



Experiments on growth series of braid groups

Jean Fromentin

► To cite this version:

| Jean Fromentin. Experiments on growth series of braid groups. 2021. hal-02929264v2

HAL Id: hal-02929264

<https://hal.science/hal-02929264v2>

Preprint submitted on 27 Jan 2021 (v2), last revised 14 Apr 2021 (v3)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

EXPERIMENTS ON GROWTH SERIES OF BRAID GROUPS

JEAN FROMENTIN

ABSTRACT. We introduce an algorithmic framework to investigate spherical and geodesic growth series of braid groups relatively to the Artin's or Birman–Ko–Lee's generators. We present our experimentations in the case of three and four strands and conjecture rational expressions for the spherical growth series with respect to the Birman–Ko–Lee's generators.

1. INTRODUCTION

Originally introduced as the group of isotopy classes of n -strands geometric braids, the braid group B_n admits many finite presentations by generators and relations. From each finite semigroup generating set S of B_n we can define at least two growth series. The spherical growth series counts elements of B_n by their distance from the identity in the Cayley graph $\text{Cay}(B_n, S)$ of B_n with respect to S . The geodesic growth series counts geodesic paths starting from the identity by length in $\text{Cay}(B_n, S)$.

In case of Artin's generators $\Sigma_n = \{\sigma_1^{\pm 1}, \dots, \sigma_{n-1}^{\pm 1}\}$ of B_n the only known significant results are for $n \leq 3$. L. Sabalka determines [24] both the spherical and geodesic growth series of B_3 . To this end, he constructs an explicit deterministic finite automaton recognizing the language of geodesic Σ_3 -words. In particular he obtains the rationality of both series. Similar results were obtained by J. Mairesse and F. Mathéus in case of Artin–Tits groups of dihedral type [23]. In page 57 of her PhD thesis [2], M. Albenque gives the first 13 terms of the spherical series of B_4 relatively to Σ_4 .

Here we introduce a new algorithmic framework to compute the first terms of the spherical and geodesic growth series of B_n relatively to both Artin's or Birman–Ko–Lee's generators. Experimentations allow us to conjecture rational expressions for the spherical growth series of B_3 and B_4 and geodesic growth series of B_3 relatively to the Birman–Ko–Lee's generators. We also obtain the first 26 terms of the spherical and geodesic growth series of B_4 with respect to Σ_4 but this is not enough to formulate any conjecture in this case. Experiments presented in this paper were carried out using the **CALCULCO** computing platform [25].

The paper is organized as follows. Section 2 recalls basic definitions and presents already known result on the subject. In section 3 we describe a first algorithm to explore spherical and geodesic combinatorics of braids relatively to Artin's or Birman–Ko–Lee generators. Section 4 is devoted to the notion of braid template which allows us to parallelize the algorithms obtained in the previous section. In section 5 we show how to reduce the exploration space by introducing reduced braid templates. Experimentation results are detailed in the last section.

2020 *Mathematics Subject Classification.* Primary 20F36, 20F10; Secondary 20F69, 68R15.
Key words and phrases. Braid group, spherical growth series, geodesic growth series, algorithm.

2. CONTEXT

2.1. Growth series. Let S be a finite generating set of a semigroup M . We denote by S^* the set of all words on the alphabet S , which are called S -words. The empty word is denoted by ε . For every S -word u , we denote by $|u|$ its length and by \bar{u} the element of M it represents. We say that two S -words u and v are equivalent, denoted $u \equiv v$, if they represent the same element in M .

Definition 2.1. The S -length of an element $x \in M$, denoted $|x|_S$, is the length of a shortest S -word representing x . An S -word u satisfying $|u| = |\bar{u}|_S$ is *geodesic*.

The S -length of an element $x \in M$ corresponds to the distance between x and the identity in the Cayley graph of M with respect to the finite generating set S .

Definition 2.2. For any $\ell \in \mathbb{N}$, we denote by $g(M, S; \ell)$ the number of geodesic S -words of length ℓ . The *geodesic* growth series of M with respect to S is

$$\mathcal{G}(M, S) = \sum_{\ell \in \mathbb{N}} g(M, S; \ell) t^\ell.$$

If the language of geodesic S -words is regular then the series $\mathcal{G}(M, S)$ is rational.

Definition 2.3. For any $\ell \in \mathbb{N}$, we denote by $s(M, S; \ell)$ the number of elements in M of length ℓ . The *spherical* growth series of M with respect to S is

$$\mathcal{S}(M, S) = \sum_{x \in M} t^{|x|_S} = \sum_{\ell \in \mathbb{N}} s(M, S; \ell) t^\ell.$$

If there exists a regular language composed of geodesic S -words in bijection with M then the series $\mathcal{S}(M, S)$ is rational.

2.2. Artin's braid presentation. The first presentation of the braid group B_n was given by E. Artin in [4] :

$$B_n \simeq \left\langle \sigma_1, \dots, \sigma_{n-1} \mid \begin{array}{ll} \sigma_i \sigma_j = \sigma_j \sigma_i & \text{for } |i - j| \geq 2 \\ \sigma_i \sigma_j \sigma_i = \sigma_j \sigma_i \sigma_j & \text{for } |i - j| = 1 \end{array} \right\rangle. \quad (1)$$

Definition 2.4. For all $n \geq 2$, we denote by Σ_n^+ the set $\{\sigma_1, \dots, \sigma_{n-1}\}$ and by Σ_n the set $\Sigma_n^+ \sqcup (\Sigma_n^+)^{-1}$.

Artin's presentation of B_n implies that Σ_n^+ is a set of group generators of B_n . However the braid σ_1^{-1} cannot be represented by any Σ_n^+ -word. For our purpose, it is fundamental to view a monoid (or a group) as a quotient of a finitely generated free monoid. As a monoid, the braid group B_n is presented by generators Σ_n and relation of (1) plus relations

$$\sigma_i \sigma_i^{-1} = \sigma_i^{-1} \sigma_i = \varepsilon \quad \text{for all } 1 \leq i \leq n-1. \quad (2)$$

In [24], L. Sabalka constructed an explicit deterministic finite state automaton recognizing the language of geodesic Σ_3 -words. He obtains the following rational value for the geodesic growth series of B_3 relatively to the Artin's generators Σ_3 :

$$\mathcal{G}(B_3, \Sigma_3) = \frac{t^4 + 3t^3 + t + 1}{(t^2 + 2t - 1)(t^2 + t - 1)}. \quad (3)$$

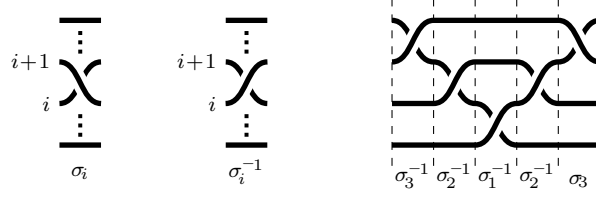


FIGURE 1. Geometric interpretation of Artin's generators and representation of a 4-strands braid as a Σ_4 -word.

Moreover, using the finite state automaton recognizing the language of short-lex normal form of B_3 [17] he obtains :

$$\mathcal{S}(B_3, \Sigma_3) = \frac{(t+1)(2t^3 - t^2 + t - 1)}{(t-1)(2t-1)(t^2 + t - 1)}. \quad (4)$$

The positive braid monoid B_n^+ is the submonoid of B_n generated by Σ_n^+ . Since every Σ_n^+ -word is geodesic, the geodesic growth series $\mathcal{G}(B_n^+, \Sigma_n^+)$ is irrelevant. An explicit rational formula for the spherical growth series $\mathcal{S}(B_n^+, \Sigma_n^+)$ was obtained by A. Bronfman in [8] and later by M. Albenque in [1]. These results were extended to positive braid monoids of type B and D in [3] and for each Artin–Tits monoids of spherical type in [18].

2.3. Dual's braid presentation. In [7], J. Birman, K.H. Ko and S.J. Lee introduced a new generator family of B_n , called Birman-Ko-Lee's or dual generators.

Definition 2.5. For $1 \leq p < q$ we define $a_{p,q}$ to be the braid

$$a_{p,q} = \sigma_p \cdots \sigma_{q-2} \sigma_{q-1}^{-1} \sigma_{q-2}^{-1} \cdots \sigma_p^{-1}. \quad (5)$$

For all $n \geq 2$, we put $\Sigma_n^{+*} = \{a_{p,q} \mid 1 \leq p < q \leq n\}$ and $\Sigma_n^* = \Sigma_n^{+*} \sqcup (\Sigma_n^{+*})^{-1}$.

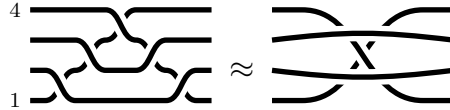


FIGURE 2. The letter $a_{1,4}$ codes for the braid in which strands 1 and 4 cross under strands 2 and 3.

We write $[p, q]$ for the interval $\{p, \dots, q\}$ of \mathbb{N} , and we say that $[p, q]$ is nested in $[r, s]$ if we have $r < p < q < s$.

Lemma 2.6. [7] *In terms of Σ_n^{+*} , the group B_n is presented by the relations*

$$a_{p,q} a_{r,s} = a_{r,s} a_{p,q} \quad \text{for } [p, q] \text{ and } [r, s] \text{ disjoint or nested,} \quad (6)$$

$$a_{p,q} a_{q,r} = a_{q,r} a_{p,r} = a_{p,r} a_{p,q} \quad \text{for } 1 \leq p < q < r \leq n. \quad (7)$$

Note that the definition of $a_{p,q}$ given here is not exactly that of [7] but it is coherent with previous papers of the author.

As for Artin's generators, the braid group B_n admits a monoid presentation with generators Σ_n^* , relations (6) and (7) together with

$$a_{p,q} a_{p,q}^{-1} = a_{p,q}^{-1} a_{p,q} = \varepsilon \quad \text{for all } 1 \leq p < q \leq n. \quad (8)$$

Except in the case $n = 2$, which is trivial, there are no results in the literature on the growth series of B_n with respect to Σ_n^* .

The Birman–Ko–Lee monoid B_n^{+*} , also called dual braid monoid in [5] is the submonoid of B_n generated by Σ_n^{+*} . The term *dual* was used by D. Bessis since the Garside structure of B_n^+ and B_n^{+*} share symmetric combinatorial values. In [3], M. Albenque and P. Nadeau give a rational expression for the spherical growth series $\mathcal{S}(B_n^{+*}, \Sigma_n^{+*})$; they also treat the case of dual braid monoids of type **B**.

2.4. Some words about Garside presentations. The two monoids B_n^+ and B_n^{+*} equip the braid group B_n with two Garside structures : the classical one [21] and the dual one [7, 5]. The reader can consult [14] and [13] for a general introduction to Garside theory. Here it is sufficient to know that each Garside structure provides *simple* elements which generate the corresponding Garside monoid. Let us denote by C_n and D_n the simple elements of the Garside monoid B_n^+ and B_n^{+*} respectively.

In [11], P. Dehornoy starts the study of the spherical combinatorics of B_n^+ relatively to C_n . In particular he formulates a divisibility conjecture which has been proven by F. Hivert, J.-C. Novelli and J.-Y. Thibon in [22]. A similar result was obtained for braid monoids of type **B** in [19]. The spherical combinatorics of B_n^{+*} relatively to D_n was also considered by P. Biane and P. Dehornoy in [6]: they reduce the computation of $s(B_n^{+*}, D_n; 2)$ to that of free cumulants for a product of independent variables.

R. Charney establishes in [9] that the spherical growth series of Artin–Tits groups of spherical type with respect to their standard simple elements are rationals. In particular she obtains the rationality of $\mathcal{S}(B_n, C_n)$. This result was generalized for all Garside groups by P. Dehornoy in [10]. This implies in particular the rationality of $\mathcal{S}(B_n, D_n)$.

3. COUNTING BRAIDS

We fix an integer $n \geq 2$ and S_n denotes either Σ_n (Artin’s generators of B_n) or Σ_n^* (dual generators of B_n).

Definition 3.1. For $n \geq 2$ and $\ell \in \mathbb{N}$ we denote by $B_n(S_n, \ell)$ the set of braids of B_n whose S_n -length is ℓ .

Since the equality $s(B_n, S_n; \ell) = \text{card}(B_n(S_n, \ell))$ holds, we compute $s(B_n, S_n; \ell)$ by constructing the set $B_n(S_n, \ell)$. Each braid of B_n with S_n -length ℓ is the product of a braid of S_n -length $\ell - 1$ and a generator $x \in S_n$. In particular we have

$$B_n(S_n, \ell) \subseteq \{\beta \cdot x \text{ for } (\beta, x) \in B_n(S_n, \ell - 1) \times S_n\}, \quad (9)$$

and so we can construct $B_n(S_n, \ell)$ by induction on $\ell \geq 1$.

3.1. Representative sets. From an algorithmic point of view, a braid is naturally represented by a word. We extend this notion to any subset of $B_n(S_n, \ell)$.

Definition 3.2. We say that a set W of S_n -words represents a subset X of B_n whenever W is a set of unique geodesic representatives for X .

Example 3.3. For all $n \geq 2$, the set $\{\varepsilon\}$ represents $B_n(S_n, 0)$. Since relations (1), (2), together with relations (6)–(8) of Artin and dual semigroup presentation of B_n preserve parity of word length we have the following property:

$$\text{two } S_n\text{-words } u \text{ and } v \text{ are equivalent only if } |u| \equiv |v| \pmod{2}. \quad (10)$$

In particular any S_n -word of length ≤ 1 is geodesic. As two different letters of S_n represent different braids of B_n the set S_n represents $B_n(S_n, 1)$.

The previous example gives a representative set of $B_n(S_n, \ell)$ for $\ell \leq 1$. We now tackle the construction of a representative set W_ℓ of $B_n(S_n, \ell)$ for $\ell \geq 2$. Using an inductive argument we can assume we already have obtained a set $W_{\ell-1}$ representing $B_n(S_n, \ell-1)$ and then consider the set

$$W' = \{wx \text{ for } (w, x) \in W_{\ell-1} \times S_n\}. \quad (11)$$

A first step to obtain W_ℓ consists in removing all non-geodesic words from W' . For this we have to test if a given word of W' is geodesic or not. A naive general solution consists in testing if a word $u \in W'$ is equivalent to a S_n -word of length at most $\ell-1$. However, as words of W' are obtained by appending a letter to a geodesic word, we can restrict the search space:

Lemma 3.4. *For $\ell \geq 2$, let u be a geodesic S_n -word of length $\ell-1$ and x a letter of S_n . If the S_n -word $v = ux$ is not geodesic then there exists a geodesic S_n -word w of length $\ell-2$ which is equivalent to v .*

Proof. Assume v is not geodesic. There exists a S_n -geodesic word w equivalent to v and satisfying $|w| < |v|$. By (10) we must have $|w| \leq |v| - 2 = \ell - 2$. From the equality $v = ux$ we obtain $u \equiv vx^{-1}$ and so $u \equiv wx^{-1}$. Since u is geodesic we must have $|wx^{-1}| \geq \ell - 1$, implying $|w| \geq \ell - 2$ and so $|w| = \ell - 2$. \square

3.2. Geodesic words. For all $\ell \in \mathbb{N}$ the number $g(B_n, S_n; \ell)$ can be obtained at no cost during the construction of a representative set of $B_n(S_n, \ell)$.

Definition 3.5. For a braid $\beta \in B_n$ we denote by $\omega_{S_n}(\beta)$ the number of geodesic S_n -words representing β .

Proposition 3.6. *For $\beta \in B_n$ a braid with $\ell = |\beta|_{S_n} \geq 1$, we have*

$$\omega_{S_n}(\beta) = \sum_{\substack{x \in S_n \\ |\beta x^{-1}|_{S_n} = \ell-1}} \omega_{S_n}(\beta x^{-1}).$$

Proof. Let W be the set of geodesic S_n -words representing β . The cardinality of W is then $\omega_{S_n}(\beta)$. For all $x \in S_n$ we denote by W_x the words of W ending with x . Since all words of W have length $\ell \geq 1$ we must have

$$W = \bigsqcup_{x \in S_n} W_x.$$

Let us fix an element $y \in S_n$. By construction, any word of W_y has length $\ell-1$, represents the braid βy^{-1} and is geodesic. Hence W_y is not empty if and only if the S_n -length of βy^{-1} is $\ell-1$, which gives

$$\omega_{S_n}(\beta) = \text{card}(W) = \sum_{x \in S_n} \text{card}(W_x) = \sum_{\substack{x \in S_n \\ |\beta x^{-1}|_{S_n} = \ell-1}} \text{card}(W_x).$$

Assume βy^{-1} has S_n -length $\ell-1$. Since for any geodesic S_n -word v representing βy^{-1} , the word vy is a geodesic representative of β , the braid βy^{-1} has exactly $\omega_{S_n}(\beta y^{-1})$ geodesic representatives in W_y . Therefore $\text{card}(W_y) = \omega_{S_n}(\beta y^{-1})$ and the result follows. \square

3.3. A first algorithm. We can now give a first algorithm returning a representative set W_ℓ of $B_n(S_n, \ell)$ for $\ell \geq 2$. In order to determine $g(B_n, S_n; \ell)$ we also compute the value of ω_{S_n} for all words in W_ℓ .

In order to construct by induction a representative set W , we must test if a given word u is equivalent to a word occurring in W :

Definition 3.7. For a set W of S_n -words we say that a S_n -word u *appears* in W , denoted by $u \triangleleft W$, if u is equivalent to a word v of W .

In an algorithmic context a S_n -word is represented as an array of integers plus another integer ω which eventually correspond to $\omega_{S_n}(\bar{u})$. Whenever two variables u and v stand for the S_n -words u and v we use:

- $u \cdot \omega$ to design the integer ω associated to the word u ;
- $u v$ to design the product uv .

Algorithm 1 – REPSET : For $\ell \geq 2$, returns a set W_ℓ representing $B_n(S_n, \ell)$ from two sets $W_{\ell-1}$ and $W_{\ell-2}$ representing $B_n(S_n, \ell-1)$ and $B_n(S_n, \ell-2)$ respectively. For each word $u \in W_{\ell-1}$, the value of $u \cdot \omega$ is assumed to be $\omega_{S_n}(\bar{u})$.

```

1: function REPSET( $W_{\ell-1}, W_{\ell-2}$ )
2:    $W_\ell \leftarrow \emptyset$ 
3:   for  $x \in S_n$  do
4:     for  $u \in W_{\ell-1}$  do
5:        $v \leftarrow ux$ 
6:       if  $v \not\triangleleft W_{\ell-2}$  then
7:         if  $v \not\triangleleft W_\ell$  then                                 $\triangleright$  a new braid  $\bar{v}$  of  $S_n$ -length  $\ell$  is found
8:            $W_\ell \leftarrow W_\ell \sqcup \{v\}$ 
9:            $v \cdot \omega \leftarrow u \cdot \omega$ 
10:        else                                               $\triangleright v$  is another geodesic word representing  $\bar{v}$ 
11:           $w \leftarrow$  the word in  $W_\ell$  equivalent to  $v$ 
12:           $w \cdot \omega \leftarrow w \cdot \omega + u \cdot \omega$ 
13:        end if
14:      end if
15:    end for
16:  end for
17:  return  $W_\ell$ 
18: end function

```

Proposition 3.8. Let $\ell \geq 2$ be an integer. Running on sets $W_{\ell-1}$ and $W_{\ell-2}$ representing $B_n(S_n, \ell-1)$ and $B_n(S_n, \ell-2)$ respectively, algorithm REPSET returns a representing set W_ℓ of $B_n(S_n, \ell)$. Moreover for all $u \in W_\ell$, the value of $u \cdot \omega$ is the integer $\omega_{S_n}(\bar{u})$.

Proof. Let W' be the set of (11) and W_ℓ be the set returning by REPSET. The two “for loops” on line 3 and 4 guarantee $W_\ell \subseteq W'$. By lemma 3.4 and hypotheses on $W_{\ell-1}$ and $W_{\ell-2}$, condition $v \not\triangleleft W_{\ell-2}$ of line 6 tests if the word $v = ux$ is geodesic. The second if statement line 7 guarantees we append a word v in W_ℓ if and only if v does not appear in W_ℓ . The set W_ℓ is then a representative set of $B_n(S_n, \ell)$. The result about ω_{S_n} is a direct consequence of Proposition 3.6. \square

To be complete we must explain how to test if a S_n -word u appears in a set of S_n -words. This can be achieved using a normal form (like the Garside’s normal form) but such a normal form doesn’t provide geodesic representatives. As, for our

future research, we want to store braids using geodesic representatives, we prefer to use another method.

3.4. Dynnikov's coordinates. Originally defined in [16] from the geometric interpretation of the braid group B_n as the mapping class group of the n -punctured disk of \mathbb{R}^2 , the Dynnikov's coordinates admit a purely algebraic definition from the action of B_n on \mathbb{Z}^{2n} .

For $x \in \mathbb{Z}$, we denote by x^+ the non-negative integer $\max(x, 0)$ and by x^- the non-positive integer $\min(x, 0)$. We first define an action of Artin's generators on \mathbb{Z}^4 .

Definition 3.9. For all $i \in [1, n-1]$ and all $(x_1, y_1, x_2, y_2) \in \mathbb{Z}^4$ we put

$$(x_1, y_1, x_2, y_2) \cdot \sigma_i = (x'_1, y'_1, x'_2, y'_2) \quad \text{and} \quad (x_1, y_1, x_2, y_2) \cdot \sigma_i^{-1} = (x''_1, y''_1, x''_2, y''_2)$$

where

$$\begin{aligned} x'_1 &= x_1 + y_1^+ + (y_2^+ - t_1)^+ & x''_1 &= x_1 - y_1^+ - (y_2^+ + t_2)^+ \\ y'_1 &= y_2 - t_1^+ & y''_1 &= y_2 + t_2^- \\ x'_2 &= x_2 + y_2^- + (y_1^- + t_1)^- & x''_2 &= x_2 - y_2^- - (y_1^- - t_2)^- \\ y'_2 &= y_1 + t_1^+ & y''_2 &= y_1 - t_2^- \end{aligned}$$

with $t_1 = x_1 - y_1^- - x_2 + y_2^+$ and $t_2 = x_1 + y_1^- - x_2 - y_2^+$.

We can now define an action of Σ_n -words on \mathbb{Z}^{2n} .

Definition 3.10. For $i \in [1, n-1]$, $e = \pm 1$ and $(a_1, b_1, \dots, a_n, b_n) \in \mathbb{Z}^{2n}$ we put

$$(a_1, b_1, \dots, a_n, b_n) \cdot \sigma_i^e = (a'_1, b'_1, \dots, a'_n, b'_n)$$

where $(a'_i, b'_i, a'_{i+1}, b'_{i+1}) = (a_i, b_i, a_{i+1}, b_{i+1}) \cdot \sigma_i^e$ and $a'_k = a_k$, $b'_k = b_k$ for k not belonging to $\{i, i+1\}$.

Definition 3.11. For a Σ_n -word u we define $\text{Dyn}(u)$ to be $(0, 1, \dots, 0, 1) \cdot u$. Similarly for an Σ_n^* -word v we define $\text{Dyn}(v)$ to be $\text{Dyn}(u)$ where u is the Σ_n -word obtained from v using relation (5) of Definition 2.5.

Naturally defined on braid words, Dynnikov's coordinates is a braid invariant.

Proposition 3.12. For all S_n -words u and v we have $\text{Dyn}(u) = \text{Dyn}(v)$ if and only if $u \equiv v$.

Proof. Direct consequence of Corollary 2.24 page 225 of [15]. \square

We now go back to the problem of testing if a given S_n -word appears in a set W of S_n -words. A solution consists in representing the set W in machine by an array. To test if the word u appears in W we can compute $\text{Dyn}(u)$ and compare it to all the values of $\text{Dyn}(v)$ whenever v go through W . This method needs $1 + \text{card}(W)$ computations of Dynnikov's coordinates. If words in W are sorted by their Dynnikov's coordinates we can test if u appear in W using at most $\log_2(\text{card}(W))$ computations of Dynnikov's coordinates. A more efficient solution is obtained using an `unordered_set` [26] based on a hash function. The insertion and lookup complexity is then constant in average on a RAM machine depending of the hash function.

As the objective of the current paper is to deepen our knowledge on combinatorics of B_4 , we define a hash function for four strand braids. Assume β is a braid of B_4 given by a S_4 -word u . The hash of β is

$$\text{hash}(\beta) = \sum_{i=1}^4 (\text{rem}(a_i, 256) \times 256^{2i-2} + \text{rem}(b_i, 256) \times 256^{2i-1}),$$

where $(a_1, b_1, \dots, a_4, b_4) = \text{Dyn}(u)$ and $\text{rem}(k, 256)$ is the positive remainder of k modulo 256. By construction, $\text{hash}(\beta)$ is an integer lying in $[0, 2^{64} - 1]$ and so our hash function is very well suited for 64 bits computers.

3.5. Space complexity. Here again we focus on the case $n = 4$. The smallest addressable unit of memory on common computers is the byte which can have 256 different values. As the set Σ_4 has 6 elements we can store three Σ_4 -letters using one byte ($6^3 = 216$). Hence a Σ_4 -word of length ℓ requires $\lceil \frac{\ell}{3} \rceil$ bytes to be stored. Since there are 12 elements in Σ_4^* , a Σ_4^* -word of length ℓ requires $\lceil \frac{\ell}{2} \rceil$ bytes to be stored.

Assume we want to determine a representative set of $B_4(\Sigma_4, 21)$. The memory needed by the algorithm REPSET is at least the space needed to store Σ_4 -words of W_{21} . By Table 2 of Section 6 there are approximately $60 \cdot 10^9$ elements in this set. With the above storage method of a Σ_4 -word, the algorithm needs $7 \cdot 60 \cdot 10^9$ bytes, *i.e.*, 391Go of memory to run, which is too much. To reduce the memory requirement we can split the sets $B_n(S_n, \ell)$ in many subsets depending of the values of certain braid invariants.

In case we want to determine $g(B_n, S_n; \ell)$ we also store the value of $\omega_{S_n}(\bar{u})$ for all words in obtained representative sets.

4. BRAID TEMPLATE

Here again n is an integer ≥ 2 and S_n denotes either Σ_n or Σ_n^* . Each braid invariant ι corresponds to a map from B_n to a set X .

Definition 4.1. A set of braid invariants ι_1, \dots, ι_m is said to be *inductively stable* if for every braid $\beta \in B_n(S_n, \ell)$ and every $x \in S_n$, and every $k = 1, \dots, m$, the value of $\iota_k(\beta \cdot x)$ depends only on $\iota_1(\beta), \dots, \iota_m(\beta)$ and x but not on β itself.

The aim of this section is to determine an inductively stable set of braid invariants in order to split in many pieces the determination of a representative set of $B_n(S_n, \ell)$.

4.1. Permutation. For $n \geq 2$ we denote by \mathfrak{S}_n the set of all bijections of $\{1, \dots, n\}$ into itself. The transposition $(i \ i+1)$ of \mathfrak{S}_n exchanging i and $i+1$ is denoted s_i .

Definition 4.2. We denote by $\pi : B_n \rightarrow \mathfrak{S}_n$ the surjective homomorphism of (B_n, \cdot) to (\mathfrak{S}_n, \circ) defined by $\pi(\sigma_i) = s_i$.

If β is a braid of B_n then $\pi(\beta)$ is the permutation of \mathfrak{S}_n such that the strand ending at position i starts at position $\pi(\beta)(i)$.

Example 4.3. For $\beta = \sigma_1 \sigma_2^{-1} \sigma_1 \sigma_2$ we have $\pi(\beta) = s_1 s_2 s_1 s_2 = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix}$, as illustrated on the following diagram :



As π is an homomorphism, for all $\beta \in B_n$ and $x \in S_n$ we have $\pi(\beta \cdot x) = \pi(\beta) \circ \pi(x)$ and so the singleton $\{\pi\}$ is inductively stable.

Lemma 4.4. *For $1 \leq i < j \leq n$ we have $\pi(a_{p,q}) = (p \ q)$.*

Proof. As π is an homomorphism, Definition 2.5 gives

$$\begin{aligned} \pi(a_{p,q}) &= \pi(\sigma_p) \circ \dots \circ \pi(\sigma_{q-1}) \circ \pi(\sigma_{q-2})^{-1} \circ \dots \circ \pi(\sigma_p)^{-1} \\ &= (p \ p+1) \circ \dots \circ (q-1 \ q) \circ (q-2 \ q-1) \circ \dots \circ (p \ p+1) \\ &= (p \ q). \end{aligned}$$

□

4.2. Linking numbers. Assume β is a braid of B_n and let i and j be two different integers of $[1, n]$. The linking number of the two strands i and j in β is the algebraic number of crossings in β involving the strands i and j . A positive crossing (σ_k) counts for $+1$ whereas a negative one (σ_k^{-1}) counts for -1 :

$$\begin{array}{cc} \text{X} & \rightarrow +1 \\ \text{X} & \rightarrow -1 \end{array}$$

Definition 4.5. For $\beta \in B_n$ and i, j two different integers of $[1, n]$ we denote by $\ell_{i,j}(\beta)$ the linking number of strands i and j in β . The map $\ell_{i,j} : B_n \rightarrow \mathbb{Z}$ is then a braid invariant.

A priori, our definition of linking numbers depends of a diagram coding the braid and not on the braid itself. An immediate argument using relations (1) and (2) guarantees this is not the case. The reader can consult [12] page 29 for a more formal definition of linking number¹ based of an integral definition and a geometric realization of β in \mathbb{R}^3 .

Lemma 4.6. *Let i, j be two integers satisfying $1 \leq i < j \leq n$ and $e = \pm 1$.*

– For all $k \in [1, n-1]$ we have

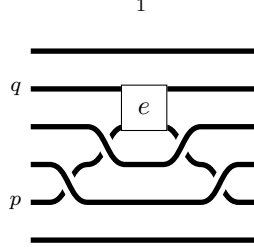
$$\ell_{i,j}(\sigma_k^e) = \begin{cases} e & \text{if } i = k \text{ and } j = k+1, \\ 0 & \text{otherwise.} \end{cases}$$

– For all $1 \leq p < q \leq n$ we have

$$\ell_{i,j}(a_{p,q}^e) = \begin{cases} e & \text{if } i = p \text{ and } j = q, \\ 1 & \text{if } i = p \text{ and } j < q, \\ -1 & \text{if } p < i \text{ and } j = q, \\ 0 & \text{otherwise.} \end{cases}$$

Proof. The case of σ_k^e is immediate. The different values of $\ell_{i,j}(a_{p,q}^e)$ can be obtained from the following diagram of $a_{p,q}^e = \sigma_p \dots \sigma_{q-2} \sigma_{q-1}^e \sigma_{q-2}^{-1} \dots \sigma_p^{-1}$:

¹In fact, the two definitions are slightly different but we have $\ell_{i,j}(\beta) = 2\lambda_{i,j}(\beta)$.



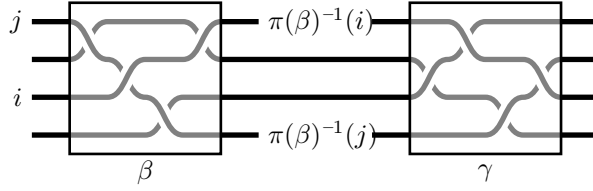
□

Lemma 4.7. For β and γ two braids of B_n and $1 \leq i < j \leq n$ we have

$$\ell_{i,j}(\beta \cdot \gamma) = \ell_{i,j}(\beta) + \ell_{\pi(\beta)^{-1}(i), \pi(\beta)^{-1}(j)}(\gamma),$$

with the convention $\ell_{p,q} = \ell_{q,p}$ for $p > q$.

Proof. Immediate as soon as we consider the following diagram :



□

Corollary 4.8. The set of invariants $\{\pi\} \cup \{\ell_{i,j}, 1 \leq i < j \leq n\}$ is inductively stable.

Proof. A direct consequence of Lemma 4.7 together with the fact that π is a homomorphism. □

4.3. Template. We now introduce the notion of template of a braid which will be used to parallelize the determination of a representative set of $B_n(S_n, \ell)$.

Definition 4.9. The *template* of a braid $\beta \in B_n$ is the tuple

$$\tau(\beta) = (\pi(\beta), \ell_{1,2}(\beta), \ell_{1,3}(\beta), \ell_{2,3}(\beta), \dots, \ell_{1,n}(\beta), \ell_{n-1,n}(\beta)) \in \mathfrak{S}_n \times \mathbb{Z}^{\frac{n(n+1)}{2}},$$

where integer $\ell_{i,j}(\beta)$ appears before $\ell_{r,s}(\beta)$ whenever (i,j) is smaller than (r,s) with respect to the co-lexicographic ordering on \mathbb{N}^2 : $(i,j) < (p,q)$ if $j < q$ or if $j = q$ and $i < p$. For a braid template t we denote by $t[\pi]$, *resp.* $t[\ell_{i,j}]$ the corresponding component. For $\ell \in \mathbb{N}$ we denote by $T_n(S_n, \ell)$ the set $\{\tau(\beta), \beta \in B_n(S_n, \ell)\}$ and by T_n the set $\{\tau(\beta), \beta \in B_n\}$ of all templates on B_n .

Lemma 4.10. For all $\beta \in B_n$ and all $x \in S_n$, the template $\tau(\beta) * x = \tau(\beta \cdot x)$ depends only of $\tau(\beta)$ and x .

Proof. A direct consequence of Corollary 4.8 and Definition 4.9. □

Example 4.11. Let t be a template of T_3 with $t[\pi]$ the cycle $(1 \ 3 \ 2)$. Let us compute the template $t * a_{1,3}^{-1}$. We write $t = (\pi, \ell_{1,2}, \ell_{1,3}, \ell_{2,3})$. The inverse of π is the cycle $(1 \ 2 \ 3)$ and so we obtain $\pi^{-1}(\{1,2\}) = \{2,3\}$, $\pi^{-1}(\{1,3\}) = \{1,2\}$ and $\pi^{-1}(\{2,3\}) = \{1,3\}$. Eventually, from $\ell_{1,2}(a_{1,3}^{-1}) = 1$, $\ell_{1,3}(a_{1,3}^{-1}) = -1$ and $\ell_{2,3}(a_{1,3}^{-1}) = -1$ we obtain

$$\begin{aligned} t * a_{1,3}^{-1} &= ((1 \ 3 \ 2) \circ (1 \ 3), \ell_{1,2} + \ell_{2,3}(a_{1,3}^{-1}), \ell_{1,3} + \ell_{1,2}(a_{1,3}^{-1}), \ell_{2,3} + \ell_{1,3}(a_{1,3}^{-1})) \\ &= ((1 \ 2), \ell_{1,2} - 1, \ell_{1,3} + 1, \ell_{2,3} - 1). \end{aligned}$$

Definition 4.12. For $\ell \in \mathbb{N}$ and $t \in T_n$ we denote by $B_n(S_n, \ell, t)$ the set of all braids of B_n with S_n -length ℓ and template t .

By very definitions we have

$$B_n(S_n, \ell) = \bigsqcup_{t \in T_n(S_n, \ell)} B_n(S_n, \ell, t). \quad (12)$$

Algorithm 2 – TEMPREPSET is a “template” version of Algorithm 1 – REPSET for which we assume we dispose of a function $\text{LOAD}(n, \ell, t)$ loading a representative set of $B_n(S_n, \ell, t)$ from a storage memory like a hard disk. We also assume we have a function $\text{SAVE}(W, n, \ell, t)$ saving a representative set of $B_n(S_n, \ell, t)$ to that storage memory.

Algorithm 2 – TEMPREPSET : For an integer $\ell \geq 1$ and a template t of T_n , saves a representative set $\mathbb{W}_{\ell, t}$ of $B_n(S_n, \ell, t)$ and returns the pair $(\text{card}(\mathbb{W}_{\ell, t}), \sum_{u \in \mathbb{W}_{\ell, t}} \omega_{S_n}(\bar{u}))$

```

1: function TEMPREPSET( $\ell, t$ )
2:    $\mathbb{W}_{\ell, t} \leftarrow \emptyset$ 
3:    $\mathbb{W}_{\ell-2, t} \leftarrow \text{LOAD}(n, \ell-2, t)$   $\triangleright \mathbb{W}_{\ell-2, t}$  is empty whenever  $\ell = 1$ .
4:    $n_g \leftarrow 0$ 
5:   for  $x \in S_n$  do
6:      $t_x \leftarrow t * x^{-1}$ 
7:      $\mathbb{W}_{\ell-1, x} \leftarrow \text{LOAD}(n, \ell-1, t_x)$ 
8:     for  $u \in \mathbb{W}_{\ell-1, x}$  do
9:        $v \leftarrow u x$ 
10:      if  $v \not\in \mathbb{W}_{\ell-2, t}$  then
11:        if  $v \not\in \mathbb{W}_{\ell, t}$  then
12:           $\mathbb{W}_{\ell, t} \leftarrow \mathbb{W}_{\ell, t} \sqcup \{v\}$ 
13:           $v \cdot \omega \leftarrow u \cdot \omega$ 
14:        else
15:           $w \leftarrow$  the word in  $\mathbb{W}_{\ell, t}$  equivalent to  $v$ 
16:           $w \cdot \omega \leftarrow w \cdot \omega + u \cdot \omega$ 
17:        end if
18:         $n_g \leftarrow n_g + u \cdot \omega$ 
19:      end if
20:    end for
21:  end for
22:   $\text{SAVE}(\mathbb{W}_{\ell, t}, n, \ell, t)$ 
23:  return  $(\text{card}(\mathbb{W}_{\ell, t}), n_g)$ 
24: end function

```

In order to compute a representative set of $B_n(S_n, \ell)$ using Algorithm TEMPREPSET we must first compute the template set $T_n(S_n, \ell)$. From inclusion (9) we obtain

$$T_n(S_n, \ell) \subseteq \{t * x \text{ for } (t, x) \in T_n(S_n, \ell-1) \times S_n\}. \quad (13)$$

A template t from the set in the right-hand side of (13) belongs to $T_n(S_n, \ell)$ if and only if there exists a braid $\beta \in B_n(S_n, \ell)$ such that $\tau(\beta) = t$. Hence a full run consists in calling the function TEMPREPSET for each template t from the set in the right-hand side of (13). Such a template t will belong to $T_n(S_n, \ell)$ if and only if the returned value is different from $(0, 0)$. Putting all pieces together we obtain Algorithm 3 – COMBI.

Algorithm 3 – COMBI : Returns a pair of arrays of positive integers (n_s, n_g) satisfying relations $n_s[\ell] = s(B_n, S_n; \ell)$ and $n_g[\ell] = g(B_n, S_n; \ell)$ for all $\ell \leq \ell_{\max}$.

```

1: function COMBI( $\ell_{\max}$ )
2:    $n_s[0] \leftarrow 1$ 
3:    $n_g[0] \leftarrow 1$ 
4:    $T \leftarrow \{(1_{\Sigma_n}, 0, \dots, 0)\}$   $\triangleright$  template set  $T_n(S_n, 0)$ 
5:   for  $\ell$  from 1 to  $\ell_{\max}$  do
6:      $T' \leftarrow \emptyset$ 
7:      $n_s[\ell] \leftarrow 0$ ;  $n_g[\ell] \leftarrow 0$ 
8:     for  $t \in T$  do
9:       for  $\mathbf{x} \in S_n$  do
10:         $t_{\mathbf{x}} \leftarrow t * \mathbf{x}$ 
11:         $(n'_s, n'_g) \leftarrow \text{TEMPREPSET}(\ell, t_{\mathbf{x}})$ 
12:        if  $(n'_s, n'_g) \neq (0, 0)$  then
13:           $T' \leftarrow T' \cup \{t'\}$ 
14:           $n_s[\ell] \leftarrow n_s[\ell] + n'_s$ 
15:           $n_g[\ell] \leftarrow n_g[\ell] + n'_g$ 
16:        end if
17:      end for
18:    end for
19:     $T \leftarrow T'$   $\triangleright$  template set  $T_n(S_n, \ell)$ 
20:  end for
21:  return  $(n_s, n_g)$ 
22: end function

```

5. REDUCED BRAID TEMPLATES

Here again n is an integer ≥ 2 and S_n denotes either Σ_n or Σ_n^* . Experiments using Algorithm 2 – TEMPREPSET suggest that some sets $B_n(S_n, \ell, t)$ are in bijection for a given ℓ . We can use this fact to improve the efficiency of Algorithm 3 – COMBI and reduce the needed storage space.

5.1. Stable word maps.

Definition 5.1. A bijection μ of the set of S_n -words is S_n -stable if

- i) for all S_n -word w we have $|\mu(w)| = |w|$;
- ii) for all S_n -words u and v we have $\mu(u) \equiv \mu(v) \Leftrightarrow u \equiv v$;
- iii) for all S_n -word u the template $\tau(\mu(u))$ depends only on $\tau(\bar{u})$.

For such a S_n -stable map μ we denote by μ^T the map of T_n defined by

$$\mu^T(t) = \tau(\overline{\mu(u)})$$

where u is any S_n -word satisfying $\tau(\bar{u}) = t$. We also define a bijection $\bar{\mu}$ of B_n by

$$\bar{\mu}(\beta) = \overline{\mu(u)},$$

where u is any S_n -word satisfying $\bar{u} = \beta$.

Whenever μ is S_n -stable, Condition iii) of Definition 5.1 guarantees that the template of the image by $\bar{\mu}$ of a braid β does not depend on β but on its template t and so μ^T is well defined.

Lemma 5.2. For every S_n -stable bijection μ , we have

- i) μ^T is a permutation of T_n ,
- ii) a S_n -word u is geodesic if and only if $\mu(u)$ is.

Proof. By *i*) and *ii*) of Definition 5.1 we obtain that μ induces a permutation on the finite set $B_n(S_n, \ell)$. It follows that μ^T induces a permutation on $T_n(S_n, \ell)$ and so *i*) is established since T_n is the disjoint union of $T_n(S_n, \ell)$ for $\ell \geq 0$.

Let us now prove *ii*). Let u be a S_n -word. If the word $v = \mu(u)$ is not geodesic then there exists a strictly shorter S_n -word v' equivalent to v . As μ is a bijection we put $u' = \mu^{-1}(v')$. We obtain $\mu(u) = v \equiv v' = \mu(u')$. From conditions *ii*) and *i*) of 5.1 we have $u \equiv u'$ together with $|u| = |v| > |v'| = |u'|$ and so u is not geodesic. A similar argument establishes the converse implication. \square

5.2. Examples. Let us now introduce some useful examples of S_n -stable bijections. Eventually such a S_n -stable bijection μ will be used to obtain a representative set of $T_n(S_n, \ell, \mu^T(t))$ from a representative set of $T_n(S_n, \ell, t)$. This is why it is necessary to specify how to obtain $\mu^T(t)$ from t in propositions 5.3, 5.4, 5.8 and 5.13. However the reader may choose to ignore these parts without affecting the understanding of the rest of the article.

5.2.1. *First examples.*

Proposition 5.3. *The map inv_{S_n} of S_n -words defined by*

$$\text{inv}_{S_n}(x_1 \cdots x_t) = x_t^{-1} \cdots x_1^{-1}$$

is S_n -stable. Moreover for all template $t \in T_n$ we have

$$\text{inv}_{S_n}^T(t)[\pi] = t[\pi]^{-1} \quad \text{and} \quad \text{inv}_{S_n}^T(t)[\ell_{i,j}] = -t[\ell_{t[\pi](i), t[\pi](j)}] \quad \text{for } 1 \leq i < j \leq n.$$

Proof. Condition *i*) of Definition 5.1 is immediate. For two S_n -words u and v , the relation $u \equiv v$ is equivalent to $v^{-1}u \equiv \varepsilon$ which is itself equivalent to $v^{-1} \equiv u^{-1}$, hence Condition *ii*) is established. Let u be an S_n -word and v be $\text{inv}_{S_n}(u)$. By definition, we have $\bar{v} = \bar{u}^{-1}$. Since π is an homomorphism we have $\pi(\bar{v}) = \pi(\bar{u})^{-1}$. Let $1 \leq i < j \leq n$ be two integers. From $1 = \bar{v}\bar{u}$, Lemma 4.7 implies

$$0 = \ell_{i,j}(1) = \ell_{i,j}(\bar{v}) + \ell_{\pi(\bar{u})(i), \pi(\bar{u})(j)}(\bar{u})$$

and so $\ell_{i,j}(\bar{v}) = -\ell_{\pi(\bar{u})(i), \pi(\bar{u})(j)}(\bar{u})$. Therefore Condition *iii*) is also satisfied. \square

We now point out a divergence between the Artin and dual presentations of the braid group B_n .

Proposition 5.4. *For $n \geq 3$, the map of S_n -words θ_{S_n} defined by*

$$\theta_{S_n}(x_1 \cdots x_t) = x_1^{-1} \cdots x_t^{-1}$$

is S_n -stable if and only if $S_n = \Sigma_n$. Moreover for all template $t \in T_n$ we have

$$\theta_{\Sigma_n}^T[\pi] = t[\pi]^{-1} \quad \text{and} \quad \theta_{\Sigma_n}^T[\ell_{i,j}] = -t[\ell_{i,j}] \quad \text{for } 1 \leq i < j \leq n.$$

Proof. By construction, Condition *i*) of Definition 5.1 is satisfied. Let us establish Condition *ii*) for θ_{Σ_n} . It is sufficient to prove $\theta(u) \equiv \theta(v)$ whenever $u = v$ is a relation of the Artin's semigroup presentation of B_n . Let $i \in [1, n-1]$. We have $\theta(\sigma_i \sigma_i^{-1}) = \sigma_i^{-1} \sigma_i \equiv \varepsilon$, $\theta(\sigma_i^{-1} \sigma_i) = \sigma_i \sigma_i^{-1} \equiv \varepsilon$ and so we get

$$\theta(\sigma_i \sigma_i^{-1}) = \theta(\sigma_i^{-1} \sigma_i) = \theta(\varepsilon).$$

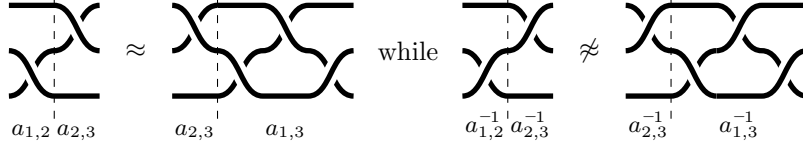
Assume now i and j are integers of $[1, n-1]$ satisfying $|i - j| \geq 2$. From $\sigma_i \sigma_j \equiv \sigma_j \sigma_i$ we obtain successively

$$\sigma_j^{-1} \sigma_i \sigma_j \equiv \sigma_i, \quad \sigma_j^{-1} \sigma_i \equiv \sigma_i \sigma_j^{-1}, \quad \sigma_i^{-1} \sigma_j^{-1} \sigma_i \equiv \sigma_j^{-1}, \quad \sigma_i^{-1} \sigma_j^{-1} \equiv \sigma_j^{-1} \sigma_i^{-1},$$

and so $\theta(\sigma_i \sigma_j) = \sigma_i^{-1} \sigma_j^{-1} \equiv \sigma_j^{-1} \sigma_i^{-1} = \theta(\sigma_j \sigma_i)$. A similar sequence of equivalences implies $\theta(\sigma_i \sigma_j \sigma_i) \equiv \theta(\sigma_j \sigma_i \sigma_j)$ for i, j in $[1, n-1]$ with $|i - j| \leq 1$.

Let u be an Σ_n -word. For $x \in \Sigma_n$, the permutation $\pi(\bar{x})$ is a transposition and so the relation $\pi(\bar{x}) = \pi(\overline{x^{-1}})$ holds. Hence we obtain $\pi(\theta_{\Sigma_n}(u)) = \pi(\bar{u})$. We denote by u_k the prefix of u of length k . An immediate induction on k , together with $\pi(\theta_{\Sigma_n}(u_k)) = \pi(\bar{u_k})$ and Lemma 4.7 establish $\ell_{i,j}(\theta_{\Sigma_n}(u)) = -\ell_{i,j}(\bar{u})$. Condition *iii*) is then satisfied by θ_{Σ_n} .

Let us focus now on the map $\theta_{\Sigma_n^*}$. In B_4 we have the relation $a_{1,2}a_{2,3} \equiv a_{2,3}a_{1,3}$ while $a_{1,2}^{-1}a_{2,3}^{-1}$ is not equivalent to $a_{2,3}^{-1}a_{1,3}^{-1}$ as shown by the following diagrams.



The non isotopy of the two right-most diagrams can be established evaluating $\ell_{1,3}$ for example. Indeed we have $\ell_{1,3}(a_{1,2}^{-1}a_{2,3}^{-1}) = -1$ and $\ell_{1,3}(a_{2,3}^{-1}a_{1,3}^{-1}) = 1$. \square

5.2.2. Garside homomorphisms. We now consider the “word version” of the classical and dual Garside automorphisms of B_n .

Definition 5.5. The Garside automorphism of B_n is $\bar{\Phi}_n(\beta) = \Delta_n \beta \Delta_n^{-1}$ where Δ_n is given by $\Delta_2 = \sigma_1$ and $\Delta_k = \sigma_1 \cdots \sigma_{k-1} \Delta_{k-1}$ for $k \geq 3$.

For example we have $\Delta_4 = \sigma_1 \sigma_2 \sigma_3 \cdot \Delta_3 = \sigma_1 \sigma_2 \sigma_3 \cdot \sigma_1 \sigma_2 \cdot \Delta_1 = \sigma_1 \sigma_2 \sigma_3 \cdot \sigma_1 \sigma_2 \cdot \sigma_1$, which corresponds to the following diagram:



For all $k \in [1, n]$ we have:

$$\pi(\Delta_n)(k) = n+1-k. \quad (14)$$

As we can notice in the previous diagram, the braid Δ_n can be represented by a diagram in which each two strands cross exactly once implying

$$\ell_{i,j}(\Delta_n) = 1 \quad \text{and} \quad \ell_{i,j}(\Delta_n^{-1}) = -1. \quad (15)$$

The result involving Δ_n^{-1} is a direct consequence of that of Δ_n together with Proposition 5.3. The following lemma is a well-known result about the Garside automorphism Φ_n .

Lemma 5.6. For $n \geq 3$, the automorphism $\bar{\Phi}_n$ has order 2 and for every integer k in $[1, n-1]$ we have $\bar{\Phi}_n(\sigma_k) = \sigma_{n-k}$.

Proof. Let $k \in [1, n-1]$. Relation $\bar{\Phi}_n(\sigma_k) = \sigma_{n-k}$ is an easy verification from the Artin presentation of B_n (see Lemma I.3.6 of [12]). We conclude with $\bar{\Phi}_n^2(\sigma_k) = \bar{\Phi}_n(\sigma_{n-k}) = \sigma_{n-(n-k)} = \sigma_k$. \square

Definition 5.7. We denote by Φ_n the homomorphism of Σ_n -words defined for every integer k in $[1, n]$ by $\Phi_n(\sigma_k) = \sigma_{n-k}$.

By Lemma 5.6, for every Σ_n -word u we have

$$\overline{\Phi_n(u)} = \overline{\Phi_n(\bar{u})} = \Delta_n \bar{u} \Delta_n^{-1}. \quad (16)$$

Proposition 5.8. *The map Φ_n is Σ_n -stable. Moreover for every template $t \in T_n$ we have:*

$$\begin{aligned} (\Phi_n^T(t)[\pi])(k) &= n+1-t[\pi](n+1-k) \quad \text{for all } k \in [1, n], \\ \Phi_n^T(t)[\ell_{i,j}] &= t[\ell_{n+1-j, n+1-i}] \quad \text{for all } 1 \leq i < j \leq n. \end{aligned}$$

Proof. Condition *i*) and *ii*) of Definition 5.1 are easily established since Φ_n is defined from the conjugation $\overline{\Phi_n}$ which induces a bijection on Σ_n . We now prove Condition *iii*) of Definition 5.1. Let u be a Σ_n -word. By (16) we have

$$\pi(\overline{\Phi_n(u)}) = \pi(\Delta_n) \circ \pi(\bar{u}) \circ \pi(\Delta_n)^{-1} = \pi(\Delta_n) \circ \pi(\bar{u}) \circ \pi(\Delta_n).$$

Relation (14) implies that for all integer $k \in [1, n]$ we have

$$\pi(\overline{\Phi_n(u)})(k) = n+1-\pi(\bar{u})(n+1-k). \quad (17)$$

Let $1 \leq i < j \leq n$ be two integers. Lemma 4.7 together with (15) give

$$\begin{aligned} \ell_{i,j}(\overline{\Phi_n(u)}) &= \ell_{i,j}(\Delta_n \bar{u} \Delta_n^{-1}) = \ell_{i,j}(\Delta_n \bar{u}) + \ell_{\pi(\Delta_n \bar{u})^{-1}(i), \pi(\Delta_n \bar{u})^{-1}(j)}(\Delta_n^{-1}) \\ &= \ell_{i,j}(\Delta_n \bar{u}) - 1 \\ &= \ell_{i,j}(\Delta_n) + \ell_{\pi(\Delta_n)^{-1}(i), \pi(\Delta_n)^{-1}(j)}(\bar{u}) - 1 \\ &= \ell_{\pi(\Delta_n)^{-1}(i), \pi(\Delta_n)^{-1}(j)}(\bar{u}) \\ &= \ell_{n+1-i, n+1-j}(\bar{u}) = \ell_{n+1-j, n+1-i}(\bar{u}). \quad \square \end{aligned}$$

Definition 5.9. The dual Garside automorphism of B_n is $\bar{\phi}_n(\beta) = \delta_n \beta \delta_n^{-1}$ where δ_n is given by $\delta_n = a_{1,2} \cdots a_{n-1,n} = \sigma_1 \cdots \sigma_{n-1}$.

For example we have $\delta_4 = \sigma_1 \sigma_2 \sigma_3$ and $\delta_4^{-1} = \sigma_3^{-1} \sigma_2^{-1} \sigma_1^{-1}$ which correspond to the following diagrams:

$$\delta_4 \simeq \begin{array}{c} \text{---} \\ \text{---} \end{array} \quad \delta_4^{-1} \simeq \begin{array}{c} \text{---} \\ \text{---} \end{array} \quad (18)$$

Notation 5.10. For all $n \in \mathbb{N}$ and $k \in [0, n+1]$ we put

$$[k]_n = \begin{cases} 1 & \text{if } k = n+1, \\ n & \text{if } k = 0, \\ k & \text{otherwise.} \end{cases}$$

Moreover for all integers i and j the symbol $\mathbf{1}_{i=j}$ equals 1 if the relation $i = j$ holds and 0 otherwise.

As we can directly see on diagrams of (18), for all $k \in [1, n]$ we have

$$\pi(\delta_n)(k) = [k+1]_n, \quad (19)$$

moreover for all $1 \leq i < j \leq n$ we have

$$\ell_{i,j}(\delta_n) = \mathbf{1}_{i=1} \quad \text{and} \quad \ell_{i,j}(\delta_n^{-1}) = -\mathbf{1}_{j=n}. \quad (20)$$

Lemma 5.11. *The automorphism $\bar{\phi}_n$ has order n and for all $1 \leq p < q \leq n$ we have*

$$\bar{\phi}_n(a_{p,q}) = a_{[p+1]_n, [q+1]_n}$$

with the convention $a_{i,j} = a_{j,i}$ whenever $j > i$ holds.

Proof. Computation of $\bar{\phi}_n(a_{p,q})$ is an easy verification from Birman–Ko–Lee’s presentation of B_n . The result on the order of $\bar{\phi}_n$ is then an immediate consequence. \square

Definition 5.12. We denote by ϕ_n the homomorphism of Σ_n^* -words defined for all integers p and q with $1 \leq p < q \leq n$ by

$$\phi_n(a_{p,q}) = a_{[p+1]_n, [q+1]_n}$$

Proposition 5.13. *The map ϕ_n is Σ_n^* -stable. Moreover for every template $t \in T_n$ we have*

$$\begin{aligned} (\phi_n^T(t)[\pi])(k) &= [1 + t[\pi]([k-1]_n)]_n \quad \text{for all } k \in [1, n], \\ \phi_n^T(t)[\ell_{i,j}] &= t[\ell_{[i-1]_n, [j-1]_n}] + \mathbf{1}_{i=1} - \mathbf{1}_{[1+t[\pi](n)]_n=j} \quad \text{for all } 1 \leq i < j \leq n. \end{aligned}$$

Proof. The proof is similar to that of Proposition 5.8. We detail only the case of Condition *iii*). Let u be an Σ_n^* -word and k be in $[1, n]$. From (19) we obtain

$$\begin{aligned} \pi(\overline{\phi_n(u)})(k) &= \pi(\delta_n)(\pi(\bar{u})(\pi(\delta_n)^{-1}(k))) \\ &= \pi(\delta_n)(\pi(\bar{u})([k-1]_n)) \\ &= [1 + \pi(\bar{u})([k-1]_n)]_n. \end{aligned}$$

Let $1 \leq i < j \leq n$ be two integers. Lemma 4.7 implies

$$\ell_{i,j}(\overline{\phi_n(u)}) = \ell_{i,j}(\delta_n \cdot \bar{u} \cdot \delta_n^{-1}) = \ell_{i,j}(\delta_n \cdot \bar{u}) + \ell_{\pi(\delta_n \cdot \bar{u})^{-1}(i), \pi(\delta_n \cdot \bar{u})^{-1}(j)}(\delta_n^{-1}).$$

From (20) we get that $\ell_{\pi(\delta_n \cdot \bar{u})^{-1}(i), \pi(\delta_n \cdot \bar{u})^{-1}(j)}(\delta_n^{-1})$ is non zero iff $\pi(\delta_n \cdot \bar{u})^{-1}(j) = n$, i.e., iff $\pi(\delta_n \cdot \bar{u})(n) = j$ which is equivalent to $[1 + \pi(\bar{u})(n)]_n = j$. We then obtain

$$\begin{aligned} \ell_{i,j}(\overline{\phi_n(u)}) &= \ell_{i,j}(\delta_n \cdot \bar{u}) + \begin{cases} -1 & \text{if } [1 + \pi(\bar{u})(n)]_n = j, \\ 0 & \text{otherwise,} \end{cases} \\ &= \ell_{i,j}(\delta_n \cdot \bar{u}) - \mathbf{1}_{[1+\pi(\bar{u})(n)]_n=j}. \end{aligned}$$

Moreover, always by (20) we have

$$\begin{aligned} \ell_{i,j}(\delta_n \cdot \bar{u}) &= \ell_{i,j}(\delta_n) + \ell_{\pi(\delta_n)^{-1}(i), \pi(\delta_n)^{-1}(j)} \\ &= \mathbf{1}_{i=1} + \ell_{[i-1]_n, [j-1]_n}(\bar{u}), \end{aligned}$$

with the convention $\ell_{p,q} = \ell_{q,p}$ for $p > q$. Eventually we obtain

$$\ell_{i,j}(\overline{\phi_n(u)}) = \ell_{[i-1]_n, [j-1]_n}(\bar{u}) + \mathbf{1}_{i=1} - \mathbf{1}_{[1+\pi(\bar{u})(n)]_n=j}. \quad \square$$

5.3. Action on templates. We now describe an action of a subgroup of bijections of T_n on T_n itself. Eventually, for any template $t \in T_n$, braids of $B_n(S_n, \ell, t)$ shall be in bijection with $B_n(S_n, \ell, t')$ whenever t' belongs in the orbit of t .

Definition 5.14. We define G_{Σ_n} , *resp.* $G_{\Sigma_n^*}$, to be the subgroup of bijections of T_n generated by $\{\text{inv}_{\Sigma_n}^T, \theta_{\Sigma_n}^T, \Phi_n^T\}$, *resp.* by $\{\text{inv}_{\Sigma_n^*}^T, \phi_n^T\}$. For $t \in T_n$, we denote

$$G_{\Sigma_n} \star t = \{g(t), g \in G_{\Sigma_n}\} \quad \text{and} \quad G_{\Sigma_n^*} \star t = \{g(t), g \in G(\Sigma_n^*)t\}$$

the orbits of t under the action of G_{Σ_n} , *resp.* $G_{\Sigma_n^*}$.

Lemma 5.15. *We have $G_{\Sigma_n} \simeq (\mathbb{Z}/2\mathbb{Z})^3$ and $G_{\Sigma_n^*} \simeq \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/n\mathbb{Z}$.*

Proof. Let $u = \sigma_{i_1}^{e_1} \cdots \sigma_{i_m}^{e_m}$ be a Σ_n -word with $e_1, \dots, e_m \in \{-1, +1\}$. From

$$\begin{aligned} \text{inv}_{\Sigma_n}(\theta_{\Sigma_n}(u)) &= \text{inv}_{\Sigma_n}(\sigma_{i_1}^{-e_1} \cdots \sigma_{i_m}^{-e_m}) = \sigma_{i_m}^{e_m} \cdots \sigma_{i_1}^{e_1}, \\ \theta_{\Sigma_n}(\text{inv}_{\Sigma_n}(u)) &= \theta_{\Sigma_n}(\sigma_{i_m}^{-e_m} \cdots \sigma_{i_1}^{-e_1}) = \sigma_{i_m}^{e_m} \cdots \sigma_{i_1}^{e_1}, \end{aligned}$$

we obtain that the maps inv_{Σ_n} and θ_{Σ_n} commute on Σ_n -words. Let t be a template of T_n and v be a Σ_n -word representing a braid of template t . We have

$$(\text{inv}_{\Sigma_n}^T \circ \theta_{\Sigma_n}^T)(t) = \tau \left(\overline{(\text{inv}_{\Sigma_n} \circ \theta_{\Sigma_n})(v)} \right) = \tau \left(\overline{(\theta_{\Sigma_n} \circ \text{inv}_{\Sigma_n})(v)} \right) = (\theta_{\Sigma_n}^T \circ \text{inv}_{\Sigma_n}^T)(t)$$

and so $\text{inv}_{\Sigma_n}^T$ and $\theta_{\Sigma_n}^T$ commute. Similar arguments establish the commutation of θ_{Σ_n} and Φ_n , inv_{Σ_n} and Φ_n , $\text{inv}_{\Sigma_n^*}$ and ϕ_n . Hence we have

$$G_{\Sigma_n} = \langle \text{inv}_{\Sigma_n}^T \rangle \times \langle \theta_{\Sigma_n}^T \rangle \times \langle \Phi_n^T \rangle \quad \text{and} \quad G(\Sigma_n^*) = \langle \text{inv}_{\Sigma_n^*}^T \rangle \times \langle \phi_n^T \rangle.$$

The maps $\theta_{\Sigma_n}^T$ and $\text{inv}_{\Sigma_n}^T$ have order 2 since it is the case for θ_{Σ_n} and inv_{Σ_n} by construction. From Lemma 5.6 and Lemma 5.11 the map Φ_n and ϕ_n have order 2 and n respectively. The results follow. \square

From a geometric point of view, the maps $\text{inv}_{\Sigma_n}^T$, $\theta_{\Sigma_n}^T$ and Φ_n^T can be seen as reflections along the coordinate planes of the 3-space and the result on G_{Σ_n} is immediate. If we consider the base points of the braid evenly placed in a circumference, the maps $\theta_{\Sigma_n}^T$ and Φ_n^T correspond respectively to a reflection along a plane and to a rotation of order n along an axis orthogonal to this plane, establishing the result on $G_{\Sigma_n^*}$.

Example 5.16. We recall that the template of a braid $\beta \in B_4$ is

$$\tau(\beta) = (\pi(\beta), \ell_{1,2}(\beta), \ell_{1,3}(\beta), \ell_{2,3}(\beta), \ell_{1,4}(\beta), \ell_{2,4}(\beta), \ell_{3,4}(\beta)) \quad (21)$$

The template of $\sigma_1 \sigma_2^{-1}$ seen in B_4 is $t = ((1\ 2\ 3), 1, -1, 0, 0, 0, 0)$. Using Propositions 5.3, 5.4 and 5.13 we obtain

$$\begin{aligned} \text{inv}_{\Sigma_4}^T(t) &= ((1\ 3\ 2), 0, -1, 1, 0, 0, 0), \\ \theta_{\Sigma_4}^T(t) &= ((1\ 2\ 3), -1, 1, 0, 0, 0, 0), \\ \Phi_4^T(t) &= ((2\ 4\ 3), 0, 0, 0, 0, -1, 1), \\ (\text{inv}_{\Sigma_4}^T(t) \circ \theta_{\Sigma_4}^T(t)) &= ((1\ 3\ 2), 0, 1, -1, 0, 0, 0), \\ (\text{inv}_{\Sigma_4}^T(t) \circ \Phi_4^T(t)) &= ((2\ 3\ 4), 0, 0, 1, 0, -1, 0), \\ (\theta_{\Sigma_4}^T(t) \circ \Phi_4^T(t)) &= ((2\ 4\ 3), 0, 0, 0, 0, 1, -1), \\ (\text{inv}_{\Sigma_4}^T(t) \circ \theta_{\Sigma_4}^T(t) \circ \Phi_4^T(t)) &= ((2\ 3\ 4), 0, 0, -1, 0, 1, 0), \end{aligned}$$

and so the set $G \star t$ has exactly 8 elements.

From a given template $t \in T_n$ we obtain $\text{red}_{S_n}(t)$ by computing the set $G_{S_n} \star t$ and picking its minimal element.

5.4. Template reduction. Now we define a total ordering on T_n . We start with permutations of \mathfrak{S}_n .

Definition 5.17. For σ and σ' two permutations of \mathfrak{S}_n we write $\sigma < \sigma'$ whenever

$$(\sigma(1), \dots, \sigma(n)) <_{\text{CoLex}} (\sigma'(1), \dots, \sigma'(n)),$$

i.e., whenever there exists $k \in [1, n]$ such that $\sigma(n) = \sigma'(n), \dots, \sigma(k+1) = \sigma'(k+1)$ and $\sigma(k) < \sigma'(k)$.

For example, the ordering of permutations occurring in Example 5.16 is

$$(234) < (243) < (123) < (132). \quad (22)$$

Definition 5.18. For two templates $t = (\sigma, (\ell_{i,j})_{1 \leq i < j \leq n})$ and $t' = (\sigma', (\ell'_{i,j})_{1 \leq i < j \leq n})$ we write $t < t'$ whenever

$$(\sigma, \ell_{1,2}, \dots, \ell_{1,n}, \dots, \ell_{n-1,n}) <_{\text{Lex}} (\sigma', \ell'_{1,2}, \dots, \ell'_{1,n}, \dots, \ell'_{n-1,n}),$$

where we recall the integers $\ell_{i,j}(\beta)$ are enumerated following a co-lexicographic ordering on their indices (see Definition 4.9). For a template t we denote by $\text{red}_{S_n}(t)$ the minimal element of $G_{S_n} \star t$. We say that a template $t \in T_n$ is S_n -reduced if $\text{red}_{S_n}(t) = t$ holds. For an integer $\ell \in \mathbb{N}$ we denote by $R_n(S_n, \ell)$ the set of reduced templates lying in $T_n(S_n, \ell)$.

Example 5.19. We reconsider template t of Example 5.16. By (22) we obtain

$$\text{red}_{\Sigma_4}(t) = ((234), 0, 0, -1, 0, 1, 0).$$

which is equal to $(\text{inv}_{\Sigma_4}^T \circ \theta_{\Sigma_4}^T \circ \Phi_4^T)(t)$.

Proposition 5.20. For μ a S_n -stable map of S_n -words, ℓ an integer ≥ 0 and t a template of T_n we have

$$\bar{\mu}(B_n(S_n, \ell, t)) = B_n(S_n, \ell, \mu^T(t))$$

and $\text{card}(B_n(S_n, \ell, t)) = \text{card}(B_n(S_n, \ell, \mu^T(t)))$.

Proof. A direct consequence of Definition 5.1. □

Corollary 5.21. Let ℓ be an integer. We have

$$s(B_n, S_n, \ell) = \sum_{t \in R_n(S_n, \ell)} \text{card}(B_n(S_n, \ell, t)) \cdot \text{card}(G_{S_n} \star t).$$

Proof. We have

$$B_n(S_n, \ell) = \bigsqcup_{t \in T_n(S_n, \ell)} B_n(S_n, \ell, t) = \bigsqcup_{t_r \in R_n(S_n, \ell)} \bigsqcup_{t \in G_{S_n} \star t_r} B_n(S_n, \ell, t)$$

Assume r is a template of $R_n(S_n, \ell)$ and t lies in $G_{S_n} \star t_r$. Then there exists a S_n -stable bijection $\mu \in G_{S_n}$ satisfying $t = \mu^T(t_r)$. It follows from Proposition 5.20 that the set $B_n(S_n, \ell, t)$ has the same cardinality as $B_n(S_n, \ell, t_r)$. So we obtain

$$\begin{aligned} s(B_n, S_n, \ell) &= \text{card}(B_n(S_n, \ell)) = \sum_{t_r \in R_n(S_n, \ell)} \sum_{t \in G(S_n) \cdot t_r} \text{card}(B_n(S_n, \ell, t)) \\ &= \sum_{t_r \in R_n(S_n, \ell)} \text{card}(B_n(S_n, \ell, t_r)) \times \text{card}(G_{S_n} \star t_r). \end{aligned} \quad \square$$

5.5. Algorithmic improvement. We now give an improvement of the algorithms of Section 4 using Corollary 5.21. From Corollary 5.21 we know how to obtain $s(B_n, S_n, \ell)$ from an enumeration of braids associated to a reduced template. As in Section 4 we assume we have a function $\text{LOADRED}(n, \ell, t)$ loading from the storage memory a representative set of $B_n(S_n, \ell, t)$ where t is a reduced template. We also assume we have a function $\text{SAVERED}(W, n, \ell, t)$ which saves a representative set W of $B_n(S_n, \ell, t)$ whenever t is a reduced template.

Enumerating only braids with a reduced template reduces the requirements of storage space. But there is a little difficulty. The template t_x used in the call of LOAD line 6 of Algorithm 2 – TEMPREPSET is not necessarily reduced. However, thanks to Proposition 5.20 we have

$$B_n(S_n, \ell, t) = \bar{g}^{-1}(B_n(S_n, \ell, \text{red}_{S_n}(t))),$$

where $g^T(t) = \text{red}_{S_n}(t)$. Hence if W_r is a representative set of $B_n(S_n, \ell, \text{red}_{S_n}(t))$ then $W = g^{-1}(W_r)$ is a representative set of $B_n(S_n, \ell, t)$. We then obtain Algorithm 4 – LOADFROMRED that can return any representative set of $B_n(S_n, \ell, t)$ from the storage of braids of S_n -length ℓ with a reduced template.

Algorithm 4 – LOADFROMRED : Returns a representative set W of $B_n(S_n, \ell, t)$ from the storage of representative sets of braids of length ℓ having a reduced template.

```

1: function  $\text{LOADFROMRED}(n, \ell, t)$ 
2:    $t_r \leftarrow \text{red}_{S_n}(t)$  ▷ the minimal element of  $G_{S_n} \cdot t$ 
3:   determine  $g \in G_{S_n}$  such that  $t = g^T(t_r)$ 
4:    $W_r \leftarrow \text{LOADRED}(n, \ell, t_r)$ 
5:    $W \leftarrow \emptyset$ 
6:   for  $w \in W_r$  do
7:      $W \leftarrow W \sqcup \{g^{-1}(w)\}$ 
8:   end for
9:   return  $W$ 
10: end function

```

The improved version REDTEMPREPSET of Algorithm 2 – TEMPREPSET is obtained replacing calls of LOAD by LOADRED and call of SAVE by SAVERED .

By Corollary 5.21 the number $s(B_n, S_n, \ell)$ can be determined by running Algorithm REDTEMPREPSET on all reduced templates of $T_n(S_n, \ell)$. As for braids we can't determine reduced templates of $T_n(S_n, \ell)$ considering only reduced templates of $T_n(S_n, \ell-1)$. Assume we dispose of the set $R_n(S_n, \ell-1)$ of reduced templates of $T_n(S_n, \ell-1)$. First we reconstruct the set $T_n(S_n, \ell-1)$ using

$$T_n(S_n, \ell-1) = \{g(t) \text{ for } (g, t) \in G_{S_n} \times R_n(S_n, \ell-1)\}.$$

As a second step we use (13) to obtain a supset T'_ℓ of $T_n(S_n, \ell)$. Then we filter element of T'_ℓ keeping only reduced templates by testing if a template is minimal in its orbit under the action of G_{S_n} . Eventually we obtain the set $R_n(S_n, \ell)$ of reduced templates containing the reduced templates of $T_n(S_n, \ell)$. Moreover a template of $R_n(S_n, \ell)$ is a reduced template of $T_n(S_n, \ell)$ if and only if there exists a braid $\beta \in B_n(S_n, \ell)$ having this precise template. These lead to Algorithm 5 – REDCOMBI , which is an improved version of Algorithm 3 – COMBI .

Algorithm 5 – REDCOMBI : Returns a pair of arrays of number (n_s, n_g) satisfying $n_s[\ell] = s(B_n, S_n, \ell)$ and $n_g[\ell] = g(B_n, S_n, \ell)$ for all $\ell \leq \ell_{\max}$

```

1: function REDCOMBI( $\ell_{\max}$ )
2:    $n_s[0] \leftarrow 1$ ;  $n_g[0] \leftarrow 1$ 
3:    $R \leftarrow \{(1_{\mathfrak{S}_n}, 0, \dots, 0)\}$  ▷ reduced templates of  $T_n(S_n, 0)$ 
4:   for  $\ell$  from 1 to  $\ell_{\max}$  do
5:      $R' \leftarrow \emptyset$ 
6:      $n_s[\ell] \leftarrow 0$ ;  $n_g[\ell] \leftarrow 0$ 
7:     for  $t_r \in R$  do
8:       for  $t \in G_{S_n} \cdot t_r$  do
9:         for  $\mathbf{x} \in S_n$  do
10:           $t' \leftarrow t * \mathbf{x}$ 
11:          if  $t'$  is reduced and  $t' \notin R'$  then
12:             $(n'_s, n'_g) \leftarrow \text{REDTEMPREPSET}(\ell, t')$ 
13:            if  $n'_s \neq 0$  then
14:               $R' \leftarrow R' \cup \{t'\}$ 
15:               $n_s[\ell] \leftarrow n_s[\ell] + n'_s \times \text{card}(G_{S_n} \star t')$ 
16:               $n_g[\ell] \leftarrow n_g[\ell] + n'_g \times \text{card}(G_{S_n} \star t')$ 
17:            end if
18:          end if
19:        end for
20:      end for
21:    end for
22:     $R \leftarrow R'$  ▷ reduced templates of  $T_n(S_n, \ell)$ 
23:  end for
24:  return  $(n_s, n_g)$ 
25: end function

```

6. RESULTS

For our experimentations we have coded a distributed version of Algorithm 5 – REDCOMBI following a client / server model. Roughly speaking the server runs the core of Algorithm 5 while clients run Algorithm 4 – REDTEMPREPSET in parallel. Technical details are voluntarily omitted. The source code of our program is available on GitHub [20].

These programs were executed on a single computational node² of the computing platform CALCULCO [25]. This node is equipped with 256 Go of RAM together with two processors AMD Epyc 7702 with 64 cores each for a total of 128 cores. In addition of this computational node we have used a distributed storage space of 30 To storing files containing representative sets.

6.1. Three strands. As values of $\mathcal{S}(B_3, \Sigma_3)$ and $\mathcal{G}(B_3, \Sigma_3)$ are already known since the work of L. Sabalka [24] we have started our experimentation on the dual presentation of B_3 (see Table 1).

Using Padé approximant on obtained values we can conjecture rational expression for the spherical and geodesic growth series of B_3 relatively to dual generators.

²Financed by the project BQR CIMPA 2020 and the laboratory LMPA.

ℓ	$s(B_3, \Sigma_3^*, \ell)$	$g(B_3, \Sigma_3^*, \ell)$	ℓ	$s(B_3, \Sigma_3^*, \ell)$	$g(B_3, \Sigma_3^*, \ell)$
0	1	1	11	38 910	6 639 606
1	6	6	12	83 966	26 216 418
2	20	30	13	180 222	103 827 366
3	54	126	14	385 022	412 169 970
4	134	498	15	819 198	1 639 212 246
5	318	1 926	16	1 736 702	6 528 347 778
6	734	7 410	17	3 670 014	26 027 690 886
7	1 662	28 566	18	7 733 246	103 853 269 650
8	3 710	110 658	19	16 252 926	414 639 810 486
9	8 190	431 046	20	34 078 718	1 656 237 864 738
10	17 918	1 687 890	21	71 303 166	6 617 984 181 606

TABLE 1. Combinatorics of B_3 relatively to dual generators Σ_3^* .

Conjecture 6.1. *The spherical and geodesic growth series of B_3 relatively to dual generators are*

$$\mathcal{S}(B_3, \Sigma_3^*) = \frac{(t+1)(2t^2-1)}{(t-1)(2t-1)^2}, \quad \mathcal{G}(B_3, \Sigma_3^*) = \frac{12t^3 - 2t^2 + 3t - 1}{(2t-1)(3t-1)(4t-1)}.$$

If the previous conjecture is true the growth rate of $s(B_3, \Sigma_3^*, \ell)$ is 2 while that of $g(B_3, \Sigma_3^*, \ell)$ is 4.

6.2. Four strands. In her thesis [2], M. Albenque computes the value $s(B_4, \Sigma_4, \ell)$ up to $\ell \leq 12$. Running our algorithm on the 128-cores node of the CALCULCO platform we determine the spherical and geodesic combinatorics of B_4 relatively to Artin's generators up to length 25 (see Table 2). Unfortunately the obtained

ℓ	$s(B_4, \Sigma_4, \ell)$	$g(B_4, \Sigma_4, \ell)$	ℓ	$s(B_4, \Sigma_4, \ell)$	$g(B_4, \Sigma_4, \ell)$
0	1	1	13	9 007 466	281 799 158
1	6	6	14	27 218 486	1 153 638 466
2	26	30	15	82 133 734	4 710 108 514
3	98	142	16	247 557 852	19 186 676 438
4	338	646	17	745 421 660	78 004 083 510
5	1 110	2 870	18	2 242 595 598	316 591 341 866
6	3 542	12 558	19	6 741 618 346	1 283 041 428 650
7	11 098	54 026	20	20 252 254 058	5 193 053 664 554
8	34 362	229 338	21	60 800 088 680	20 994 893 965 398
9	105 546	963 570	22	182 422 321 452	84 795 261 908 498
10	322 400	4 016 674	23	547 032 036 564	342 173 680 884 002
11	980 904	16 641 454	24	1 639 548 505 920	1 379 691 672 165 334
12	2 975 728	68 614 150	25	4 911 638 066 620	5 559 241 797 216 166

TABLE 2. Combinatorics of B_4 relatively to Artin's generators Σ_4 .

values do not allow us to guess a rational expression of $\mathcal{S}(B_4, \Sigma_4)$ or of $\mathcal{G}(B_4, \Sigma_4)$. For information the storage of all braids of B_4 with geodesic Σ_4 -length ≤ 25 and reduced templates requires 26 To of disk space.

In case of dual generators we have reached length 17 (see Table 3).

Using Padé approximant on our values we can conjecture the value of the spherical growth series of B_4 relatively to dual generators.

ℓ	$s(B_4, \Sigma_4^*, \ell)$	$g(B_4, \Sigma_4^*, \ell)$	ℓ	$S(B_4, \Sigma_4^*, \ell)$	$g(B_4, \Sigma_4^*, \ell)$
0	1	1	9	7 348 366	708 368 540
1	12	12	10	35 773 324	6 128 211 364
2	84	132	11	173 885 572	52 826 999 612
3	478	1 340	12	844 277 874	454 136 092 148
4	2 500	12 788	13	4 095 929 948	3 895 624 824 092
5	12 612	117 452	14	19 858 981 932	33 359 143 410 468
6	62 570	1 053 604	15	96 242 356 958	285 259 736 104 444
7	303 356	9 311 420	16	466 262 144 180	2 436 488 694 821 748
8	1 506 212	81 488 628	17	2 258 320 991 652	20 790 986 096 580 060

TABLE 3. Combinatorics of B_4 relatively to dual generators Σ_4^* .

Conjecture 6.2. *The spherical growth series of B_4 relatively to dual generators is*

$$\mathcal{S}(B_4, \Sigma_4^*) = -\frac{(t+1)(10t^6 - 10t^5 - 3t^4 + 11t^3 - 4t^2 - 3t + 1)}{(t-1)(5t^2 - 5t + 1)(10t^4 - 20t^3 + 19t^2 - 8t + 1)} \quad (23)$$

If the previous conjecture is true, the growth rate of $s(B_4, \Sigma_4^*, \ell)$ is given by the inverse of the maximal root of the denominator of (23), which is approximately 4.8. Unfortunately we are not able to formulate such a conjecture for the geodesic growth series of B_4 relatively to dual generators.

Acknowledgments. The author wishes to thank the anonymous referee for his/her very sharp comments.

REFERENCES

- [1] M. Albenque. Bijective combinatorics of positive braids. *Electronic Notes in Discrete Mathematics*, 29:225–229, 2007.
- [2] M. Albenque. *Tresses, animaux, cartes : à l'interaction entre combinatoire et probabilité*. PhD thesis, Université Paris Diderot, 2008.
- [3] M. Albenque and P. Nadeau. Growth function for a class of monoids. In *21st International Conference on Formal Power Series and Algebraic Combinatorics (FPSAC 2009)*, Discrete Math. Theor. Comput. Sci. Proc., AK, pages 25–38. Assoc. Discrete Math. Theor. Comput. Sci., Nancy, 2009.
- [4] E. Artin. Theory of braids. *Ann. of Math. (2)*, 48:101–126, 1947.
- [5] D. Bessis. The dual braid monoid. *Ann. Sci. École Norm. Sup. (4)*, 36(5):647–683, 2003.
- [6] P. Biane and P. Dehornoy. Dual Garside structure of braids and free cumulants of products. *Sém. Lothar. Combin.*, 72:Art. B72b, 15, 2014/15.
- [7] J. Birman, K. H. Ko, and S. J. Lee. A new approach to the word and conjugacy problems in the braid groups. *Adv. Math.*, 139(2):322–353, 1998.
- [8] A. Bronfman. Growth function of a class of monoids (preprint), 2001.
- [9] R. Charney. Geodesic automation and growth functions for Artin groups of finite type. *Math. Ann.*, 301(2):307–324, 1995.
- [10] P. Dehornoy. Groupes de Garside. *Ann. Sci. École Norm. Sup. (4)*, 35(2):267–306, 2002.
- [11] P. Dehornoy. Combinatorics of normal sequences of braids. *J. Combin. Theory Ser. A*, 114(3):389–409, 2007.
- [12] P. Dehornoy. *Le calcul des tresses*. Nano. Calvage & Mounet, 2019.
- [13] P. Dehornoy, F. Digne, E. Godelle, D. Krammer, and J. Michel. *Foundations of Garside theory*, volume 22 of *EMS Tracts in Mathematics*. European Mathematical Society (EMS), Zürich, 2015. Author name on title page: Daan Kramer.
- [14] P. Dehornoy and L. Paris. Gaussian groups and Garside groups, two generalisations of Artin groups. *Proc. London Math. Soc. (3)*, 79(3):569–604, 1999.

- [15] Patrick Dehornoy, Ivan Dynnikov, Dale Rolfsen, and Bert Wiest. *Ordering braids*, volume 148 of *Mathematical Surveys and Monographs*. American Mathematical Society, Providence, RI, 2008.
- [16] I. A. Dynnikov. On a Yang-Baxter mapping and the Dehornoy ordering. *Uspekhi Mat. Nauk*, 57(3(345)):151–152, 2002.
- [17] D. B. A. Epstein, D. F. Holt, and S. E. Rees. The use of Knuth-Bendix methods to solve the word problem in automatic groups. volume 12, pages 397–414. 1991. Computational group theory, Part 2.
- [18] R. Flores and J. González-Meneses. On the growth of Artin–Tits monoids and the partial theta function. arXiv:1808.03066, 2018.
- [19] L. Foissy and J. Fromentin. A divisibility result in combinatorics of generalized braids. *J. Combin. Theory Ser. A*, 152:190–224, 2017.
- [20] J. Fromentin. Github – gbraids. <https://github.com/jfromentin/gbraids>, 2020.
- [21] F. A. Garside. The braid group and other groups. *Quart. J. Math. Oxford Ser. (2)*, 20:235–254, 1969.
- [22] F. Hivert, J.-C. Novelli, and J.-Y. Thibon. Sur une conjecture de Dehornoy. *C. R. Math. Acad. Sci. Paris*, 346(7-8):375–378, 2008.
- [23] J. Mairesse and F. Mathéus. Growth series for Artin groups of dihedral type. *Internat. J. Algebra Comput.*, 16(6):1087–1107, 2006.
- [24] L. Sabalka. Geodesics in the braid group on three strands. In *Group theory, statistics, and cryptography*, volume 360 of *Contemp. Math.*, pages 133–150. Amer. Math. Soc., Providence, RI, 2004.
- [25] Calculco platform. <https://www-calculco.univ-littoral.fr>, 2020.
- [26] Wikipedia. Standard template library. https://en.wikipedia.org/wiki/Standard_Template_Library, 2020.

UNIV. LITTORAL CÔTE D’OPALE, UR 2597, LMPA, LABORATOIRE DE MATHÉMATIQUES PURES
 ET APPLIQUÉES JOSEPH LIOUVILLE, F-62100 CALAIS, FRANCE
Email address: `fromentin@math.cnrs.fr`