1} = \frac{f(\alpha'_i)-1}{2}$ and $\nu_{2,2i} = 0$ for $i \in \{1, \dots, p\}$, and $\nu_{2,2p+j} = -\frac{f(\beta_j)}{2}$ for $j \in \{1, \dots, q\}$. We set $g_1 = w_1 h_1$ and $g_2 = w_2 h_2$. Then $g_1 \in U_{1,p}$, $g_2 \in U_{2,p}$, and $F = \varphi(\iota(g_1) B_p \iota(g_2^{-1}))$. Moreover, such an expression is unique, and $\varphi(Y) \in \mathcal{F}_n$ for all $Y \in \mathcal{B}$. So, φ restricts to a bijection from \mathcal{B} to \mathcal{F}_n .

So, in order to prove Proposition 3.2, it suffices to show that \mathcal{B} spans A_n as a R_0^a -module. Let \mathcal{M} be the submonoid of A_n generated by $X_1, \dots, X_{n-1}, y_1, \dots, y_{n-1}, u_1^{\pm 1}, \dots, u_n^{\pm 1}$, that is, the set of finite products of elements in $\{X_1, \dots, X_{n-1}, y_1, \dots, y_{n-1}, u_1^{\pm 1}, \dots, u_n^{\pm 1}\}$. By definition \mathcal{M} spans A_n as a R_0^a -module, hence we only need to show that \mathcal{M} is contained in the R_0^a -submodule $\text{Span}_{R_0^a}(\mathcal{B})$ of A_n spanned by \mathcal{B} .

Claim 4. Let $g_1, g_2 \in G$ and $p \in \{0, 1, \dots, n_0\}$. Then $\iota(g_1)B_p \iota(g_2^{-1}) \in \mathcal{B}$.

Proof of Claim 4. We write $g_1 = w_1 h_1$ and $g_2 = w_2 h_2$ with $w_1, w_2 \in \mathfrak{S}_n$ and $h_1, h_2 \in \mathbb{Z}^n$. Let $i \in \{1, \dots, p\}$ such that $w_1(2i-1) = b_i > w_1(2i) = a_i$. By using the relation $y_i X_i = u_i^{-1} X_i$, we can replace w_1 with $w_1 s_i$ and h_1 with $s_i(h_1 e_i) s_i \in \mathbb{Z}^n$, and then $w_1(2i-1) = a_i < w_1(2i) = b_i$. So, we can assume that $w_1(2i-1) < w_1(2i)$ for all $i \in \{1, \dots, p\}$. Let $i \in \{1, \dots, p-1\}$ such that $w_1(2i-1) = a_{i+1} > w_1(2i+1) = a_i$. By Claim 3 we can replace w_1 with $w_1 s_{2i} s_{2i-1} s_{2i+1} s_{2i}$ and h_1 with $(s_{2i} s_{2i+1} s_{2i-1} s_{2i}) h_1 (s_{2i} s_{2i-1} s_{2i+1} s_{2i}) \in \mathbb{Z}^n$. Then we have $w_1(2i-1) = a_i < w_1(2i+1) = a_{i+1}$ while keeping the inequalities $w_1(2i-1) < w_1(2i)$ and $w_1(2i+1) < w_1(2i+2)$. Thus, we can also assume that $w_1(1) < w_1(3) < \dots < w_1(2p-1)$. Let $j \in \{1, \dots, q-1\}$ such that $w_1(2p+j) = c_{j+1} > w_1(2p+j+1) = c_j$. By applying the relations $y_{2p+j} X_{2i-1} = X_{2i-1} y_{2p+j}$ for $i \in \{1, \dots, p\}$, we can replace w_1 with $w_1 s_{2p+j}$, h_1 with $s_{2p+j} h_1 s_{2p+j} \in \mathbb{Z}^n$, and g_2 with $g_2 s_{2p+j}$, and then $w_1(2p+j) = c_j < w_1(2p+j+1) = c_{j+1}$. So, we can also assume that $w_1(2p+1) < w_1(2p+2) < \dots < w_1(n)$. We set $h_1 = e_1^{\nu_{1,1}} \dots e_n^{\nu_{1,n}}$ and $h_2 = e_1^{\nu_{2,1}} \dots e_n^{\nu_{2,n}}$. Let $i \in \{1, \dots, p\}$. By applying the relation $u_{2i-1}^{-1} X_{2i-1} = u_{2i} X_{2i-1}$, we can replace $\nu_{1,2i}$ with 0 and $\nu_{1,2i-1}$ with $\nu_{1,2i-1} - \nu_{1,2i}$. So, we can also assume that $\nu_{1,2i} = 0$ for all $i \in \{1, \dots, p\}$. Let $j \in \{1, \dots, q\}$. By applying the relations $u_{2p+j} X_{2i-1} = X_{2i-1} u_{2p+j}$ for $i \in \{1, \dots, p\}$, we can replace $\nu_{1,2p+j}$ with 0 and $\nu_{2,2p+j}$ with $\nu_{2,2p+j} - \nu_{1,2p+j}$. Thus, we can also assume that $\nu_{1,2p+j} = 0$ for all $j \in \{1, \dots, q\}$. In conclusion, we can assume that $g_1 \in U_{1,p}$.

We can use the same argument to show that g_2 can be replaced with some $g_2' \in U_{2,p}$. So, $\iota(g_1)B_p \iota(g_2^{-1}) \in \mathcal{B}$. This concludes the proof of Claim 4.

Claim 5. Let $p \in \{0, 1, \dots, n_0\}$, $a, b \in \{1, \dots, n-1\}$ and $m \in \mathbb{Z}$, such that $a \leq b$. Then $X_a u_a^m y_{a+1} \dots y_b B_p \in \text{Span}_{R_0^a}(\mathcal{B})$.

Proof of Claim 5. Suppose $a \geq 2p+1$. Then

$$\begin{aligned} X_a u_a^m y_{a+1} \dots y_b B_p &= X_a B_p u_a^m y_{a+1} \dots y_b = \\ &X_a (y_{a-1} y_a) (y_{a-2} y_{a-1}) \dots (y_{2p+1} y_{2p+2}) (y_{2p+2} y_{2p+1}) \dots (y_{a-1} y_{a-2}) (y_a y_{a-1}) B_p u_a^m y_{a+1} \dots y_b = \\ &(y_{a-1} y_a) (y_{a-2} y_{a-1}) \dots (y_{2p+1} y_{2p+2}) X_{2p+1} B_p (y_{2p+2} y_{2p+1}) \dots (y_{a-1} y_{a-2}) (y_a y_{a-1}) u_a^m y_{a+1} \dots y_b = \\ &(y_{a-1} y_a) (y_{a-2} y_{a-1}) \dots (y_{2p+1} y_{2p+2}) B_{p+1} (y_{2p+2} y_{2p+1}) \dots (y_{a-1} y_{a-2}) (y_a y_{a-1}) u_a^m y_{a+1} \dots y_b = \\ &\iota(g_1) B_{p+1} \iota(g_2^{-1}) \in \mathcal{B}, \end{aligned}$$

where

$$\begin{aligned} g_1 &= (s_{a-1} s_a) (s_{a-2} s_{a-1}) \dots (s_{2p+1} s_{2p+2}), \\ g_2 &= s_b \dots s_{a+1} e_a^{-m} (s_{a-1} s_a) (s_{a-2} s_{a-1}) \dots (s_{2p+1} s_{2p+2}). \end{aligned}$$

Suppose $a \leq 2p$ and a is even. Let c such that $a = 2c$. Then

$$\begin{aligned} X_a u_a^m y_{a+1} \cdots y_b B_p &= X_{2c} u_{2c+1}^{-m} y_{2c+1} \cdots y_b X_{2c-1} X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &X_{2c} X_{2c-1} u_{2c+1}^{-m} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &y_{2c-1} y_{2c} y_{2c} y_{2c-1} X_{2c} X_{2c-1} u_{2c+1}^{-m} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &y_{2c-1} y_{2c} u_{2c+1} X_{2c-1} u_{2c+1}^{-m} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &\iota(s_{2c-1} s_{2c} e_{2c+1}^{1-m} s_{2c+1} \cdots s_b) B_p \in \mathcal{B}. \end{aligned}$$

Suppose $a \leq 2p$, a is odd, and $a = b$. Let c such that $a = 2c - 1$. Then

$$\begin{aligned} X_a u_a^m y_{a+1} \cdots y_b B_p &= X_{2c-1} u_{2c-1}^m X_{2c-1} X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &z_{|m|} X_{2c-1} X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = z_{|m|} B_p \in \text{Span}_{R_0^g}(\mathcal{B}). \end{aligned}$$

Suppose $a \leq 2p$, a is odd, and $a < b$. Let c such that $a = 2c - 1$. Then

$$\begin{aligned} X_a u_a^m y_{a+1} \cdots y_b B_p &= X_{2c-1} u_{2c-1}^m y_{2c} y_{2c+1} \cdots y_b X_{2c-1} X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &X_{2c-1} u_{2c}^{-m} y_{2c} X_{2c-1} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &X_{2c-1} y_{2c} u_{2c+1}^{-m} X_{2c-1} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &X_{2c-1} y_{2c} X_{2c-1} u_{2c+1}^{-m} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \\ &X_{2c-1} u_{2c+1}^{-m} y_{2c+1} \cdots y_b X_1 \cdots X_{2c-3} X_{2c+1} \cdots X_{2p-1} = \iota(e_{2c+1}^{-m} s_{2c+1} \cdots s_b) B_p \in \mathcal{B}. \end{aligned}$$

Claim 6. Let $g \in G$ and $p \in \{0, 1, \dots, n_0\}$. Then $X_1 \iota(g) B_p \in \text{Span}_{R_0^g}(\mathcal{B})$.

Proof of Claim 6. We write g in the form $g = hw$ with $h = e_1^{\nu_1} \cdots e_n^{\nu_n} \in \mathbb{Z}^n$ and $w \in \mathfrak{S}_n$. We have

$$X_1 \iota(g) B_p = X_1 u_1^{\nu_1} u_2^{\nu_2} \cdots u_n^{\nu_n} \iota(w) B_p = \iota(e_3^{\nu_3} \cdots e_n^{\nu_n}) X_1 \iota(e_1^{\nu_1 - \nu_2} w) B_p.$$

Thus, by Claim 4, we can assume that $h = e_1^m$ with $m \in \mathbb{Z}$. There exist $w_1 \in \langle s_3, \dots, s_{n-1} \rangle$, $a \in \{1, \dots, n-1\}$, and $b \in \{0, 1, \dots, n-1\}$ such that $w = w_1 s_2 s_3 \cdots s_a s_1 s_2 \cdots s_b$. We have

$$X_1 \iota(g) B_p = X_1 u_1^m \iota(w_1) y_2 \cdots y_a y_1 \cdots y_b B_p = \iota(w_1) X_1 u_1^m y_2 \cdots y_a y_1 \cdots y_b B_p.$$

Thus, by Claim 4, we can assume that $w = s_2 \cdots s_a s_1 \cdots s_b$. Suppose $a \leq b$. Then

$$\begin{aligned} X_1 \iota(g) B_p &= X_1 u_1^m y_2 \cdots y_a y_1 \cdots y_b B_p = \\ &X_1 u_1^m (y_2 y_1) (y_3 y_2) \cdots (y_a y_{a-1}) y_a y_{a+1} \cdots y_b B_p = \\ &(y_2 y_1) (y_3 y_2) \cdots (y_a y_{a-1}) X_a u_a^m y_a y_{a+1} \cdots y_b B_p = \\ &(y_2 y_1) (y_3 y_2) \cdots (y_a y_{a-1}) X_a y_a u_{a+1}^m y_{a+1} \cdots y_b B_p = \\ &(y_2 y_1) (y_3 y_2) \cdots (y_a y_{a-1}) X_a u_{a+1}^{m-1} y_{a+1} \cdots y_b B_p = \\ &\iota((s_2 s_1) (s_3 s_2) \cdots (s_a s_{a-1})) X_a u_a^{1-m} y_{a+1} \cdots y_b B_p \in \text{Span}_{R_0^g}(\mathcal{B}). \end{aligned}$$

The last inclusion follows from Claim 4 and Claim 5. Suppose $a > b$. Then

$$\begin{aligned} X_1 \iota(g) B_p &= X_1 u_1^m y_2 \cdots y_a y_1 \cdots y_b B_p = \\ &X_1 u_1^m (y_2 y_1) (y_3 y_2) \cdots (y_{b+1} y_b) y_{b+2} \cdots y_a B_p = \\ &\iota((s_2 s_1) (s_3 s_2) \cdots (s_{b+1} s_b)) X_{b+1} u_{b+1}^m y_{b+2} \cdots y_a B_p \in \text{Span}_{R_0^g}(\mathcal{B}). \end{aligned}$$

Again, the last inclusion follows from Claim 4 and Claim 5. This concludes the proof of Claim 6.

As pointed out just before Claim 4, the following claim ends the proof of Proposition 3.2.

Claim 7. The set \mathcal{M} is contained in $\text{Span}_{R_0^a}(\mathcal{B})$.

Proof of Claim 7. Let $Y \in \mathcal{M}$. By using the relations $y_i y_j X_i = X_j y_i y_j$ for $|i - j| = 1$, we see that Y can be written in the form $Y = \iota(g_0) X_1 \iota(g_1) X_1 \cdots X_1 \iota(g_k)$, where $k \geq 0$ and $g_0, g_1, \dots, g_k \in G$. We argue by induction on k . The cases $k = 0$ and $k = 1$ follow directly from Claim 4. So, we can assume that $k \geq 2$ and that the inductive hypothesis holds. By the inductive hypothesis, $\iota(g_1) X_1 \cdots X_1 \iota(g_k) \in \text{Span}_{R_0^a}(\mathcal{B})$. Thus, we just have to show that $\iota(g_0) X_1 \iota(g'_1) B_p \iota(g_2'^{-1}) \in \text{Span}_{R_0^a}(\mathcal{B})$ for all $p \in \{0, 1, \dots, n_0\}$ and all $g'_1, g'_2 \in G$. By Claim 6 we have $X_1 \iota(g'_1) B_p \in \text{Span}_{R_0^a}(\mathcal{B})$, hence, by Claim 4, $\iota(g_0) X_1 \iota(g'_1) B_p \iota(g_2'^{-1}) \in \text{Span}_{R_0^a}(\mathcal{B})$. This concludes the proof of Claim 7. \square

Recall that the Temperley–Lieb algebra TL_n is the algebra over $R_0^f = \mathbb{Z}[z]$ defined by the presentation with generators E_1, \dots, E_{n-1} and relations

$$E_i^2 = z E_i \text{ for } 1 \leq i \leq n-1, \quad E_i E_j = E_j E_i \text{ for } |i-j| \geq 2, \quad E_i E_j E_i = E_i \text{ for } |i-j| = 1.$$

We see in the presentation given in Proposition 3.2 that the relations $F_i^2 = z_0 F_i$, for $1 \leq i \leq n-1$, and $F_i F_j = F_j F_i$, for $|i-j| \geq 2$, hold in ATL_n . We also know that the relations $F_i F_j F_i = F_i$, for $|i-j| = 1$, hold (see Claim 2 in the proof of Proposition 3.2). So, we have a ring homomorphism $\iota : \text{TL}_n \rightarrow \text{ATL}_n$ which sends z to z_0 , and E_i to F_i for all $i \in \{1, \dots, n-1\}$.

Proposition 3.3 *Let $n \geq 2$. Then the above defined homomorphism $\iota : \text{TL}_n \rightarrow \text{ATL}_n$ is injective.*

Proof We see from the presentations of VTL_n and ATL_n that there is a ring homomorphism $\varphi : \text{ATL}_n \rightarrow \text{VTL}_n$ which sends z_m to z for all $m \in \mathbb{N}$, F_i to E_i for all $i \in \{1, \dots, n-1\}$, w_i to v_i for all $i \in \{1, \dots, n-1\}$, and $t_j^{\pm 1}$ to 1 for all $j \in \{1, \dots, n\}$. By Proposition 2.4 the composition $\varphi \circ \iota : \text{TL}_n \rightarrow \text{VTL}_n$ is injective, hence $\iota : \text{TL}_n \rightarrow \text{ATL}_n$ is also injective. \square

Recall that $\mathcal{Z}^* = \{z_k\}_{k=1}^\infty$, $R^a = \mathbb{Z}[A^{\pm 1}, \mathcal{Z}^*]$, and that R_0^a is embedded into R^a via the identification $z_0 = -A^2 - A^{-2}$. For each $n \geq 1$ we set $\text{ATL}_n(R^a) = R^a \otimes \text{ATL}_n$. This is a R^a -algebra and a free R^a -module freely generated by \mathcal{F}_n .

Theorem 3.4 *Let $n \geq 1$. There exists a homomorphism $\rho_n^a : R^a[\text{VB}_n] \rightarrow \text{ATL}_n(R^a)$ which sends σ_i to $-A^{-2} 1 - A^{-4} F_i$ and τ_i to w_i for all $i \in \{1, \dots, n-1\}$.*

Proof The proof is almost identical to that of Theorem 2.5. We set $S_i = -A^{-2} 1 - A^{-4} F_i$. It is easily checked as in the proof of Theorem 2.5 that $(-A^{-2} 1 - A^{-4} F_i)(-A^2 1 - A^4 F_i) = 1$, hence S_i is invertible and $S_i^{-1} = -A^2 1 - A^4 F_i$. For $i \in \{1, \dots, n-1\}$ we have $w_i^2 = 1$, hence w_i is also invertible. It remains to see that the following relations hold.

$$\begin{aligned} w_i^2 &= 1, \quad \text{for } 1 \leq i \leq n-1, \\ S_i S_j &= S_j S_i, \quad w_i w_j = w_j w_i, \quad w_i S_j = S_j w_i, \quad \text{for } |i-j| \geq 2, \\ S_i S_j S_i &= S_j S_i S_j, \quad w_i w_j w_i = w_j w_i w_j, \quad w_i w_j S_i = S_j w_i w_j, \quad \text{for } |i-j| = 1. \end{aligned}$$

The only relation which does not follow directly from the presentation of $\text{ATL}_n(R^a)$ is $S_i S_j S_i = S_j S_i S_j$, for $|i-j| = 1$. But the latter can be proved in the same way as in the proof of Theorem 2.5. \square

Remark (1) The sequence $\{\rho_n^a : R^a[\text{VB}_n] \rightarrow \text{ATL}_n(R^a)\}_{n=1}^\infty$ is compatible with the tower of algebras $\{\text{ATL}_n(R^a)\}_{n=1}^\infty$.

- (2) As in the case of virtual Temperley–Lieb algebras (see Section 2), setting $\rho_n^a(\sigma_i) = -A^{-2}1 - A^{-4}F_i$ instead of $\rho_n^a(\sigma_i) = A1 + A^{-1}F_i$ allows to include in ρ_n^a the corrective with the writhe and to define directly the arrow polynomial without passing through the arrow Kauffman bracket.
- (3) For each $n \geq 1$ and $\beta \in B_n$ we have $\rho_n^a(\beta) = \rho_n^f(\beta) \in \text{TL}_n(R^f)$.

Recall that $V_n = \{0, 1\} \times \{1, \dots, n\}$ is ordered by $(0, 1) < (0, 2) < \dots < (0, n) < (1, n) < \dots < (1, 2) < (1, 1)$. Let E be a flat virtual tangle. A cycle of length ℓ in the closure \hat{E} of E is a ℓ -tuple $\hat{\gamma} = (\gamma_1, \dots, \gamma_\ell)$ in E , where $\gamma_i = \{(a_i, b_{i-1}), (c_i, b_i)\}$, satisfying the following properties.

- (a) $a_{i+1} = 1$ if $c_i = 0$, and $a_{i+1} = 0$ if $c_i = 1$, for all $i \in \{1, \dots, \ell - 1\}$.
- (b) $b_0 = b_\ell < b_i$ for all $i \in \{1, \dots, \ell - 1\}$, $a_1 = 0$, and $c_\ell = 1$.

Let $F = (E, f)$ be an arrow flat n -tangle. We define the *parity* of an element $\alpha = \{(a, b), (c, d)\} \in E$ by $\varpi(\alpha) = -1$ if $a = c$, and $\varpi(\alpha) = 1$ if $a \neq c$. Let $\hat{\gamma} = (\gamma_1, \dots, \gamma_\ell)$ be a cycle in \hat{E} . We write $\gamma_i = \{(a_i, b_{i-1}), (c_i, b_i)\}$ for all i , and we define the *cumulated parity* of γ_i relative to $\hat{\gamma}$ by $\varpi^c(\gamma_i) = \prod_{j=1}^{i-1} \varpi(\gamma_j)$ if $(a_i, b_{i-1}) < (c_i, b_i)$, and $\varpi^c(\gamma_i) = \prod_{j=1}^i \varpi(\gamma_j)$ if $(c_i, b_i) < (a_i, b_{i-1})$. Then we set

$$h(\hat{\gamma}) = \sum_{i=1}^{\ell} \varpi^c(\gamma_i) f(\gamma_i).$$

It is easily seen that $h(\hat{\gamma})$ is an even number. The *number of zigzags* of $\hat{\gamma}$ is defined by $\zeta(\hat{\gamma}) = \frac{|h(\hat{\gamma})|}{2}$. Let $\hat{\gamma}_1, \dots, \hat{\gamma}_m$ be the cycles of \hat{E} . Then we set

$$T_n^{la}(F) = z_{\zeta(\hat{\gamma}_1)} z_{\zeta(\hat{\gamma}_2)} \cdots z_{\zeta(\hat{\gamma}_m)}.$$

We define $T_n^{la} : \text{ATL}_n(R^a) \rightarrow R^a$ by extending linearly the map $T_n^{la} : \mathcal{F}_n \rightarrow R^a$.

Example The closure of the arrow flat tangle of Figure 3.5 is illustrated in Figure 3.8. Here \hat{E} has a unique cycle $\hat{\gamma}$ and $h(\hat{\gamma}) = 1 - (-6) - 3 = 4$, hence $T_n^{la}(F) = z_2$.

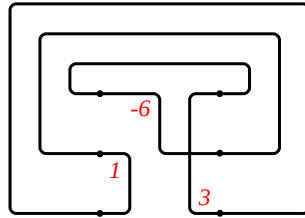


Figure 3.8: Closure of an arrow flat tangle

Theorem 3.5 The sequence $\{T_n^{la} : \text{ATL}_n(R^a) \rightarrow R^a\}_{n=1}^\infty$ is a Markov trace.

Proof For each $n \geq 2$ and each $i \in \{1, \dots, n - 1\}$ we set $S_i = -A^{-2}1 - A^{-4}F_i$. We need to prove that the following equalities hold.

- (1) $T_n^{la}(xy) = T_n^{la}(yx)$ for all $n \geq 1$ and all $x, y \in \text{ATL}_n(\mathbb{R}^a)$;
- (2) $T_n^{la}(x) = T_{n+1}^{la}(xS_n) = T_{n+1}^{la}(xS_n^{-1}) = T_{n+1}^{la}(xw_n)$ for all $n \geq 1$ and all $x \in \text{ATL}_n(\mathbb{R}^a)$;
- (3) $T_n^{la}(x) = T_{n+1}^{la}(xS_n^{-1}w_{n-1}S_n)$ for all $n \geq 2$ and all $x \in \text{ATL}_n(\mathbb{R}^a)$;
- (4) $T_n^{la}(x) = T_{n+1}^{la}(xw_nw_{n-1}S_{n-1}w_nS_{n-1}^{-1}w_{n-1}w_n)$ for all $n \geq 2$ and all $x \in \text{ATL}_n(\mathbb{R}^a)$.

Proof of (1). We can assume that $x = F = (E, f)$ and $y = F' = (E', f')$ are arrow flat n -tangles. As in the definition of the multiplication in ATL_n , for $\alpha \in E \sqcup E'$, we set $f^*(\alpha) = f(\alpha)$ if $\alpha \in E$ and $f^*(\alpha) = f'(\alpha)$ if $\alpha \in E'$. A long cycle of length $2p$ in $E \sqcup E'$ is a $2p$ -tuple $\hat{\gamma} = (\gamma_1, \dots, \gamma_{2p})$ in $E \sqcup E'$, where $\gamma_i = \{(a_i, b_{i-1}), (c_i, b_i)\}$, satisfying the following properties.

- (a) $\gamma_i \in E$ if i is odd, $\gamma_i \in E'$ if i is even, $a_{i+1} = 1$ if $c_i = 0$, $a_{i+1} = 0$ if $c_i = 1$ (The indices are taken in $\{1, \dots, 2p\}$ modulo $2p$. In particular, $b_{2p} = b_0$).
- (b) $(a_1, b_0) < (a_i, b_{i-1})$ for all $i \in \{3, 5, \dots, 2p-1\}$ and $(a_1, b_0) < (c_i, b_i)$ for all $i \in \{1, 3, \dots, 2p-1\}$.

The cumulated parity of γ_i relative to $\hat{\gamma}$ is $\varpi^c(\gamma_i) = \prod_{j=1}^{i-1} \varpi(\gamma_j)$ if $(a_i, b_{i-1}) < (c_i, b_i)$ and $\varpi^c(\gamma_i) = \prod_{j=1}^i \varpi(\gamma_j)$ if $(a_i, b_{i-1}) > (c_i, b_i)$. We set

$$h(\hat{\gamma}) = \sum_{i=1}^{2p} \varpi^c(\gamma_i) f^*(\gamma_i).$$

We see that $h(\hat{\gamma})$ is an even number. Then we define the number of zigzags of $\hat{\gamma}$ by $\zeta(\hat{\gamma}) = \frac{|h(\hat{\gamma})|}{2}$. Let $\hat{\gamma}_1, \dots, \hat{\gamma}_m$ be the long cycles of $E \sqcup E'$. Then

$$T_n^{la}(FF') = z_{\zeta(\hat{\gamma}_1)} z_{\zeta(\hat{\gamma}_2)} \cdots z_{\zeta(\hat{\gamma}_m)}.$$

Let $\hat{\gamma} = (\gamma_1, \dots, \gamma_{2p})$ be a long cycle of $E \sqcup E'$. There exists a unique long cycle $\hat{\gamma}'$ of $E' \sqcup E$ of one the following forms

$$(\gamma_i, \gamma_{i+1}, \dots, \gamma_{2p}, \gamma_1, \gamma_2, \dots, \gamma_{i-1}) \text{ or } (\gamma_i, \gamma_{i-1}, \dots, \gamma_1, \gamma_{2p}, \gamma_{2p-1}, \dots, \gamma_{i+1}),$$

with $i \in \{2, 4, \dots, 2p\}$. In addition, each long cycle of $E' \sqcup E$ is of this form, and $h(\hat{\gamma}') = \pm h(\hat{\gamma})$, hence $\zeta(\hat{\gamma}') = \zeta(\hat{\gamma})$. We conclude that $T_n^{la}(FF') = T_n^{la}(F'F)$.

Proof of (2). From now on the proof of Theorem 3.5 is almost identical to that of Theorem 2.6. We can assume that $x = F = (E, f)$ is an arrow flat n -tangle. We see in Figure 3.9 that the following equalities hold.

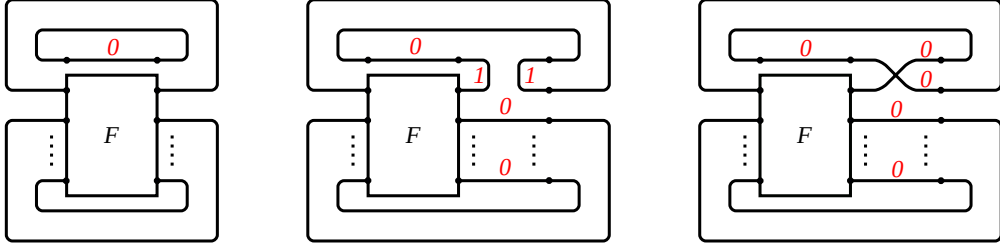
$$T_{n+1}^{la}(F) = z_0 T_n^{la}(F), \quad T_{n+1}^{la}(FF_n) = T_n^{la}(F), \quad T_{n+1}^{la}(Fw_n) = T_n^{la}(F).$$

Recall that $S_n^{-1} = -A^2 1 - A^4 F_n$ (see the proof of Theorem 3.4). It follows that

$$\begin{aligned} T_{n+1}^{la}(FS_n) &= -A^{-2} T_{n+1}^{la}(F) - A^{-4} T_{n+1}^{la}(FF_n) = (-A^{-2} z_0 - A^{-4}) T_n^{la}(F) = T_n^{la}(F), \\ T_{n+1}^{la}(FS_n^{-1}) &= -A^2 T_{n+1}^{la}(F) - A^4 T_{n+1}^{la}(FF_n) = (-A^2 z_0 - A^4) T_n^{la}(F) = T_n^{la}(F). \end{aligned}$$

Proof of (3). We can again assume that $x = F = (E, f)$ is a flat n -tangle. We have

$$\begin{aligned} FS_n^{-1}w_{n-1}S_n &= F(-A^2 1 - A^4 F_n)w_{n-1}(-A^{-2} 1 - A^{-4} F_n) = \\ &= Fw_{n-1} + A^2 FF_n w_{n-1} + A^{-2} Fw_{n-1} F_n + FF_n w_{n-1} F_n = \\ &= Fw_{n-1} + A^2 FF_n w_{n-1} + A^{-2} Fw_{n-1} F_n + FF_n. \end{aligned}$$

Figure 3.9: $n + 1$ -closure of F , FF_n , and Fw_n

By the above, it follows that

$$\begin{aligned}
& T'_{n+1}{}^a(FS_n^{-1}w_{n-1}S_n) = \\
& T'_{n+1}{}^a(Fw_{n-1}) + A^{-2}T'_{n+1}{}^a(Fw_{n-1}F_n) + A^2T'_{n+1}{}^a(FF_nw_{n-1}) + T'_{n+1}{}^a(FF_n) = \\
& z_0T'_n{}^a(Fw_{n-1}) + A^{-2}T'_n{}^a(Fw_{n-1}) + A^2T'_{n+1}{}^a(w_{n-1}FF_n) + T'_n{}^a(F) = \\
& (-A^2 - A^{-2})T'_n{}^a(Fw_{n-1}) + A^{-2}T'_n{}^a(Fw_{n-1}) + A^2T'_n{}^a(w_{n-1}F) + T'_n{}^a(F) = \\
& (-A^2 - A^{-2})T'_n{}^a(Fw_{n-1}) + A^{-2}T'_n{}^a(Fw_{n-1}) + A^2T'_n{}^a(Fw_{n-1}) + T'_n{}^a(F) = T'_n{}^a(F).
\end{aligned}$$

Proof of (4). We can again assume that $x = F = (E, f)$ is an arrow flat n -tangle. Then

$$\begin{aligned}
& Fw_nw_{n-1}S_{n-1}w_nS_{n-1}^{-1}w_{n-1}w_n = \\
& Fw_nw_{n-1}(-A^{-2}1 - A^{-4}F_{n-1})w_n(-A^21 - A^4F_{n-1})w_{n-1}w_n = \\
& (Fw_nw_{n-1}w_nw_{n-1}w_n) + A^2(Fw_nw_{n-1}w_nF_{n-1}w_{n-1}w_n) + \\
& A^{-2}(Fw_nw_{n-1}F_{n-1}w_nw_{n-1}w_n) + (Fw_nw_{n-1}F_{n-1}w_nF_{n-1}w_{n-1}w_n) = \\
& (Fw_{n-1}w_nw_{n-1}w_{n-1}w_n) + A^2(Fw_nF_nw_{n-1}w_nw_{n-1}w_n) + \\
& A^{-2}(Fw_nw_{n-1}w_nw_{n-1}F_nw_n) + (Fw_nw_{n-1}F_{n-1}w_{n-1}w_n) = \\
& (Fw_{n-1}) + A^2(Fw_nF_nw_{n-1}w_{n-1}w_nw_{n-1}) + \\
& A^{-2}(Fw_{n-1}w_nw_{n-1}w_{n-1}F_nw_n) + (Fw_nt_{n-1}^{-1}F_{n-1}t_{n-1}w_n) = \\
& (Fw_{n-1}) + A^2(Fw_nF_nw_nw_{n-1}) + A^{-2}(Fw_{n-1}w_nF_nw_n) + (Ft_{n-1}^{-1}w_nF_{n-1}w_nt_{n-1}) = \\
& (Fw_{n-1}) + A^2(Ft_n^{-1}F_nt_nw_{n-1}) + A^{-2}(Fw_{n-1}t_n^{-1}F_nt_n) + (Ft_{n-1}^{-1}w_{n-1}F_nw_{n-1}t_{n-1}).
\end{aligned}$$

By the above, it follows that

$$\begin{aligned}
& T_{n+1}^{t_a}(Fw_n w_{n-1} S_{n-1} w_n S_{n-1}^{-1} w_{n-1} w_n) = \\
& T_{n+1}^{t_a}(Fw_{n-1}) + A^2 T_{n+1}^{t_a}(Ft_n^{-1} F_n t_n w_{n-1}) + \\
& A^{-2} T_{n+1}^{t_a}(Fw_{n-1} t_n^{-1} F_n t_n) + T_{n+1}^{t_a}(Ft_{n-1}^{-1} w_{n-1} F_n w_{n-1} t_{n-1}) = \\
& z_0 T_n^{t_a}(Fw_{n-1}) + A^2 T_{n+1}^{t_a}(t_n w_{n-1} Ft_n^{-1} F_n) + \\
& A^{-2} T_{n+1}^{t_a}(t_n Fw_{n-1} t_n^{-1} F_n) + T_{n+1}^{t_a}(w_{n-1} t_{n-1} Ft_{n-1}^{-1} w_{n-1} F_n) = \\
& (-A^2 - A^{-2}) T_n^{t_a}(Fw_{n-1}) + A^2 T_n^{t_a}(t_n w_{n-1} Ft_n^{-1}) + \\
& A^{-2} T_n^{t_a}(t_n Fw_{n-1} t_n^{-1}) + T_n^{t_a}(w_{n-1} t_{n-1} Ft_{n-1}^{-1} w_{n-1}) = \\
& (-A^2 - A^{-2}) T_n^{t_a}(Fw_{n-1}) + A^2 T_n^{t_a}(Ft_n^{-1} t_n w_{n-1}) + \\
& A^{-2} T_n^{t_a}(Fw_{n-1} t_n^{-1} t_n) + T_n^{t_a}(Ft_{n-1}^{-1} w_{n-1} w_{n-1} t_{n-1}) = \\
& (-A^2 - A^{-2}) T_n^{t_a}(Fw_{n-1}) + A^2 T_n^{t_a}(Fw_{n-1}) + A^{-2} T_n^{t_a}(Fw_{n-1}) + T_n^{t_a}(F) = T_n^{t_a}(F). \quad \square
\end{aligned}$$

Corollary 3.6 For each $n \geq 1$ we set $T_n^a = T_n^{t_a} \circ \rho_n^a : R^a[\text{VB}_n] \rightarrow R^a$. Then the sequence $\{T_n^a : R^a[\text{VB}_n] \rightarrow R^a\}_{n=1}^\infty$ is a Markov trace.

Recall that $R^f = \mathbb{Z}[A^{\pm 1}]$ is a subring of $R^a = \mathbb{Z}[A^{\pm 1}, \mathcal{Z}^*]$ and that, for $n \geq 1$, we have an embedding $\iota_n : \text{TL}_n(R^f) \rightarrow \text{ATL}_n(R^a)$ which sends E_i to F_i for all $i \in \{1, \dots, n-1\}$ (see Proposition 3.3). The next proposition is a version of Theorem 3.1 (2) in terms of Temperley–Lieb algebras.

Proposition 3.7 Let $n \geq 1$. Then $T_n^{t_a}(\iota_n(x)) = T_n^{t_f}(x) \in R^f$ for all $x \in \text{TL}_n(R^f)$.

We denote by \mathcal{E}_n^ν the set of flat virtual n -tangles $E \in \mathcal{E}_n$ such that, for each $\alpha = \{(a, b), (c, d)\} \in E$, $d-b$ is odd if $a = c$, and $d-b$ is even if $a \neq c$. We denote by VTL_n^ν the R_0^f -submodule of VTL_n spanned by \mathcal{E}_n^ν . For each $E \in \mathcal{E}_n^\nu$ we define $\iota_n^\nu(E) = (E, f) \in \mathcal{F}_n$ as follows. Let $\alpha = \{(a, b), (c, d)\} \in E$. If $a = c$, we set $f(\alpha) = |d-b|$, and if $a = 0$ and $c = 1$, we set $f(\alpha) = d-b$. We define $\iota_n^\nu : \text{VTL}_n^\nu \rightarrow \text{ATL}_n$ by identifying z with z_0 and extending linearly the map $\iota_n^\nu : \mathcal{E}_n^\nu \rightarrow \mathcal{F}_n$. The key point in the proof of Proposition 3.7 is the following.

Lemma 3.8 Let $n \geq 1$.

- (1) VTL_n^ν is a subalgebra of VTL_n and $\iota_n^\nu : \text{VTL}_n^\nu \rightarrow \text{ATL}_n$ is a ring homomorphism.
- (2) Let $\text{VTL}_n^\nu(R^f) = R^f \otimes \text{VTL}_n^\nu$, and let $\iota_n^\nu : \text{VTL}_n^\nu(R^f) \rightarrow \text{ATL}_n(R^a)$ be the homomorphism induced by $\iota_n^\nu : \text{VTL}_n^\nu \rightarrow \text{ATL}_n$. Then $T_n^{t_a}(\iota_n^\nu(x)) = T_n^{t_f}(x) \in R^f$ for all $x \in \text{VTL}_n^\nu(R^f)$.

Proof Let $E, E' \in \mathcal{E}_n^\nu$. Set $\iota_n^\nu(E) = (E, f)$, $\iota_n^\nu(E') = (E', f')$, and $\iota_n^\nu(E) * \iota_n^\nu(E') = (E * E', g)$. We first show that $E * E' \in \mathcal{E}_n^\nu$ and that $(E * E', g) = \iota_n^\nu(E * E')$. Let $\hat{\alpha}$ be an arc in $E \sqcup E'$ of length ℓ , and let $\partial \hat{\alpha} = \{x', y'\}$, with $x' = (a, b) < y' = (c, d)$.

Suppose $a = c = 0$ and $\ell = 1$. Then $\partial \hat{\alpha} = \alpha_1 = \{(0, b), (0, d)\}$, $d-b$ is odd, and $g(\partial \hat{\alpha}) = d-b = |d-b|$.

Suppose $a = c = 0$ and $\ell > 1$. Then ℓ is odd, say $\ell = 2p+1$. There exists a sequence $a_0, a_1, \dots, a_{2p+1}$ in $\{1, \dots, n\}$ such that $\hat{\alpha}$ is of the form $\hat{\alpha} = (\alpha_0, \beta_1, \gamma_2, \dots, \gamma_{2p-2}, \beta_{2p-1}, \alpha_{2p})$,

where $\alpha_0 = \{(0, a_0), (1, a_1)\} \in E$, $\beta_i = \{(0, a_i), (0, a_{i+1})\} \in E'$ for all $i \in \{1, 3, \dots, 2p-1\}$, $\gamma_i = \{(1, a_i), (1, a_{i+1})\} \in E$ for all $i \in \{2, 4, \dots, 2p-2\}$, and $\alpha_{2p} = \{(1, a_{2p}), (0, a_{2p+1})\} \in E$. We also have $x' = (0, a_0)$, $y' = (0, a_{2p+1})$, and $a_0 = b < a_{2p+1} = d$. The numbers $a_1 - a_0$ and $a_{2p+1} - a_{2p}$ are even, and the number $a_{i+1} - a_i$ is odd for every $i \in \{1, \dots, 2p-1\}$, hence $a_{2p+1} - a_0 = d - b$ is odd. We have $\varpi^c(\alpha_0) = 1$, hence $\varpi^c(\alpha_0)f^*(\alpha_0) = a_1 - a_0$. Let $i \in \{1, 3, \dots, 2p-1\}$. We have $\varpi^c(\beta_i) = 1$ if $a_i < a_{i+1}$ and $\varpi^c(\beta_i) = -1$ if $a_i > a_{i+1}$. In both cases we have $\varpi^c(\beta_i)f^*(\beta_i) = a_{i+1} - a_i$. Let $i \in \{2, 4, \dots, 2p-2\}$. We have $\varpi^c(\gamma_i) = 1$ if $a_i < a_{i+1}$ and $\varpi^c(\gamma_i) = -1$ if $a_i > a_{i+1}$. In both cases we have $\varpi^c(\gamma_i)f^*(\gamma_i) = a_{i+1} - a_i$. We have $\varpi^c(\alpha_{2p}) = -1$, hence $\varpi^c(\alpha_{2p})f^*(\alpha_{2p}) = a_{2p+1} - a_{2p}$. So, $g(\hat{\alpha}) = g(\partial\hat{\alpha}) = a_{2p+1} - a_0 = d - b = |d - b|$.

Suppose $a = c = 1$ and $\ell = 1$. Then $\partial\hat{\alpha} = \alpha_1 = \{(1, b), (1, d)\}$, $b - d$ is odd, and $g(\partial\hat{\alpha}) = b - d = |b - d|$. Suppose $a = c = 1$ and $\ell > 1$. Then we show in the same way as for the case $a = c = 0$ and $\ell > 1$ that $b - d$ is odd and $g(\hat{\alpha}) = g(\partial\hat{\alpha}) = b - d = |b - d|$.

Suppose $a = 0$ and $c = 1$. Then $\ell \geq 2$ and ℓ is even, say $\ell = 2p + 2$. There exists a sequence $a_0, a_1, \dots, a_{2p+2}$ in $\{1, \dots, n\}$ such that $\hat{\alpha}$ is of the form $\hat{\alpha} = (\alpha_0, \beta_1, \gamma_2, \dots, \beta_{2p-1}, \gamma_{2p}, \delta_{2p+1})$, where $\alpha_0 = \{(0, a_0), (1, a_1)\} \in E$, $\beta_i = \{(0, a_i), (0, a_{i+1})\} \in E'$ for all $i \in \{1, 3, \dots, 2p-1\}$, $\gamma_i = \{(1, a_i), (1, a_{i+1})\} \in E$ for all $i \in \{2, 4, \dots, 2p\}$, and $\delta_{2p+1} = \{(0, a_{2p+1}), (1, a_{2p+2})\} \in E'$. We also have $x' = (0, b) = (0, a_0)$ and $y' = (1, d) = (1, a_{2p+2})$. The numbers $a_1 - a_0$ and $a_{2p+2} - a_{2p+1}$ are even and $a_{i+1} - a_i$ is odd for each $i \in \{1, \dots, 2p\}$, hence $d - b = a_{2p+2} - a_0$ is even. We have $\varpi^c(\alpha_0) = 1$, hence $\varpi^c(\alpha_0)f^*(\alpha_0) = a_1 - a_0$. Let $i \in \{1, 3, \dots, 2p-1\}$. We have $\varpi^c(\beta_i) = 1$ if $a_i < a_{i+1}$ and $\varpi^c(\beta_i) = -1$ if $a_i > a_{i+1}$. In both cases we have $\varpi^c(\beta_i)f^*(\beta_i) = a_{i+1} - a_i$. Let $i \in \{2, 4, \dots, 2p\}$. We have $\varpi^c(\gamma_i) = 1$ if $a_i < a_{i+1}$ and $\varpi^c(\gamma_i) = -1$ if $a_i > a_{i+1}$. In both cases we have $\varpi^c(\gamma_i)f^*(\gamma_i) = a_{i+1} - a_i$. We have $\varpi^c(\delta_{2p+1}) = 1$, hence $\varpi^c(\delta_{2p+1})f^*(\delta_{2p+1}) = a_{2p+2} - a_{2p+1}$. So, $g(\hat{\alpha}) = g(\partial\hat{\alpha}) = a_{2p+2} - a_0 = d - b$.

The above shows that $E * E' \in \mathcal{E}_n^\nu$ and $\iota_n^\nu(E * E') = \iota_n^\nu(E) * \iota_n^\nu(E')$.

Let $\hat{\gamma}$ be a cycle in $E \sqcup E'$ of length ℓ . Then $\ell \geq 2$ and ℓ is even, say $\ell = 2p$. There exists a sequence a_0, a_1, \dots, a_{2p} in $\{1, \dots, n\}$ such that $\hat{\gamma}$ is of the form $\hat{\gamma} = (\alpha_1, \beta_2, \dots, \alpha_{2p-1}, \beta_{2p})$, where $\alpha_i = \{(1, a_{i-1}), (1, a_i)\} \in E$ for all $i \in \{1, 3, \dots, 2p-1\}$ and $\beta_i = \{(0, a_{i-1}), (0, a_i)\} \in E'$ for all $i \in \{2, 4, \dots, 2p\}$. We also have $a_{2p} = a_0$. Let $i \in \{1, 3, \dots, 2p-1\}$. We have $\varpi^c(\alpha_i) = 1$ if $a_{i-1} > a_i$ and $\varpi^c(\alpha_i) = -1$ if $a_{i-1} < a_i$. In both cases we have $\varpi^c(\alpha_i)f^*(\alpha_i) = a_{i-1} - a_i$. Let $i \in \{2, 4, \dots, 2p\}$. We have $\varpi^c(\beta_i) = 1$ if $a_{i-1} > a_i$ and $\varpi^c(\beta_i) = -1$ if $a_{i-1} < a_i$. In both cases we have $\varpi^c(\beta_i)f^*(\beta_i) = a_{i-1} - a_i$. Thus, $h(\hat{\gamma}) = a_0 - a_{2p} = 0$, hence $\zeta(\hat{\gamma}) = 0$. So, if m is the number of cycles in $E \sqcup E'$, then $\iota_n^\nu(E) \iota_n^\nu(E') = z_0^m (\iota_n^\nu(E) * \iota_n^\nu(E'))$, hence $\iota_n^\nu(E) \iota_n^\nu(E') = \iota_n^\nu(EE')$. This concludes the proof of the first part of the lemma.

Let $E \in \mathcal{E}_n^\nu$ and let $(E, f) = \iota_n^\nu(E)$. In order to prove the second part of the lemma, it suffices to show that, if $\hat{\gamma}$ is a cycle of \hat{E} , then $\zeta(\hat{\gamma}) = 0$, that is, $h(\hat{\gamma}) = 0$. Let $\hat{\gamma}$ be a cycle of \hat{E} . Then $\hat{\gamma}$ is of the form

$$\hat{\gamma} = (\alpha_{1,1}, \dots, \alpha_{1,p_1}, \beta_1, \gamma_{1,1}, \dots, \gamma_{1,q_1}, \delta_1, \dots, \alpha_{r,1}, \dots, \alpha_{r,p_r}, \beta_r, \gamma_{r,1}, \dots, \gamma_{r,q_r}, \\ \delta_r, \alpha_{r+1,1}, \dots, \alpha_{r+1,p_{r+1}}),$$

where

$$\alpha_{i,j} = \{(0, a_{i,j-1}), (1, a_{i,j})\}, \beta_i = \{(0, b_{i,0}), (0, b_{i,1})\}, \gamma_{i,j} = \{(1, c_{i,j-1}), (0, c_{i,j})\}, \\ \delta_i = \{(1, d_{i,0}), (1, d_{i,1})\}, a_{i,p_i} = b_{i,0}, b_{i,1} = c_{i,0}, c_{i,q_i} = d_{i,0}, d_{i,1} = a_{i+1,0}, a_{r+1,p_{r+1}} = a_{1,0}.$$

We have $\varpi^c(\alpha_{i,j}) = 1$, hence $\varpi^c(\alpha_{i,j})f(\alpha_{i,j}) = a_{i,j} - a_{i,j-1}$. We have $\varpi^c(\beta_i) = -1$ if $b_{i,0} > b_{i,1}$ and $\varpi^c(\beta_i) = 1$ if $b_{i,0} < b_{i,1}$. In both cases we have $\varpi^c(\beta_i)f(\beta_i) = b_{i,1} - b_{i,0}$. We have $\varpi^c(\gamma_{i,j}) = -1$, hence $\varpi^c(\gamma_{i,j})f(\gamma_{i,j}) = c_{i,j} - c_{i,j-1}$. We have $\varpi^c(\delta_i) = -1$ if $d_{i,0} > d_{i,1}$ and $\varpi^c(\delta_i) = 1$ if $d_{i,0} < d_{i,1}$. In both cases we have $\varpi^c(\delta_i)f(\delta_i) = d_{i,1} - d_{i,0}$. Combining these equalities we get $h(\hat{\gamma}) = a_{r+1,p_{r+1}} - a_{1,0} = 0$, hence $\zeta(\hat{\gamma}) = 0$. \square

Proof of Proposition 3.7 We have $E_i \in \text{VTL}_n^\nu(R^f)$ for all $i \in \{1, \dots, n-1\}$, $\text{TL}_n(R^f)$ is generated by E_1, \dots, E_{n-1} , and $\text{VTL}_n^\nu(R^f)$ is a subalgebra of $\text{VTL}_n(R^f)$, hence $\text{TL}_n(R^f) \subset \text{VTL}_n^\nu(R^f)$. Moreover, since $\iota_n(E_i) = \iota_n^\nu(E_i)$ for all $i \in \{1, \dots, n-1\}$, we have $\iota_n(x) = \iota_n^\nu(x)$ for all $x \in \text{TL}_n(R^f)$. We conclude from Lemma 3.8 that $T_n^a(\iota_n(x)) = T_n^a(x) \in R^f$ for all $x \in \text{TL}_n(R^f)$. \square

Now, it remains to prove the following.

Theorem 3.9 Let $I^a : \mathcal{VL} \rightarrow R^a$ be the invariant defined from the Markov trace of Corollary 3.6. Then I^a coincides with the arrow polynomial.

Proof The proof is similar to that of Theorem 2.8. Let β be a virtual braid on n strands and let $\hat{\beta}$ be its closure. It is easily seen that the relations $\langle\langle L \rangle\rangle = A\langle\langle L_1 \rangle\rangle + A^{-1}\langle\langle L_2 \rangle\rangle$ and $\langle\langle L \rangle\rangle = A^{-1}\langle\langle L_1 \rangle\rangle + A\langle\langle L_2 \rangle\rangle$ in the definition of the arrow Kauffman bracket corresponds in terms of closed virtual braids to replacing each σ_i with $A1 + A^{-1}F_i$ and each σ_i^{-1} with $A^{-1}1 + AF_i$. Once we have replaced each σ_i with $A1 + A^{-1}F_i$ and each σ_i^{-1} with $A^{-1}1 + AF_i$, we get a linear combination $\sum_{i=1}^{\ell} a_i F^{(i)}$, where $F^{(i)} = (E^{(i)}, f^{(i)}) \in \mathcal{F}_n$ and $a_i \in R^a$ for all i . For $i \in \{1, \dots, \ell\}$ let $\hat{\gamma}_{i,1}, \dots, \hat{\gamma}_{i,m_i}$ be the cycles of $\hat{E}^{(i)}$. Then

$$\langle\langle \hat{\beta} \rangle\rangle = \sum_{i=1}^{\ell} a_i z_{\zeta(\hat{\gamma}_{i,1})} z_{\zeta(\hat{\gamma}_{i,2})} \cdots z_{\zeta(\hat{\gamma}_{i,m_i})}.$$

Recall that $w : \mathcal{VL} \rightarrow \mathbb{Z}$ denotes the writhe. Let $\omega : \text{VB}_n \rightarrow \mathbb{Z}$ be the homomorphism which sends σ_i to 1 and τ_i to 0 for all $i \in \{1, \dots, n-1\}$. Then $w(\hat{\beta}) = \omega(\beta)$, and therefore $\vec{f}(\hat{\beta}) = (-A^3)^{-\omega(\beta)} \langle\langle \hat{\beta} \rangle\rangle$. So, in the above procedure, if we replace each σ_i with $(-A^3)^{-1}(A1 + A^{-1}F_i) = -A^{-2}1 - A^{-4}F_i$ and each σ_i^{-1} with $(-A^3)(A^{-1}1 + AF_i) = -A^21 - A^4F_i$, then we get directly $\vec{f}(\hat{\beta})$. It is clear that this procedure also leads to $T_n^a(\beta)$. \square

References

- [1] **H A Dye, L H Kauffman**, *Virtual crossing number and the arrow polynomial*, J. Knot Theory Ramifications 18 (2009), no. 10, 1335–1357.
- [2] **V F R Jones**, *A polynomial invariant for knots via von Neumann algebras*, Bull. Amer. Math. Soc. (N.S.) 12 (1985), no. 1, 103–111.
- [3] **V F R Jones**, *Hecke algebra representations of braid groups and link polynomials*, Ann. of Math. (2) 126 (1987), no. 2, 335–388.
- [4] **S Kamada**, *Braid presentation of virtual knots and welded knots*, Osaka J. Math. 44 (2007), no. 2, 441–458.

- [5] **L H Kauffman**, *State models and the Jones polynomial*, *Topology* 26 (1987), no. 3, 395–407.
- [6] **L H Kauffman**, *Virtual knot theory*, *European J. Combin.* 20 (1999), no. 7, 663–690.
- [7] **L H Kauffman**, *A survey of virtual knot theory*, *Knots in Hellas '98 (Delphi)*, 143–202, Ser. Knots Everything, 24, World Sci. Publ., River Edge, NJ, 2000.
- [8] **L H Kauffman**, *An extended bracket polynomial for virtual knots and links*, *J. Knot Theory Ramifications* 18 (2009), no. 10, 1369–1422.
- [9] **L H Kauffman, S Lambropoulou**, *Virtual braids and the L-move*, *J. Knot Theory Ramifications* 15 (2006), no. 6, 773–811.
- [10] **Z Li, F Lei, J Li**, *Virtual braids, virtual Temperley-Lieb algebra and f -polynomial*, *Chin. Ann. Math. Ser. B* 38 (2017), no. 6, 1275–1286.
- [11] **Y Miyazawa**, *A multi-variable polynomial invariant for virtual knots and links*, *J. Knot Theory Ramifications* 17 (2008), no. 11, 1311–1326.
- [12] **V V Vershinin**, *On homology of virtual braids and Burau representation*, *Knots in Hellas '98, Vol. 3 (Delphi)*, *J. Knot Theory Ramifications* 10 (2001), no. 5, 795–812.
- [13] **Y Zhang, L H Kauffman, M-L Ge**, *Virtual Extension of Temperley-Lieb Algebra*, preprint, 2006, arXiv:math-ph/0610052.

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