

# Posets of twisted involutions in Coxeter groups

## Verbände getwisteter Involutionen in Coxetergruppen

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# Eidesstattliche Erklärung

Ich erkläre hiermit an Eides statt, dass ich die vorliegende Masterarbeit „Verbände getwisteter Involutionen in Coxetergruppen“ selbstständig verfasst sowie alle benutzten Quellen und Hilfsmittel vollständig angegeben habe und dass die Arbeit nicht bereits als Prüfungsarbeit vorgelegen hat.

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Ort, Datum

Christian Hoffmeister



# Deutsche Zusammenfassung

Regelmäßige Flächen und Körper sowie ihre Symmetriegruppen sind in der Mathematik seit jeher von großem Interesse. Mit der Einführung von Coxetergruppen durch Harold Scott MacDonald Coxeter im Jahr 1934 konnten diese Symmetriegruppen abstrakt gefasst werden und zugleich eine deutlich größere Klasse von Gruppen untersucht werden. Heutzutage spielen Coxetergruppen in vielen Bereichen der Mathematik eine große Rolle.

Für ein sogenanntes Coxetersystem  $(W, S)$ , bestehend aus einer Menge von involutorischen Erzeugern  $S$  und der von ihnen erzeugten Gruppe  $W$ , sei  $\theta$  ein Automorphismus von  $W$  der  $S$  festhält und maximal Ordnung 2 hat. Dann heißt die Menge  $\mathcal{I}_\theta$  der Elemente  $w \in W$ , die von  $\theta$  auf ihr inverses abgebildet werden, die Menge der  $\theta$ -getwisteten Involutionen. Es existiert dann eine spezielle Abbildung  $(w, s) \mapsto w\underline{s}$ , welche die Eigenschaft hat, dass der Orbit des neutralen Elements von  $W$  bzgl. dieser Abbildung gerade die Menge der  $\theta$ -getwisteten Involutionen ist und mit dessen Hilfe sich eine bestimmte Halbordnung  $\preceq$  auf dieser Menge definieren lässt. Der Verband  $(\mathcal{I}_\theta, \preceq)$  heißt dann getwistete schwache Ordnung  $Wk(W, \theta)$ . Für ein Element  $w \in \mathcal{I}_\theta$  und eine Teilmenge von Erzeugern  $S' \subseteq S$  heißt die Menge aller getwisteten Involutionen, die von der Form  $w\underline{s}_1 \dots \underline{s}_n$  mit  $s_1, \dots, s_n \in S'$  sind, das  $S'$ -Residuum von  $w$ , geschrieben als  $wC_{S'}$ .

Im Rahmen dieser Arbeit heißt  $Wk(W, \theta)$  3-residuell zusammenhängend, falls folgendes gilt: Seien  $K, S_1, S_2, S_3 \subseteq S$  Mengen von Erzeugern, wobei  $K$  sphärisch ist und von  $\theta$  festgehalten wird und sich die  $S_1, S_2, S_3$  paarweise nicht leer schneiden. Weiter sei  $w_K$  das maximale Element im Residuum  $wC_K$ . Dann gilt

$$wC_{S_1} \cap wC_{S_2} \cap wC_{S_3} \subseteq wC_{S_1 \cap S_2 \cap S_3}.$$

Die offene Fragestellung, um die es in dieser Arbeit gehen soll, ist, für welche Paare  $((W, S), \theta)$  die getwistete schwache Ordnung 3-residuell zusammenhängend ist. Um dies zu überprüfen, wird in dieser Arbeit nach einer Einleitung in die Theorie zuerst ein effizienter Algorithmus entwickelt, um den Verband  $Wk(W, \theta)$  berechnen zu können. Dann werden diese Ergebnisse benutzt, um mit einem weiteren Algorithmus nach Gegenbeispielen für den 3-residuellen Zusammenhang zu suchen. Dies ist für endliche Coxetersysteme in Gänze möglich. Für unendliche Coxetersysteme jedoch, scheitert dieses Vorgehen im Allgemeinen. Es wird jedoch gezeigt, wie sich mit diesem Vorgehen zumindest einige unendliche Coxetersysteme behandeln lassen, nämlich die affinen und kompakten hyperbolischen. Zum Abschluss der Arbeit wird dann noch ein kurzer Exkurs in die Gebäudetheorie gemacht. Dabei wird gezeigt, dass für alle  $Wk(W, \theta)$ , für die der 3-residuelle Zusammenhang gezeigt werden konnte, auch gilt, dass für jedes sogenannte Zwillingsgebäude vom Typ  $W$  das sogenannte Flipflop-System  $\mathcal{C}^\theta$  residuell zusammenhängend ist.



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# Introduction

TODO



# 1. Preliminaries

We start up with collecting some definitions and facts to ensure a uniform terminology and state of knowledge.

## 1.1. Posets

Posets are sets  $M$  with a partial order  $\leq$ . In particular, there are pairs  $(a, b) \in M \times M$  of distinct elements such that neither  $a \leq b$  nor  $a \geq b$ . The following definitions and examples define this more precisely.

**Definition 1.1.** Let  $M$  be a set. A binary relation  $\leq$  is called a **partial order** over  $M$  if for all  $a, b, c \in M$  it satisfies the conditions

1.  $a \leq a$  (**reflexivity**),
2.  $a \leq b \wedge b \leq a \Rightarrow a = b$  (**antisymmetry**) and
3.  $a \leq b \wedge b \leq c \Rightarrow a \leq c$  (**transitivity**).

In this case  $(M, \leq)$  is called a **poset**. If two elements  $a \leq b \in M$  are immediate neighbors, i.e. there is no third element  $c \in M$  with  $a < c < b$  we say that  $b$  **covers**  $a$ .

**Definition 1.2.** A poset is called **graded poset** if there is a map  $\rho : M \rightarrow \mathbb{N}$  such that for all  $a, b \in M$  with  $b$  covers  $a$  we have  $\rho(b) = \rho(a) + 1$ . In this case  $\rho$  is called the **rank function** of the graded poset.

**Definition 1.3.** A poset is called **directed poset** if for any two elements  $a, b \in M$  there is an element  $c \in M$  with  $a \leq c$  and  $b \leq c$ . It is called **bounded poset** if it has a unique minimal and maximal element, denoted by  $\hat{0}$  and  $\hat{1}$ .

**Definition 1.4.** Let  $(M, \leq)$  be a poset and  $a, b \in M$ . Then we call  $\{c \in M : a \leq c \leq b\}$  an **interval** and denote it by  $[a, b]_{\leq}$ . The set  $\{c \in M : a < c < b\}$  is called an **open interval** and is denoted by  $(a, b)_{\leq}$ . In both cases we can omit the  $\leq$ -index if the relation is clear from context.

**Definition 1.5.** The **Hasse diagram** of the poset  $(M, \leq)$  is the graph obtained in the following way: Add a vertex for each element in  $M$ . Then add a directed edge from vertex  $a$  to  $b$  whenever  $b$  covers  $a$ .

**Example 1.6.** Suppose we have an arbitrary set  $M$ . Then the powerset  $\mathcal{P}(M)$  can be partially ordered by the subset relation, so  $(\mathcal{P}(M), \subseteq)$  is a poset. Indeed this poset is always graded with the cardinality function as rank function. In Figure 1.1 we see the Hasse diagram of this poset with  $M = \{x, y, z\}$ .

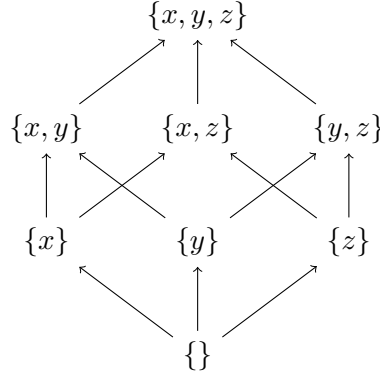


Figure 1.1.: Hasse diagram of the set of all subsets of  $\{x, y, z\}$  ordered by the subset relation

**Definition 1.7.** Let  $(M_i, \leq_i), i = 1, \dots, n$  be a finite set of posets. We call the poset  $(M_1 \times \dots \times M_n, \leq)$  with  $(a_1, \dots, a_n) \leq (b_1, \dots, b_n)$  iff  $a_i \leq_i b_i$  for  $i = 1, \dots, n$  a **direct product of posets** and denote it by  $(M_1, \leq_1) \times \dots \times (M_n, \leq_n)$ .

## 1.2. Coxeter groups

A Coxeter group, named after Harold Scott MacDonald Coxeter, is an abstract group generated by involutions with specific relations between these generators. A simple class of Coxeter groups are the symmetry groups of regular polyhedras in the Euclidean space.

The symmetry group of the square for example can be generated by two reflections  $s, t$ , whose stabilized hyperplanes enclose an angle of  $\pi/4$ . In this case the map  $st$  is a rotation in the plane by  $\pi/2$ . So we have  $s^2 = t^2 = (st)^4 = \text{id}$ . In fact, this reflection group is determined up to isomorphism by  $s, t$  and these three relations [Hum92, Theorem 1.9]. Furthermore it turns out, that the finite reflection groups in the Euclidean space are precisely the finite Coxeter groups [Hum92, Theorem 6.4].

In this chapter we compile some basic well-known facts on Coxeter groups, based on [Hum92].

**Definition 1.8.** Let  $S = \{s_1, \dots, s_n\}$  be a finite set of symbols and

$$R = \{m_{ij} \in \mathbb{N} \cup \infty : 1 \leq i, j \leq n\}$$

a set numbers (or  $\infty$ ) with  $m_{ii} = 1$ ,  $m_{ij} \geq 1$  and  $m_{ij} = m_{ji}$ . Then the free represented group

$$W = \langle S \mid (s_i s_j)^{m_{ij}} \rangle$$

is called a **Coxeter group** and  $(W, S)$  the corresponding **Coxeter system**. The cardinality of  $S$  is called the **rank** of the Coxeter system (and the Coxeter group).

From the definition we see, that Coxeter groups only depend on the cardinality of  $S$  and the relations between the generators in  $S$ . A common way to visualize this information are Coxeter graphs.

**Definition 1.9.** Let  $(W, S)$  be a Coxeter system. Create a graph by adding a vertex for each generator in  $S$ . Let  $(s_i s_j)^m = 1$ . In case  $m = 2$  the two corresponding vertices have no connecting edge. In case  $m = 3$  they are connected by an unlabeled edge. For  $m > 3$  they have an connecting edge with label  $m$ . We call this graph the **Coxeter graph** of our Coxeter system  $(W, S)$ .

**Definition 1.10.** Let  $(W, S)$  be a Coxeter system. For an arbitrary element  $w \in W$  we call a product  $s_{i_1} \cdots s_{i_n} = w$  of generators  $s_{i_1} \cdots s_{i_n} \in S$  an **expression** of  $w$ . Any expression that can be obtained from  $s_{i_1} \cdots s_{i_n}$  by omitting some (or all) generators is called a **subexpression** of  $w$ .

The present relations between the generators of a Coxeter group allow us to rewrite expressions. Hence an element  $w \in W$  can have more than one expression. Obviously any element  $w \in W$  has infinitely many expressions, since any expression  $s_{i_1} \cdots s_{i_n} = w$  can be extended by applying  $s_1^2 = 1$  from the right. But there must be a smallest number of generators needed to receive  $w$ . For example the neutral element  $e$  can be expressed by the empty expression. Or each generator  $s_i \in S$  can be expressed by itself, but any expression with less factors (i.e. the empty expression) is unequal to  $s_i$ .

**Definition 1.11.** Let  $(W, S)$  be a Coxeter system and  $w \in W$  an element. Then there are some (not necessarily distinct) generators  $s_i \in S$  with  $s_1 \cdots s_r = w$ . We call  $r$  the **expression length**. The smallest number  $r \in \mathbb{N}_0$  for that  $w$  has an expression of length  $r$  is called the **length** of  $w$  and each expression of  $w$  that is of minimal length is called **reduced expression**. The map

$$l : W \rightarrow \mathbb{N}_0$$

that maps each element in  $W$  to its length is called **length function**.

**Definition 1.12.** Let  $(W, S)$  be a Coxeter system. We define

$$D_R(w) := \{s \in S : l(ws) < l(w)\}$$

as the **right descending set** of  $w$ . The analogue left version

$$D_L(w) := \{s \in S : l(sw) < l(w)\}$$

is called **left descending set** of  $w$ . Since the left descending set is not need in this paper we will often call the right descending just **descending set** of  $w$ .

The next lemma yields some useful identities and relations for the length function.

**Lemma 1.13.** [Hum92, Section 5.2] *Let  $(W, S)$  be a Coxeter system,  $s \in S$ ,  $u, w \in W$  and  $l : W \rightarrow \mathbb{N}$  the length function. Then*

1.  $l(w) = l(w^{-1})$ ,
2.  $l(w) = 0$  iff  $w = e$ ,
3.  $l(w) = 1$  iff  $w \in S$ ,

- 4.  $l(uw) \leq l(u) + l(w)$ ,
- 5.  $l(uw) \geq l(u) - l(w)$  and
- 6.  $l(ws) = l(w) \pm 1$ .

*Remark 1.14.* Note, that  $l(ws) = l(w) \pm 1$  has a left analogue by  $l(sw) = l(w^{-1}s) = l(w^{-1}) \pm 1 = l(w) \pm 1$ .

### 1.3. Exchange and Deletion Condition

We now obtain a way to get a reduced expression of an arbitrary element  $s_1 \cdots s_r = w \in W$ .

**Definition 1.15.** Let  $(W, S)$  be a Coxeter system. Any element  $w \in W$  that is conjugated to an generator  $s \in S$  is called **reflection**. Hence the set of all reflections in  $W$  is

$$T = \bigcup_{w \in W} wSw^{-1}.$$

**Theorem 1.16** (Strong Exchange Condition). [Hum92, Theorem 5.8] *Let  $(W, S)$  be a Coxeter system,  $w \in W$  an arbitrary element and  $s_1 \cdots s_r = w$  with  $s_i \in S$  a not necessarily reduced expression for  $w$ . For each reflection  $t \in T$  with  $l(wt) < l(w)$  there exists an index  $i$  for which  $wt = s_1 \cdots \hat{s}_i \cdots s_r$ , where  $\hat{s}_i$  means omission. In case we start from a reduced expression, then  $i$  is unique.*

The Strong Exchange Condition can be weaken, when insisting on  $t \in S$  to receive the following corollary.

**Corollary 1.17** (Exchange Condition). [Hum92, Theorem 5.8] *Let  $(W, S)$  be a Coxeter system,  $w \in W$  an arbitrary element and  $s_1 \cdots s_r = w$  with  $s_i \in S$  a not necessarily reduced expression for  $w$ . For each generator  $s \in S$  with  $l(ws) < l(w)$  there exists an index  $i$  for which  $ws = s_1 \cdots \hat{s}_i \cdots s_r$ , where  $\hat{s}_i$  means omission. In case we start from a reduced expression, then  $i$  is unique.*

*Proof.* Directly from Strong Exchange Condition. □

*Remark 1.18.* Note that both, Strong Exchange Condition and Exchange Condition, have an analogue left-sided version

$$l(tw) < l(w) \Rightarrow tw = ts_1 \cdots s_k = s_1 \cdots \hat{s}_i \cdots s_k$$

for all reflections  $t \in T$ , hence for all generators  $s \in S$  in particular.

**Corollary 1.19** (Deletion Condition). [Hum92, Corollary 5.8] *Let  $(W, S)$  be a Coxeter system,  $w \in W$  and  $w = s_1 \cdots s_r$  with  $s_i \in S$  an unreduced expression of  $w$ . Then there exist two indices  $i, j \in \{1, \dots, r\}$  with  $i < j$ , such that  $w = s_1 \cdots \hat{s}_i \cdots \hat{s}_j \cdots s_r$ , where  $\hat{s}_i$  and  $\hat{s}_j$  mean omission.*



*Proof.* Since the expression is unreduced there must be an index  $j$  for that the twisted length shrinks. That means for  $w' = s_1 \cdots s_{j-1}$  is  $l(w's_j) < l(w')$ . Using the Exchange Condition we get  $w's_j = s_1 \cdots \hat{s}_i \cdots s_{j-1}$  yielding  $w = s_1 \cdots \hat{s}_i \cdots \hat{s}_j \cdots s_r$ .  $\square$

This corollary allows us to reduce expressions, i.e. to find a subexpression that is reduced. Due to the Deletion Condition any unreduced expression can be reduced by omitting an even number of generators (we just have to apply the Deletion Condition inductively).

The Strong Exchange Condition, the Exchange Condition and the Deletion Condition, are some of the most powerful tools when investigating properties of Coxeter groups. The second can be used to prove a very handy property of Coxeter groups. The intersection of two parabolic subgroups is again a parabolic subgroup.

**Definition 1.20.** Let  $(W, S)$  be a Coxeter system. For a subset of generators  $I \subset S$  we call the subgroup  $W_I \leq W$  that is generated by the elements in  $I$  with the corresponding relations, a **parabolic subgroup** of  $W$ .

**Lemma 1.21.** [Hum92, Section 5.8] *Let  $(W, S)$  be a Coxeter system and  $I, J \subset S$  two subsets of generators. Then  $W_I \cap W_J = W_{I \cap J}$ .*

A related fact, is the following lemma.

**Lemma 1.22.** [Hum92, Section 5.8] *Let  $(W, S)$  be a Coxeter system and  $w \in W$ . Let  $w = s_1 \cdots s_k$  be any reduced expression for  $w$ . Then the set of used generators  $\{s_1, \dots, s_k\} \subset S$  is independent of the particular chosen reduced expression. It only depends on  $w$  itself.*

This means that two reduced expressions for an element  $w \in W$  use exactly the same generators.

## 1.4. Finite Coxeter groups

Coxeter groups can be finite and infinite. A simple example for the former category is the following. Let  $S = \{s\}$ . Due to definition it must be  $s^2 = e$ . So  $W$  is isomorphic to  $\mathbb{Z}_2$  and finite. An example for an infinite Coxeter group can be obtained from  $S = \{s, t\}$  with  $s^2 = t^2 = e$  and  $(st)^\infty = e$  (so we have no relation between  $s$  and  $t$ ). Obviously the element  $st$  has infinite order forcing  $W$  to be infinite. But there are infinite Coxeter groups without a  $\infty$ -relation, as well. An example for this is  $W$  obtained from  $S = \{s_1, s_2, s_3\}$  with  $s_1^2 = s_2^2 = s_3^2 = (s_1 s_2)^3 = (s_2 s_3)^3 = (s_3 s_1)^3 = e$ . But how can one decide whether  $W$  is finite or not?

To provide a general answer to this question we fallback to a certain class of Coxeter groups, the irreducible ones.

**Definition 1.23.** A Coxeter system is called **irreducible** if the corresponding Coxeter graph is connected. Else, it is called **reducible**.

If a Coxeter system is reducible, then its graph has more than one component and each component corresponds to a parabolic subgroup of  $W$ .

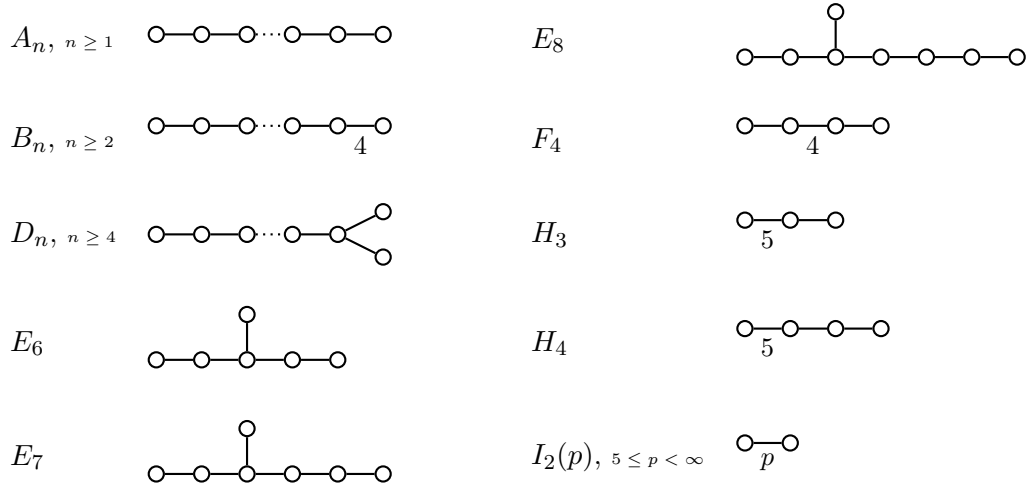


Figure 1.2.: All types of irreducible finite Coxeter systems

**Proposition 1.24.** [Hum92, Proposition 6.1] *Let  $(W, S)$  be a reducible Coxeter system. Then there exists a partition of  $S$  into  $I, J$  with  $(s_i s_j)^2 = e$  whenever  $s_i \in I, s_j \in J$  and  $W$  is isomorph to the direct product of the two parabolic subgroups  $W_I$  and  $W_J$ .*

This proposition tells us, that an arbitray Coxeter system is finite iff its irreducible parabolic subgroups are finite. Therefore we can indeed fallback to irreducible Coxeter systems without loss of generality. If we could categorize all irreducible finite Coxeter systems, then we could categorize all finite Coxeter systems. This is done by the following theorem:

**Theorem 1.25.** [Hum92, Theorem 6.4] *The irreducible finite Coxeter systems are exactly the ones in Figure 1.2.*

This allows us to decide with ease whether a given Coxeter system is finite. Take its irreducible parabolic subgroups and check if each is of type  $A_n, B_n, D_n, E_6, E_7, E_8, F_4, H_3, H_4$  or  $I_2(p)$ .

## 1.5. Affine and compact hyperbolic Coxeter groups

Two other important classes of Coxeter systems are the so-called affine and compact hyperbolic ones. The affine ones arise from the finite ones by appending another generator in a certain manner. The compact hyperbolic seem quite exceptional, but we will see what makes them interesting soon.

**Definition 1.26.** A irreducible Coxeter systems  $(W, S)$  is called **affine** if it is one of those from Figure 1.3.

**Definition 1.27.** A irreducible Coxeter systems  $(W, S)$  is called **compact hyperbolic** if it is one of those from the Figures 1.4, 1.5 or 1.6. In this paper the compact hyperbolic Coxeter systems are denoted with  $X$ , but note that this is not common in literature.

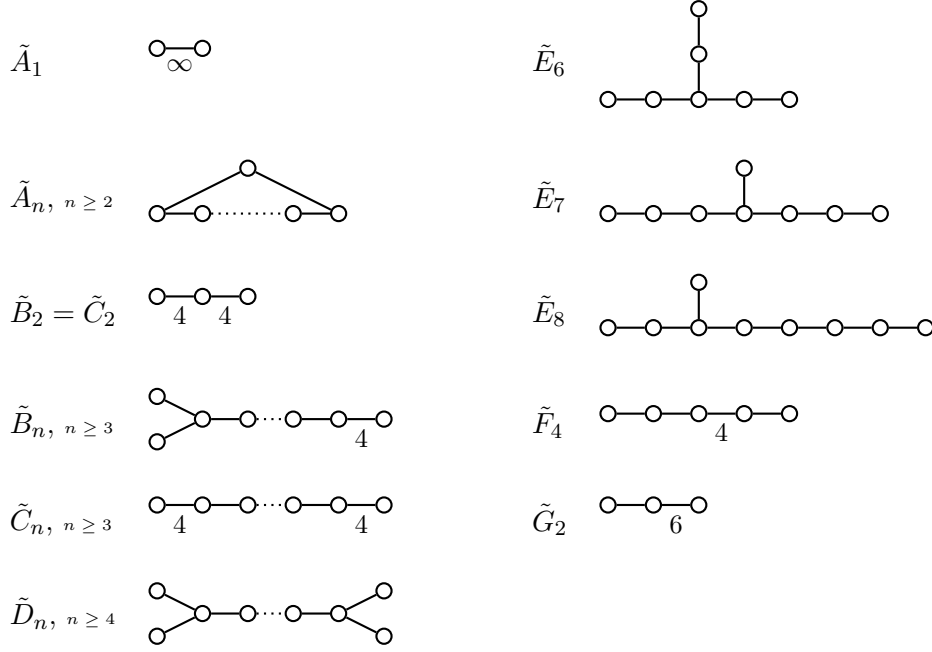


Figure 1.3.: All types of affine Coxeter systems

For a less arbitrarily introduction of affine and compact hyperbolic Coxeter systems refer to [Hum92, Section 2.5, 6.7 – 6.9]. We use this approach, since we are only interested in them because of the following corollary and lemma.

**Corollary 1.28.** *Let  $(W, S)$  be a affine or compact hyperbolic Coxeter system. Then every proper parabolic subgroup  $W_{S'}$  with  $S' \subsetneq S$  is either itself irreducible and finite or a direct product of irreducible finite Coxeter systems. In particular every proper parabolic subgroup is finite.*

*Proof.* This is immediate by simple inspection.  $\square$

**Lemma 1.29.** *The affine and compact hyperbolic Coxeter systems  $(W, S)$  are precisely the ones, satisfying the following two conditions:*

1.  $(W, S)$  is infinite.
2.  $(W, S)$  is irreducible.
3. For each  $S' \subsetneq S$  the parabolic subgroup  $W_{S'}$  is finite.

*Proof.* Obviously they are irreducible, by Theorem 1.25 they are infinite and by Corollary 1.28 each proper parabolic subgroup is finite. For a proof that they are the only ones satisfying this see [Hum92], [Che69].  $\square$

## 1.6. Bruhat ordering

We now investigate ways to partially order the elements of a Coxeter group. Furthermore, this ordering should be compatible with the length function, i.e. for  $w, v \in W$  we have  $l(w) < l(v)$  whenever  $w < v$ .

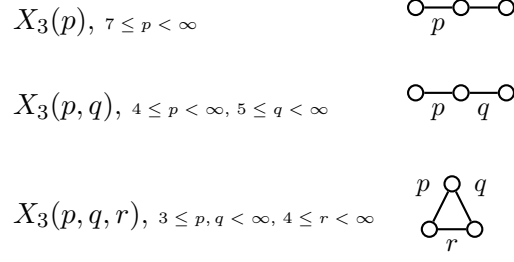


Figure 1.4.: All types of compact hyperbolic Coxeter systems of rank 3

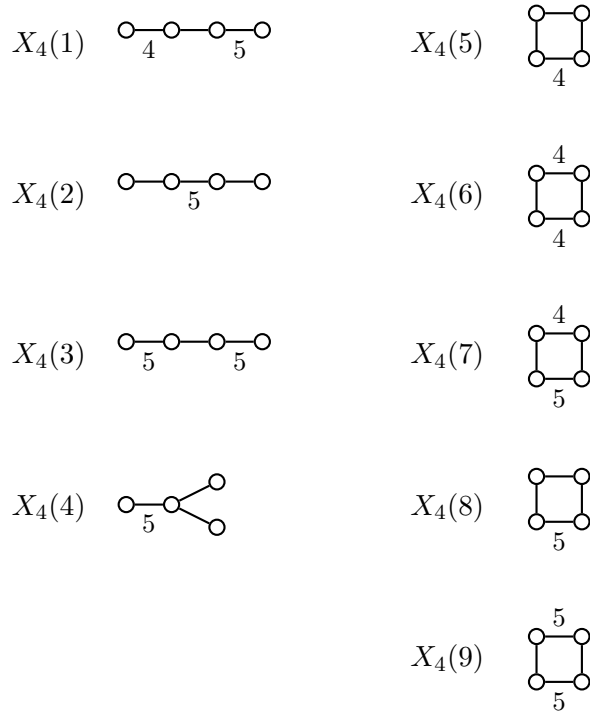


Figure 1.5.: All compact hyperbolic Coxeter systems of rank 4

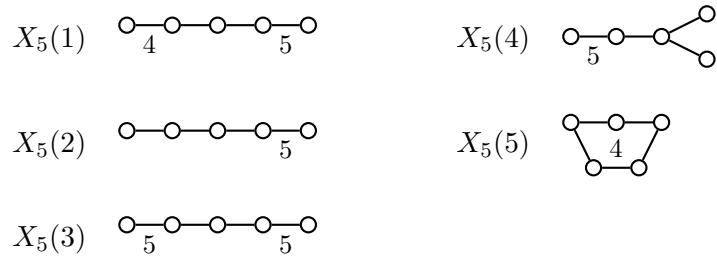


Figure 1.6.: All compact hyperbolic Coxeter systems of rank 5

**Definition 1.30.** Let  $(W, S)$  be a Coxeter system and  $T = \cup_{w \in W} wSw^{-1}$  the set of all reflections in  $W$ . We write  $w' \rightarrow w$  if there is a  $t \in T$  with  $w't = w$  and  $l(w') < l(w)$ . If there is a sequence  $w' = w_0 \rightarrow w_1 \rightarrow \dots \rightarrow w_m = w$ , we say  $w' < w$ . The resulting relation  $w' \leq w$  is called **Bruhat ordering**, denoted by  $\text{Br}(W)$ .

**Lemma 1.31.** [Hum92, Section 5.9] *Let  $(W, S)$  be a Coxeter system. Then  $\text{Br}(W)$  is a poset.*

*Proof.* The Bruhat ordering is reflexive by definition. Since the elements in sequences  $e \rightarrow w_1 \rightarrow w_2 \rightarrow \dots$  are strictly ascending in length, it must be antisymmetric. By concatenation of sequences we get the transitivity.  $\square$

We now show, that  $\text{Br}(W)$  is graded. By definition we already have  $v < w$  iff  $l(v) < l(w)$ , but its not that obvious that two immediately adjacent elements differ in length by exactly 1. Beforehand let us just mention two other partial orderings that are graded by definition:

**Definition 1.32.** Let  $(W, S)$  be a Coxeter system. The ordering  $\leq_R$  defined by  $u \leq_R w$  iff  $uw = w$  for some  $u \in W$  with  $l(u) + l(v) = l(w)$  is called the **right weak ordering**. The left-sided version  $u \leq_L w$  iff  $vu = w$  is called the **left weak ordering**.

To ensure the Bruhat ordering is graded as well, we need another characterization of the Bruhat ordering in terms of subexpressions.

**Proposition 1.33.** [Hum92, Proposition 5.9] *Let  $(W, S)$  be a Coxeter system,  $u, w \in W$  with  $u \leq w$  and  $s \in S$ . Then  $us \leq w$  or  $us \leq ws$  or both.*

*Proof.* We can reduce the proof to the case  $u \rightarrow w$ , i.e.  $ut = w$  for a  $t \in T$  with  $l(v) < l(u)$ . Let  $s = t$ . Then  $us \leq w$  and we are done. In case  $s \neq t$  there are two alternatives for the lengths. We can have  $l(us) = l(u) - 1$  which would mean  $us \rightarrow u \rightarrow w$ , so  $us \leq w$ . So assume  $l(us) = l(u) + 1$ . For the reflection  $t' = sts$  we get  $(us)t' = ussts = uts = ws$ . So we have  $us \leq ws$  iff  $l(us) < l(ws)$ . Suppose this is not the case. Since we have assumed  $l(us) = l(u) + 1$  any reduced expression  $u = s_1 \dots s_r$  for  $u$  yields a reduced expression  $us = s_1 \dots s_r s$  for  $us$ . With the Strong Exchange Condition we can obtain  $ws = ust'$  from  $us$  by omitting one factor. This omitted factor cannot be  $s$  since  $s \neq t$ . This means  $ws = s_1 \dots \hat{s}_i \dots s_r s$  and so  $ws = s_1 \dots \hat{s}_i \dots s_r$ , contradicting to our assumption  $l(u) < l(w)$ .  $\square$

**Theorem 1.34** (Subword property). [Hum92, Theorem 5.10] *Let  $(W, S)$  be a Coxeter system and  $w \in W$  with a fixed, but arbitrary, reduced expression  $w = s_1 \dots s_r$ ,  $s_i \in S$ . Then  $u \leq w$  (in the Bruhat ordering) iff  $u$  can be obtained as a subexpression of this reduced expression.*

*Proof.* First we show that any  $w' < w$  occurs as a subexpression. For that we start with the case  $w' \rightarrow w$ , say  $w't = w$ . We have  $l(w') < l(w)$  and hence by Strong Exchange Condition we get

$$w' = w'tt = wt = s_1 \dots \hat{s}_i \dots s_r$$

for some  $i$ . This step can be iterated. In return, suppose we have a subexpression  $w' = s_{i_1} \cdots s_{i_q}$ . We induce on  $r = l(w)$ . For  $r = 0$  we have  $w = e$ , hence  $w' = e$ , too and so  $w' \leq w$ . Now suppose  $r > 0$ . If  $i_q < r$ , then  $s_{i_1} \cdots s_{i_q}$  is a subexpression of  $ws_r = s_1 \cdots s_{r-1}$ , too. Since  $l(ws_r) = r - 1 < r$ , we can conclude

$$s_{i_1} \cdots s_{i_q} \leq s_1 \cdots s_{r-1} = ws_r < w$$

by induction hypothesis. If  $i_q = r$ , then we use our induction hypothesis to get  $s_{i_1} \cdots s_{i_{q-1}} \leq s_1 \cdots s_{r-1}$ . By Proposition 1.33 we get

$$s_{i_1} \cdots s_{i_q} \leq s_1 \cdots s_{r-1} < w$$

or

$$s_{i_1} \cdots s_{i_q} \leq s_1 \cdots s_r = w,$$

both finishing our induction.  $\square$

**Corollary 1.35.** *Let  $u, w \in W$ . Then the interval  $[u, w]$  in the Bruhat order  $\text{Br}(W)$  is finite.*

*Proof.* We have  $[u, w] \subseteq [e, w]$ . All elements  $v \in [e, w]$  can be obtained as subexpressions of one fixed reduced expression for  $w$ . Let  $s_1 \dots s_k = w$  be such a reduced expression. Then there are at most  $2^k$  many subexpressions, hence  $[u, w]$  is finite.  $\square$

This characterization of the Bruhat ordering is very handy. With it and the following short lemma we will be in the position to show that  $\text{Br}(W)$  is graded with rank function  $l$ .

**Lemma 1.36.** [Hum92, Lemma 5.11] *Let  $(W, S)$  be a Coxeter system,  $u, w \in W$  with  $u < w$  and  $l(w) = l(u) + 1$ . In case there is a generator  $s \in S$  with  $u < us$  but  $us \neq w$ , then both  $w < ws$  and  $us < ws$ .*

*Proof.* Due to Proposition 1.33 we have  $us \leq w$  or  $us \leq ws$ . Since  $l(us) = l(w)$  and  $us \neq w$  the first case is impossible. So  $us \leq ws$  and because of  $u \neq w$  already  $us < ws$ . In turn,  $l(w) = l(us) < l(ws)$ , forcing  $w < ws$ .  $\square$

**Proposition 1.37.** [Hum92, Proposition 5.11] *Let  $(W, S)$  be a Coxeter system and  $u < w$ . Then there are elements  $w_0, \dots, w_m \in W$  such that  $u = w_0 < w_1 < \dots < w_m = w$  with  $l(w_i) = l(w_{i-1}) + 1$  for  $1 \leq i \leq m$ .*

*Proof.* We induce on  $r = l(u) + l(w)$ . In case  $r = 1$  we have  $u = e$  and  $w = s$  for a  $s \in S$  and are done. Conversely suppose  $r > 1$ . Then there is a reduced expression  $w = s_1 \cdots s_r$  for  $w$ . Let us fix this expression. Then  $l(ws_r) < l(w)$ . Thanks to Subword property there must be a subexpression of  $w$  with  $u = s_{i_1} \cdots s_{i_q}$  for some  $i_1 < \dots < i_q$ . We distinguish between two cases:

$u < us$ : If  $i_q = r$ , then  $us = s_{i_1} \cdots s_{i_q} s = s_{i_1} \cdots s_{i_{q-1}}$  which is also a subexpression of  $ws$ . This yields  $u < us \leq ws < w$ . Since  $l(ws) < r$  there is, by induction, a sequence of the desired form. The last step from  $ws$  to  $w$  also differs in length by exactly 1, so we are done. If  $i_q < r$  then  $u$  is itself already a subexpression of

$ws$  and we can again find a sequence from  $u$  to  $ws$  strictly ascending in length by 1 in each step and have one last step from  $ws$  to  $w$  also increasing in length by 1.

$us < u$ : Then by induction we can find a sequence from  $us$  to  $w$ , say  $us = w_0 < \dots < w_m = w$ , where the lengths of neighbored elements differ by exactly 1. Since  $w_0s = u > us = w_0$  and  $w_ms = ws < w = w_m$  there must be a smallest index  $i \geq 1$ , such that  $w_is < w_i$ , which we choose. Suppose  $w_i \neq w_{i-1}s$ . We have  $w_{i-1} < w_{i-1}s \neq w_i$  and due to Lemma 1.36 we get  $w_i < w_is$ . This contradicts to the minimality of  $i$ . So  $w_i = w_{i-1}s$ . For all  $1 \leq j < i$  we have  $w_j \neq w_{j-1}s$ , because of  $w_j < w_js$ . Again we apply Lemma 1.36 to receive  $w_{j-1}s < w_js$ . Altogether we can construct a sequence

$$u = w_0s < w_1s < \dots < w_{i-1}s = w_i < w_{i+1} < \dots < w_m = w,$$

which matches our assumption.  $\square$

**Corollary 1.38.** *Let  $(W, S)$  be a Coxeter system and  $\text{Br}(W)$  the Bruhat ordering poset of  $W$ . Then  $\text{Br}(W)$  is graded with  $l : W \rightarrow \mathbb{N}$  as rank function.*

*Proof.* Let  $u, w \in W$  with  $w$  covering  $u$ . Then Proposition 1.37 says there is a sequence  $u = w_0 < \dots < w_m = w$  with  $l(w_i) = l(w_{i-1}) + 1$  for  $1 \leq i \leq m$ . Since  $w$  covers  $u$  it must be  $m = 1$  and so  $u < w$  with  $l(w) = l(u) + 1$ .  $\square$

**Theorem 1.39** (Lifting Property). [Deo77, Theorem 1.1] *Let  $(W, S)$  be a Coxeter system and  $v, w \in W$  with  $v \leq w$ . Suppose  $s \in S$  with  $s \in D_R(w)$ . Then*

1.  $vs \leq w$ ,
2.  $s \in D_R(v) \Rightarrow vs \leq ws$ .

*Proof.* We use the alternative subexpression characterization of the Bruhat ordering from Subword property.

1. Since  $s \in D_R(w)$  there exists a reduced expression  $w = s_1 \cdots s_r$  with  $s_r = s$ . Due to  $v \leq w$  we can obtain  $v$  as a subexpression  $v = s_{i_1} \cdots s_{i_q}$  from  $w$ . If  $i_q = r$  then  $vs = s_{i_1} \cdots s_{i_q}s = s_{i_1} \cdots s_{i_{q-1}}$  is also a subexpression of  $w$ . Else if  $i_q \neq r$ , then  $v$  is a subexpression of  $ws = s_1 \cdots s_{r-1}$  and so  $vs$  is again a subexpression of  $w = s_1 \cdots s_{r-1}s$ . In both cases we get  $vs \leq w$ .
2. If we additionally assume  $s \in D_R(v)$  then we can always find a reduced expression  $w = s_1 \cdots s_r$  with  $s_r = s$  having  $u = s_{i_1} \cdots s_{i_q}$  as subexpression with  $s_{i_q} = s$ . This yields  $vs = s_{i_1} \cdots s_{i_{q-1}} \leq s_1 \cdots s_{r-1} = ws$ .  $\square$

*Remark 1.40.* Note that the Lifting Property has an analogue left-sided version: Let  $(W, S)$  be a Coxeter system and  $v, w \in W$  with  $v \leq w$ . Suppose  $s \in S$  with  $s \in D_L(w)$ . Then

1.  $sv \leq w$ ,
2.  $s \in D_L(v) \Rightarrow sv \leq sw$ .

The Lifting Property seems quite innocent, but when trying to investigate facts around the Bruhat ordering it proves to be one of the key tools in many cases.

**Proposition 1.41.** [Den09, Proposition 7] *The poset  $\text{Br}(W)$  is directed.*

*Proof.* Let  $u, v \in W$ . We need to find an element  $w \in W$  with  $u \leq w$  and  $v \leq w$ . For that, we induce on  $r = l(u) + l(w)$ . For  $r = 0$  we have  $u = v = e$  and can choose  $w = e$ . So let  $r > 0$ . Because of symmetry we can assume  $l(u) > 0$ , hence  $u \neq e$  and so there is a  $s \in S$  with  $us < u$ . By induction hypothesis there is a  $w \in W$  with  $us \leq w$  and  $v \leq w$ . Consider two cases:

$ws < w$ : Then  $s \in D_R(w)$  and with Lifting Property we have  $u = uss \leq w$ , so both  $u \leq w$  and  $v \leq w$ .

$ws > w$ : Then  $s \in D_R(ws)$  and  $us \leq w < ws$ , hence again by Lifting Property we have  $u = uss \leq ws$ , so both  $u \leq ws$  and  $v \leq w < ws$ .  $\square$

**Corollary 1.42.** [Den09, Proposition 8]

1. *Let  $W$  be finite, then there exists a unique element  $w_0 \in W$  with  $w \leq w_0$  for all  $w \in W$ .*
2. *If  $W$  contains an element  $w$ , with  $D_R(w) = S$ , then  $W$  is finite and  $w$  is the unique element  $w_0$ .*

*Proof.* 1. Assume there are two elements  $u, v \in W$  of maximal rank. Since  $\text{Br}(W)$  is directed, there is an element  $w \in W$  with  $u \leq w$  and  $v \leq w$ . Because  $\text{Br}(W)$  is graded, we have  $l(w) > l(u) = l(v)$ , contradicting to the maximality of  $u$  and  $v$ .

2. We want to show, that  $v < w$  for all  $v \in W$ . For that, we induce on  $r = l(v)$ . If  $r = 0$ , then  $v = e \leq w$ . Let  $r > 0$ . Then there is a  $s \in S$  with  $us < u$ . By induction,  $us \leq w$ . Since  $s \in D_R(w)$ , we have  $uss = u \leq w$  by Lifting Property and are done with our induction. This yields  $W = [e, w]$  and since by Corollary 1.35 intervals in the Bruhat order are finite,  $W$  is finite, too.  $\square$

**Corollary 1.43.** *Let  $(W, S)$  be a finite Coxeter system. Then  $\text{Br}(W)$  is graded, directed and bounded.*

*Proof.*  $\text{Br}(W)$  is graded due to Corollary 1.38, directed due to Proposition 1.41 and bounded due to Corollary 1.42.  $\square$

**Corollary 1.44.** *Let  $(W, S)$  be a Coxeter system and  $w, v \in W$  with  $w < v$ . Then the interval  $[w, v]$  is a finite, graded, directed and bounded poset.*

*Proof.* The poset structure and the graduation transfers directly from  $\text{Br}(W)$ . By Corollary 1.35 intervals in  $\text{Br}(W)$  are finite. Since  $v$  is the unique maximal element and  $w$  the unique minimal element, it is bounded. By definition of intervals we have  $u \leq v$  for every element  $u \in [w, v]$ , hence it is directed.  $\square$



## 2. Twisted involutions in Coxeter groups

In this section we focus on a certain subset of elements in Coxeter groups, the so called twisted involutions. From now on (and in the next sections) we fix some symbols to have always the same meaning (some needed definitions follow later):

- $(W, S)$  A Coxeter system with generators  $S$  and Coxeter group  $W$ .
- $s$  A generator in  $S$ .
- $u, v, w$  A element in the Coxeter group  $W$ .
- $\theta$  A Coxeter system automorphism of  $(W, S)$  with  $\theta^2 = \text{id}$ .
- $\mathcal{I}_\theta$  The set of  $\theta$ -twisted involutions of  $W$ .
- $\underline{S}$  A set of symbols,  $\underline{S} = \{\underline{s} : s \in S\}$ .

### 2.1. Introduction to twisted involutions

Twisted involutions generalize the property of being involutive with respect to an involutory automorphism  $\theta$ . For  $\theta = \text{id}$  the set of  $\theta$ -twisted involutions, denoted by  $\mathcal{I}_\theta$  coincides with the set of ordinary involutions in  $W$  (cf. Example 2.3). As we will see the set of this  $\theta$ -twisted involutions equals the  $e$ -orbit of a special action, defined in Definition 2.5. For  $\mathcal{I}_\theta$  and the mentioned map many properties of ordinary Coxeter groups hold. In particular there is a analogue to the Exchange Condition and Deletion Condition.

**Definition 2.1.** An automorphism  $\theta : W \rightarrow W$  with  $\theta(S) = S$  is called a **Coxeter system automorphism** of  $(W, S)$ . We always assume  $\theta^2 = \text{id}$ .

**Definition 2.2.** We define the **set of  $\theta$ -twisted involutions** of  $W$  as

$$\mathcal{I}_\theta(W) := \{w \in W : \theta(w) = w^{-1}\}.$$

If  $\theta$  is clear from the context we just say **set of twisted involutions**. Every element  $w \in \mathcal{I}_\theta(W)$  is called a  **$\theta$ -twisted involution**, resp. **twisted involution**. Often, when  $W$  is clear from the context, we will omit it and just write  $\mathcal{I}_\theta$ .

**Example 2.3.** Let  $\theta = \text{id}_W$ . Then  $\theta$  is a Coxeter system automorphism and the set of all id-twisted involutions coincides with the set of all ordinary involutions of  $W$ .

The next example is more helpfull, since it reveals a way to think of  $\mathcal{I}_\theta$  as a generalization of ordinary Coxeter groups.

**Example 2.4.** [Hul07, Example 3.2] Let  $\theta$  be an automorphism of  $W \times W$  with  $\theta : (u, w) \mapsto (w, u)$ . Then  $\theta$  is a Coxeter system automorphism of the Coxeter system  $(W \times W, S \times S)$  and the set of twisted involutions is

$$\mathcal{I}_\theta = \{(w, w^{-1}) \in W \times W : w \in W\}.$$

This yields a canonical bijection between  $\mathcal{I}_\theta$  and  $W$ .

The map we define right now is of great importance to this whole paper, since it is needed to define the poset, the main thesis is about.

**Definition 2.5.** Let  $\underline{S} := \{\underline{s} : s \in S\}$  be a set of symbols. Each element in  $\underline{S}$  acts from the right on  $W$  by the following definition:

$$w\underline{s} = \begin{cases} ws & \text{if } \theta(s)ws = w, \\ \theta(s)ws & \text{else.} \end{cases}$$

This action can be extended on the whole free monoid over  $\underline{S}$  by

$$w\underline{s}_1\underline{s}_2 \dots \underline{s}_k = (\dots((w\underline{s}_1)\underline{s}_2) \dots)\underline{s}_k.$$

If  $w\underline{s} = \theta(s)ws$ , then we say  $\underline{s}$  **acts by twisted conjugation** on  $w$ . Else we say  $\underline{s}$  **acts by multiplication** on  $w$ .

Note that this is no group action. For example let  $W$  be a Coxeter group with two generators  $s, t$  satisfying  $\text{ord}(st) = 3$  and let  $\theta = \text{id}$ . Then  $sts = tst$ , but

$$e\underline{sts} = \underline{sts} = t\underline{sts} = st\underline{st} = t \neq s = t\underline{stt} = st\underline{st} = \underline{tst} = e\underline{tst}.$$

**Definition 2.6.** Let  $k \in \mathbb{N}$  and  $s_i \in S$  for all  $1 \leq i \leq k$ . Then an expression  $e\underline{s}_1 \dots \underline{s}_k$ , or just  $\underline{s}_1 \dots \underline{s}_k$ , is called  **$\theta$ -twisted expression**. If  $\theta$  is clear from the context, we omit  $\theta$  and call it **twisted expression**. A twisted expression is called **reduced twisted expression** if there is no  $k' < k$  with  $\underline{s}'_1 \dots \underline{s}'_{k'} = \underline{s}_1 \dots \underline{s}_k$ .

**Lemma 2.7.** [Hul07, Lemma 3.4] Let  $w \in \mathcal{I}_\theta$  and  $s \in S$ . Then

$$w\underline{s} = \begin{cases} ws & \text{if } l(\theta(s)ws) = l(w), \\ \theta(s)ws & \text{else.} \end{cases}$$

*Proof.* Suppose  $\underline{s}$  acts by multiplication on  $w$ . Then  $\theta(s)ws = w$  and so  $l(\theta(s)ws) = l(w)$ . Conversely, suppose  $l(\theta(s)ws) = l(w)$ . If  $w\underline{s} = ws$ , then we are done. So assume  $\theta(s)ws \neq w$ . Then  $w$  must have a reduced expression beginning with  $\theta(s)$  or ending with  $s$  (else, we could not have  $l(\theta(s)ws) = l(w)$ ). Without loss of generality suppose that  $\theta(s)s_1 \dots s_k$  is such an expression for  $w$ . Since  $w$  is a  $\theta$ -twisted involution, i.e.  $\theta(w) = w^{-1}$ , we have  $l(ws) < l(w)$ . Since  $l(\theta(s)ws) = l(w)$ , no reduced expression for  $w$  both begins with  $\theta(s)$  and ends with  $s$  and hence Exchange Condition yields  $ws = s_1 \dots s_k$ , which implies  $\theta(s)ws = w$ , contradicting to our assumption.  $\square$

**Lemma 2.8.** We have  $l(ws) < l(w)$  iff  $l(w\underline{s}) < l(w)$ .

*Proof.* Suppose  $\underline{s}$  acts by multiplication on  $w$ . Then  $w\underline{s} = ws$  and there is nothing to prove. So suppose  $\underline{s}$  acts by twisted conjugation on  $w$ . If  $l(ws) < l(w)$ , then Lemma 1.13 yields  $l(ws) + 1 = l(w)$ . Assuming  $l(w\underline{s}) = l(\theta(s)ws) = l(w)$  would imply, that  $\underline{s}$  acts by multiplication on  $w$  due to Lemma 2.7, which is a contradiction. So  $l(w\underline{s}) = l(\theta(s)ws) < l(w)$ . Conversely, suppose  $l(w\underline{s}) < l(w)$ . Then Lemma 1.13 says  $l(w\underline{s}) = l(\theta(s)ws) = l(w) - 2$  and so  $l(ws) = l(w) - 1$ .  $\square$

**Lemma 2.9.** *For all  $w \in W$  and  $s \in S$  we have  $w\underline{s}\underline{s} = w$ .*

*Proof.* For  $w\underline{s}$  there are two cases. Suppose  $\underline{s}$  acts by multiplication on  $w$ , i.e.  $\theta(s)ws = w$ . For  $w\underline{s}\underline{s}$  there are again two possible options:

$$w\underline{s}\underline{s} = \begin{cases} wss = w & \text{if } \theta(s)wss = ws, \\ \theta(s)wss = ws & \text{else.} \end{cases}$$

The second option contradicts itself.

Now suppose  $\underline{s}$  acts by twisted conjugation on  $w$ . This means  $\theta(s)ws \neq w$  and for  $(\theta(s)ws)\underline{s}$  there are again two possible options:

$$(\theta(s)ws)\underline{s} = \begin{cases} \theta(s)wss = \theta(s)w & \text{if } \theta(s)\theta(s)wss = \theta(s)ws, \\ \theta(s)\theta(s)wss = w & \text{else.} \end{cases}$$

The first option is impossible since  $\theta(s)\theta(s)wss = w$  and we have assumed  $\theta(s)ws \neq w$ . Hence the only possible cases yield  $w\underline{s}\underline{s} = w$ .  $\square$

*Remark 2.10.* Lemma 2.9 allows us to rewrite equations of twisted expressions. For example

$$u = w\underline{s} \iff u\underline{s} = w\underline{s}\underline{s} = w.$$

This can be iterated to get

$$u = w\underline{s}_1 \dots \underline{s}_k \iff u\underline{s}_k \dots \underline{s}_1 = w.$$

**Lemma 2.11.** *For all  $\theta$ ,  $w \in W$  and  $s \in S$  it holds that  $w \in \mathcal{I}_\theta$  iff  $w\underline{s} \in \mathcal{I}_\theta$ .*

*Proof.* Let  $w \in \mathcal{I}_\theta$ . For  $w\underline{s}$  there are two cases. Suppose  $\underline{s}$  acts by multiplication on  $w$ . Then we get

$$\theta(ws) = \theta(\theta(s)wss) = \theta^2(s)\theta(w) = sw^{-1} = (ws^{-1})^{-1} = (ws)^{-1}.$$

Suppose  $\underline{s}$  acts by twisted conjugation on  $w$ . Then we get

$$\theta(\theta(s)ws) = \theta^2(s)\theta(w)\theta(s) = sw^{-1}\theta(s) = (\theta^{-1}(s)ws^{-1})^{-1} = (\theta(s)ws)^{-1}.$$

In both cases  $w\underline{s} \in \mathcal{I}_\theta$ .

Now let  $w\underline{s} \in \mathcal{I}_\theta$ . Suppose  $\underline{s}$  acts by multiplication on  $w$ . Then

$$\theta(w) = \theta(\theta(s)ws) = \theta^2(s)\theta(ws) = s(ws)^{-1} = ss^{-1}w^{-1} = w^{-1}.$$

Suppose  $\underline{s}$  acts by twisted conjugation on  $w$ . Then

$$\begin{aligned} \theta(w) &= \theta(\theta(s)\theta(s)wss) = \theta^2(s)\theta(\theta(s)ws)\theta(s) \\ &= s(\theta(s)ws)^{-1}\theta(s) = s(s^{-1}w^{-1}\theta(s^{-1})\theta(s)) = w^{-1}. \end{aligned}$$

In both cases  $w \in \mathcal{I}_\theta$ .  $\square$

A remarkable property of the action from Definition 2.5 is its  $e$ -orbit. As the following lemma shows, it coincides with  $\mathcal{I}_\theta$ .

**Lemma 2.12.** [Hul07, Proposition 3.5] *The set of  $\theta$ -twisted involutions coincides with the set of all  $\theta$ -twisted expressions.*

*Proof.* By Lemma 2.11, each twisted expression is in  $\mathcal{I}_\theta$ , since  $e \in \mathcal{I}_\theta$ . So let  $w \in \mathcal{I}_\theta$ . If  $l(w) = 0$ , then  $w = e \in \mathcal{I}_\theta$ . So assume  $l(w) = r > 0$  and that we have already proven, that every twisted involution  $w' \in \mathcal{I}_\theta$  with  $\rho(w') < r$  has a twisted expression. If  $w$  has a reduced twisted expression ending with  $\underline{s}$ , then  $w$  also has a reduced expression (in  $S$ ) ending with  $s$  and so  $l(ws) < l(w)$ . With Lemma 2.8 we get  $l(w\underline{s}) < l(w)$ . By induction  $w\underline{s}$  has a twisted expression and hence  $w = (w\underline{s})\underline{s}$  has one, too.  $\square$

In the same way, we can use regular expressions to define the length of an element  $w \in W$ , we can use the twisted expressions to define the twisted length of an element  $w \in \mathcal{I}_\theta$ .

**Definition 2.13.** Let  $\mathcal{I}_\theta$  be the set of twisted involutions. Then we define  $\rho(w)$  as the smallest  $k \in \mathbb{N}$  for that a twisted expression  $w = \underline{s}_1 \dots \underline{s}_k$  exists. This is called the **twisted length** of  $w$ .

**Lemma 2.14.** [Hul05, Theorem 4.8] *The Bruhat ordering, restricted to the set of twisted involutions  $\mathcal{I}_\theta$ , is a graded poset with  $\rho$  as rank function. We denote this poset by  $\text{Br}(\mathcal{I}_\theta)$ .*

We now establish many properties from ordinary Coxeter groups for twisted expressions and  $\text{Br}(\mathcal{I}_\theta)$ . As seen in Example 2.4 there is a Coxeter system  $(W', S')$  and an Coxeter system automorphism  $\theta$  with  $\text{Br}(W) \cong \text{Br}(\mathcal{I}_\theta(W'))$ . So the hope that many properties can be transferred is eligible.

**Lemma 2.15.** [Hul07, Lemma 3.8] *Let  $w \in \mathcal{I}_\theta$  and  $s \in S$ . Then  $\rho(w\underline{s}) = \rho(w) \pm 1$ . In fact it is  $\rho(w\underline{s}) = \rho(w) - 1$  iff  $s \in D_R(w)$ .*

*Proof.* Since  $\text{Br}(\mathcal{I}_\theta)$  is graded with rank function  $\rho$  and either  $w\underline{s}$  covers  $w$  or  $w$  covers  $w\underline{s}$  we have  $\rho(w\underline{s}) = \rho(w) \pm 1$ . Now suppose  $w\underline{s} < w$ . Then we have  $\rho(w\underline{s}) < \rho(w)$  iff  $w\underline{s} < w$  iff  $l(w\underline{s}) < l(w)$  iff  $l(ws) < l(w)$  iff  $s \in D_R(w)$ .  $\square$

**Lemma 2.16** (Lifting property 2). [Hul07, Lemma 3.9] *Let  $v, w \in W$  with  $v \leq w$ . Suppose  $s \in S$  with  $s \in D_R(w)$ . Then*

1.  $v\underline{s} \leq w$ ,
2.  $s \in D_R(v) \Rightarrow v\underline{s} \leq w\underline{s}$ .

*Proof.* Whenever a relation comes from the ordinary Lifting Property, we denote it by  $<_{LP}$  in this proof.

$v\underline{s} = vs \wedge w\underline{s} = ws$ : Same situation as in Lifting Property.

$v\underline{s} = vs \wedge w\underline{s} = \theta(s)ws$ : The first part  $v\underline{s} = vs \leq_{LP} w$  is immediate. Suppose  $s \in D_R(v)$ . Then  $vs \leq_{LP} ws \Rightarrow v = \theta(s)vs \leq ws \Rightarrow v\underline{s} = vs \leq \theta(s)ws = w\underline{s}$ .

$v\underline{s} = \theta(s)vs \wedge w\underline{s} = ws$ : We have  $\theta(s)w = ws$  and therefore  $\theta(s) \in D_L(w)$ . Suppose  $s \in D_R(v)$ . Then  $\theta(s) \in D_R(vs)$  and hence  $v\underline{s} = \theta(s)vs \leq vs \leq_{LP} ws = w\underline{s} \leq w$ . In return suppose  $s \notin D_R(v)$ . Since  $vs \leq_{LP} w$  and  $\theta(s) \in D_L(w)$  we can apply the left analogue of Lifting Property on  $vs, w, \theta(s)$  to get  $v\underline{s} = \theta(s)vs \leq_{LP} w$ .

$v\underline{s} = \theta(s)vs \wedge w\underline{s} = \theta(s)ws$ : Let  $s \in D_R(w)$ . Then  $vs \leq_{LP} ws$ . Since  $\theta(s) \in D_L(vs)$  and  $\theta(s) \in D_L(ws)$  we can apply the left-sided Lifting Property to get  $v\underline{s} = \theta(s)vs \leq_{LP} \theta(s)ws = w\underline{s} \leq w$ . In return let  $s \notin D_R(w)$ . Since  $l(\theta(s)ws) = l(w) - 2$  we have  $\theta(s) \in D_L(w)$ . So we can use the Lifting Property to get  $vs \leq_{LP} w$  and then with the left-sided Lifting Property  $v\underline{s} = \theta(s)vs \leq_{LP} w$ .  $\square$

**Proposition 2.17** (Exchange property for twisted expressions). [Hul07, Proposition 3.10] *Suppose  $\underline{s}_1 \dots \underline{s}_k$  is a reduced twisted expression. If  $\rho(\underline{s}_1 \dots \underline{s}_k \underline{s}) < k$  for some  $s \in S$ , then  $\underline{s}_1 \dots \underline{s}_k \underline{s} = \underline{s}_1 \dots \hat{\underline{s}}_i \dots \underline{s}_k$  for some  $i \in \{1, \dots, k\}$ .*

*Proof.* Let  $w = \underline{s}_1 \dots \underline{s}_k$  and  $v = \underline{s}_1 \dots \underline{s}_k \underline{s}$ . Assume  $v\underline{s}_k \dots \underline{s}_{i+1} \underline{s}_i < v\underline{s}_k \dots \underline{s}_{i+1}$  for all  $i$ . Then we would get  $\rho(v\underline{s}_k \dots \underline{s}_1) < k - k = 0$ . Hence there is an index  $i$  with  $v\underline{s}_k \dots \underline{s}_{i+1} \underline{s}_i > v\underline{s}_k \dots \underline{s}_{i+1}$  and we choose  $i$  maximal with this property. Since  $w > v$  we conclude by repetition of Lifting property 2, that  $w\underline{s}_k \dots \underline{s}_{i+1} \geq v\underline{s}_k \dots \underline{s}_i$ . By Lemma 2.15 we have  $\rho(v) = k - 1$  and so  $\rho(w\underline{s}_k \dots \underline{s}_{i+1}) = \rho(v\underline{s}_k \dots \underline{s}_i)$ . Because  $\text{Br}(\mathcal{I}_\theta)$  is graded with rank function  $\rho$ , both twisted expressions must represent the same element. Therefore we have  $w\underline{s}_k \dots \underline{s}_{i+1} = v\underline{s}_k \dots \underline{s}_i$  yielding  $v = w\underline{s}_k \dots \underline{s}_{i+1} \underline{s}_i \dots \underline{s}_k = \underline{s}_1 \dots \hat{\underline{s}}_i \dots \underline{s}_k$ .  $\square$

**Proposition 2.18** (Deletion property for twisted expressions). [Hul07, Proposition 3.11] *Let  $w = \underline{s}_1 \dots \underline{s}_k$  be a not reduced twisted expression. Then there are two indices  $1 \leq i < j \leq k$  such that  $w = \underline{s}_1 \dots \hat{\underline{s}}_i \dots \hat{\underline{s}}_j \dots \underline{s}_k$ .*

*Proof.* Choose  $j$  minimal, so we have  $\underline{s}_1 \dots \underline{s}_j$  is not reduced. By Exchange property for twisted expressions there is an index  $i$  with  $\underline{s}_1 \dots \underline{s}_j = \underline{s}_1 \dots \hat{\underline{s}}_i \dots \underline{s}_{j-1}$  yielding our hypothesis  $w = \underline{s}_1 \dots \underline{s}_j \dots \underline{s}_k = \underline{s}_1 \dots \hat{\underline{s}}_i \dots \hat{\underline{s}}_j \dots \underline{s}_k$ .  $\square$

When applying the Exchange property for twisted expressions to a twisted expression, there is no hint which  $\underline{s}_i$  can be omitted. Consider the following situation: Let  $w \in \mathcal{I}_\theta$  and  $w\underline{s}_1 \dots \underline{s}_k = w\underline{t}_1 \dots \underline{t}_k$  two reduced twisted expressions. Then in the twisted expression  $w\underline{s}_1 \dots \underline{s}_k \underline{t}_k$  we can omit the  $\underline{t}_k$  and one other  $\underline{s}$  by Exchange property for twisted expressions and get still the same element. It would be nice, when the second omitted  $\underline{s}$  is one of the  $\underline{s}_i$  in general, but unfortunately this proves to be false:

**Example 2.19.** Let  $W = A_3$ ,  $\theta = \text{id}$  and  $w = \underline{s}_3$ . Then  $w\underline{s}_2 \underline{s}_1 \underline{s}_2 = w\underline{s}_1 \underline{s}_2 \underline{s}_3$ , but  $w\underline{s}_1 \underline{s}_2 \underline{s}_3 \underline{s}_2 \notin \{w\underline{s}_1 \underline{s}_2, w\underline{s}_1 \underline{s}_3, w\underline{s}_2 \underline{s}_3\}$ . Hence the omission cannot be chosen after the prefix  $w$ , but at least  $w\underline{s}_1 \underline{s}_2 \underline{s}_3 \underline{s}_2 = \underline{s}_1 \underline{s}_2 \underline{s}_3$  works, as guaranteed by Exchange property for twisted expressions.

## 2.2. Twisted weak ordering

In this section we introduce the twisted weak ordering  $Wk(\theta)$  on the set  $\mathcal{I}_\theta$  of  $\theta$ -twisted involutions.

**Definition 2.20.** For  $v, w \in \mathcal{I}_\theta$  we define  $v \preceq w$  iff there are  $\underline{s}_1, \dots, \underline{s}_k \in \underline{S}$  with  $w = v\underline{s}_1 \dots \underline{s}_k$  and  $\rho(v) = \rho(w) - k$ . We call the poset  $(\mathcal{I}_\theta, \preceq)$  **twisted weak ordering**, denoted by  $Wk(W, \theta)$ . When the Coxeter group  $W$  is clear from the context, we just write  $Wk(\theta)$ .

**Lemma 2.21.** *The poset  $Wk(\theta)$  is a graded poset with rank function  $\rho$ .*

*Proof.* Follows immediately from the definition of  $\preceq$ .  $\square$

By a diagram of a poset  $Wk(\theta)$ , we do not just mean the ordinary Hasse diagram. Suppose  $w, v \in Wk(\theta)$  with  $w\underline{s} = v$ . We encode the information if  $\underline{s}$  acts as twisted involution or as multiplication on  $w$  by drawing either a solid or a dashed edge from  $w$  to  $v$ . Another possible extension is to label (or color) the edges to encode the involved  $\underline{s}$ . For simplification of terminology we still just speak of the Hasse diagram of  $Wk(\theta)$ . The next example shows such a (extended) Hasse diagram.

**Example 2.22.** In Figure 2.1 we see the (extended) Hasse diagram of  $Wk(A_4, \text{id})$ .

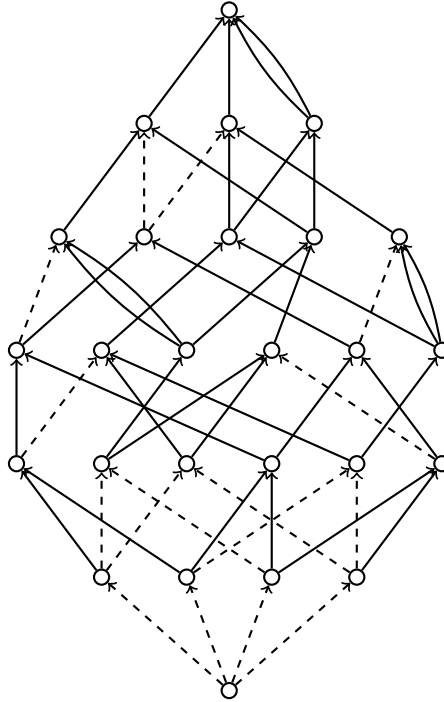


Figure 2.1.: Hasse diagram of  $Wk(A_4, \text{id})$

**Lemma 2.23.** *The poset  $Wk(\theta)$  is a subposet of  $\text{Br}(\mathcal{I}_\theta)$ .*

*Proof.* Both posets are defined on  $\mathcal{I}_\theta$ . Let  $w, v \in \mathcal{I}_\theta$  be two twisted involutions. Assume  $w \preceq v$  with  $w\underline{s} = v$  for some  $s \in S$ . If  $\underline{s}$  acts by multiplication on  $w$ , then

$ws = v$  and since  $s \in T$  ( $T$  the set of all reflections in  $W$ ) and  $l(w\underline{s}) = l(w) + 1$  we have  $w \leq v$ . If conversely  $\underline{s}$  acts by twisted conjugation on  $w$ , then  $v = \theta(s)ws = w(w^{-1}\theta(s)w)(e^{-1}se)$  and since  $w^{-1}\theta(s)w, s \in T$  and  $l(w\underline{s}) = l(\theta(s)w) + 1 = l(w) + 2$  we have again  $w \leq v$ .  $\square$

**Proposition 2.24.** *For all  $w \in \mathcal{I}_\theta$  and  $s \in S$  we have  $w\underline{s} \prec w$  iff  $s \in D_R(w)$  and  $w\underline{s} \succ w$  iff  $s \notin D_R(w)$  as well as  $w\underline{s} < w$  iff  $s \in D_R(w)$  and  $w\underline{s} > w$  iff  $s \notin D_R(w)$ .*

*Proof.* We have  $w\underline{ss} = w$  and  $\rho(w\underline{s}) = \rho(w) - 1$  iff  $s \in D_R(w)$  and  $\rho(w\underline{s}) = \rho(w) + 1$  iff  $s \notin D_R(w)$  by Lemma 2.15. By Lemma 2.23 both statements are true for  $\text{Br}(\mathcal{I}_\theta)$ , too.  $\square$

**Definition 2.25.** Let  $v, w \in W$  with  $\rho(w) - \rho(v) = n$ . A sequence  $v = w_0 \prec w_1 \prec \dots \prec w_n = w$  is called a **geodesic** from  $v$  to  $w$ .

**Proposition 2.26.** *Let  $v, w \in W$  with  $v \prec w$ . Then all geodesics from  $v$  to  $w$  have the same count of twisted conjugated and multiplicative steps.*

*Proof.* Suppose we have two geodesics from  $v$  to  $w$ , where the first has  $n$  and the second  $m$  multiplicative steps. Then  $l(w) + n + 2(k - n) = l(v) = l(w) + m + 2(k - m)$ , hence  $n = m$ .  $\square$

**Proposition 2.27.** *Let  $w \in W$  and  $w\underline{s} \succ w$ . Then  $|\{t \in S \setminus D_R(w) : w\underline{t} = w\underline{s}\}| \in \{1, 2\}$ .*

*Proof.* Suppose  $t \in S \setminus D_R(w)$  with  $w\underline{t} = w\underline{s}$ . Because of the ordinary length either both  $\underline{s}$  and  $\underline{t}$  act by multiplication on  $w$ , or both act by twisted conjugation on  $w$ . Suppose they act by multiplication, then  $ws = w\underline{s} = w\underline{t} = wt$ , hence  $s = t$ . Conversely, assume they act by twisted conjugation. Then  $\theta(s)ws = w\underline{s} = w\underline{t} = \theta(t)wt$ . Because of  $\theta(t)wtt = \theta(t)w = \theta(s)wst$  we have  $l(\theta(s)wst) < l(\theta(s)ws)$  and so by Exchange Condition there are three possible cases

$$\theta(t)w = \theta(s)wst = \begin{cases} \theta(s)w & \Rightarrow s = t, \\ ws & \Rightarrow \theta(t) = wsw^{-1} \text{ or} \\ \theta(s)\overline{w}s & \Rightarrow w = \theta(t)\theta(s)\overline{w}s, \end{cases}$$

where  $\overline{w}$  denotes a well chosen subexpression of  $w$ . The first case is trivial, the second determines  $t$  unambiguously. The third case is impossible, since by Exchange Condition and Remark 1.18 we would have a reduced expression for  $w$  beginning with  $\theta(s)$  or ending with  $s$  (or both), yielding  $l(\theta(s)ws) \leq l(w)$ , which contradicts to  $\rho(w\underline{s}) = \rho(\theta(s)ws) > \rho(w)$ . Therefore, there cannot be more than two distinct  $s, t \in S \setminus D_R(w)$  with  $w\underline{s} = w\underline{t}$ .  $\square$

**Corollary 2.28.** *Let  $w \in \mathcal{I}_\theta$  and  $s, t \in S$  be two distinct generators. If  $w\underline{s} = w\underline{t}$ , then  $\text{ord}(st) = 2$ .*

*Proof.* By the proof of Proposition 2.27 we see, that  $w\underline{s} = w\underline{t}$  for two distinct  $s, t \in S$  implies that  $\theta(t)w = ws$  holds and that  $\underline{s}$  and  $\underline{t}$  act by twisted conjugation on  $w$ . Since  $\theta(w) = w^{-1}$  we also have  $\theta(s)w = wt$  by

$$\theta(t)w = ws \iff \theta(\theta(t)w) = \theta(ws) \iff tw^{-1} = w^{-1}\theta(s) \iff wt = \theta(s)w.$$

Hence we have  $wts = \theta(s)ws = \theta(t)wt = wst$ , yielding  $st = ts$  and  $\text{ord}(st) = 2$ .  $\square$

### 2.3. Residues

Residues in  $Wk(\theta)$  are subsets of  $\theta$ -twisted involutions that can be "reached" from a fixed starting point by using just certain  $\underline{s} \in \underline{S}$  as the following definition specifies.

**Definition 2.29.** Let  $w \in \mathcal{I}_\theta$  and  $I \subseteq S$  be a subset of generators. Then we define

$$wC_I := \{w\underline{s}_1 \dots \underline{s}_k : k \in \mathbb{N}_0, s_i \in I\}$$

as the *I-residue* of  $w$  or just **residue**. To emphasize the size of  $I$ , say  $|I| = n$ , we also speak of a **rank- $n$ -residue**.

**Example 2.30.** Let  $w \in \mathcal{I}_\theta$ . Then  $wC_\emptyset = \{w\}$  and  $wC_S = \mathcal{I}_\theta$ .

**Lemma 2.31.** Let  $w \in \mathcal{I}_\theta$  and  $I \subset S$ . If  $v \in wC_I$ , then  $vC_I = wC_I$ .

*Proof.* Suppose  $v \in wC_I$ . Then  $v = w\underline{s}_1 \dots \underline{s}_n$  for some  $s_i \in I$ . Suppose  $u = wt_1 \dots t_m \in wC_I$  is any other element in  $wC_I$  with  $t_i \in I$ . Then

$$u = wt_1 \dots t_m = (v\underline{s}_n \dots \underline{s}_1)t_1 \dots t_m$$

and so  $u \in vC_I$ . This yields  $wC_I \subset vC_I$ . Since  $w \in vC_I$  we can swap  $v$  and  $w$  to get the other inclusion.  $\square$

**Corollary 2.32.** Let  $v, w \in \mathcal{I}_\theta$  and  $I \subset S$ . Then either  $vC_I \cap wC_I = \emptyset$  or  $vC_I = wC_I$ .

*Proof.* Immediately follows from Lemma 2.31.  $\square$

**Proposition 2.33.** [Hul07, Lemma 5.6] Let  $w \in \mathcal{I}_\theta$ ,  $I \subseteq S$  be a set of generators. Then there exists a unique element  $w_0 \in wC_I$  with  $w_0 \preceq w_0\underline{s}$  for all  $s \in I$ .

*Proof.* Suppose there is no such element. Then for each  $w \in wC_I$  we can find a  $s \in I$  with  $w' = w\underline{s} \preceq w$  and  $e' \in wC_I$ . By repetition of Deletion property for twisted expressions we get  $e \in wC_I$ , but  $e$  has the property, which we assumed that no element in  $wC_I$  has. Hence there must be at least one such element. Now suppose there are two distinct elements  $u, v$  with the desired property. Note that this means, that  $u$  and  $w$  have no reduced twisted expression ending with some  $\underline{s} \in I$ . Let  $v$  have a reduced twisted expression  $v = \underline{s}_1 \dots \underline{s}_k$ . Since  $u$  and  $v$  are both in  $wC_I$  there must be a twisted  $v$ -expression for  $u$

$$u = v\underline{s}_{k+1} \dots \underline{s}_{k+l} = \underline{s}_1 \dots \underline{s}_{k+l}$$



with  $s_n \in I$  for  $k+1 \leq n \leq k+l$ . This twisted expression cannot be reduced, since it ends with  $\underline{s}_{k+l} \in I$ . Then Deletion property for twisted expressions yields that this twisted expression contains a reduced twisted subexpression for  $u$ . It cannot end with  $\underline{s}_n$  for  $k+1 \leq n \leq k+l$ . Hence, it is a twisted subexpression of  $\underline{s}_1 \dots \underline{s}_k = v$ , too. So  $u \leq v$  by Subword property. Because of symmetry we have  $v \leq u$  and so  $u = v$ , contradicting to our assumption  $u \neq v$ .  $\square$

**Corollary 2.34.** *Let  $w \in \mathcal{I}_\theta$ ,  $I \subseteq S$  be a set of generators and let  $\rho_{\min} := \min\{\rho(v) : v \in wC_I\}$  be the minimal twisted length within the residue  $wC_I$ . Then there is a unique element  $w_{\min} \in wC_I$  with  $\rho(w_{\min}) = \rho_{\min}$ . We denote this element by  $\min(w, I)$ .*

*Proof.* The minimal rank  $\rho_{\min}$  exists, since the image of  $\rho$  is in  $\mathbb{N}_0$ , which is well-ordered, and  $wC_I \neq \emptyset$ . Suppose we have an element  $w_{\min}$  with  $\rho(w_{\min}) = \rho_{\min}$ . This means, that in particular all  $w_{\min}\underline{s}$  with  $s \in I$  must be of larger twisted length, i.e.  $w_{\min} \prec w_{\min}\underline{s}$  for all  $s \in I$ . With Proposition 2.33 this element must be unique.  $\square$

We proceed with some properties of rank-2-residues. Our interest in these residues stems from the fact, that their properties are needed later in Section 2.4 to construct an effective algorithm for calculating the twisted weak ordering, i.e. calculating the Hasse diagram of  $Wk(W, \theta)$  for arbitrary Coxeter systems  $(W, S)$  and Coxeter system automorphisms  $\theta$ .

**Definition 2.35.** Let  $s, t \in S$  be two distinct generators. We define:

$$[\underline{st}]^n := \begin{cases} (\underline{st})^{\frac{n}{2}} & n \text{ even,} \\ (\underline{st})^{\frac{n-1}{2}} \underline{s} & n \text{ odd.} \end{cases}$$

This definition allows us to express rank-2-residues differently. Suppose we have an element  $w \in \mathcal{I}_\theta$  and two distinct generators  $s, t \in S$ . Thanks to Lemma 2.31 and Corollary 2.34 we can assume, that  $w = \min(w, \{s, t\})$ . Then

$$wC_{\{s,t\}} = \{w\} \cup \{w[\underline{st}]^n : n \in \mathbb{N}\} \cup \{w[\underline{ts}]^n : n \in \mathbb{N}\}.$$

This encourages the following definition.

**Definition 2.36.** Let  $w \in \mathcal{I}_\theta$  and let  $s, t \in S$  be two distinct generators. Suppose  $w = \min(w, \{s, t\})$ . Then we call  $\{w[\underline{st}]^n : n \in \mathbb{N}\}$  the **s-branch** and  $\{w[\underline{ts}]^n : n \in \mathbb{N}\}$  the **t-branch** of  $wC_{\{s,t\}}$ .

One question arises immediately: Are the  $s$ - and the  $t$ -branch disjoint? With the following propositions, corollaries and lemmas we will get a much better idea of the structure of rank-2-residues and answer this question.

**Proposition 2.37.** *Let  $w \in \mathcal{I}_\theta$  and let  $s, t \in S$  be two distinct generators. Without loss of generality suppose  $w = \min(w, \{s, t\})$ . If there is a  $v \in wC_{\{s,t\}}$  with  $v\underline{s} \prec v$  and  $v\underline{t} \prec v$ , then it is unique with this property in  $wC_{\{s,t\}}$ . Hence  $wC_{\{s,t\}}$  consists of two geodesics from  $w$  to  $v$  intersecting only in these two elements. Else, the  $s$ - and  $t$ -branch are disjoint, strictly ascending in twisted length and of infinite size.*

size. □

Figure 2.2.

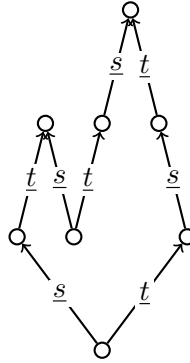


Figure 2.2.: Impossible concave structure of a rank-2-residues

**Proposition 2.38.** *Let  $w \in S$  and  $s, t \in S$  be two distinct generators with  $w\underline{s} \prec w$ . If  $\underline{s}$  acts by multiplication on  $w$ , then  $w\underline{st} \succ w\underline{s}$  or  $w\underline{t} \prec w$ .*

*Proof.* Suppose  $w\underline{st} \prec w\underline{s} \prec w$ , hence  $l(w\underline{st}) < l(w\underline{s}) < l(w)$  in particular. If  $\underline{t}$  acts by multiplication on  $w\underline{s}$ , then we have  $l(w\underline{st}) = l(\theta(s)(wt)) = l(w) - 2$ . If it acts by twisted conjugation, then we have  $l(w\underline{st}) = l(\theta(t)\theta(s)(wt)) = l(w) - 3$ . In both cases we have  $l(wt) < l(w)$ , hence  $t \in D_R(w)$  and so  $w\underline{t} \prec w$ .  $\square$

Note that this proposition could be strengthened by insisting on an exclusive or, since we cannot have both cases at the same time. By the proof of Proposition 2.27 we see that we cannot have  $w\overline{st} = w$ , since double edges are always twisted conjugations. Hence having  $w\overline{st} \succ w\overline{s} \prec w \succ w\overline{t}$  would contradict to the convexity from Proposition 2.37. The next corollary ensures that multiplicative actions in  $Wk(\theta)$  can only occur at the top or bottom end of rank-2-residues.

**Corollary 2.39.** *Let  $w \in S$  and let  $s, t \in S$  be two distinct generators and suppose  $\underline{s}$  acts by multiplication on  $w$ . Then  $w$  or  $w\underline{s}$  is the unique minimal or maximal element in  $wC_{\{s,t\}}$ .*

*Proof.* Suppose  $w$  is not maximal, i.e.  $w\underline{t} \succ w$ . Then by Proposition 2.38 we have  $w\underline{st} \succ w\underline{s}$ , hence  $w\underline{s}$  is minimal. Suppose  $w$  is not minimal, i.e.  $w\underline{st} \prec w\underline{s}$ . Then with the same argument we have  $w\underline{t} \prec w$ , hence  $w$  is maximal. Supposing  $w\underline{s}$  not to be maximal or not to be minimal yields analogue results.  $\square$

Again, this corollary can be strengthened by insisting on an exclusive or with the same arguments as before.

**Definition 2.40.** Let  $w \in \mathcal{I}_\theta$ ,  $s, t \in S$  be two distinct generators with  $\text{ord}(st) < \infty$  and  $C := wC_{\{s,t\}}$  the corresponding rank-2-residue. We classify rank-2-residues according to Figure 2.3.

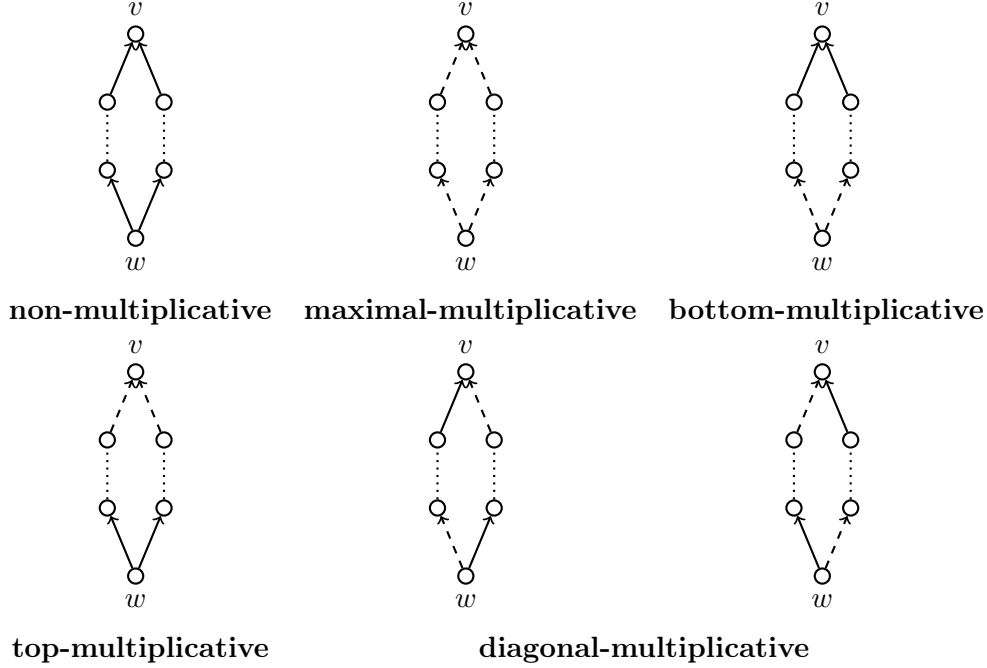


Figure 2.3.: Classification of rank-2-residues

**Lemma 2.41.** Let  $s, t \in S$  be two distinct generators and  $w \in S$  with  $w = \min(w, \{s, t\})$ . Suppose  $v \in wC_{\{s,t\}}$  with  $v\bar{s} \prec v$  and  $v\bar{t} \prec v$ . Then  $wC_{\{s,t\}}$  is either non-, maximal-, bottom-, top- or diagonal-multiplicative. In particular the twisted conjugations and multiplications are distributed axisymmetrically or pointsymmetrically.

*Proof.* If  $u$  covers  $w$ , then there are only two edges and the assumption holds. So suppose  $wC_{\{s,t\}}$  contains at least four edges. Due to Corollary 2.39 the actions by multiplication can only occur next to  $w$  and  $v$ . Hence there are  $2^4 = 16$  configurations possible. Proposition 2.26 wipes out ten out of the 16 configurations. The remaining are those from Figure 2.3.  $\square$

**Example 2.42.** In Figure 2.4 we see three Hasse diagrams of  $Wk(A_4, \text{id})$ . The left one only contains edges with labels  $s_1, s_2$ , the middle one only edges with labels  $s_1, s_3$  and the right one only edges with labels  $s_1, s_4$ .

**Corollary 2.43.** Let  $w \in \mathcal{I}_\theta$  with  $\rho(w) = k$ ,  $s, t$  be two distinct generators and  $s \notin D_R(w)$ . Suppose  $w[\underline{ts}]^{2n-1} = w\bar{s}$  and suppose  $n$  to be the smallest number with this property. Then  $w[\underline{ts}]^{n-1}$  is the minimal element  $\min(w, \{s, t\})$  and  $w[\underline{ts}]^{2n-1}$  is

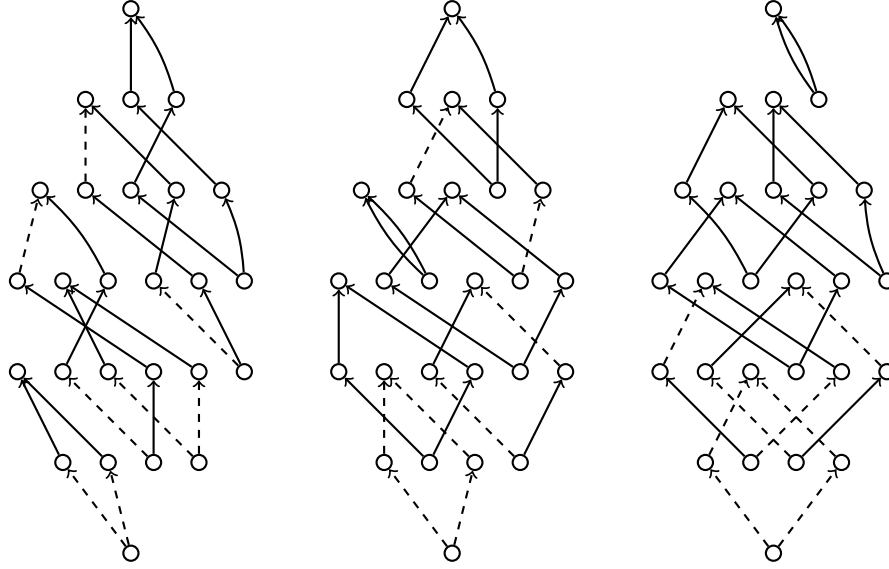


Figure 2.4.: Hasse diagrams of  $Wk(A_4, \text{id})$  after removing  $s_3, s_4$  edges in the left,  $s_2, s_4$  edges in the middle and  $s_2, s_3$  edges in the right diagram

the maximal element. Define

$$\begin{aligned} a_1 &= l(w\underline{s}) - l(w) - 1, \\ a_2 &= l(w[\underline{ts}]^{n-1}) - l(w[\underline{ts}]^{n-2}) - 1, \\ a_3 &= l(w[\underline{ts}]^n) - l(w[\underline{ts}]^{n-1}) - 1 \text{ and} \\ a_4 &= l(w[\underline{ts}]^{2n-1}) - l(w[\underline{ts}]^{2n-2}) - 1. \end{aligned}$$

Note that  $a_1, a_2, a_3, a_4 \in \{0, 1\}$  contain the information if edges next to the minimal and the maximal element of  $wC_{\{s,t\}}$  are twisted conjugations or multiplications. Then each can be deduced from the three remaining ones with the equation  $a_1 + a_2 = a_3 + a_4$ .

*Proof.* The minimality of  $w[\underline{ts}]^{n-1}$  and the maximality of  $w[\underline{ts}]^{2n-1}$  is due to Proposition 2.37. The soundness of the equation follows from the symmetric distribution of twisted conjugations and mutipliations from Lemma 2.41.  $\square$

**Lemma 2.44.** Let  $w \in S$ ,  $s, t \in S$  be two distinct generators and  $m = \text{ord}(st) < \infty$ . Then  $|wC_{\{s,t\}}| \leq 2m$ .

*Proof.* Let  $w$  be the  $Wk$ -minimal element and  $v$  be the  $Wk$ -maximal element in our residue. Due to Lemma 2.41 there are five different cases we have to consider:

**Non-multiplicative:** We have  $w(\underline{st})^m = (ts)^m w(st)^m = w$ .

**Maximal-multiplicative:** Due to  $\theta(s)w = ws$  and  $\theta(t)w = wt$  we have

$$w(\underline{st})^{m/2+1} = \theta(\hat{t}(st)^{m/2-1}\hat{s})w(st)^{m/2+1} = w(st)^m = w.$$

(**TODO** Show that this situation only occurs for even  $m$ )

**Bottom-multiplicative:** Again we are in a case, where  $\theta(s)w = ws$  and  $\theta(t)w = wt$  hold. Hence we have

$$w(\underline{st})^{(m+1)/2} = \theta(\hat{t}(st)^{(m-1)/2}\hat{s})w(st)^{(m+1)/2} = w(st)^m = w.$$

(**TODO** Show that this situation only occurs for odd  $m$ )

**Top-multiplicative:** Analogue to the previous case if we start from  $u$  instead of  $w$ .

**Diagonal-multiplicative:** Suppose  $m$  is even. Then we have

$$w(\underline{st})^m = \theta(\underbrace{ts \cdots st}_{m-1} \hat{s} \underbrace{ts \cdots st}_{m-1})w(st)^m = \theta(\underbrace{ts \cdots s}_{m-2} \underbrace{s \cdots st}_{m-2})w = \dots = w.$$

If  $m$  is odd, then we have the completely analogue situation

$$w(\underline{st})^m = \theta(\underbrace{ts \cdots ts}_{m-1} \hat{t} \underbrace{st \cdots st}_{m-1} \hat{s})w(st)^m = \theta(\underbrace{ts \cdots t}_{m-2} \underbrace{t \cdots st}_{m-2})w = \dots = w.$$

So in all cases we have  $w(\underline{st})^k = w$  for a  $k \leq \text{ord}(st)$  and hence the residue can have at most  $2 \cdot \text{ord}(st)$  many distinct elements.  $\square$

**Proposition 2.45.** *Let  $w \in S$  and  $s, t \in S$  be two distinct generators with  $\text{ord}(st) < \infty$ . Suppose  $k \in \mathbb{N}$  to be the smallest number with  $w = w(\underline{st})^k$ . Then for any  $n \in \mathbb{N}$  with  $w = w(\underline{st})^n$  we have  $k \mid n$ .*

*Proof.* Let  $n = qk + r$  for  $q \in \mathbb{N}_0$  and  $r \in \{0, \dots, k-1\}$ . Then

$$w = w(\underline{st})^n = w(\underline{st})^{qk+r} = w(\underline{st})^{qk}(\underline{st})^r = w(\underline{st})^{q(k-1)}(\underline{st})^r = \dots = w(\underline{st})^r.$$

For  $r > 0$  we would have a contradiction to the minimality of  $k$ , hence  $r = 0$ ,  $q > 0$  and therefore  $k \mid n$ .  $\square$

**Corollary 2.46.** *Let  $w \in S$  and  $s, t \in S$  be two distinct generators with  $w\underline{s} \neq w\underline{t}$ . Suppose  $w = w(\underline{st})^m = w(\underline{st})^n$ . Then  $\gcd(m, n) > 1$ .*

*Proof.* Let  $k$  be the same as in Proposition 2.45. Since  $w\underline{s} \neq w\underline{t}$  we have  $k > 1$ . Both,  $k \mid n$  and  $k \mid m$ , hence  $\gcd(m, n) \geq k > 1$ .  $\square$

This constraints the possible size of rank-2-residues.

## 2.4. Twisted weak ordering algorithms

Now we address the problem of calculating  $Wk(\theta)$  for an arbitrary Coxeter group  $W$ , given in form of a set of generating symbols  $S = \{s_1, \dots, s_n\}$  and the relations in form of  $m_{ij} = \text{ord}(s_i s_j)$ . From this input we want to calculate the Hasse diagram, i.e. the vertex set  $\mathcal{I}_\theta$  and the edges labeled with  $\underline{s}$ . Thanks to Lemma 2.12 the vertex set can be obtained by walking the  $e$ -orbit of the action from Definition 2.5. The only element of twisted length 0 is  $e$ . Suppose we have already calculated the Hasse diagram until the twisted length  $k$ , i.e. we know all vertices  $w \in \mathcal{I}_\theta$  with  $\rho(w) \leq k$  and all edges connecting two vertices  $u, v$  with  $\rho(u) + 1 = \rho(v) \leq k$ .

Let  $\rho_k := \{w \in \mathcal{I}_\theta : \rho(w) = k\}$ . Then all vertices in  $\rho_{k+1}$  are of the form  $w\underline{s}$  for some  $w \in \rho_k, s \in S$ . For each  $(w, s) \in \rho_k \times S$ , we calculate  $w\underline{s}$ . If  $\rho(w\underline{s}) = k + 1$  then  $w \prec w\underline{s}$ . To avoid having to check the twisted length we use Lemma 2.15. We already know the set  $S_w \subseteq S$  of all generators yielding an edge into  $w$ . Due to the lemma we have  $\rho(w\underline{s}) = k - 1$  for all  $s \in S_w$  and  $\rho(w\underline{s}) = k + 1$  for all  $s \in S \setminus S_w$ . Hence we only calculate  $w\underline{s}$  for  $s \in S \setminus S_w$  and know  $w \prec w\underline{s}$  without checking the twisted length explicitly. The last problem to solve is the possibility of two different  $(w, s), (v, t) \in \rho_k \times S$  with  $w\underline{s} = v\underline{t}$ . To deal with this, we have to compare a potential new twisted involution  $w\underline{s}$  with each element of twisted length  $k + 1$ , already calculated. The concrete problem of comparing two elements in a free presented group, called **word problem for groups**, will not be addressed here. We suppose, that whatever computer system is used to implement our algorithm, supplies a suitable way to do that. The only thing to note is that solving the wordproblem is not a cheap operation. Reducing the count of element comparisons is a major demand to any algorithm, calculating  $Wk(\theta)$ . For a general approach on effective element multiplication in arbitrary Coxeter groups see [Cas01, Cas08].

The steps discussed have been compiled in to an algorithm by [BHH06, Algorithm 2.4] and [HH12, Algorithm 3.1.1]. We take this as our starting point. Since the runtime is far from being optimal, we use the structural properties of rank-2-residues from Section 2.3 to improve the algorithm. As we will show, these optimizations yield an algorithm with an asymptotical perfect runtime behavior. TWOA1 and its optimizations have essentially the same structure in common. This is shown in TWOABase.

**Algorithm 2.47** (TWOABase).

```

1: procedure TWISTEDWEAKORDERINGALGORITHMBASE( $(W, S), k_{max}$ )
2:    $V \leftarrow \{(e, 0)\}$ 
3:    $E \leftarrow \{\}$ 
4:   for  $k \leftarrow 0$  to  $k_{max}$  do
5:     for all  $(w, k_w) \in V$  with  $k_w = k$  do
6:       for all  $s \in S$  with  $\nexists (\cdot, w, s) \in E$  do ▷ Only for  $s \notin D_R(w)$ 
7:         if  $w\underline{s} \notin V$  then ▷ Check if  $w\underline{s}$  already known
8:            $V \leftarrow V \cup \{(w\underline{s}, k + 1)\}$ 
9:         end if
10:         $E \leftarrow E \cup \{(w, w\underline{s}, l(w\underline{s}) - l(w)), s\}$ 
11:      end for
12:    end for
13:     $k \leftarrow k + 1$ 
14:  end for
15:  return  $(V, E)$  ▷ The poset graph
16: end procedure

```

*Remark 2.48.* Note, that if  $W$  is finite,  $k_{max}$  does not have to be evaluated explicitly. When  $k$  reaches the maximal twisted length in  $Wk(\theta)$ , then the only vertex of twisted length  $k$  is the unique element  $w_0 \in W$  of maximal ordinary length. Since  $s \in D_R(w_0)$  for all  $s \in S$ , there is no  $s' \in S$  remaining to calculate  $w_0\underline{s'}$  for. This condition can

be checked to terminate the algorithm without knowing  $k_{max}$  before. When  $W$  is infinite, there is no maximal element and  $\mathcal{I}_\theta$  is infinite, too. In this case  $k_{max}$  is used to terminate after having calculated a finite part of  $Wk(\theta)$ .

**Lemma 2.49.** *TWOABase is a deterministic algorithm iff the decision at line 7 is taken by a deterministic algorithm.*

*Proof.* The outer loop (line 4) is strictly ascending in  $k \in \{0, \dots, k_{max}\}$  and so finite. The innermost loop (line 6) is finite since  $S$  is finite and the inner loop (line 5) is finite, since  $V$  starts as finite set and in each step there are added at most  $|V| \cdot |S|$  many new vertices. Therefore the algorithm terminates. The soundness is due to the arguments at the beginning of Section 2.4.  $\square$

For all runtime investigations in the paper, we consider  $|S|$  and  $\text{ord}(st)$  (for all  $s, t \in S$  with  $\text{ord}(st) < \infty$ ) to be constant. This is suitable, since they are tiny compared to  $|\mathcal{I}_\theta|$ .

**Proposition 2.50.** *Let  $A$  be a concrete algorithm instance of TWOABase. By this we mean an algorithm  $A$ , that has the form of TWOABase together with an algorithm  $D$  to decide  $w\underline{s} \in V$  at line 7. Then for  $k = k_{max}$  and  $n = \{w \in \mathcal{I}_\theta : \rho(w) \leq k\}$  we have  $A \in \mathcal{O}(n \cdot D)$ .*

*Proof.* The body of the inner loop (line 5) is executed precisely  $n$  times and the body contains of  $D$  and some instructions with constant runtime.  $\square$

The poset graph is build up from the unique element of rank 0, the neutral element  $e$ . Then all elements of rank 1 are calculated including all edges between elements of rank 0 and rank 1. This is repeated until the rank  $k_{max}$  is reached. As we will see, the if-statement at line 7 in TWOABase is the crucial point in the algorithm. The naive way of checking  $w\underline{s} \in V$  is to calculate  $w\underline{s}$  as group element in  $W$  and then do a element comparison of  $w\underline{s}$  in  $W$  with all elements already in  $V$  with twisted length  $k + 1$ . This is exactly what TWOA1 does.

**Algorithm 2.51** (TWOA1). This algorithm is based on TWOABase. It uses the following function to determine if  $w\underline{s} \in V$  at line 7 in TWOABase.

```

1: procedure CHECKIFALREADYKNOWN( $(W, S), w, s, V, E$ )
2:    $y \leftarrow ws$ 
3:    $z \leftarrow \theta(s)y$ 
4:   if  $z = w$  then                                      $\triangleright$  Explicit element comparison in  $W$ 
5:      $x \leftarrow y$ 
6:   else
7:      $x \leftarrow z$ 
8:   end if
9:   for all  $(v, k_v) \in V$  with  $k_v = k + 1$  do           $\triangleright$  Check if  $x$  already known
10:    if  $x = v$  then                                        $\triangleright$  Explicit element comparison
11:      return true
12:    end if
13:  end for
    
```

14:     **return false**  
 15: **end procedure**

**Lemma 2.52.** *TWOA1 is a deterministic algorithm.*

*Proof.* Since the algorithm for  $w\underline{s} \in V$  just compares  $w\underline{s}$  with all elements in  $V$  of same twisted length it is sound. For  $k \in \mathbb{N}_0$  we have  $|\{w \in W : \rho(w) = k\}| < \infty$  and therefore it terminates.  $\square$

**Lemma 2.53.** *Let  $k \in \mathbb{N}$ ,  $n = |\{w \in \mathcal{I}_\theta : \rho(w) \leq k\}|$ . Then  $\text{TWOA1} \in \mathcal{O}(n^2/k)$ .*

*Proof.* We omit the detailed worst case analysis of TWOA1. Instead we give an outline of the proof. Let  $D$  be the algorithm to check  $w\underline{s} \in V$ . When  $D$  is executed, then  $w\underline{s}$  is compared to all  $w \in V$  with  $\rho(w) = k + 1$ . If  $w\underline{s}$  is the first element of twisted length  $k + 1$ , then there is nothing to compare. If it is the last element with this twisted length, that is not already known, then there are almost as many comparisons needed, as elements with this twisted length exist in  $\mathcal{I}_\theta$ . Overall we can assume  $D \in \mathcal{O}(n/k)$ . By Proposition 2.50 we get  $\text{TWOA1} \in \mathcal{O}(n^2/k)$ .  $\square$

Any algorithm calculating  $Wk(\theta)$  must be at least linear in the size of  $\mathcal{I}_\theta$  (since this is the size of the vertex result set). Our goal is to improve TWOA1 so that we get an algorithm in  $\mathcal{O}(|\mathcal{I}_\theta|)$ , i.e. an asymptotical perfect algorithm for calculating  $Wk(\theta)$ . As already seen the element comparison of a potential new element with all already known elements of same twisted length (TWOA1 at line 9) is the bottleneck. Here the rank-2-residues become key. Suppose we have a  $w \in \mathcal{I}_\theta$  with  $\rho(w) = k$  and  $s \in S$ . In TWOA1 we would now check if  $w\underline{s}$  is a new vertex or if we already calculated it by comparing it with all already known vertices of twisted length  $k + 1$ . Assume we have already calculated it. This means there is another twisted involution  $v$  with  $\rho(v) = k$  and another generator  $t \in S$  with  $v\underline{t} = w\underline{s}$ . With Proposition 2.37  $w\underline{s}$  is the unique element of maximal twisted length in the rank-2-residue  $wC_{\{s,t\}}$ . This yields a necessary condition for  $w\underline{s}$  to be equal to a already known vertex, allowing us to replace the ineffective search all method in TWOA1 at line 9.

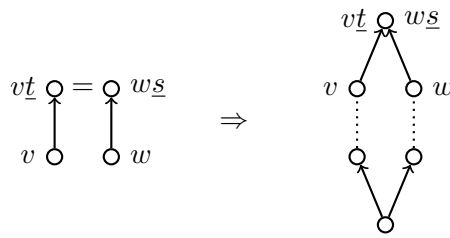


Figure 2.5.: Optimization of TWOA1

**Corollary 2.54.** *Let  $k \in \mathbb{N}$  and suppose we are in the situation described at the beginning of Section 2.4. Let  $\rho_i := \{w \in \mathcal{I}_\theta : \rho(w) = i\}$  and  $\rho'_{k+1}$  the set of the already calculated vertices with twisted length  $k + 1$ . If  $w\underline{s} \in \rho'_{k+1}$  for some  $w \in \rho_k$ ,  $s \in S$ , say  $w\underline{s} = v\underline{t}$  with  $v \in \rho_k$  and  $t \in S \setminus \{s\}$ , then  $w\underline{s} = w[\underline{ts}]^n$  for some  $n \in \mathbb{N}$  with  $w[\underline{ts}]^j \in \rho_0 \cup \dots \cup \rho_k \cup \rho'_{k+1}$  for  $1 \leq j \leq n$ .*



*Proof.* The equality  $w\underline{s} = w[\underline{ts}]^n$  for some  $n \in \mathbb{N}$  is due to Proposition 2.37. All vertices in this rank-2-residue except  $v\underline{t}$  have a twisted length of  $k$  or lower. For  $v\underline{t}$  we supposed it is already known, hence  $v\underline{t} \in \rho'_{k+1}$ . Therefore all vertices  $w[\underline{ts}]^j$ ,  $1 \leq j \leq n$  are in  $\rho_0 \cup \dots \cup \rho_k \cup \rho'_{k+1}$ .  $\square$

This can be checked effectively. Both,  $w$  and  $s$  are fixed. Start with  $M = \emptyset$ . For all already known edges from or to  $w$  being labeled with  $\underline{t} \in \underline{S} \setminus \{\underline{s}\}$  we do the following: Walk  $w[\underline{ts}]^i$  for  $i = 0, 1, \dots$  until  $\rho(w[\underline{ts}]^i) = k + 1$ . Note that walking in this case really means walking the graph. All involved vertices and edges have already been calculated. So there is no need for more calculations in  $W$  to find  $w[\underline{ts}]^i$ . By Proposition 2.37 such a path must exist (in a completely calculated graph). But we could be in the case, where the last step from  $w[\underline{ts}]^{i-1}$  to  $w[\underline{ts}]^i$  has not been calculated yet. If it is already calculated, then add this element to  $M$  by setting  $M = M \cup \{w[\underline{ts}]^i\}$ . If not, do not add it to  $M$ .

Now  $M$  contains all already known elements of twisted length  $k + 1$ , satisfying the necessary condition from Corollary 2.54. Furthermore  $|M| < |S|$ . So for each pair  $(w, s)$  we have to do at most  $|S| - 1$  many element comparisons to determine if  $w\underline{s}$  is new or already known, no matter how many elements of twisted length  $k + 1$  are already known. This can be used to massively improve TWOA1:

**Algorithm 2.55** (TWOA2). This algorithm is based on TWOABase. It uses the following function to determine if  $w\underline{s} \in V$  at line 7 in TWOABase.

```

1: procedure CHECKIFALREADYKNOWN( $(W, S), w, s, V, E$ )
2:    $y \leftarrow ws$ 
3:    $z \leftarrow \theta(s)y$ 
4:   if  $z = w$  then ▷ Explicit element comparison in  $W$ 
5:      $x \leftarrow y$ 
6:   else
7:      $x \leftarrow z$ 
8:   end if
9:   for all  $t \in S \setminus \{s\}$  do
10:    if  $\text{ord}(st) < \infty$  then
11:       $v \leftarrow w$ 
12:       $k \leftarrow 1$ 
13:       $(z_0, z_1) \leftarrow (s, t)$ 
14:      while true do ▷ Walk  $wC_{\{s,t\}} \cap V$  down
15:         $e \leftarrow (v_0, v_1, a, l) \in E$  with  $v_1 = v$  and  $a = z_k \bmod 2$ 
16:        if  $e = \text{null}$  then
17:          break
18:        end if
19:         $v \leftarrow v_0$ 
20:         $k \leftarrow k + 1$ 
21:      end while
22:      while true do ▷ Walk  $wC_{\{s,t\}} \cap V$  up the other branch
23:         $e \leftarrow (v_0, v_1, a, l) \in E$  with  $v_0 = v$  and  $a = z_k \bmod 2$ 
24:        if  $e = \text{null}$  then

```

```

25:          break
26:        end if
27:         $v \leftarrow v_1$ 
28:         $k \leftarrow k - 1$ 
29:      end while
30:      if  $k = 0$  then                                 $\triangleright$  Check if  $\rho(v) = \rho(w) + 1$ 
31:        if  $x = v$  then                                 $\triangleright$  Explicit element comparison in  $W$ 
32:          return true
33:        end if
34:      end if
35:    end if
36:  end for
37:  return false
38: end procedure

```

**Lemma 2.56.** *TWOA2 is a deterministic algorithm.*

*Proof.* The outer loop (line 9) is executed  $|S| - 1$  times. Its body is only called if  $\text{ord}(st)$  is finite. Due to Lemma 2.44 the both inner while loops (lines 14,22) are executed at most  $2 \cdot \text{ord}(st)$  times. So TWOA2 terminates. The soundness of this improvement is due to Corollary 2.54.  $\square$

**Lemma 2.57.** *Let  $k \in \mathbb{N}$ ,  $n = |\{w \in \mathcal{I}_\theta : \rho(w) \leq k\}|$ . Then  $\text{TWOA2} \in \mathcal{O}(n)$ .*

*Proof.* Let  $D$  be the algorithm to check  $w\underline{s} \in V$ . As seen in the proof of Lemma 2.56, the execution count for each while loop in  $D$  does not exceed

$$(|S| - 1) \cdot \max\{\text{ord}(st) : t \in S \setminus \{s\}, \text{ord}(st) < \infty\}.$$

Since we considered  $|S|$  and  $\text{ord}(st)$  constant we have  $D \in \mathcal{O}(1)$  and so with Proposition 2.50 we have  $\text{TWOA2} \in \mathcal{O}(n)$ .  $\square$

Many more explicit element comparisons can be avoided. In some cases we can deduce the equality  $v\underline{t} = w\underline{s}$  as well as  $l(w\underline{s}) - l(w)$  just from the already calculated structure of the rank-2-residue  $wC_{\{s,t\}}$ , while in other cases we can preclude that  $v\underline{t}$  equals  $w\underline{s}$ . The following two corollaries show examples of restrictions that rank-2-residues are subjected to:

**Corollary 2.58.** *Let  $w \in \mathcal{I}_\theta$  with  $\rho(w) = k$ ,  $s, t$  be two distinct generators and  $s \notin D_R(w)$ . Suppose  $n \in \mathbb{N}$  to be the smallest number for that  $\rho(w[\underline{ts}]^{2n-1}) = k + 1$  holds. Then:*

1. *If  $n = \text{ord}(st)$ , then  $w[\underline{ts}]^{2n-1} = w\underline{s}$ .*
2. *If  $n \geq 2$  and  $l(w[\underline{ts}]^{2n-1}) - l(w[\underline{ts}]^{2n-2}) = 1$ , then  $w[\underline{ts}]^{2n-1} = w\underline{s}$ .*

*Proof.* 1. Follows immediately from Lemma 2.44.

2. Because of the length difference the step from  $w[\underline{ts}]^{2n-2}$  to  $w[\underline{ts}]^{2n-1}$  is a multiplication, not a twisted conjugation, and because of  $n \geq 1$  this step cannot be next to the smallest element in  $wC_{\{s,t\}}$ . Hence  $w[\underline{ts}]^{2n-1} = w\underline{s}$  by Corollary 2.39.  $\square$

**Corollary 2.59.** *Let  $w \in S$  and  $s, t \in S$  be two distinct generators. Then the following table shows all possible  $n \in \mathbb{N}$  with  $w(\underline{st})^n = w$  regarding  $\text{ord}(st)$  and the distribution of multiplications and twisted conjugations in  $wC_{\{s,t\}}$  (see Figure 2.3).*

	$\text{ord}(st)$						
	2	3	4	5	6	7	8
<i>non-multiplicative</i>	1,2	3	2,4	5	2,3,4,6	7	2,4,6,8
<i>diagonal-multiplicative</i>	2	3	2,4	5	2,3,4,6	7	2,4,6,8
<i>maximal-multiplicative</i>	2	–	3	–	2,4	–	5
<i>bottom- and top-multiplicative</i>	–	2	–	3	–	2,4	–

*Proof.* In each case we get a  $m$  with  $w = (\underline{st})^m$  from the proof of Lemma 2.44. By Corollary 2.46 any  $n$  with this property has a non trivial divisor in common with  $m$  if  $w\underline{s} \neq w\underline{t}$ . The situation  $w\underline{st} = w$  for  $s \neq t$  can only occur if  $\text{ord}(st) = 2$  and if  $\underline{s}$  and  $\underline{t}$  act by twisted conjugation on  $w$  due to Corollary 2.28 and the proof of Proposition 2.27.  $\square$

We use these restrictions to further improve TWA2:

**Proposition 2.60.** *Let  $w \in \mathcal{I}_\theta$  with  $\rho(w) = k$ ,  $s, t \in S$  be two distinct generators with  $m := \text{ord}(st) < \infty$  and  $n \in \mathbb{N}$  the smallest number with  $\rho(w[\underline{ts}]^n) = k + 1$ . Note that  $n$  has to be odd in this case. We define  $v := w[\underline{ts}]^{n-1}$ ,  $h := (n + 1)/2$  and*

$$\begin{aligned}
 a_1 &= l(w\underline{s}) - l(w) - 1, \\
 a_2 &= l(w[\underline{ts}]^{h-1}) - l(w[\underline{ts}]^{h-2}) - 1, \\
 a_3 &= l(w[\underline{ts}]^h) - l(w[\underline{ts}]^{h-1}) - 1 \text{ and} \\
 a_4 &= l(w[\underline{ts}]^{2h-1}) - l(w[\underline{ts}]^{2h-2}) - 1.
 \end{aligned}$$

*Then the following decision tree allows to decide of  $w\underline{t} = w\underline{s}$  or  $w\underline{t} \neq w\underline{s}$  in many cases without explicit element comparison.*

1.  $h = 1$ :
  - a)  $m = 2$ :
    - i.  $a_4 = 1$ : Maybe  $v\underline{t} = w\underline{s}$ . If it is the case, then  $a_1 = 1$ .
    - ii.  $a_4 = 0$ : Then  $v\underline{t} \neq w\underline{s}$ .
  - b)  $m > 2$ : Then  $v\underline{t} \neq w\underline{s}$ .
2.  $h > 1$ :
  - a)  $a_4 = 0$ : Then  $v\underline{t} = w\underline{s}$  and  $a_1 = a_3 + a_4 - a_2$ .
  - b)  $(a_2, a_3) = (1, 1)$ :
    - i.  $h = m$ : Then  $v\underline{t} = w\underline{s}$  and  $a_1 = 1$ .

- ii.  $\gcd(h, m) > 1$ : Maybe  $v\underline{t} = w\underline{s}$ . If it is the case, then  $a_1 = 1$ .
- iii. else: Then  $v\underline{t} \neq w\underline{s}$ .
- c)  $(a_2, a_3) = (1, 0)$ :
  - i.  $h = m$ : Then  $v\underline{t} = w\underline{s}$  and  $a_1 = 0$ .
  - ii.  $\gcd(h, m) > 1$ : Maybe  $v\underline{t} = w\underline{s}$ . If it is the case, then  $a_1 = 0$ .
  - iii. else: Then  $v\underline{t} \neq w\underline{s}$ .
- d)  $(a_2, a_3) = (0, 0)$ :
  - i.  $h = (m + 1)/2$ : Then  $v\underline{t} = w\underline{s}$  and  $a_1 = 1$ .
  - ii.  $\gcd(h, (m + 1)/2) > 1$ : Maybe  $v\underline{t} = w\underline{s}$ . If it is the case, then  $a_1 = 1$ .
  - iii. else: Then  $v\underline{t} \neq w\underline{s}$ .

*Proof.* First of all we convince ourselves that this decision tree is complete. This is immediate, since by  $h \geq 0$ ,  $m \geq 2$  and Lemma 2.41. Suppose  $h = 1$ . This means  $v = w$ . In case  $v\underline{t} = w\underline{s}$ , then we have a double edge between  $w$  and  $w\underline{s}$ . By Corollary 2.28 this is possible only if  $m = \text{ord}(st) = 2$  and  $a_4 = l(w\underline{t}) - l(w) - 1 = 1$ . Now suppose  $h > 1$  and  $a_4 = 0$ . By Proposition 2.38 either  $v\underline{s} \succ v$  or  $v\underline{ts} \prec v\underline{t}$ . Since  $h > 1$  we cannot have  $v\underline{s} \succ v$ , hence  $v\underline{ts} \prec v\underline{t}$ . Then  $v\underline{t}$  is the unique maximal element in  $wC_{\{s,t\}}$  and so  $w\underline{s} = v\underline{t}$ . Now suppose  $h > 1$  and  $a_4 = 1$  and furthermore suppose  $(a_2, a_3) = (1, 1)$  (the other cases are analogue). If  $h = m$ , then by Lemma 2.44  $v\underline{t}$  is again the unique maximal element and  $v\underline{t} = w\underline{s}$ . If  $h < m$  then by Corollary 2.46  $v\underline{t} = w\underline{s}$  is only possible if  $\gcd(h, m) > 1$ . In all cases the deduction of  $a_1$  is possible with Corollary 2.43.  $\square$

**Algorithm 2.61** (TWOA3). In general this algorithm proceeds like TWOA2. But instead of comparing  $w\underline{s}$  with the list of all possible already known elements  $v\underline{t}$ , it uses the decision tree from Proposition 2.60 to either directly find  $v\underline{t}$  with  $v\underline{t} = w\underline{s}$  or at least to sort out elements from the list, that cannot be equal to  $w\underline{s}$ . The information needed for the decision tree, namely  $w, s, t, h, a_2, a_3, a_4$  (cf. Proposition 2.60), can easily be extracted, when searching for the already calculated elements  $v\underline{t}$  with  $\rho(v\underline{t}) = \rho(w) + 1$ . This algorithm then applies the decision tree to each of them to decide if  $w\underline{s} = v\underline{t}$ , or if  $w\underline{s} \neq v\underline{t}$  or if explicit element comparison is needed, to get a final answer to this question. We will omit the concrete details and refer to the appendix, where a implementation of this algorithm can be found.

**Lemma 2.62.** *TWOA3 is a deterministic algorithm.*

*Proof.* By construction TWOA3 has the same loops as TWOA2, which is an deterministic algorithm. In addition TWOA3 uses the decision tree from Proposition 2.60. Since the decision tree has no loops, is terminates and we have already proved its correctness. Hence TWOA3 is correct and it terminates.  $\square$

**Lemma 2.63.** *Let  $k \in \mathbb{N}$ ,  $n = |\{w \in \mathcal{I}_\theta : \rho(w) \leq k\}|$ . Then  $\text{TWOA3} \in \mathcal{O}(n)$ .*

*Proof.* Since the decision tree has constant runtime the asymptotical runtime of TWOA3 cannot be worse than the asymptotical runtime of TWOA2.  $\square$

## 2.5. Implementing the twisted weak ordering algorithms

In this section we will look at a concrete implementation of the algorithm TWOA1 from [BHH06] and [HH12] and of the improved versions TWOA2 and TWOA3 that we have just introduced. The source codes of the test implementations can be found in the appendix, Section A. They are written in [GAP12], using the [Neu12] package for reading and writing the results to hard disk. It supplies a powerful programming language and can handle with free represented groups, in particular it allows comparisons of elements in such groups. The following algorithm benchmarks have been executed on a computer running Debian Linux in Verion 6.0.5 with an Intel® Core™ i7-965 CPU (4 cores at 3.2 GHz) and 8 GiB RAM. Note that our implementations do not support multithreading.

At first we compare the count of element comparisons needed for our three algorithms. For this we calculate  $Wk(W, \text{id})$  for a selection of finite Coxeter systems and count the comparisons. In Figure 2.6 we see the count of needed element comparisons plotted against the size of the set of id-twisted involutions.

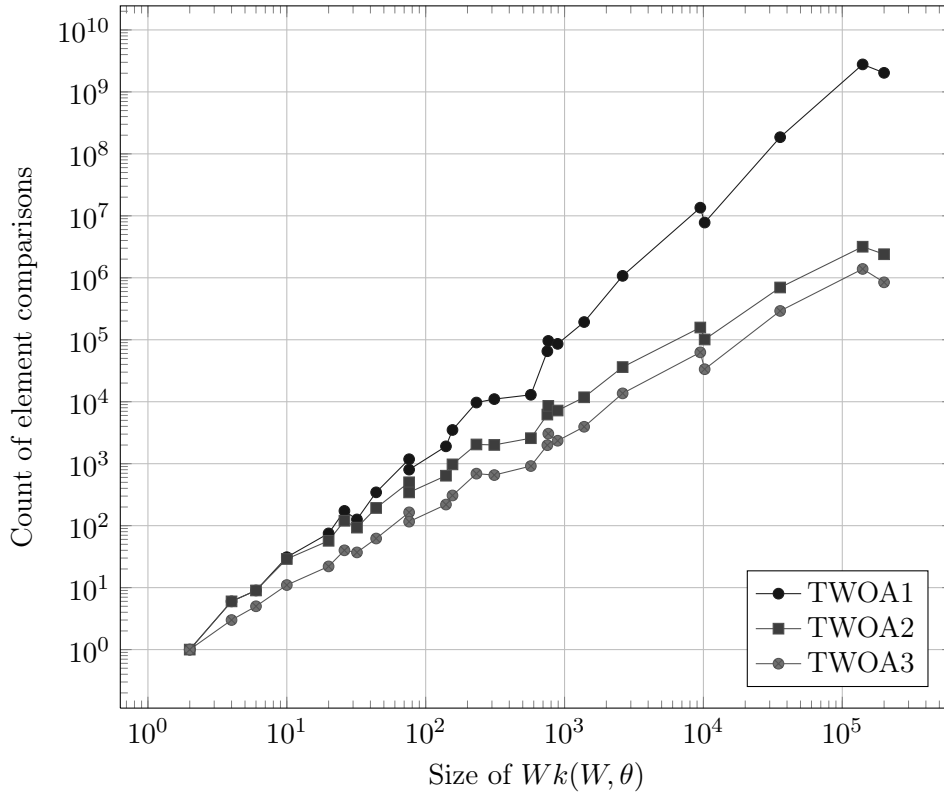


Figure 2.6.: Element comparisons needed for calculating  $Wk(\text{id})$

The first observation is the much lower count of needed element comparisons of TWOA2 and TWOA3 in comparison to TWOA1, just as we intended it with our improvements. Figure 2.7 plots the runtimes against the size of  $Wk(\theta)$ . The complete table of benchmark results can be found in the appendix, Section B.

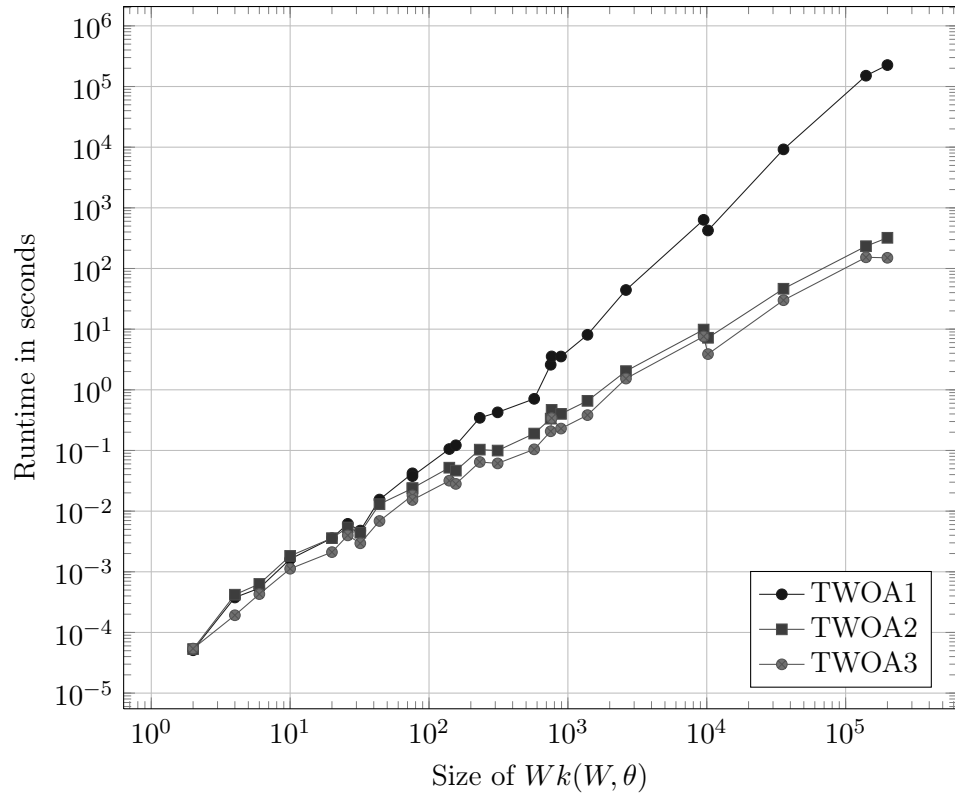


Figure 2.7.: Runtime for calculating  $Wk(id)$

### 3. Twisted weak ordering 3-residually connectedness

**Definition 3.1.** Let  $(W, S)$  be a Coxeter system and  $\theta : W \rightarrow W$  an automorphism of  $W$  with  $\theta^2 = \text{id}$  and  $\theta(S) = S$ . We call  $Wk(\theta)$  **3-residually connected** if the following holds: For every possible spherical  $K \subseteq S$  (i.e.  $\langle K \rangle \leq W$  is finite) and every  $S_1, S_2, S_3 \subseteq S$  with pairwise non-empty intersection the statement

$$(3RC) \quad w_K C_{S_{12}} \cap w_K C_{S_{23}} \cap w_K C_{S_{31}} \subseteq w_K C_T$$

holds, whereas  $w_K$  denotes the longest element in  $\langle K \rangle$ ,  $S_{ij} = S_i \cap S_j$  and  $T = S_1 \cap S_2 \cap S_3$ .

For arbitrary sets  $S_{12}, S_{23}, S_{31}$  that do not come from pairwise intersections it is easy to find pairs of Coxeter systems and Coxeter system automorphism that do not satisfy the (modified) 3-residually connectedness, as seen in Example 3.3. The following proposition shows us, what distinguishes our special configuration of sets of generators from the arbitrary configuration.

**Proposition 3.2.** *Let  $M$  be a set and  $S_{12}, S_{23}, S_{31} \subseteq M$  three subsets. Then there are three sets  $S_1, S_2, S_3 \subseteq M$  with  $S_{ij} = S_i \cap S_j$  iff no element  $x \in M$  is precisely in two of the sets  $S_{ij}$ .*

*Proof.* Let  $S_{12}, S_{23}, S_{31}$  be the pairwise intersection of three sets  $S_1, S_2, S_3$ . If an element  $x \in M$  is in none or in one of the sets  $S_i$ , then it is in none of the sets  $S_{ij}$ . If it is in two of the sets  $S_i$ , say  $x \in S_1, S_2$ , then  $x \in S_{12}$ , but  $x$  is not in one of the other two  $S_{ij}$ . If  $x$  is in all three  $S_i$ , then it is in all three  $S_{ij}$ , too. Hence there is no  $x \in M$ , that is in precisely two of the sets  $S_{ij}$ . Conversely, suppose  $S_{12}, S_{23}, S_{31}$  to be arbitrary with the constraint, that there is no element  $x \in M$  in precisely two of them. Then we can construct three sets  $S_1, S_2, S_3$ , whose pairwise intersections coincides with the sets  $S_{ij}$  by  $x \in S_i \wedge x \in S_j$  iff  $x \in S_{ij}$ . With this construction and the previous considerations, it is clear that these  $S_i$  have the  $S_{ij}$  as pairwise intersection. Note that this construction is not unique in general, since when there is a  $x \in M$ , that is in none of the sets  $S_{ij}$ , then we could add it to  $S_1, S_2$  or  $S_3$  or just omit it without changing there pairwise intersection.  $\square$

#### 3.1. Special cases

In this section we investigate some results and examples, in special situations. We fix some notation, namely let  $K \subseteq S$  be spherical,  $S_1, S_2, S_3 \subseteq S$  have a pairwise non-empty intersection,  $S_{ij} = S_i \cap S_j$ ,  $T = S_1 \cap S_2 \cap S_3$  and  $w_K$  denote the longest element in  $\langle K \rangle$ .

**Example 3.3.** Let  $W = A_3$  and  $\theta$  be the Coxeter system automorphism swapping  $s_1$  and  $s_3$  and let  $w = s_1 s_3 = s_3 s_1$ . We have  $e_{\underline{s}_1} = s_3 s_1 = w = s_1 s_3 = e_{\underline{s}_3}$ . Hence  $w \in eC_{\{s_1\}}$  and  $w \in eC_{\{s_3\}}$  but  $w \notin eC_{\{s_1\} \cap \{s_1\} \cap \{s_3\}} = eC_{\emptyset} = \{e\}$ .

Such a trivial counterexample like in Example 3.3 can not occur in the situation from Definition 3.1.

**Proposition 3.4.** Let  $w, v \in \mathcal{I}_\theta$  with  $\rho(v) - \rho(w) = 1$  and let  $v \in wC_{S_{ij}}$  for  $1 \leq i < j \leq 3$ . Then we have  $v \in wC_T$ .

*Proof.* By Proposition 2.27 there are at most two (not necessarily distinct)  $s, t \in S$  with  $w\underline{s} = v$  and  $w\underline{t} = v$ . Each set  $S_{12}, S_{23}, S_{31}$  must at least contain  $s$  or  $t$ , hence  $s$  or  $t$  is at least in two sets, say  $s \in S_{12}, S_{23}$ . Hence  $s \in S_1, S_2, S_3$  and therefore  $v \in wC_T$ .  $\square$

A property, that is much stronger than 3-residually connectedness, reads  $wC_I \cap wC_J = wC_{I \cap J}$ . If  $Wk(\theta)$  satisfies this, then its 3-residually connectedness could be concluded immediately. Unfortunately it proves to be false in general. Again, double-edges yield a simple counterexample.

**Example 3.5.** Let  $w \in \mathcal{I}_\theta$  and  $s, t$  two distinct generators with  $w\underline{s} = w\underline{t} = v$ . Then  $wC_{\{s\}} \cap wC_{\{t\}} = \{w, v\} \neq \{w\} = wC_{\emptyset} = wC_{\{s\} \cap \{t\}}$ .

**Proposition 3.6.** Suppose one of the following cases is current for some pairwise distinct  $i, j, k \in \{1, 2, 3\}$ :

1.  $S_i = \emptyset$ ,
2.  $S_i \subseteq S_j$  or
3.  $S_i = S$ .

Then **(3RC)** holds.

*Proof.* 1. We have  $\bigcap_{1 \leq m < n \leq 3} wKC_{S_{mn}} \subseteq wKC_{S_{ij}} \subseteq wKC_{S_i} = wKC_{\emptyset} = wKC_T$ .

2. We have  $S_{ij} = S_i$ , hence  $T = S_i \cap S_j \cap S_k = S_{ij} \cap S_k = S_i \cap S_k = S_{ik}$ . Therefore  $\bigcap_{1 \leq m < n \leq 3} wKC_{S_{mn}} \subseteq wKC_{S_{ik}} = wKC_T$ .

3. We have  $S_j \subseteq S = S_i$  and so with 3.6.2 we are done.  $\square$

**Corollary 3.7.** Suppose  $|S| \leq 2$ . Then  $Wk(\theta)$  is 3-residually connected.

*Proof.* If one set of  $S_1, S_2, S_3$  is empty or equal to  $S$ , then we are done by 3.6.1 and 3.6.3. Else at least two sets of  $S_1, S_2, S_3$  must be equal. In this case we are done by 3.6.2.  $\square$



### 3.2. Reducible case

**Lemma 3.8.** *Let  $(W, S_1 \dot{\cup} S_2)$  be a reducible Coxeter system with  $\text{ord}(st) = 2$  for  $s \in S_1, t \in S_2$ . Let  $\theta = \text{id}$ ,  $s_1, \dots, s_m, s \in S_1$  and  $t_1, \dots, t_n, t \in S_2$ . Then*

1.  $\underline{s}$  acts by twisted conjugation on  $\underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n$  if and only if it acts by twisted conjugation on  $\underline{s}_1 \dots \underline{s}_m$ ,
2.  $\underline{t}$  acts by twisted conjugation on  $\underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n$  if and only if it acts by twisted conjugation on  $\underline{t}_1 \dots \underline{t}_m$ , and
3.  $\underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n \underline{s} = \underline{s}_1 \dots \underline{s}_m \underline{s} \underline{t}_1 \dots \underline{t}_n$ .

*Proof.* We have  $\underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n = t_{i_q} \dots t_{i_1} s_{j_r} \dots s_{j_1} s_1 \dots s_m t_1 \dots t_n$  for some well chosen indices  $1 \leq i_1 < \dots < i_q \leq m$  and  $1 \leq j_1 < \dots < j_r \leq n$ .

1. We prove this by a straight forward chain of equivalences.

$$\begin{aligned}
 & s(\underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n)s = \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n \\
 \iff & s(t_{i_q} \dots t_{i_1} s_{j_r} \dots s_{j_1} s_1 \dots s_m t_1 \dots t_n)s = t_{i_q} \dots t_{i_1} s_{j_r} \dots s_{j_1} s_1 \dots s_m t_1 \dots t_n \\
 \iff & (t_{i_q} \dots t_{i_1} t_1 \dots t_n) s s_{j_r} \dots s_{j_1} s_1 \dots s_m s = (t_{i_q} \dots t_{i_1} t_1 \dots t_n) s_{j_r} \dots s_{j_1} s_1 \dots s_m \\
 \iff & s s_{j_r} \dots s_{j_1} s_1 \dots s_m s = s_{j_r} \dots s_{j_1} s_1 \dots s_m \\
 \iff & s(\underline{s}_1 \dots \underline{s}_m)s = \underline{s}_1 \dots \underline{s}_m
 \end{aligned}$$

2. This part is almost the same as before.

$$\begin{aligned}
 & t(\underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n)t = \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n \\
 \iff & t(t_{i_q} \dots t_{i_1} s_{j_r} \dots s_{j_1} s_1 \dots s_m t_1 \dots t_n)t = t_{i_q} \dots t_{i_1} s_{j_r} \dots s_{j_1} s_1 \dots s_m t_1 \dots t_n \\
 \iff & t t_{i_q} \dots t_{i_1} t_1 \dots t_n t(s_{j_r} \dots s_{j_1} s_1 \dots s_m) = t_{i_q} \dots t_{i_1} t_1 \dots t_n (s_{j_r} \dots s_{j_1} s_1 \dots s_m) \\
 \iff & t t_{i_q} \dots t_{i_1} t_1 \dots t_n t = t_{i_q} \dots t_{i_1} t_1 \dots t_n \\
 \iff & t(\underline{t}_1 \dots \underline{t}_n)t = \underline{t}_1 \dots \underline{t}_n
 \end{aligned}$$

Note that the last equivalence is not true in general. Suppose  $v \in \mathcal{I}_\theta$  to be an arbitrary twisted expression. In general we cannot deduce the action of  $\underline{s}$  on a subexpression of  $v$  from the action of  $\underline{s}$  on  $v$  itself. But with the first part of this lemma we can first conclude, that  $\underline{t}_1$  acts by twisted conjugation on  $e$  if and only if it acts by twisted conjugation on  $\underline{s}_1 \dots \underline{s}_m$ . Again with the same argument  $\underline{t}_2$  acts by twisted conjugation on  $\underline{t}_1$  iff it acts by twisted conjugation on  $\underline{s}_1 \dots \underline{s}_m \underline{t}_1$  and so forth.

3. To avoid having to repeat the proof for twisted conjugative and multiplicative action of  $\underline{s}$  we set  $s' = s$  if  $\underline{s}$  acts by twisted conjugation and else  $s' = e$ .

$$\begin{aligned}
 & \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n \underline{s} \\
 = & s'(t_{i_q} \dots t_{i_1} s_{j_r} \dots s_{j_1} s_1 \dots s_m t_1 \dots t_n)s \\
 = & t_{i_q} \dots t_{i_1} (s' s_{j_r} \dots s_{j_1} s_1 \dots s_m s) t_1 \dots t_n \\
 = & t_{i_q} \dots t_{i_1} (s_1 \dots \underline{s}_m \underline{s}) t_1 \dots t_n \\
 = & s_1 \dots \underline{s}_m \underline{s} \underline{t}_1 \dots \underline{t}_n
 \end{aligned}$$

Again note that the last two equalities need the two previous parts of this lemma.  $\square$

**Corollary 3.9.** *Let  $(W, S_1 \dot{\cup} S_2)$  be Coxeter system with  $\text{ord}(st) = 2$  whenever  $s \in S_1, t \in S_2$ . In particular  $W$  is reducible. Let  $W := W_{S_1}$  and  $W_2 := W_{S_2}$  be the parabolic subgroups of  $W$  corresponding to  $S_1$  and  $S_2$ . Then we have  $Wk(W, \text{id}) \cong Wk(W_1, \text{id}) \times Wk(W_2, \text{id})$ .*

*Proof.* We denote the relation in  $W$  (resp. in  $W_1, W_2$ ) by  $\preceq_W$  (resp. by  $\preceq_{W_1}, \preceq_{W_2}$ ). By Lemma 3.8 for every element  $w \in \mathcal{I}_{\text{id}}(W)$  we can find a twisted expression like  $w = \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n$  with  $s \in S_1, t \in S_2$ . Hence the map

$$\varphi : \mathcal{I}_{\text{id}}(W_1) \times \mathcal{I}_{\text{id}}(W_2) \rightarrow \mathcal{I}_{\text{id}}(W) : (\underline{s}_1 \dots \underline{s}_m, \underline{t}_1 \dots \underline{t}_n) \mapsto \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n$$

is surjective. The injectivity is due to Proposition 1.24. It remains to show that  $\preceq_W$  satisfies Definition 1.7. Let  $v_1, w_1 \in \mathcal{I}_{\text{id}}(W_1)$ ,  $v_2, w_2 \in \mathcal{I}_{\text{id}}(W_2)$  and  $v = v_1 v_2 = \varphi(v_1, v_2), w = w_1 w_2 = \varphi(w_1, w_2) \in \mathcal{I}_{\text{id}}(W)$ . Suppose  $v_i \preceq_{W_i} w_i$  for  $i = 1, 2$ . Then we have

$$\begin{aligned} v_1 &= \underline{s}_1 \dots \underline{s}_m, & w_1 &= \underline{s}_1 \dots \underline{s}_m \dots \underline{s}_{m'} = v_1 \underline{s}_{m+1} \dots \underline{s}_{m'}, \\ v_2 &= \underline{t}_1 \dots \underline{t}_n \text{ and} & w_2 &= \underline{t}_1 \dots \underline{t}_n \dots \underline{t}_{n'} = v_2 \underline{t}_{n+1} \dots \underline{t}_{n'} \end{aligned}$$

for some well chosen generators  $s_i \in S_1, t_i \in S_2$  and  $0 \leq m \leq m', 0 \leq n \leq n'$ . Hence

$$\begin{aligned} v &= v_1 v_2 = \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n \preceq_W \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n \underline{s}_{m+1} \dots \underline{s}_{m'} \underline{t}_{n+1} \dots \underline{t}_{n'} \\ &= \underline{s}_1 \dots \underline{s}_m \underline{s}_{m+1} \dots \underline{s}_{m'} \underline{t}_1 \dots \underline{t}_n \underline{t}_{n+1} \dots \underline{t}_{n'} = w_1 w_2 = w. \end{aligned}$$

In return suppose  $v \preceq_W w$ . Then we have

$$\begin{aligned} v &= \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n \text{ and} \\ w &= \underline{s}_1 \dots \underline{s}_m \underline{t}_1 \dots \underline{t}_n \underline{s}_{m+1} \dots \underline{s}_{m'} \underline{t}_{n+1} \dots \underline{t}_{n'} \end{aligned}$$

for some well chosen generators  $s_i \in S_1, t_i \in S_2$  and  $0 \leq m \leq m', 0 \leq n \leq n'$ . Again with similar arguments we have

$$\begin{aligned} v_1 &= \underline{s}_1 \dots \underline{s}_m \preceq_{W_1} \underline{s}_1 \dots \underline{s}_m \underline{s}_{m+1} \dots \underline{s}_{m'} = w_1 \text{ and} \\ w_1 &= \underline{t}_1 \dots \underline{t}_n \preceq_{W_2} \underline{t}_1 \dots \underline{t}_n \underline{t}_{n+1} \dots \underline{t}_{n'} = w_2. \end{aligned} \quad \square$$

*Remark 3.10.* Note that Lemma 3.8 and Corollary 3.9 still hold if we drop the premise  $\theta = \text{id}$  and instead insist on  $\theta(S_i) = S_i$  for  $i = 1, 2$ . They also remain true if we have a partition of the generator set in more than two subsets. Hence for  $(W, S_1 \dot{\cup} \dots \dot{\cup} S_n)$  with  $\text{ord}(st) = 2$  whenever  $s \in S_i, t \in S_j, i \neq j$  we have

$$Wk(W, \text{id}) = Wk(W_{S_1}, \text{id}) \times \dots \times Wk(W_{S_n}, \text{id}).$$

**Theorem 3.11.** *Let  $(W, S)$  be a reducible Coxeter system with  $S = S' \cup S''$  and  $\text{ord}(st) = 2$  whenever  $s \in S', t \in S''$  and let  $\theta = \text{id}$ . Then  $Wk(W, \text{id})$  is 3-residually connected if and only if  $Wk(W_{S'}, \text{id})$  and  $Wk(W_{S''}, \text{id})$  are 3-residually connected.*

*Proof.* If  $Wk(W, \text{id})$  is 3-residually connected, then  $Wk(W_{S'}, \text{id})$  and  $Wk(W_{S''}, \text{id})$  are so in particular. In return suppose  $Wk(W_{S'}, \text{id})$  and  $Wk(W_{S''}, \text{id})$  to be 3-residually connected. For a set  $M \subseteq S$  we define  $M' := M \cap S'$  and  $M'' := M \cap S''$ , hence  $M = M' \dot{\cup} M''$ . This is compatible with our definition of  $S_{ij}$  and  $T$ :

$$\begin{aligned} S_{ij} &= S_i \cap S_j = (S'_i \dot{\cup} S''_i) \cap (S'_j \dot{\cup} S''_j) = (S'_i \cap S'_j) \dot{\cup} (S''_i \cap S''_j) = S'_{ij} \dot{\cup} S''_{ij} \\ T &= S_1 \cap S_2 \cap S_3 = (S'_{12} \dot{\cup} S''_{12}) \cap (S'_3 \dot{\cup} S''_3) = (S'_{12} \cap S'_3) \dot{\cup} (S''_{12} \cap S''_3) = T' \dot{\cup} T'' \end{aligned}$$

Let  $w_K = \underline{s}'_1 \dots \underline{s}'_{m'} \underline{s}''_1 \dots \underline{s}''_{m''}$  with  $s'_i \in K'$ ,  $s''_i \in K''$ . Then  $w_{K'} = \underline{s}'_1 \dots \underline{s}'_{m'}$  (resp.  $w_{K''} = \underline{s}''_1 \dots \underline{s}''_{m''}$ ) is the corresponding longest elements in  $\langle K' \rangle \leq W_{S'} \leq W$  (resp.  $\langle K'' \rangle \leq W_{S''} \leq W$ ). We have three twisted expressions

$$\begin{aligned} w &= w_K \underline{a}'_1 \dots \underline{a}'_{n'} \underline{a}''_1 \dots \underline{a}''_{n''} \\ &= w_K \underline{b}'_1 \dots \underline{b}'_{n'} \underline{b}''_1 \dots \underline{b}''_{n''} \\ &= w_K \underline{c}'_1 \dots \underline{c}'_{n'} \underline{c}''_1 \dots \underline{c}''_{n''} \end{aligned}$$

with  $a'_i, a''_i \in S_1$ ,  $b'_i, b''_i \in S_2$  and  $c'_i, c''_i \in S_3$ . Thanks to Lemma 3.8 we can assume without loss of generality that  $a', b', c' \in S'$  and  $a'', b'', c'' \in S''$ . Hence we have also

$$\begin{aligned} w' &= w_{K'} \underline{a}'_1 \dots \underline{a}'_{n'} = \underline{s}'_1 \dots \underline{s}'_{m'} \underline{a}'_1 \dots \underline{a}'_{n'} \\ &= w_{K'} \underline{b}'_1 \dots \underline{b}'_{n'} = \underline{s}'_1 \dots \underline{s}'_{m'} \underline{b}'_1 \dots \underline{b}'_{n'} \\ &= w_{K'} \underline{c}'_1 \dots \underline{c}'_{n'} = \underline{s}'_1 \dots \underline{s}'_{m'} \underline{c}'_1 \dots \underline{c}'_{n'} \end{aligned}$$

and so  $w' \in w_{K'} C_{T'}$ , since **(3RC)** holds in  $Wk(W_{S'}, \text{id})$ . Analogue we get  $w'' \in w_{K''} C_{T''}$ . Hence

$$w' = \underline{s}'_1 \dots \underline{s}'_{m'} \underline{d}'_1 \dots \underline{d}'_{l'} \text{ and } w'' = \underline{s}''_1 \dots \underline{s}''_{m''} \underline{d}''_1 \dots \underline{d}''_{l''}$$

for  $d'_i \in T'$  and  $d''_i \in T''$ . This yields a twisted expression

$$\begin{aligned} w &= w' w'' = \underline{s}'_1 \dots \underline{s}'_{m'} \underline{d}'_1 \dots \underline{d}'_{l'} \underline{s}''_1 \dots \underline{s}''_{m''} \underline{d}''_1 \dots \underline{d}''_{l''} \\ &= \underline{s}'_1 \dots \underline{s}'_{m'} \underline{s}''_1 \dots \underline{s}''_{m''} \underline{d}'_1 \dots \underline{d}'_{l'} \underline{d}''_1 \dots \underline{d}''_{l''} \\ &= w_K \underline{d}'_1 \dots \underline{d}'_{l'} \underline{d}''_1 \dots \underline{d}''_{l''} \end{aligned}$$

with  $d'_i, d''_i \in T' \dot{\cup} T'' = T$ . Thus  $w \in w_K C_T$ .  $\square$

### 3.3. Computational testing for 3-residually connectedness

In section 2.4 we introduced an effective algorithm to calculate the poset graph for an arbitrary  $Wk(\theta)$  until a given maximal twisted length. So the idea is obvious to use these data and simply test for every combination of  $K, S_1, S_2, S_3$  if they yield a counterexample to **(3RC)**. If no counterexample can be found we have proved that  $Wk(\theta)$  is 3-residually connected. If  $(W, S)$  is itself finite, then there is not problem with this approach. For infinite Coxeter systems we cannot calculate the whole poset graph. But there are some infinite ones, that can also be addressed in this way.

**Proposition 3.12.** *Suppose the parabolic subgroup  $W_{S'}$  to be finite for any  $S' \subsetneq S$ . Define*

$$E := \{w \in \mathcal{I}_\theta : K, S_1, S_2, S_3 \subseteq S, w \in w_K C_{S_{12}} \cap w_K C_{S_{23}} \cap w_K C_{S_{31}}, w \notin w_K C_T\}$$

and assume  $E \neq \emptyset$ , i.e.  $Wk(\theta)$  is not 3-residually connected. Then there is a  $\rho_E \in \mathbb{N}_0$  with  $\max_{w \in E} \rho(w) \leq \rho_E$ .

*Proof.* For any counterexample the sets  $S_1, S_2, S_3$  cannot equal  $S$  by 3.6.3, hence by assumption the sets  $S_1, S_2, S_3$  are spherical. But then  $S_{12}, S_{23}, S_{31}$  as well as  $\theta(S_{12}), \theta(S_{23}), \theta(S_{31})$  must be spherical, too. Let  $w \in E$ , then  $w \in W_{\theta(S_{12})} w_K W_{S_{12}}$ , hence  $l(w) \leq l(w_{\theta(S_{12})}) + l(w_K) + l(w_{S_{12}})$ . Since there is only a finite count of proper subsets of  $S$ , we can choose

$$l_E = \max_{K, S' \subsetneq S} l(w_{\theta(S')}) + l(w_K) + l(w_{S'}) \leq \max_{S' \subsetneq S} 3 \cdot l(w_{S'}) = 3 \cdot \max_{s \in S} l(w_{S \setminus \{s\}}) < \infty$$

as upper bound for  $l(w), w \in E$ . For all  $w' \in \mathcal{I}_\theta$  we have  $\rho(w') \leq l(w')$  and so  $\rho_E = l_E$  is an upper bound for  $\rho(w), w \in E$ , too.  $\square$

*Remark 3.13.* Note, that this proposition also gives a manual, how to calculate the upper bound, since the length of the longest element in a finite Coxeter group can be easily calculate. There are 4 families of finite Coxeter groups and 6 finite Coxeter groups of exceptional type (cf. Theorem 1.25). The length of the longest element in each of them can be seen in Table 3.1. For more details on how to calculate those values (resp. formulas) see [Fra01, Section 1.2] and [Hum92, Section 2.11].

**Proposition 3.14.** *Let  $(W, S) = (W_1 \times W_2, S_1 \cup S_2)$  be a reducible Coxeter group. Then the length of the longest element in  $W$  is the sum of the lengths of the longest elements in  $W_1$  and  $W_2$ .*

*Proof.* This is immediate, since  $\text{ord}(st) = 2$  for  $s \in S_1, t \in S_2$ .  $\square$

$W$	$A_n$	$B_n$	$D_n$	$E_6$	$E_7$	$E_8$	$F_4$	$H_3$	$H_4$	$I_2(m)$
$l(w_0)$	$n(n+1)/2$	$n^2$	$n(n-1)$	36	63	120	24	15	60	$m$

Table 3.1.: Length of longest element in finite Coxeter groups

**Example 3.15.** Let  $W = \tilde{A}_2$  with  $S = \{s_1, s_2, s_3\}$ . Because of symmetry we can calculate  $l_E$  with the set  $S' = \{s_1, s_2\}$ . Then  $\langle S' \rangle \cong A_2$ , hence the length of the longest word in  $\langle S' \rangle$  is 3. Therefore  $l_E = \rho_E = 9$ . This means, to validate if  $\tilde{A}_2$  is 3-residually connected, we only need to calculate the poset graph of  $Wk(\theta)$  until we have all twisted involutions of twisted length 9.

Now we actually want to calculate the maximum element length over all proper parabolic subgroups for some Coxeter groups, where this value is finite. Table 3.2 shows the results for some interesting one, e.g. the affine Coxeter groups. In order to simplify notation in the table we sometimes does not properly distinguish between

certain cases, i.e. we use types like  $B_{n-3}$  without insisting on  $n \geq 5$ . For  $n = 3$  we would have  $B_0$ . In this case, we will consider this type as invalid possibility. For  $n = 4$  we would have  $B_1$ , which is not defined either. But in this case we will treat this type as  $A_1$ , which seems suitable.

$W$	All possible types for $W_{S \setminus \{s\}}$	$\max_{s \in S} l(w_{S \setminus \{s\}})$
$\tilde{A}_1$	$A_1$	1
$\tilde{A}_n (n \geq 2)$	$A_n$	$n(n+1)/2$
$\tilde{B}_2 = \tilde{C}_2$	$A_1 \times A_1, I_2(4)$	4
$\tilde{B}_n (n \geq 3)$	$B_n, D_n, D_{n-1} \times A_1, D_{n-m} \times B_m, A_3 \times B_{n-3}, B_{n-2} \times A_1 \times A_1$	$n^2$
$\tilde{C}_n (n \geq 3)$	$B_n, B_{n-1} \times A_1, B_{n-m} \times B_m$	$n^2$
$\tilde{D}_n (n \geq 4)$	$D_n, D_{n-2} \times A_1 \times A_1, D_{n-m} \times D_m$	$n(n-1)$
$\tilde{E}_6$	$E_6, A_5 \times A_1, A_2 \times A_2 \times A_2$	36
$\tilde{E}_7$	$E_7, D_6 \times A_1, A_5 \times A_2, A_7, A_3 \times A_3 \times A_1$	63
$\tilde{E}_8$	$E_8, E_7 \times A_1, E_6 \times A_2, D_5 \times A_3, A_4 \times A_4, A_5 \times A_2 \times A_1, A_8, A_7 \times A_1, D_8$	120
$\tilde{F}_4$	$F_4, B_3 \times A_1, A_2 \times A_2, A_3 \times A_1, B_4$	24
$\tilde{G}_2$	$I_2(6), A_1 \times A_1, A_2$	6

Table 3.2.: Maximum element lengths in proper parabolic subgroups

**Theorem 3.16.** *For all pairs  $(W, \theta)$  of Coxeter groups and Coxeter system automorphisms from Table 3.3 the twisted weak ordering  $Wk(W, \theta)$  is 3-residually connected.*

$W$	$\theta$
$A_n, 1 \leq n \leq 9$	$\text{id}, (s_1, \dots, s_n) \mapsto (s_n, \dots, s_1)$
$BC_n, 2 \leq n \leq 7$	$\text{id}$
$D_n, 4 \leq n \leq 6$	$\text{id}$
$E_6$	$\text{id}, (s_1, s_2, s_3, s_4, s_5, s_6) \mapsto (s_6, s_5, s_3, s_4, s_2, s_1)$
$E_7$	$\text{id}$
$E_8$	$\text{id}$
$F_4$	$\text{id}$
$H_3$	$\text{id}$
$H_4$	$\text{id}$
$I_2(p), 5 \leq p$	$\text{id}, (s_1, s_2) \mapsto (s_2, s_1)$
$\tilde{A}_n, 1 \leq n \leq 6$	$\text{id}$
$\tilde{B}_2$	$\text{id}$
$\tilde{B}_3$	$\text{id}$
$\tilde{C}_3$	$\text{id}$
$\tilde{G}_2$	$\text{id}$

Table 3.3.: Some 3-residually connected weak orderings

*Proof.* The cases with  $|S| \leq 2$  are immediate by Corollary 3.7. The other cases from

the table have been proved by a simple algorithm. In the calculated poset graph we iterate over all  $K \subseteq S$  and then over all... **TODO**  $\square$

## 4. Residually connectedness of flip-flop systems

This section is heavily based on [Hor09], but we will only introduce the bare minimum needed for our purposes. So for more details refer to [Hor09].

### 4.1. Chamber systems

**Definition 4.1.** A **chamber system over  $I$**  is a pair  $\mathcal{C} = (C, (\sim_i, i \in I))$ , with a nonempty set  $C$ , whose members are called **chambers** and a family of equivalence relations  $\sim_i$ , indexed by  $i \in I$ , that satisfies the implication

$$c \sim_i d \wedge c \sim_j d \Rightarrow c = d \vee i = j$$

for all  $c, d \in C$  and  $i, j \in I$ . The cardinality  $|I|$  is called the **rank** of  $\mathcal{C}$ . For all chamber systems we will assume that they have finite rank. If for two chambers  $c, d$  we have  $c \sim_i d$ , then  $c$  is called **i-adjacent** to  $d$  or just **adjacent**.

So the main assertion for chamber systems is, that two distinct chambers  $c, d \in C$  are at most adjacent by one  $i \in I$ . For the rest of this section  $\mathcal{C} = (C, (\sim_i, i \in I))$  will denote a chamber system.

**Example 4.2.** For an arbitrary Coxeter system let  $W$  act as set of chambers and for each generator  $s \in S$  define a equivalence relation  $w \sim_s v$  if and only if either  $w = v$  or  $ws = v$ . That this are really equivalence relations is easy to check. So suppose  $w \sim_s v$ ,  $w \sim_t v$  for two distinct generators  $s, t \in S$ . The assumption  $w \neq v$  immediately yields a contradiction by  $ws = v = wt \iff s = t$ . Hence this is indeed a chamber system.

The previous example is just a special case of a quite general recipe to create chamber systems from groups, the so-called coset chamber systems.

**Definition 4.3.** [BC, Definition 3.6.3] Let  $G$  be an arbitrary group with a subgroup  $B$  and a family of subgroups  $(G_i, i \in I)$  such that  $B \subseteq G_i$  for  $i \in I$ . Choose the chamber set  $C$  as the set of all  $B$ -cosets  $gB$  for some  $g \in G$  and define the equivalence relations  $(\sim_i, i \in I)$  by  $gB \sim_i hB$  iff  $gG_i = hG_i$ . Then we call this chamber system the **coset chamber system** of  $G$  on  $B$  with respect to  $(G_i, i \in I)$ .

**Lemma 4.4.** *Coset chamber systems are chamber systems.*

*Proof.* As easy to check the  $\sim_i$  are equivalence relations. So suppose  $gB \sim_i hB$  and  $gB \sim_j hB$  and let  $gB \neq hB$ , i.e.  $h^{-1}g \notin B$ . **TODO** Different definitions of chamber system at Horn and Buekenhout/Cohen?  $\square$

If two chambers  $c, d \in C$  in a chamber system are not adjacent, then there might be a chain of subsequent adjacent chambers with  $c$  as first and  $d$  as last chamber.

**Definition 4.5.** Let  $G = (c_0, \dots, c_k)$  be a finite sequence of chambers  $c_i \in C$  with  $c_{i-1}$  adjacent to  $c_i$  for all  $1 \leq i \leq k$ . Then  $G$  is called a **gallery** in  $\mathcal{C}$  whereas the integer  $k$  is called the **length** of  $G$ . The first element  $c_0$  of a gallery  $G$  is denoted by  $\alpha(G)$  and the last by  $\omega(G)$ . If for two chambers  $c, d \in C$  there is a gallery  $G$  with  $\alpha(G) = c$  and  $\omega(G) = d$ , then we say that  $G$  **joins**  $c$  and  $d$ . A gallery with  $\alpha(G) = \omega(G)$  is called **closed** and a gallery  $G = (c_0, \dots, c_k)$  with  $c_{i-1} \neq c_i$  for all  $1 \leq i \leq k$  is called **simple**. If a gallery  $G$  of length  $k$  joins two chambers  $c, d$  and there is no joining gallery of shorter length, then we call  $G$  a **minimal gallery joining  $c$  and  $d$** .

Note, that two chambers are adjacent if and only if they can be joined by a gallery of length 1.

**Definition 4.6.** The chamber system  $\mathcal{C}$  is called **connected** if any two chambers  $c, d \in C$  can be joined by a gallery.

**Definition 4.7.** Let  $G = (c_0, \dots, c_k)$  be a gallery and let  $J \subset I$  be a subset. If for  $1 \leq i \leq k$  there is a  $j \in J$  with  $c_{i-1} \sim_j c_i$ , then we call  $G$  a  **$J$ -gallery**. Two chambers  $c, d \in C$ , that have a  $J$ -gallery joining them, are called  **$J$ -equivalent**, denoted by  $c \sim_J d$ .

**Definition 4.8.** For a chamber  $c \in C$  and a subset  $J \subseteq I$ , we call the set  $R_J(c) := \{d \in C : c \sim_J d\}$  a  **$J$ -residue**. The set  $J$  is also called the **type** of a residue  $R_J(c)$ . If  $|J| = 1$ , say  $J = \{i\}$ , then  $R_J(c) = R_{\{i\}}(c)$  is called a  **$i$ -panel**.

Note that for any chamber system  $(C, (\sim_i, i \in I))$ ,  $c \in C$  and  $J \subseteq I$ , the chamber system  $(R_J(c), (\sim_j, j \in J))$  is connected by construction.

**Definition 4.9.** Let  $\mathcal{C}$  be a chamber system over  $I$ . We call it a **residually connected** chamber system if the following holds: For every  $J \subseteq I$  and every family of residues  $(R_{I \setminus \{j\}}, j \in J)$  with pairwise nonempty intersection we have

$$\bigcap_{j \in J} R_{I \setminus \{j\}} = R_{I \setminus J}(c)$$

for some  $c \in C$ .

**Lemma 4.10.** [BC, Lemma 3.4.9] *For a connected chamber system  $\mathcal{C}$  over  $I$  the following statements are equivalent.*

1.  $\mathcal{C}$  is residually connected.
2. If  $J, K, L$  are subsets of  $I$  and if  $R_J, R_K, R_L$  are  $J$ -,  $K$ -,  $L$ -residues which have pairwise non-empty intersections, then  $R_J \cap R_K \cap R_L$  is a  $(R \cap K \cap L)$ -residue.



## 4.2. Buildings

**Definition 4.11.** A **building** of type  $(W, S)$  is a pair  $(\mathcal{C}, \delta)$  with a nonempty set  $\mathcal{C}$  and a map  $\delta : \mathcal{C} \times \mathcal{C} \rightarrow W$ , called **distance function**, so that for  $x, y \in \mathcal{C}$  and  $w = \delta(x, y)$  we have

$$(\text{Bu1}) \quad w = e \iff x = y;$$

$$(\text{Bu2}) \quad \text{for } z \in \mathcal{C} \text{ with } \delta(y, z) = s \in S \text{ we have } \delta(x, z) \in \{w, ws\}, \text{ and if in addition } l(ws) = l(w) + 1 \text{ then we have } \delta(x, z) = ws;$$

$$(\text{Bu3}) \quad \text{for } s \in S \text{ there exists a } z \in \mathcal{C} \text{ with } \delta(y, z) = s \text{ and } \delta(x, z) = ws.$$

For the rest of the subsection let  $(\mathcal{C}, \delta)$  always be a building of type  $(W, S)$ .

**Definition 4.12.** Then cardinality of  $S$  is called the **rank** of the building.

**Definition 4.13.** For each  $s \in S$  we define  $c, d \in \mathcal{C}$  to be  $s$ -adjacent if and only iff  $\delta(c, d) \in \{e, s\}$ . Then  $(\mathcal{C}, (\sim_s, s \in S))$  is called the **associated chamber system** to  $(\mathcal{C}, \delta)$ .

**Lemma 4.14.** *Then the associated chamber system is a chamber system.*

*Proof.* Let  $c, d \in \mathcal{C}$  and  $s, t \in S$  with  $c \sim_s d$  and  $c \sim_t d$ . If  $c \neq d$ , then  $\delta(c, d) = s$  and  $\delta(c, d) = t$ , hence  $s = t$ .  $\square$

**Definition 4.15.** A **gallery**, **residue** or **panel** in a building is a gallery, residue or panel in the associated chamber system.

**Definition 4.16.** We call the building  $(\mathcal{C}, \delta)$  **thick** (resp. **thin**), if for every chamber  $c \in \mathcal{C}$  and every  $s \in S$  there are at least three (resp. exactly two) chambers  $s$ -adjacent to  $c$ .

**Example 4.17.** For a Coxeter system  $(W, S)$  define a map

$$\delta_S : W \times W \rightarrow W : (x, y) \mapsto x^{-1}y.$$

Then  $\delta_S(x, y) = e \iff x = y$ . Furthermore for  $z \in W$  with  $\delta_S(y, z) = s$ , i.e.  $z = ys$ , we have  $\delta_S(x, z) = x^{-1}z = x^{-1}ys = \delta(x, y)s$ . For  $s \in S$  and  $x, y \in W$  choose  $z = ys$ . Then  $\delta_S(y, z) = s$  and as before  $\delta_S(x, z) = \delta_S(x, y)s$ . Hence  $(W, \delta_S)$  is a building of type  $(W, S)$ . More precisely, it is a thin building, since for every  $s \in S$  and  $x, y \in W$  we have  $\delta_S(x, y) = x^{-1}y \in \{e, s\}$  if and only if  $x = y$  or  $y = xs$ , hence there are exactly two chambers  $s$ -adjacent to  $x$ .

This example for a thin building of type  $(W, S)$  can be indeed called "the" thin building of type  $(W, S)$  as the following lemma shows.

**Lemma 4.18.** [BC, Theorem 4.2.8] *Let  $(\mathcal{C}, \delta)$  be a thin. Then it is isometric to the building  $(W, \delta_S)$  (cf. Example 4.17).*

**Definition 4.19.** We call a subset  $\Sigma \subseteq \mathcal{C}$  an **apartment** if  $(\Sigma, \delta|_\Sigma)$  is isometric to  $(W, \delta_S)$  from Example 4.17, or equivalent if  $(\Sigma, \delta|_\Sigma)$  is thin.

**Theorem 4.20.** [BC, Theorem 11.2.5] *For any two chambers  $c, d \in \mathcal{C}$  there is an apartment  $\Sigma$  with  $c, d \in \Sigma$ . In particular every building contains at least one apartment.*

*Proof.* The proof for the first statement can be found in [BC, Theorem 11.2.5]. The second is an immediate conclusion of the first, since because of  $|S| \geq 1$  and the third building axiom every building must at least contain two chambers. And so there is at least one pair of chambers, that has to be contained in an apartment by the first statement.  $\square$

So thin buildings are precisely those, that contain exactly one apartment, i.e. are apartments themselves.

**Definition 4.21.** The building  $(\mathcal{C}, \delta)$  is called **spherical** if  $W$  is finite. In this case  $W$  has a longest element  $w_0$  and two chambers  $c, d$  are called **opposite** if  $\delta(c, d) = w_0$ , denoted by  $c \text{ opp } d$ .

**Definition 4.22.** A set of chambers  $M \subseteq \mathcal{C}$  is called **connected** if any two chambers in  $M$  can be joined by a gallery completely contained in  $M$ . If in addition, every minimal gallery joining two chambers in  $M$  is completely contained in  $M$ , then  $M$  is called **convex**.

### 4.3. Twin buildings

**Definition 4.23.** Let  $(\mathcal{C}_+, \delta_+)$  and  $(\mathcal{C}_-, \delta_-)$  be two buildings of same type  $(W, S)$ . Then we call the triple  $(\mathcal{C}_+, \mathcal{C}_-, \delta^*)$  with

$$\delta^* : (\mathcal{C}_+ \times \mathcal{C}_-) \cup (\mathcal{C}_- \times \mathcal{C}_+) \rightarrow W$$

a **twin building of type**  $(W, S)$  and  $\delta^*$  a **codistance function** if for  $\varepsilon \in \{+, -\}$ ,  $x \in \mathcal{C}_\varepsilon$ ,  $y \in \mathcal{C}_{-\varepsilon}$  and  $w = \delta^*(x, y)$  we have

$$(\text{Tw1}) \quad \delta^*(y, x) = w^{-1};$$

$$(\text{Tw2}) \quad \text{for } z \in \mathcal{C}_{-\varepsilon} \text{ with } \delta_{-\varepsilon}(y, z) = s \in S \text{ and } l(ws) = l(w) - 1 \text{ we have } \delta^*(x, z) = ws;$$

$$(\text{Tw3}) \quad \text{for every } s \in S \text{ there is a } z \in \mathcal{C}_{-\varepsilon} \text{ with } \delta_{-\varepsilon}(y, z) = s \text{ and } \delta^*(x, z) = ws.$$

For the rest of this subsection let  $(\mathcal{C}_+, \mathcal{C}_-, \delta^*)$  be a twin building.

**Definition 4.24.** A **gallery**, **residue** or **panel** in a twin building  $(\mathcal{C}_+, \mathcal{C}_-, \delta^*)$  is a gallery, residue or panel in either  $\mathcal{C}_+$  or  $\mathcal{C}_-$ .

**Definition 4.25.** Two chambers  $c \in \mathcal{C}_+$ ,  $d \in \mathcal{C}_-$  are called **opposite**, denoted by  $c \text{ opp } d$  if  $\delta^*(c, d) = e$ . Two residues  $R_+ \subseteq \mathcal{C}_+$ ,  $R_- \subseteq \mathcal{C}_-$  are called **opposite** if they have the same type and contain opposite chambers.

**Definition 4.26.** A pair  $(\Sigma_+, \Sigma_-)$  with  $\Sigma_+ \subseteq \mathcal{C}_+$  and  $\Sigma_- \subseteq \mathcal{C}_-$  is called a **twin apartment** if  $\Sigma_+$  is an apartment in  $\mathcal{C}_+$ ,  $\Sigma_-$  is an apartment in  $\mathcal{C}_-$  and every chamber in  $\mathcal{C}_+ \cup \mathcal{C}_-$  is precisely opposite to one other chamber in  $\mathcal{C}_+ \cup \mathcal{C}_-$ .

**Example 4.27.** [Hor09, Example 1.6.8] For an arbitrary spherical building  $(\mathcal{C}_+, \delta_+)$  of type  $(W, S)$  there is a natural associated twin building  $(\mathcal{C}_+, \mathcal{C}_-, \delta^*)$ . Here  $\mathcal{C}_-$  is just a copy of  $\mathcal{C}_+$ , i.e. for every chamber  $c_+ \in \mathcal{C}_+$  there is a chamber  $c_- \in \mathcal{C}_-$ , with distance function

$$\delta_- : (c_-, d_-) \mapsto w_0 \delta_+(c_+, d_+) w_0.$$

As codistance function we defined

$$\delta^* : (c_\varepsilon, d_{-\varepsilon}) \mapsto \begin{cases} \delta_+(c_+, d_+) w_0, & \varepsilon = +; \\ w_0 \delta_+(c_+, d_+), & \varepsilon = -. \end{cases}$$

In this case, being opposite as defined for buildings and being opposite as defined for twin buildings coincide, by

$$c_+ \text{ opp } d_+ \iff \delta_+(c_+, d_+) = w_0 \iff \delta_+(c_+, d_+) w_0 = e \iff c_+ \text{ opp } d_-.$$

## 4.4. Building flips and flip-flop systems

In this section let  $\mathcal{C} = (\mathcal{C}_+, \mathcal{C}_-, \delta^*)$  be a twin building of type  $(W, S)$ .

**Definition 4.28.** Let  $\tilde{\theta}$  be a permutation of  $\mathcal{C}_+ \cup \mathcal{C}_-$  satisfying

$$\text{(Fl1)} \quad \tilde{\theta}^2 = \text{id},$$

$$\text{(Fl2)} \quad \tilde{\theta}(\mathcal{C}_+) = \mathcal{C}_- \text{ and }$$

$$\text{(Fl3)} \quad \text{for } \varepsilon \in \{+, -\}, x, y \in \mathcal{C}_+ \text{ and } z \in \mathcal{C}_- \text{ we have } x \sim y \text{ iff } \tilde{\theta}(x) \sim \tilde{\theta}(y) \text{ and } x \text{ opp } z \text{ iff } \tilde{\theta}(x) \text{ opp } \tilde{\theta}(z).$$

Then we call  $\tilde{\theta}$  a **building quasi-flip** of  $\mathcal{C}$ . If in addition

$$\text{(Fl3a)} \quad \text{for } \varepsilon \in \{+, -\}, x, y \in \mathcal{C}_+ \text{ and } z \in \mathcal{C}_- \text{ we have } \delta_\varepsilon(x, y) = \delta_{-\varepsilon}(\tilde{\theta}(x), \tilde{\theta}(y)) \text{ and } \delta^*(x, z) = \delta^*(\tilde{\theta}(x), \tilde{\theta}(z)),$$

then we call  $\tilde{\theta}$  a **building flip** of  $\mathcal{C}$ .

So building (quasi-)flips permute the two halves of a twin building while preserving adjacency and opposition and building flips also flip the distance and preserve the codistance. The next lemma gives a first idea, how building quasi-flips are coherent to the poset  $Wk(\theta)$ .

**Lemma 4.29.** [Hor09, Lemma 2.1.4] *Let  $\tilde{\theta}$  be a building quasi-flip of  $\mathcal{C}$ . Then  $\tilde{\theta}$  induces an involutory (i.e. order at most 2) Coxeter system automorphism  $\theta$  on  $(W, S)$ , so that for  $\varepsilon \in \{+, -\}, x, y \in \mathcal{C}_+$  and  $z \in \mathcal{C}_-$  we have  $\theta(\delta_\varepsilon(x, y)) = \delta_{-\varepsilon}(\tilde{\theta}(x), \tilde{\theta}(y))$  and  $\theta(\delta^*(x, z)) = \delta^*(\tilde{\theta}(x), \tilde{\theta}(z))$ .*

Of course the coherence between building quasi-flips and  $Wk(\theta)$  is not clear by any means, but at least do building quasi-flips admit a Coxeter system and an involutory Coxeter system automorphism, hence every building quasi-flip has a corresponding twisted weak ordering poset  $Wk(W, \theta)$ . But there are some definitions left until we have our objects of interest.

**Definition 4.30.** For a chamber  $c \in \mathcal{C}_+ \cup \mathcal{C}_-$  we call  $\delta^{\tilde{\theta}}(c) := \delta^*(c, \tilde{\theta}(c))$  the  $\tilde{\theta}$ -codistance of  $c$  and  $l^{\tilde{\theta}}(c) = l(\delta^{\tilde{\theta}}(c))$  the **numerical  $\theta$ -codistance** of  $c$ .

**Definition 4.31.** We call a building (quasi-)flip **proper** if there is a chamber  $c \in \mathcal{C}_+ \cup \mathcal{C}_-$  with  $\delta^{\tilde{\theta}}(c) = e \iff l^{\tilde{\theta}}(c) = 0$ .

**Definition 4.32.** Let  $\tilde{\theta}$  be a building quasi-flip of  $\mathcal{C}$  and let  $R \subseteq \mathcal{C}_+$  be an arbitrary residue. The **minimal numerical  $\tilde{\theta}$ -codistance** of  $R$  is defined as  $\min_{c \in R} l^{\tilde{\theta}}(c)$ .

According to the definition of  $c_+ \text{ opp } d_-$ , i.e.  $l(\delta^*(c_+, d_-)) = 0$ , we can consider the chambers that actually reach the minimal numerical  $\tilde{\theta}$ -codistance as those, that are mapped away "as far as possible". In particular if  $\min_{c \in R} l^{\tilde{\theta}}(c) = 0$ , this are precisely those chambers, mapped to their opposite.

**Definition 4.33.** Let  $\tilde{\theta}$  be a building quasi-flip of  $\mathcal{C}$  and let  $R \subseteq \mathcal{C}_+$  be an arbitrary residue. The (sub)chamber system of all chambers with minimal numerical  $\tilde{\theta}$ -codistance

$$R^{\tilde{\theta}} := \{c \in R : l^{\tilde{\theta}}(c) = \min_{d \in R} l^{\tilde{\theta}}(d)\}$$

together with the equivalence relations inherited from  $\mathcal{C}_+$  is called the **induced flip-flop system** on  $R$ . In case  $R = \mathcal{C}_+$ , we call  $C^{\tilde{\theta}} := C_+^{\tilde{\theta}} = R^{\tilde{\theta}}$  the **flip-flop system** associated to  $\tilde{\theta}$ .

# Appendix



## A. Source codes

### File misc.gap

```
1 GroupAutomorphismByPermutation := function (G, generatorPermutation)
2   local automorphism, generators;
3
4   generators := GeneratorsOfGroup(G);
5
6   if generatorPermutation = "id" or generatorPermutation = [1..Length(
7     generators)] then
8     automorphism := IdentityMapping(G);
9     SetName(automorphism, "id");
10
11    return automorphism;
12  elif generatorPermutation = "-id" then
13    generatorPermutation := Reversed([1..Length(GeneratorsOfGroup(G))]);
14  fi;
15
16  automorphism := GroupHomomorphismByImages(G, G, generators, generators{
17    generatorPermutation});
18  SetName(automorphism, Concatenation("(", JoinStringsWithSeparator(
19    generatorPermutation, ","), ")"));
20
21  return automorphism;
22 end;
23
24 GroupAutomorphismIdNeg := function (G)
25   return GroupAutomorphismByPermutation(G, Reversed([1..Length(
26     GeneratorsOfGroup(G))]));
27 end;
28
29 GroupAutomorphismId := function (G)
30   return GroupAutomorphismByPermutation(G, [1..Length(GeneratorsOfGroup(G))
31     ]);
32 end;
33
34 FindElement := function (list, selector)
35   local i;
36
37   for i in [1..Length(list)] do
38     if (selector(list[i])) then
39       return list[i];
40     fi;
41   od;
42
43   return fail;
44 end;
45
46 StringToFilename := function(str)
47   local result, c;
48
49   result := "";
50
51   for c in str do
52     if IsDigitChar(c) or IsAlphaChar(c) or c = '-' or c = '_' then
```

```
48         Add(result, c);
49     else
50         Add(result, '_');
51     fi;
52 od;
53
54     return result;
55 end;
56
57 IO_ReadLinesIterator := function (file)
58     local IsDone, Next, ShallowCopy;
59
60     IsDone := function (iter)
61         return iter!.nextLine = "" or iter!.nextLine = fail;
62     end;
63
64     Next := function (iter)
65         local line;
66
67         line := iter!.nextLine;
68
69         if line = fail then
70             Error>LastSystemError();
71             return fail;
72         fi;
73
74         iter!.nextLine := IO_ReadLine(iter!.file);
75
76         return Chomp(line);
77     end;
78
79     ShallowCopy := function (iter)
80         return fail;
81     end;
82
83     return IteratorByFunctions(rec(IsDoneIterator := IsDone, NextIterator :=
84         Next,
85         ShallowCopy := ShallowCopy, file := file, nextLine := IO_ReadLine(file
86         ));
87 end;
88
89 IO_ReadLinesIteratorCSV := function (file, seperator)
90     local IsDone, Next, ShallowCopy;
91
92     IsDone := function (iter)
93         return iter!.nextLine = "" or iter!.nextLine = fail;
94     end;
95
96     Next := function (iter)
97         local line, lineSplitted, result, i;
98
99         line := iter!.nextLine;
100        if line = fail then
101            Error>LastSystemError();
102            return fail;
103        fi;
104        iter!.nextLine := IO_ReadLine(iter!.file);
105
106        lineSplitted := SplitString(Chomp(line), iter!.seperator);
107        result := rec();
108
109        for i in [1..Minimum(Length(iter!.headers), Length(lineSplitted))] do
110            result.(iter!.headers[i]) := EvalString(lineSplitted[i]);
111        od;
```



---

```

110
111     return result;
112 end;
113
114 ShallowCopy := function (iter)
115     return fail;
116 end;
117
118 return IteratorByFunctions(rec(IsDoneIterator := IsDone, NextIterator :=
    Next,
    ShallowCopy := ShallowCopy, file := file, seperator := seperator,
    headers := SplitString(Chomp(IO_ReadLine(file)), seperator),
    nextLine := IO_ReadLine(file)));
122 end;

```

## File coxeter.gap

```

1 Read("coxeter-generators.gap");
2
3 coxeterElementComparisons := 0;
4
5 CoxeterElementsCompare := function (w1, w2)
6     coxeterElementComparisons := coxeterElementComparisons + 1;
7     return w1 = w2;
8 end;
9
10 CoxeterMatrixEntry := function(matrix, i, j)
11     local temp, rank;
12     rank := -1/2 + Sqrt(1/4 + 2*Length(matrix)) + 1;
13
14     if (i = j) then
15         return 1;
16     fi;
17
18     if (i > j) then
19         temp := i;
20         i := j;
21         j := temp;
22     fi;
23
24     return matrix[(rank-1)*(rank)/2 - (rank-i)*(rank-i+1)/2 + (j-i-1) + 1];
25 end;

```

## File coxeter-generators.gap

```

1 # Generates a coxeter group with given rank and relations. The relations have
  to
2 # be given in a linear list of the upper right entries (above diagonal) of the
3 # coxeter matrix.
4 #
5 # Example:
6 # To generate the coxeter group A_4 with the following coxeter matrix:
7 #
8 # | 1 3 2 2 |
9 # | 3 1 3 2 |
10 # | 2 3 1 3 |
11 # | 2 2 3 1 |
12 #
13 # A4 := CoxeterGroup(4, [3,2,2, 3,2, 3]);
14 CoxeterGroup := function (rank, upperTriangleOfCoxeterMatrix)
15     local generatorNames, relations, F, S, W, i, j, k;
16

```

```

17     generatorNames := List([1..rank], n -> Concatenation("s", String(n)));
18
19     F := FreeGroup(generatorNames);
20     S := GeneratorsOfGroup(F);
21
22     relations := [];
23
24     Append(relations, List([1..rank], n -> S[n]^2));
25
26     k := 1;
27     for i in [1..rank] do
28         for j in [i+1..rank] do
29             Add(relations, (S[i]*S[j])^(upperTriangleOfCoxeterMatrix[k]));
30             k := k + 1;
31         od;
32     od;
33
34     W := F / relations;
35
36     return W;
37 end;
38
39 CoxeterGroup_An := function (n)
40     local upperTriangleOfCoxeterMatrix, W;
41
42     upperTriangleOfCoxeterMatrix := Flat(List(Reversed([1..n-1]), m ->
43         Concatenation([3], List([1..m-1], o -> 2))));
44
45     #W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);
46     W := GroupWithGenerators(List([1..n], s -> (s,s+1)));
47
48     SetName(W, Concatenation("A_{", String(n), "}"));
49     SetSize(W, Factorial(n + 1));
50
51     return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
52 end;
53
54 CoxeterGroup_BCn := function (n)
55     local upperTriangleOfCoxeterMatrix, W;
56
57     upperTriangleOfCoxeterMatrix := Flat(List(Reversed([1..n-1]), m ->
58         Concatenation([3], List([1..m-1], o -> 2))));
59     upperTriangleOfCoxeterMatrix[Length(upperTriangleOfCoxeterMatrix)] := 4;
60
61     W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);
62
63     SetName(W, Concatenation("BC_{", String(n), "}"));
64     SetSize(W, 2^n * Factorial(n));
65
66     return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
67 end;
68
69 CoxeterGroup_Dn := function (n)
70     local upperTriangleOfCoxeterMatrix, W;
71
72     upperTriangleOfCoxeterMatrix := Flat(List(Reversed([1..n-1]), m ->
73         Concatenation([3], List([1..m-1], o -> 2))));
74     upperTriangleOfCoxeterMatrix[Length(upperTriangleOfCoxeterMatrix)] := 2;
75     upperTriangleOfCoxeterMatrix[Length(upperTriangleOfCoxeterMatrix) - 1] :=
76         3;
77     upperTriangleOfCoxeterMatrix[Length(upperTriangleOfCoxeterMatrix) - 2] :=
78         3;
79
80     W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);

```

---

```

76
77     SetName(W, Concatenation("D_{", String(n), "}"));
78     SetSize(W, 2^(n-1) * Factorial(n));
79
80     return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
81 end;
82
83 CoxeterGroup_E6 := function ()
84     local upperTriangleOfCoxeterMatrix, W;
85
86     upperTriangleOfCoxeterMatrix := [3, 2, 2, 2, 2, 3, 2, 2, 2, 3, 3, 2, 2,
      2, 3];
87
88     W := CoxeterGroup(6, upperTriangleOfCoxeterMatrix);
89
90     SetName(W, "E_6");
91     SetSize(W, 2^7 * 3^4 * 5);
92
93     return rec(group := W, rank := 6, matrix := upperTriangleOfCoxeterMatrix);
94 end;
95
96 CoxeterGroup_E7 := function ()
97     local upperTriangleOfCoxeterMatrix, W;
98
99     upperTriangleOfCoxeterMatrix := [3, 2, 2, 2, 2, 2, 3, 2, 2, 2, 2, 3, 3,
      2, 2, 2, 2, 2, 3, 2, 3];
100
101     W := CoxeterGroup(7, upperTriangleOfCoxeterMatrix);
102
103     SetName(W, "E_7");
104     SetSize(W, 2^10 * 3^4 * 5 * 7);
105
106     return rec(group := W, rank := 7, matrix := upperTriangleOfCoxeterMatrix);
107 end;
108
109 CoxeterGroup_E8 := function ()
110     local upperTriangleOfCoxeterMatrix, W;
111
112     upperTriangleOfCoxeterMatrix := [3, 2, 2, 2, 2, 2, 2, 3, 2, 2, 2, 2, 2,
      3, 3, 2, 2, 2, 2, 2, 2, 3, 2, 2, 3, 2, 3];
113
114     W := CoxeterGroup(8, upperTriangleOfCoxeterMatrix);
115
116     SetName(W, "E_8");
117     SetSize(W, 2^14 * 3^5 * 5^2 * 7);
118
119     return rec(group := W, rank := 8, matrix := upperTriangleOfCoxeterMatrix);
120 end;
121
122 CoxeterGroup_F4 := function ()
123     local upperTriangleOfCoxeterMatrix, W;
124
125     upperTriangleOfCoxeterMatrix := [3, 2, 2, 4, 2, 3];
126
127     W := CoxeterGroup(4, upperTriangleOfCoxeterMatrix);
128
129     SetName(W, "F_4");
130     SetSize(W, 2^7 * 3^2);
131
132     return rec(group := W, rank := 4, matrix := upperTriangleOfCoxeterMatrix);
133 end;
134
135 CoxeterGroup_H3 := function ()
136     local upperTriangleOfCoxeterMatrix, W;

```

```

137
138     upperTriangleOfCoxeterMatrix := [5, 2, 3];
139
140     W := CoxeterGroup(3, upperTriangleOfCoxeterMatrix);
141
142     SetName(W, "H_3");
143     SetSize(W, 120);
144
145     return rec(group := W, rank := 3, matrix := upperTriangleOfCoxeterMatrix);
146 end;
147
148 CoxeterGroup_H4 := function ()
149     local upperTriangleOfCoxeterMatrix, W;
150
151     upperTriangleOfCoxeterMatrix := [5, 2, 2, 3, 2, 3];
152
153     W := CoxeterGroup(4, upperTriangleOfCoxeterMatrix);
154
155     SetName(W, "H_4");
156     SetSize(W, 14400);
157
158     return rec(group := W, rank := 4, matrix := upperTriangleOfCoxeterMatrix);
159 end;
160
161 CoxeterGroup_I2m := function (m)
162     local upperTriangleOfCoxeterMatrix, W;
163
164     upperTriangleOfCoxeterMatrix := [m];
165
166     W := CoxeterGroup(2, upperTriangleOfCoxeterMatrix);
167
168     SetName(W, Concatenation("I_2(", String(m), ")"));
169     SetSize(W, 2*m);
170
171     return rec(group := W, rank := 2, matrix := upperTriangleOfCoxeterMatrix);
172 end;
173
174 CoxeterGroup_TildeAn := function (n)
175     local upperTriangleOfCoxeterMatrix, W;
176
177     upperTriangleOfCoxeterMatrix := Flat(List(Reversed([1..n]), m ->
178         Concatenation([3], List([1..m-1], o -> 2))));
179
180     if n = 1 then
181         upperTriangleOfCoxeterMatrix[1] := 0;
182     else
183         upperTriangleOfCoxeterMatrix[n] := 3;
184     fi;
185
186     W := CoxeterGroup(n + 1, upperTriangleOfCoxeterMatrix);
187
188     SetName(W, Concatenation("\\tilde A_{", String(n), "}"));
189     SetSize(W, infinity);
190
191     return rec(group := W, rank := n + 1, matrix :=
192         upperTriangleOfCoxeterMatrix);
193 end;
194
195 CoxeterGroup_A1xA1 := function ()
196     local upperTriangleOfCoxeterMatrix, W, n;
197
198     n := 2;
199     upperTriangleOfCoxeterMatrix := [2];
200

```

---

```

199     W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);
200
201     SetName(W, "A_1 \\times A_1");
202     SetSize(W, Factorial(2)*Factorial(2));
203
204     return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
205 end;
206
207 CoxeterGroup_A2xA2 := function ()
208     local upperTriangleOfCoxeterMatrix, W, n;
209
210     n := 4;
211     upperTriangleOfCoxeterMatrix := [3,2,2, 2,2, 3];
212
213     W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);
214
215     SetName(W, "A_2 \\times A_2");
216     SetSize(W, Factorial(3)*Factorial(3));
217
218     return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
219 end;
220
221 CoxeterGroup_A3xA3 := function ()
222     local upperTriangleOfCoxeterMatrix, W, n;
223
224     n := 6;
225     upperTriangleOfCoxeterMatrix := [3,2,2,2,2, 3,2,2,2, 2,2,2, 3,2, 3];
226
227     W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);
228
229     SetName(W, "A_3 \\times A_3");
230     SetSize(W, Factorial(4)*Factorial(4));
231
232     return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
233 end;
234
235 CoxeterGroup_A1xA1xA1 := function ()
236     local upperTriangleOfCoxeterMatrix, W, n;
237
238     n := 3;
239     upperTriangleOfCoxeterMatrix := [2,2, 2];
240
241     W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);
242
243     SetName(W, "A_1 \\times A_1 \\times A_1");
244     SetSize(W, Factorial(2)*Factorial(2)*Factorial(2));
245
246     return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
247 end;
248
249 CoxeterGroup_A2xA2xA2 := function ()
250     local upperTriangleOfCoxeterMatrix, W, n;
251
252     n := 6;
253     upperTriangleOfCoxeterMatrix := [3,2,2,2,2, 2,2,2,2, 3,2,2, 2,2, 3];
254
255     W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);
256
257     SetName(W, "A_2 \\times A_2 \\times A_2");
258     SetSize(W, Factorial(3)*Factorial(3)*Factorial(3));
259
260     return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
261 end;
262

```

```
263 CoxeterGroup_A3xA3xA3 := function ()
264   local upperTriangleOfCoxeterMatrix, W, n;
265
266   n := 9;
267   upperTriangleOfCoxeterMatrix := [3,2,2,2,2,2,2, 3,2,2,2,2,2,2,
      2,2,2,2,2,2, 3,2,2,2,2,2, 3,2,2,2, 2,2,2, 3,2, 3];
268
269   W := CoxeterGroup(n, upperTriangleOfCoxeterMatrix);
270
271   SetName(W, "A_3 \\times A_3 \\times A_3");
272   SetSize(W, Factorial(4)*Factorial(4)*Factorial(4));
273
274   return rec(group := W, rank := n, matrix := upperTriangleOfCoxeterMatrix);
275 end;
```

## File twistedinvolutionweakordering.gap

```
1 LoadPackage("io");
2
3 Read("misc.gap");
4 Read("coxeter.gap");
5 Read("twoa-persist.gap");
6 Read("twoa-misc.gap");
7 Read("twoa1.gap");
8 Read("twoa2.gap");
9 Read("twoa3.gap");
10
11 TwistedInvolutionWeakOrderingResiduum := function (vertex, labels)
12   local visited, queue, residuum, current, edge;
13
14   visited := [ vertex.absIndex ];
15   queue := [ vertex ];
16   residuum := [];
17
18   while Length(queue) > 0 do
19     current := queue[1];
20     Remove(queue, 1);
21     Add(residuum, current);
22
23     for edge in current.outEdges do
24       if edge.label in labels and not edge.target.absIndex in visited
25       then
26         Add(visited, edge.target.absIndex);
27         Add(queue, edge.target);
28       fi;
29     od;
30
31     for edge in current.inEdges do
32       if edge.label in labels and not edge.source.absIndex in visited
33       then
34         Add(visited, edge.source.absIndex);
35         Add(queue, edge.source);
36       fi;
37     od;
38   od;
39   return residuum;
40 end;
41
42 TwistedInvolutionWeakOrderingLongestWord := function (vertex, labels)
43   local current;
44   current := vertex;
```

---

```

45
46   while Length(Filtered(current.outEdges, e -> e.label in labels)) > 0 do
47       current := Filtered(current.outEdges, e -> e.label in labels)[1].
           target;
48   od;
49
50   return current;
51 end;

```

## File twoa-misc.gap

```

1 DetectPossibleRank2Residuums := function(startVertex, startLabel, labels)
2   local comb, trace, v, e, k, possibleTraces;
3   possibleTraces := [];
4
5   for comb in List(Filtered(labels, label -> label <> startLabel), label ->
6     rec(startVertex := startVertex, st := [startLabel, label])) do
7     trace := [ rec(vertex := startVertex, edge := rec(label := comb.st[1],
8       type := -1)) ];
9
10    v := startVertex;
11    e := fail;
12    k := 1;
13
14    while true do
15      e := FindElement(v.inEdges, e -> e.label = comb.st[k mod 2 + 1]);
16      if e = fail then
17        break;
18      fi;
19
20      v := e.source;
21      k := k + 1;
22      Add(trace, rec(vertex := v, edge := e));
23    od;
24
25    while true do
26      e := FindElement(v.outEdges, e -> e.label = comb.st[k mod 2 + 1]);
27      if e = fail then
28        break;
29      fi;
30
31      v := e.target;
32      k := k - 1;
33      Add(trace, rec(vertex := v, edge := e));
34    od;
35
36    if k = 0 then
37      Add(possibleTraces, trace);
38    fi;
39  od;
40
41  return possibleTraces;
42 end;

```

## File twoa-persist.gap

```

1 TwistedInvolutionWeakOrderingPersistReadResults := function(filename)
2   local fileD, fileV, fileE, csvLine, data, vertices, edges, newEdge, source
3     , target, i;
4
5   fileD := IO_File(Concatenation("results/", filename, "-data"), "r");
6   fileV := IO_File(Concatenation("results/", filename, "-vertices"), "r",
7     1024*1024);

```

```
6      fileE := IO_File(Concatenation("results/", filename, "-edges"), "r",
7                          1024*1024);
8
9      data := NextIterator(IO_ReadLinesIteratorCSV(fileD, ";"));
10     vertices := [];
11     edges := [];
12
13     i := 1;
14     for csvLine in IO_ReadLinesIteratorCSV(fileV, ";") do
15         Add(vertices, rec(absIndex := i, twistedLength := csvLine.
16                             twistedLength, name := csvLine.name, inEdges := [], outEdges :=
17                             []));
18         i := i + 1;
19     od;
20
21     i := 1;
22     for csvLine in IO_ReadLinesIteratorCSV(fileE, ";") do
23         source := vertices[csvLine.sourceIndex + 1];
24         target := vertices[csvLine.targetIndex + 1];
25         newEdge := rec(absIndex := i, source := source, target := target,
26                         label := csvLine.label, type := csvLine.type);
27
28         Add(source.outEdges, newEdge);
29         Add(target.inEdges, newEdge);
30         Add(edges, newEdge);
31         i := i + 1;
32     od;
33
34     IO_Close(fileD);
35     IO_Close(fileV);
36     IO_Close(fileE);
37
38     return rec(data := data, vertices := vertices, edges := edges);
39 end;
40
41 TwistedInvolutionWeakOrderingPersistResultsInit := function(filename)
42     local fileD, fileV, fileE;
43
44     if (filename = fail) then return fail; fi;
45
46     fileD := IO_File(Concatenation("results/", filename, "-data"), "w");
47     fileV := IO_File(Concatenation("results/", filename, "-vertices"), "w",
48                     1024*1024);
49     fileE := IO_File(Concatenation("results/", filename, "-edges"), "w",
50                     1024*1024);
51
52     IO_Write(fileD, "name;rank;size;generators;matrix;automorphism;wk_size;
53                 wk_max_length\n");
54     IO_Write(fileV, "twistedLength;name\n");
55     IO_Write(fileE, "sourceIndex;targetIndex;label;type\n");
56
57     return rec(fileD := fileD, fileV := fileV, fileE := fileE);
58 end;
59
60 TwistedInvolutionWeakOrderingPersistResultsClose := function(persistInfo)
61     if (persistInfo = fail) then return; fi;
62
63     IO_Close(persistInfo.fileD);
64     IO_Close(persistInfo.fileV);
65     IO_Close(persistInfo.fileE);
66 end;
67
68 TwistedInvolutionWeakOrderingPersistResultsInfo := function(persistInfo, W,
69                     matrix, theta, numVertices, maxTwistedLength)
70     if (persistInfo = fail) then return; fi;
```



---

```

62
63     IO_Write(persistInfo.fileD, "\", ReplacedString(Name(W), "\", "\\\"),
        "\");");
64     IO_Write(persistInfo.fileD, Length(GeneratorsOfGroup(W)), ";");
65     if (Size(W) = infinity) then
66         IO_Write(persistInfo.fileD, "\"infinity\");");
67     else
68         IO_Write(persistInfo.fileD, Size(W), ";");
69     fi;
70     IO_Write(persistInfo.fileD, "[", JoinStringsWithSeparator(List(
        GeneratorsOfGroup(W), n -> Concatenation "\", String(n), "\""), ",")
        , "];");
71     IO_Write(persistInfo.fileD, "[", JoinStringsWithSeparator(matrix, ","),
        "];");
72     IO_Write(persistInfo.fileD, "\", Name(theta), "\");");
73
74     if (Size(W) = infinity) then
75         IO_Write(persistInfo.fileD, "\"infinity\");");
76         IO_Write(persistInfo.fileD, "\"infinity\"");
77     else
78         IO_Write(persistInfo.fileD, numVertices, ";");
79         IO_Write(persistInfo.fileD, maxTwistedLength, "");
80     fi;
81 end;
82
83 TwistedInvolutionWeakOrderingPersistResults := function(persistInfo, vertices,
    edges)
84     local n, e, i, tmp, bubbles;
85
86     if (persistInfo = fail) then return; fi;
87
88     # bubble sort the edges, to make sure, that double edges are neighbours in
    the list
89     bubbles := 1;
90     while bubbles > 0 do
91         bubbles := 0;
92         for i in [1..Length(edges)-1] do
93             if edges[i].source.absIndex = edges[i+1].source.absIndex and edges
                [i].target.absIndex > edges[i+1].target.absIndex then
94                 tmp := edges[i];
95                 edges[i] := edges[i+1];
96                 edges[i+1] := tmp;
97                 bubbles := bubbles + 1;
98             fi;
99         od;
100     od;
101
102     for n in vertices do
103         if n.absIndex = 1 then
104             IO_Write(persistInfo.fileV, n.twistedLength, ";\"e\"\\n");
105         else
106             IO_Write(persistInfo.fileV, n.twistedLength, ";\"", String(n.
                element), "\"\\n");
107         fi;
108     od;
109
110     for e in edges do
111         IO_Write(persistInfo.fileE, e.source.absIndex-1, ";", e.target.
            absIndex-1, ";", e.label, ";", e.type, "\\n");
112     od;
113 end;

```

## File twoa1.gap

```
1 # Calculates the poset Wk(theta).
2 TwistedInvolutionWeakOrdering1 := function (filename, W, matrix, theta)
3   local persistInfo, maxOrder, vertices, edges, absVertexIndex, absEdgeIndex
4     , prevVertex, currVertex, newEdge,
5     label, type, deduction, startTime, endTime, S, k, i, s, x, y, n;
6
7   persistInfo := TwistedInvolutionWeakOrderingPersistResultsInit(filename);
8
9   S := GeneratorsOfGroup(W);
10  maxOrder := Minimum([Maximum(Concatenation(matrix, [1])), 5]);
11  vertices := [ [], [ rec(element := One(W), twistedLength := 0, inEdges :=
12    [], outEdges := [], absIndex := 1) ] ];
13  edges := [ [], [] ];
14  absVertexIndex := 2;
15  absEdgeIndex := 1;
16  k := 0;
17
18  while Length(vertices[2]) > 0 do
19    if not IsFinite(W) then
20      if k > 200 or absVertexIndex > 10000 then
21        break;
22      fi;
23    fi;
24
25    for i in [1..Length(vertices[2])] do
26      Print(k, " ", i, " \r");
27
28      prevVertex := vertices[2][i];
29      for label in Filtered([1..Length(S)], n -> Position(List(
30        prevVertex.inEdges, e -> e.label), n) = fail) do
31        x := prevVertex.element;
32        s := S[label];
33
34        type := 1;
35        y := s^theta*x*s;
36        if (CoxeterElementsCompare(x, y)) then
37          y := x * s;
38          type := 0;
39        fi;
40
41        currVertex := fail;
42        for n in vertices[1] do
43          if CoxeterElementsCompare(n.element, y) then
44            currVertex := n;
45            break;
46          fi;
47        od;
48
49        if currVertex = fail then
50          currVertex := rec(element := y, twistedLength := k + 1,
51            inEdges := [], outEdges := [], absIndex :=
52            absVertexIndex);
53          Add(vertices[1], currVertex);
54
55          absVertexIndex := absVertexIndex + 1;
56        fi;
57
58        newEdge := rec(source := prevVertex, target := currVertex,
59          label := label, type := type, absIndex := absEdgeIndex);
60
61        Add(edges[1], newEdge);
62        Add(currVertex.inEdges, newEdge);
```

---

```

57         Add(prevVertex.outEdges, newEdge);
58
59         absEdgeIndex := absEdgeIndex + 1;
60     od;
61 od;
62
63 TwistedInvolutionWeakOrderingPersistResults(persistInfo, vertices[2],
        edges[2]);
64
65 Add(vertices, [], 1);
66 Add(edges, [], 1);
67 if (Length(vertices) > maxOrder + 1) then
68     for n in vertices[maxOrder + 2] do
69         n.inEdges := [];
70         n.outEdges := [];
71     od;
72 Remove(vertices, maxOrder + 2);
73 Remove(edges, maxOrder + 2);
74 fi;
75 k := k + 1;
76 od;
77
78 TwistedInvolutionWeakOrderingPersistResultsInfo(persistInfo, W, matrix,
        theta, absVertexIndex - 1, k - 1);
79 TwistedInvolutionWeakOrderingPersistResultsClose(persistInfo);
80
81 return rec(numVertices := absVertexIndex - 1, numEdges := absEdgeIndex -
        1, maxTwistedLength := k - 1);
82 end;

```

## File twoa2.gap

```

1 # Calculates the poset Wk(theta).
2 TwistedInvolutionWeakOrdering2 := function (filename, W, matrix, theta)
3     local persistInfo, maxOrder, vertices, edges, absVertexIndex, absEdgeIndex
4         , prevVertex, currVertex, newEdge, possibleResiduums,
5         label, type, deduction, startTime, endTime, S, k, i, s, x, y, n, h,
6         res;
7
8     persistInfo := TwistedInvolutionWeakOrderingPersistResultsInit(filename);
9
10    S := GeneratorsOfGroup(W);
11    maxOrder := Minimum([Maximum(Concatenation(matrix, [1])), 5]);
12    vertices := [ [], [ rec(element := One(W), twistedLength := 0, inEdges :=
13        [], outEdges := [], absIndex := 1) ] ];
14    edges := [ [], [] ];
15    absVertexIndex := 2;
16    absEdgeIndex := 1;
17    k := 0;
18
19    while Length(vertices[2]) > 0 do
20        if not IsFinite(W) then
21            if k > 200 or absVertexIndex > 10000 then
22                break;
23            fi;
24        fi;
25
26        for i in [1..Length(vertices[2])] do
27            Print(k, " ", i, " \r");
28
29            prevVertex := vertices[2][i];
30            for label in Filtered([1..Length(S)], n -> Position(List(
31                prevVertex.inEdges, e -> e.label), n) = fail) do

```

```
28         x := prevVertex.element;
29         s := S[label];
30
31         type := 1;
32         y := s^theta*x*s;
33         if (CoxeterElementsCompare(x, y)) then
34             y := x * s;
35             type := 0;
36         fi;
37
38         possibleResiduums := DetectPossibleRank2Residuums(prevVertex,
39             label, [1..Length(S)]);
40         currVertex := fail;
41         for res in possibleResiduums do
42             h := Length(res) / 2;
43
44             if CoxeterElementsCompare(res[h*2].vertex.element, y) then
45                 currVertex := res[h*2].vertex;
46                 break;
47             fi;
48         od;
49
50         if currVertex = fail then
51             currVertex := rec(element := y, twistedLength := k + 1,
52                 inEdges := [], outEdges := [], absIndex :=
53                 absVertexIndex);
54             Add(vertices[1], currVertex);
55
56             absVertexIndex := absVertexIndex + 1;
57         fi;
58
59         newEdge := rec(source := prevVertex, target := currVertex,
60             label := label, type := type, absIndex := absEdgeIndex);
61
62         Add(edges[1], newEdge);
63         Add(currVertex.inEdges, newEdge);
64         Add(prevVertex.outEdges, newEdge);
65
66         absEdgeIndex := absEdgeIndex + 1;
67     od;
68 od;
69
70 TwistedInvolutionWeakOrderingPersistResults(persistInfo, vertices[2],
71     edges[2]);
72
73 Add(vertices, [], 1);
74 Add(edges, [], 1);
75 if (Length(vertices) > maxOrder + 1) then
76     for n in vertices[maxOrder + 2] do
77         n.inEdges := [];
78         n.outEdges := [];
79     od;
80     Remove(vertices, maxOrder + 2);
81     Remove(edges, maxOrder + 2);
82 fi;
83 k := k + 1;
84 od;
85
86 TwistedInvolutionWeakOrderingPersistResultsInfo(persistInfo, W, matrix,
87     theta, absVertexIndex - 1, k - 1);
88 TwistedInvolutionWeakOrderingPersistResultsClose(persistInfo);
89
90 return rec(numVertices := absVertexIndex - 1, numEdges := absEdgeIndex -
91     1, maxTwistedLength := k - 1);
```

---

85 end;

## File twoa3.gap

```
1 # Calculates the poset Wk(theta).
2 TwistedInvolutionWeakOrdering3 := function (filename, W, matrix, theta)
3   local persistInfo, maxOrder, vertices, edges, absVertexIndex, absEdgeIndex
4     , prevVertex, currVertex, newEdge, possibleResiduums,
5     label, type, deduction, startTime, endTime, endTypes, S, k, i, s, x,
6     _y, y, n, m, h, res;
7
8   persistInfo := TwistedInvolutionWeakOrderingPersistResultsInit(filename);
9
10  S := GeneratorsOfGroup(W);
11  maxOrder := Minimum([Maximum(Concatenation(matrix, [1])), 5]);
12  vertices := [ [], [ rec(element := One(W), twistedLength := 0, inEdges :=
13    [], outEdges := [], absIndex := 1) ] ];
14  edges := [ [], [] ];
15  absVertexIndex := 2;
16  absEdgeIndex := 1;
17  k := 0;
18
19  while Length(vertices[2]) > 0 do
20    if not IsFinite(W) then
21      if k > 200 or absVertexIndex > 10000 then
22        break;
23      fi;
24    fi;
25
26    for i in [1..Length(vertices[2])] do
27      Print(k, " ", i, " \r");
28
29      prevVertex := vertices[2][i];
30      for label in Filtered([1..Length(S)], n -> Position(List(
31        prevVertex.inEdges, e -> e.label), n) = fail) do
32        x := prevVertex.element;
33        s := S[label];
34        y := x*s;
35        _y := s^theta*y;
36        type := -1;
37
38        possibleResiduums := DetectPossibleRank2Residuums(prevVertex,
39          label, [1..Length(S)]);
40        currVertex := fail;
41        for res in possibleResiduums do
42          m := CoxeterMatrixEntry(matrix, res[1].edge.label, res[2].
43            edge.label);
44          h := Length(res) / 2;
45
46          if h = 1 then
47            if m = 2 and res[h*2].edge.type = 1 and
48              CoxeterElementsCompare(res[h*2].vertex.element, _y
49            ) then
50              currVertex := res[h*2].vertex;
51              type := 1;
52              break;
53            fi;
54          else
55            endTypes := [-1, res[h].edge.type, res[h+1].edge.type,
56              res[h*2].edge.type];
57            endTypes[1] := endTypes[3] + endTypes[4] - endTypes
58              [2];
59          fi;
60        end;
61      end;
62    end;
63  end;
64 end;
```

```
50         if endTypes[4] = 0 then
51             currVertex := res[h*2].vertex;
52             type := endTypes[1];
53             break;
54         elif endTypes = [1,1,1,1] then
55             if m = h or (Gcd(m,h) > 1 and
                    CoxeterElementsCompare(res[h*2].vertex.element
                    , _y)) then
56                 currVertex := res[h*2].vertex;
57                 type := 1;
58                 break;
59             fi;
60         elif endTypes = [0,1,0,1] then
61             if m = h or (Gcd(m,h) > 1 and
                    CoxeterElementsCompare(res[h*2].vertex.element
                    , y)) then
62                 currVertex := res[h*2].vertex;
63                 type := 0;
64                 break;
65             fi;
66         elif endTypes = [1,0,0,1] and m mod 2 = 1 then
67             if (m+1)/2 = h or (Gcd((m+1)/2,h) > 1 and
                    CoxeterElementsCompare(res[h*2].vertex.element
                    , _y)) then
68                 currVertex := res[h*2].vertex;
69                 type := 1;
70                 break;
71             fi;
72         fi;
73     fi;
74 od;
75
76 if currVertex = fail then
77     if CoxeterElementsCompare(x, _y) then
78         type := 0;
79         _y := y;
80     else
81         type := 1;
82     fi;
83
84     currVertex := rec(element := _y, twistedLength := k + 1,
                       inEdges := [], outEdges := [], absIndex :=
                       absVertexIndex);
85     Add(vertices[1], currVertex);
86
87     absVertexIndex := absVertexIndex + 1;
88 fi;
89
90 newEdge := rec(source := prevVertex, target := currVertex,
91               label := label, type := type, absIndex := absEdgeIndex);
92
93 Add(edges[1], newEdge);
94 Add(currVertex.inEdges, newEdge);
95 Add(prevVertex.outEdges, newEdge);
96
97 absEdgeIndex := absEdgeIndex + 1;
98 od;
99
100 TwistedInvolutionWeakOrderingPersistResults(persistInfo, vertices[2],
101                                             edges[2]);
102
103 Add(vertices, [], 1);
104 Add(edges, [], 1);
```

---

```

104         if (Length(vertices) > maxOrder + 1) then
105             for n in vertices[maxOrder + 2] do
106                 n.inEdges := [];
107                 n.outEdges := [];
108             od;
109             Remove(vertices, maxOrder + 2);
110             Remove(edges, maxOrder + 2);
111         fi;
112         k := k + 1;
113     od;
114
115     TwistedInvolutionWeakOrderingPersistResultsInfo(persistInfo, W, matrix,
116         theta, absVertexIndex - 1, k - 1);
117     TwistedInvolutionWeakOrderingPersistResultsClose(persistInfo);
118     return rec(numVertices := absVertexIndex - 1, numEdges := absEdgeIndex -
119         1, maxTwistedLength := k - 1);
119 end;

```





## B. Benchmarks

$W$	$ Wk(W, \text{id}) $	Time in seconds	Element comparisons
$A_1$	2	5.087 <sub>-5</sub>	1
$A_2$	4	3.769 <sub>-4</sub>	6
$BC_2$	6	5.359 <sub>-4</sub>	9
$A_3$	10	1.618 <sub>-3</sub>	31
$BC_3$	20	3.586 <sub>-3</sub>	75
$A_4$	26	6.173 <sub>-3</sub>	173
$H_3$	32	4.781 <sub>-3</sub>	126
$D_4$	44	1.551 <sub>-2</sub>	345
$A_5$	76	4.200 <sub>-2</sub>	1,181
$BC_4$	76	3.778 <sub>-2</sub>	802
$F_4$	140	1.056 <sub>-1</sub>	1,906
$D_5$	156	1.218 <sub>-1</sub>	3,502
$A_6$	232	3.453 <sub>-1</sub>	9,700
$BC_5$	312	4.253 <sub>-1</sub>	11,024
$H_4$	572	7.100 <sub>-1</sub>	12,938
$D_6$	752	2.589 <sub>0</sub>	65,308
$A_7$	764	3.552 <sub>0</sub>	95,797
$E_6$	892	3.540 <sub>0</sub>	85,857
$BC_6$	1,384	8.073 <sub>0</sub>	193,218
$A_8$	2,620	4.420 <sub>1</sub>	1,074,392
$A_9$	9,496	6.342 <sub>2</sub>	13,531,414
$E_7$	10,208	4.236 <sub>2</sub>	7,785,186
$A_{10}$	35,696	9.201 <sub>3</sub>	185,791,174
$A_{11}$	140,152	1.507 <sub>5</sub>	2,778,111,763
$E_8$	199,952	2.258 <sub>5</sub>	2,029,454,701

Table B.1.: Benchmark results for TWOA1

$W$	$ Wk(W, \text{id}) $	Time in seconds	Element comparisons
$A_1$	2	5.322 <sub>-5</sub>	1
$A_2$	4	4.189 <sub>-4</sub>	6
$BC_2$	6	6.300 <sub>-4</sub>	9
$A_3$	10	1.828 <sub>-3</sub>	29
$BC_3$	20	3.586 <sub>-3</sub>	57
$A_4$	26	5.369 <sub>-3</sub>	120
$H_3$	32	4.405 <sub>-3</sub>	93
$D_4$	44	1.304 <sub>-2</sub>	193
$A_5$	76	2.372 <sub>-2</sub>	501
$BC_4$	76	2.390 <sub>-2</sub>	344
$F_4$	140	5.200 <sub>-2</sub>	640
$D_5$	156	4.655 <sub>-2</sub>	975
$A_6$	232	1.032 <sub>-1</sub>	2,043
$BC_5$	312	9.964 <sub>-2</sub>	2,009
$H_4$	572	1.900 <sub>-1</sub>	2,578
$D_6$	752	3.347 <sub>-1</sub>	6,206
$A_7$	764	4.667 <sub>-1</sub>	8,569
$E_6$	892	4.013 <sub>-1</sub>	7,210
$BC_6$	1,384	6.580 <sub>-1</sub>	11,794
$A_8$	2,620	2.032 <sub>0</sub>	36,218
$A_9$	9,496	9.837 <sub>0</sub>	157,611
$E_7$	10,208	7.208 <sub>0</sub>	100,996
$A_{10}$	35,696	4.633 <sub>1</sub>	697,613
$A_{11}$	140,152	2.329 <sub>2</sub>	3,172,316
$E_8$	199,952	3.206 <sub>2</sub>	2,399,476

Table B.2.: Benchmark results for TWOA2

---

$W$	$ Wk(W, id) $	Time in seconds	Element comparisons
$A_1$	2	5.419 <sub>-5</sub>	1
$A_2$	4	1.921 <sub>-4</sub>	3
$BC_2$	6	4.286 <sub>-4</sub>	5
$A_3$	10	1.122 <sub>-3</sub>	11
$BC_3$	20	2.110 <sub>-3</sub>	22
$A_4$	26	3.984 <sub>-3</sub>	40
$H_3$	32	2.950 <sub>-3</sub>	37
$D_4$	44	6.877 <sub>-3</sub>	62
$A_5$	76	1.818 <sub>-2</sub>	164
$BC_4$	76	1.527 <sub>-2</sub>	116
$F_4$	140	3.175 <sub>-2</sub>	219
$D_5$	156	2.811 <sub>-2</sub>	307
$A_6$	232	6.456 <sub>-2</sub>	691
$BC_5$	312	6.118 <sub>-2</sub>	655
$H_4$	572	1.044 <sub>-1</sub>	916
$D_6$	752	2.072 <sub>-1</sub>	1,989
$A_7$	764	3.413 <sub>-1</sub>	3,048
$E_6$	892	2.296 <sub>-1</sub>	2,347
$BC_6$	1,384	3.827 <sub>-1</sub>	3,942
$A_8$	2,620	1.532 <sub>0</sub>	13,635
$A_9$	9,496	7.580 <sub>0</sub>	62,630
$E_7$	10,208	3.881 <sub>0</sub>	33,468
$A_{10}$	35,696	2.999 <sub>1</sub>	291,699
$A_{11}$	140,152	1.530 <sub>2</sub>	1,388,533
$E_8$	199,952	1.501 <sub>2</sub>	844,805

Table B.3.: Benchmark results for TWOA3



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