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# Posets of twisted involutions in Coxeter groups

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# 1 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 a 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 [Humphreys, 1992, Theorem 1.9]. Furthermore it turns out, that the finite reflection groups in the Euclidean space are precisely the finite Coxeter groups [Humphreys, 1992, Theorem 6.4].

In this chapter we will compile some basic facts on Coxeter groups, based on Humphreys [1992].

## 1.1 Introduction to Coxeter groups

**Definition 1.1.** 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  $m_{ii} = 1$ ,  $m_{ij} > 1$  for  $i \neq j$  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 1.2.** 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  $m$ . This graph we call the **Coxeter graph** of our Coxeter system  $(W, S)$ .

**Definition 1.3.** For an arbitrary element  $w \in W$ ,  $(W, S)$  a Coxeter system, 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) factors 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  $s_i^2 = 1$  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 1.4.** 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**.

## 1.2 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. The most useful way to achieve this is the Bruhat ordering [Humphreys, 1992, Section 5.9].

**Definition 1.5.** Let  $M$  be a set. A binary relation, in this case often denoted as “ $\leq$ ”, is called a **partial order** over  $M$ , if it fulfills the following conditions for all  $a, b, c \in M$ :

1.  $a \leq a$ , called **reflexivity**
2. if  $a \leq b$  and  $b \leq a$  then  $a = b$ , called **antisymmetry**
3. if  $a \leq b$  and  $b \leq c$  then  $a \leq c$ , called **transitivity**

In this case  $(M, \leq)$  is called a **poset**. If two elements  $a \leq b \in M$  are immediate neighbours, i.e. there is no third element  $c \in M$  with  $a \leq c \leq b$  we say that  $b$  **covers**  $a$ . A poset is called **graded poset** if there is a map  $\rho : M \rightarrow \mathbb{N}$  so that  $\rho(b) - 1 = \rho(a)$  whenever  $b$  covers  $a$ . In this case  $\rho$  is called the **rank function** of the graded poset.

**Definition 1.6.** 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 as  $\text{Br}(W)$ .

**Lemma 1.7.** 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.  $\square$

What we really want is the Bruhat ordering to be graded with the length function as rank function. By definition we already have  $v < w$  iff  $l(v) < l(w)$ , but it's not that obvious that two immediately adjacent elements differ in length by exactly 1. Before let's just mention two other partial orderings, where this property is obvious by definition:

**Definition 1.8.** Let  $(W, S)$  be a Coxeter system. The ordering  $\leq_R$  defined by  $u \leq_R w$  iff  $uv = w$  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**.

So let's ensure that the Bruhat ordering is graded as well. For this we need another characterization of the Bruhat ordering with subexpressions. As we will show it is  $u \leq w$  iff there is a reduced expression of  $u$  that is a subexpression of a reduced expression of  $w$ .

**Proposition 1.9.** *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 (WHY?) 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 it is  $us \leq ws$  iff  $l(us) < l(ws)$ . Assume this is not the case. Since we have assumed  $l(us) = l(u) + 1$  any reduced expression  $u = s_1 \cdots s_r$  for  $u$  yields a reduced expression  $us = s_1 \cdots s_r s$  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  $ws = s_1 \cdots \hat{s}_i \cdots s_r s$  and so  $ws = s_1 \cdots \hat{s}_i \cdots s_r$ , contradicting to our assumption  $l(u) < l(w)$   $\square$

**Theorem 1.10.** *Let  $(W, S)$  be a Coxeter system and  $w \in W$  with any reduced expression  $w = s_1 \cdots s_r$  and  $s_i \in S$ . Then  $u \leq w$  (in the Bruhat ordering) iff  $u$  can be obtained as a subexpression of this reduced expression.*

*Proof.* TODO See [Humphreys, 1992, Theorem 5.10].  $\square$

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 1.11.** *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 1.9 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 1.12.** *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 will induce on  $r = l(u) + l(w)$ . In case  $r = 1$  we have  $u = e$  and  $w = s$  for an  $s \in S$  and are done. So suppose  $r > 1$ . Then there is a reduced expression  $w = s_1 \cdots s_r$  for  $w$ . Let's fix this expression. Then  $l(ws_r) < l(w)$ . Thanks to Theorem 1.10 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:

1. Suppose  $u < us$ . 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 length by 1 in each step and have one last step from  $ws$  to  $w$  also increasing length by 1.

2. Suppose  $us < u$ . Then by induction we can find a sequence from  $us$  to  $w$ , say

$$us = w_0 < \dots < w_m = w,$$

where length of neighboured elements differs 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  $w_i \neq w_{i-1}s$ . It is  $w_{i-1} < w_{i-1}s \neq w_i$  and due to Lemma 1.11 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 1.11 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.  $\square$

**Theorem 1.13.** *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 1.12 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  $l(w) = l(u) + 1$ .  $\square$

TODO

### 1.3 Exchange and Deletion Condition

We now obtain a way to get a reduced expression of an arbitrary element  $s_1 \cdots s_r = w \in W$ . But first we define what a reflection is. 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 1.14** (Strong Exchange Condition). *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 started from a reduced expression, then  $i$  is unique.*

*Proof.* See [Humphreys, 1992, Theorem 5.8].  $\square$

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

**Corollary 1.15** (Exchange Condition). *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.*

*Proof.* Directly from Strong Exchange Condition.  $\square$

The Exchange Condition immediately yields another corollary for Coxeter groups:

**Corollary 1.16** (Deletion Condition). *Let  $(W, S)$  be a Coxeter system,  $w \in W$  and  $w = s_1 \cdots s_r$  with  $s_i \in S$  a 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 is called **Deletion Condition** and 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 a 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. We can use the second to prove a very handy property of Coxeter groups. The intersection of two parabolic subgroups is again a parabolic subgroup.

**Definition 1.17.** 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 1.18.** *Let  $(W, S)$  be a Coxeter system and  $I, J \subset S$  two subsets of generators. Then  $W_I \cap W_J = W_{I \cap J}$ .*

*Proof.* Let  $w \in W_{I \cap J}$ . Then  $w \in W_I$  and  $w \in W_J$ . To show the other inclusion we induce over the length  $r$ . For  $r = 0$  we have  $w = e$  and so  $w \in W_{S'}$  for any  $S' \subset S$ . So suppose we have proven the assumption for all lengths up to  $r - 1$ . Let  $w \in W_I \cap W_J$  with  $l(w) = r$ . Then we have two reduced expressions  $w = s_1 \cdots s_r = t_1 \cdots t_r$  with  $s_i \in I$  and  $t_i \in J$ . By applying  $s_r$  from the right we get  $ws_r = s_1 \cdots s_{r-1} = t_1 \cdots t_r s_r$ . The expression  $t_1 \cdots t_r s_r$  is of length  $r - 1$ , so Exchange Condition yields  $ws_r = s_1 \cdots s_{r-1} = t_1 \cdots \hat{t}_i \cdots t_r$ , hence  $ws_r \in W_I \cap W_J$ . Due to induction we know that  $ws_r \in W_{I \cap J}$ .  $\square$

## 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 isomorph 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

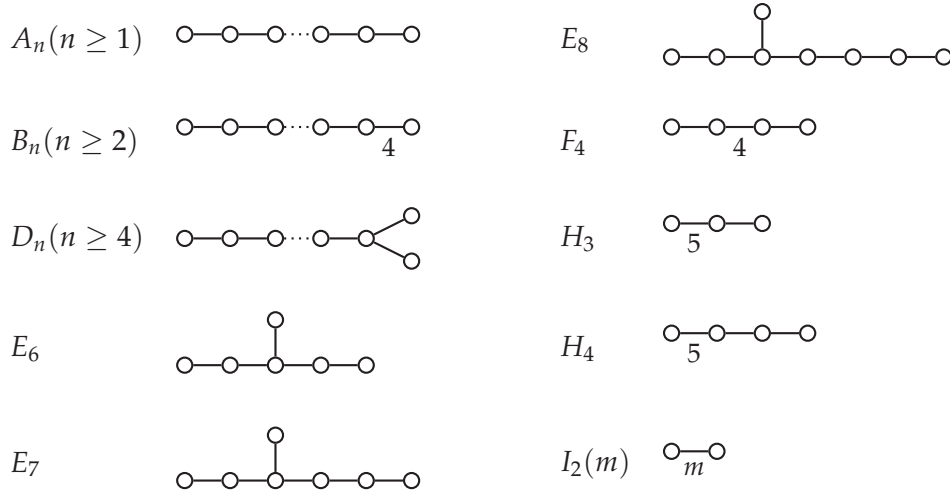


Figure 1.1: All types of irreducible finite Coxeter systems

$st$  has infinite order forcing  $W$  to be infinite. But there are also infinite Coxeter groups without an  $\infty$ -relation between two generators. An example for this is  $W$  obtained from  $S = \{s_1, s_2, s_3\}$  with  $s_1^2 = s_2^2 = s_3^2 = (s_1s_2)^3 = (s_2s_3)^3 = (s_3s_1)^3 = e$ . But how can it be seen that this  $W$  is infinite?

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

**Definition 1.19.** 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 connection component and each connection component corresponds to a parabolic subgroup of  $W$ .

**Proposition 1.20.** 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  $W_J$ .

*Proof.* See [Humphreys, 1992, Proposition 6.1]. □

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

**Theorem 1.21.** The irreducible finite Coxeter systems are exactly the ones in Figure 1.1.

*Proof.* [Humphreys, 1992, Theorem 6.4] □

Finally we can decide with ease, if a given Coxeter system is finite. Take its irreducible parabolic subgroups and check, if each is one of  $A_n, B_n, D_n, E_6, E_7, E_8, F_4, H_3, H_4$  or  $I_2(m)$ .



## 2 Twisted involutions in Coxeter groups

In this section our interest will focus on a certain subset of elements in Coxeter groups, the so called twisted involutions.

### 2.1 Introduction to twisted involutions

**Definition 2.1.** Let  $(W, S)$  be a Coxeter system. An automorphism  $\theta : W \rightarrow W$  with  $\theta(S) = S$  is called a **Coxeter system automorphism** of  $(W, S)$ .

**Definition 2.2.** Let  $(W, S)$  be a Coxeter system and  $\theta : W \rightarrow W$  a Coxeter system automorphism. Then each  $w \in W$  with  $\theta(w) = w^{-1}$  is called a **twisted involution**. The set of all twisted involutions in  $W$  regarding  $\theta$  is denoted with  $\mathcal{I}_\theta(W)$ . Often we will just omit the Coxeter group and write  $\mathcal{I}_\theta$ , when it is clear from the context which  $W$  is meant.

Lets take a quick look at some examples. First of all the trivial one.

**Example 2.3.** Let  $(W, S)$  be a Coxeter system and  $\theta = \text{id}_W$ . Then  $\theta$  is an Coxeter system automorphism and  $\mathcal{I}_\theta = \{w \in W : w = w^{-1}\}$ .

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.** Let  $(W, S)$  be a Coxeter system and  $\theta$  be the automorphis (not Coxeter system automorphism)

$$\theta : W \times W \rightarrow W \times W : (u, w) \mapsto (w, u).$$

Then 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  $W$ .

### 3 The twisted weak ordering in Coxeter groups

In this section we will introduce the twisted weak ordering  $Wk(\theta)$  on Coxeter groups.

## 4 Residuums of rank 2

**Definition 4.1** (One- and twosided operation). Let  $(W, S)$  be a Coxeter system and  $w \in W, s \in S$ . If  $w\underline{s} = \theta(s)ws$ , then we say  $s$  to operate twosided on  $w$ . Else we say  $s$  to operate onesided on  $w$ .

**Definition 4.2** (Ein- und beidseitige endende Gesamtwirkung). Seien  $(W, S)$  ein Coxeter-system,  $w \in W$  und  $s_1, \dots, s_n \in S$ . Falls  $w\underline{s_1 \cdots s_n} = \theta(s_n)(w\underline{s_1 \cdots s_{n-1}})s_n$  ist, so sagen wir, dass  $s_1 \cdots s_n$  eine beidseitig endende Gesamtwirkung auf  $w$  hat. Andernfalls sagen wir  $s_1 \cdots s_n$  hat eine einseitig endende Gesamtwirkung auf  $w$ .

**Definition 4.3.** Let  $(W, S)$  be a Coxeter system and  $s, t \in S$  two distinct generators. We define:

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

**Assumption 4.4.** Seien  $(W, S)$  ein Coxetersystem und  $s, t \in S$  zwei verschiedene Erzeuger von  $W$ . Dann gilt:

1. Sei  $m = \text{ord}(st) < \infty$ . Falls  $w\underline{[st]^n} \neq w$  ist für alle  $n \in \mathbb{N}, n < 2m$ , dann gilt  $w\underline{(st)^{2m}} = w$ .
2. In  $wC_{\{s,t\}}$  existieren keine drei Elemente derselben getwisteten Länge.
3. Falls  $s$  einseitig auf  $w$  wirkt, dann gilt  $w\underline{st} < w\underline{s}$  oder  $w\underline{t} > w$ .
4. Sei  $w\underline{[st]^n} = w$  für ein  $n \in \mathbb{N}$ . Dann ist  $n$  gerade und es gilt eine der beiden folgenden Eigenschaften:
  - a) Für jedes  $m \in \mathbb{N}$  hat das Element  $[st]^m$  genau dann eine beidseitig endende Gesamtwirkung auf  $w$ , wenn  $[st]^{n/2+m}$  eine beidseitig endende Gesamtwirkung auf  $w$  hat.
  - b) Für jedes  $m \in \mathbb{N}$  hat das Element  $[st]^m$  genau dann eine beidseitig endende Gesamtwirkung auf  $w$ , wenn  $[st]^{n-m+1}$  eine beidseitig endende Gesamtwirkung auf  $w$  hat.

**Lemma 4.5.** Let  $(W, S)$  be a Coxeter system,  $w \in W$  and  $s, t \in S$  two distinct generators. Then  $wC_{\{s,t\}}$  does not contain three elements of same twisted length.

*Proof.* Let  $(W, S)$  be a Coxeter system,  $w \in W$  with  $\text{rank } w = k$ ,  $s, t \in S$  with  $s \neq t$ . Without loss of generality we can choose  $w$  such that  $w < w\underline{s}$  and  $w < w\underline{t}$ . Assume the existence of an element  $u \in wC_{\{s,t\}}$  with  $w\underline{s} < u$  and  $w\underline{t} < u$ . Then [Hultman, 2007, Lemma 3.8] yields  $s, t \in D_R(u)$ . By using [Hultman, 2007, Lemma 3.9] we conclude that  $w\underline{s} \leq u$  and  $w\underline{t} \leq u$ . Hence there cannot exist more than two Elements of same twisted length.

If no such  $u$  exists, then  $wC_{\{s,t\}} = w \cup \{w\underline{[st]^n} : n \in \mathbb{N}\} \cup \{w\underline{[ts]^n} : n \in \mathbb{N}\}$  and the assumption still holds.  $\square$

**Lemma 4.6.** *Let  $(W, S)$  be a Coxeter system,  $w \in S$  and  $s, t \in S$  two distinct generators. If  $s$  operates onesided on  $w$  and  $w\underline{s} < w$ , then either  $w\underline{st} < w\underline{s}$  or  $w\underline{t} > w$ .*

*Proof.* We have  $\theta(s)ws = w$  and  $s \in D_R(w)$ . If  $t \notin D_R(w)$ , then we are done. So suppose  $t \in D_R(w)$ . This means  $w\underline{s} \leq w$  and  $w\underline{t} \leq w$  and [Hultman, 2007, Lemma 3.9] yields  $w\underline{st} < w$  and  $w\underline{ts} < w$ . If  $t \in D_R(w\underline{s})$ , then we are done. So suppose  $t \notin D_R(w\underline{s})$ . Then  $t \in D_R(w\underline{st})$ . Together with  $w\underline{st} \leq w$  [Hultman, 2007, Lemma 3.9(2)] says  $(w\underline{st})\underline{t} \leq w\underline{t}$ . Finally we get

$$ws = w\underline{s} = (w\underline{st})\underline{t} \leq w\underline{t} = wt.$$

Since  $w\underline{s}$  and  $w\underline{t}$  are of same twisted length they have to be equal and therefore  $s = t$  which contradicts to our assumption of two distinct generators  $s$  and  $t$ .  $\square$

## 5 Twisted weak ordering

Wir wollen nun einen Algorithmus zur Berechnung der getwisteten schwachen Ordnung  $Wk(\theta)$  einer beliebigen Coxetergruppe  $W$  erarbeiten. Also Ausgangspunkt werden wir den Algorithmus aus [Haas and Helmnick, 2012, Algorithm 3.1.1] verwenden, der im wesentlichen benutzt, dass für jede getwistete Involution  $w \in \mathcal{I}_\theta$  entweder  $w\underline{s} < w$  oder aber  $w\underline{s} > w$  gilt.

**Algorithm 5.1** (Algorithmus 1).

```

1: procedure TWISTEDWEAKORDERINGALGORITHM1( $W$ )      ▷  $W$  sei die Coxetergruppe
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      ▷ Nur die  $s$ , die nicht schon nach  $w$ 
        führen
7:          $y \leftarrow ws$ 
8:          $z \leftarrow \theta(s)y$ 
9:         if  $z = w$  then
10:           $x \leftarrow y$                                 ▷  $s$  operiert ungetwistet auf  $w$ 
11:           $t \leftarrow s$ 
12:        else
13:           $x \leftarrow z$                                 ▷  $s$  operiert getwistet auf  $w$ 
14:           $t \leftarrow \underline{s}$ 
15:        end if
16:         $isNew \leftarrow \mathbf{true}$ 
17:        for all  $(w', k_{w'}) \in V$  with  $k_{w'} = k + 1$  do  ▷ Prüfen, ob  $x$  nicht schon in
         $V$  liegt
18:          if  $x = w'$  then
19:             $isNew \leftarrow \mathbf{false}$ 
20:          end if
21:        end for
22:        if  $isNew = \mathbf{true}$  then
23:           $V \leftarrow V \cup \{(x, k + 1)\}$ 
24:           $E \leftarrow E \cup \{(w, x, t)\}$ 
25:        else
26:           $E \leftarrow E \cup \{(w, x, t)\}$ 
27:        end if
28:      end for
29:    end for
30:     $k \leftarrow k + 1$ 
31:  end for

```

			Timings		Element compares	
W	$ Wk(\text{id}, W) $	$\rho(w_0)$	TWOA1	TWOA2	TWOA1	TWOA2
$A_9$	9496	25	00:02.180	00:01.372	13,531,414	42,156
$A_{10}$	35696	30	00:31.442	00:06.276	185,791,174	173,356
$A_{11}$	140152	36	11:04.241	00:29.830	2,778,111,763	737,313
$E_6$	892	20	00:03.044	00:00.268	85,857	2,347
$E_7$	10208	35	06:11.728	00:02.840	7,785,186	29,687
$E_8$	199952	64	–	11:03.278	–	682,227

Table 5.1: Benchmark

32:     **return** ( $V, E$ ) ▷ The poset graph  
33: **end procedure**

Dieser Algorithmus berechnet alle getwisteten Involutionen und deren getwistete Länge  $(w, k_w)$  und deren Relationen  $(w', w, s)$  bzw.  $(w', w, \underline{s})$ . Zu bemerken ist, dass zur Berechnung der getwisteten Involutionen der Länge  $k$  nur die Knoten aus  $V$  benötigt werden, mit der getwisteten Länge  $k - 1$  und  $k$  sowie die Kanten aus  $E$ , die Knoten der Länge  $k - 2$  und  $k - 1$  bzw.  $k - 1$  und  $k$  verbinden. Alle vorherigen Ergebnisse können schon persistiert werden, so dass nie das komplette Ergebnis im Speicher gehalten werden muss.

Eine Operation, die hier als elementar angenommen wurde ist der Vergleich von Elementen in  $W$ . Für bestimmte Gruppen wie z.B. die  $A_n$ , welche je isomorph zu  $\text{Sym}(n + 1)$  sind, lässt sich der Vergleich von Element effizient implementieren. Will man jedoch mit Coxetergruppen im Allgemeinen arbeiten, so liegt  $W$  als frei präsentierte Gruppe vor und der Vergleich von Element ist eine sehr aufwendige Operation. Bei Algorithm 5.1 muss jedes potentiell neue Element  $x$  mit allen schon bekannten  $w'$  von gleicher getwisteter Länge verglichen werden um zu bestimmen, ob  $x$  wirklich ein noch nicht bekanntes Element aus  $\mathcal{I}_\theta$  ist.

**Algorithm 5.2** (Algorithmus 2).

```

1: procedure TWISTEDWEAKORDERINGALGORITHM2( $W$ ) ▷  $W$  sei die Coxetergruppe
2:    $V \leftarrow \{(e, 0)\}$ 
3:    $E \leftarrow \{\}$ 
4:   for  $k \leftarrow 0$  to  $k_{\max}$  do
5:     TODO
6:   end for
7:   return ( $V, E$ ) ▷ The poset graph
8: end procedure
```

Im Anhang findet sich eine Implementierung von Algorithm 5.1 und Algorithm 5.2 in GAP 4.5.4. Table 5.1 zeigt ein Benchmark anhand von fünf ausgewählten Coxetergruppen. Dabei sind die  $A_n$  als symmetrische Gruppen implementiert und die  $E_n$  als frei präsentierte Gruppen. Ausgeführt wurden die Messungen auf einem Intel Core i5-3570k mit

vier Kernen zu je 3,40 GHz. Der Algorithmus ist dabei aber nur single threaded und kann so nur auf einem Kern laufen. Um die Messergebnisse nicht durch Limitierungen des Datenspeichers zu beeinflussen, wurden die Daten in diesem Benchmark nicht stückweise persistiert sondern ausschließlich berechnet.

Wie zu erwarten ist der Geschwindigkeitsgewinn bei den Coxetergruppen vom Typ  $E_n$  deutlich größer, da in diesem Fall die Elementvergleiche deutlich aufwendiger sind als bei Gruppen vom Typ  $A_n$ .

## 6 Miscellaneous

**Definition 6.1** (Geodesic). Let  $(W, S)$  be a Coxeter system and  $w, u \in W$  with  $\rho(u) - \rho(w) = n$ . Each sequence  $w = w_0 < w_1 < \dots < w_n = u$  is called a geodesic from  $w$  to  $u$ .

**Question 6.2.** Let  $(W, S)$  be a Coxeter system,  $\theta : W \rightarrow W$  an automorphism of  $W$  with  $\theta^2 = \text{id}$  and  $\theta(S) = S$ , and  $K \subset S$  a subset of  $S$  generating a finite subgroup of  $W$  with  $\theta(K) = K$ . Furthermore let  $T, S_1, S_2, S_3 \subset S$  be four pairwise disjoint sets of generators. For which Coxeter groups  $W$  does the implication

$$w \in w_K C_{T \cup S_i}, i = 1, 2, 3 \Rightarrow w \in w_K C_T \quad (6.2.1)$$

hold for any possible  $K, \theta, T, S_1, S_2, S_3$  and  $w$ ?

**Proposition 6.3.** Let  $(W, S)$  be a Coxeter system and  $K, T, S_1, S_2, S_3$  be like in Question 6.2. Suppose we have  $w \in W$  and  $a_1, \dots, a_n \in T \cup S_1, b_1, \dots, b_n \in T \cup S_2, c_1, \dots, c_n \in T \cup S_3$  with

$$\begin{aligned} w &= w_K \underline{a_1 \cdots a_n} \\ &= w_K \underline{b_1 \cdots b_n} \\ &= w_K \underline{c_1 \cdots c_n} \end{aligned}$$

and (6.2.1) does not hold for these three expressions, i.e.  $w \notin w_K C_T$ . Then there exist  $t_1, \dots, t_m \in T$  and  $a'_1, \dots, a'_{n-m} \in T \cup S_1, b'_1, \dots, b'_{n-m} \in T \cup S_2, c'_1, \dots, c'_{n-m} \in T \cup S_3$  such that

$$\begin{aligned} w \underline{t_1 \cdots t_m} &= w_K \underline{a'_1 \cdots a'_{n-m}} \\ &= w_K \underline{b'_1 \cdots b'_{n-m}} \\ &= w_K \underline{c'_1 \cdots c'_{n-m}} \end{aligned}$$

with  $a'_{n-m}, b'_{n-m}, c'_{n-m} \notin T$ .

*Proof.* Suppose at least one element of  $a_n, b_n, c_n$  to be in  $T$ , for example  $a_n \in T$ . Then we can apply  $\underline{a_n}$  to all three expressions. Since  $\rho(w \underline{a_n}) < \rho(w)$  the exchange condition for  $\mathcal{I}_\theta$  [Hultman, 2007, Proposition 3.10] yields

$$\begin{aligned} w \underline{a_n} &= w_K \underline{a_1 \cdots a_n a_n} = w_K \underline{a_1 \cdots a_{n-1}} \\ &= w_K \underline{b_1 \cdots b_n a_n} = w_K \underline{b_1 \cdots \hat{b}_i \cdots b_n} \\ &= w_K \underline{c_1 \cdots c_n a_n} = w_K \underline{c_1 \cdots \hat{c}_j \cdots c_n} \end{aligned}$$

where  $\hat{\phantom{x}}$  means omission. The omission cannot occur within  $w_K$  since all three expressions are still of same twisted length and in the first expression we can see, that  $w_K \leq w \underline{a_n}$  still holds. This step can be repeated until  $w = w_K$  or  $a_n, b_n, c_n \notin T$ .  $\square$

**Lemma 6.4.** A counterexample to Question 6.2 can only exist, if there is an element  $u \in w C_T$  and three distinct generators  $s_1, s_2, s_3 \in D_r(u)$  such that  $u \underline{s_i} \notin w C_T$  for  $i = 1, 2, 3$ .



*Proof.* According to Proposition 6.3. □

**Lemma 6.5.** *A counterexample to Question 6.2 can only exist, if there are three not necessarily distinct elements  $a, b, c \in w_K C_{S \setminus T}$ , three distinct generators  $s_1 \in A_r(a)$ ,  $s_2 \in A_r(b)$ ,  $s_3 \in A_r(c)$  and an element  $u \notin w_K C_{S \setminus T}$  such that*

$$as_1 = bs_2 = cs_3 = u.$$

*Proof.* If there is a counterexample, then the two residuums  $w_K C_{S \setminus T}$  and  $w C_T$  are disjoint. Since we are only interested in  $w$  with  $w_K \leq w$  it follows, that any geodesic from  $w_K$  to  $w$  is contained in the union set of both residuums. Hence having one element in  $u \in w C_T$  with three distinct generators  $s_1, s_2, s_3$  with  $us_i \notin w C_T$  is equivalent to having three elements  $a, b, c \notin w C_T$  and the same three generator  $s_1, s_2, s_3$  with  $as_1 = bs_2 = cs_3 = u \in w C_T$ . □

**Lemma 6.6.** *Let  $(W, S)$  be a Coxeter system,  $w \in W$  and  $s \in S$ . Then  $s \in D_R(w)$  iff  $w_s < w$ .*

*Proof.* TODO □

## A Source codes

```

1  LoadPackage("io");
2
3  Read("misc.gap");
4  Read("coxeter.gap");
5  Read("twistedinvolutionweakordering-persist.gap");
6
7  TwistedInvolutionDeduceNodeAndEdgeFromGraph := function(matrix, startNode, startLabel,
8    labels)
9    local rank, comb, trace, possibleEqualNodes, e, k, n;
10
11    rank := -1/2 + Sqrt(1/4 + 2*Length(matrix)) + 1;
12    possibleEqualNodes := [];
13
14    for comb in List(Filtered(labels, label -> label <> startLabel), label -> rec(
15      startNode := startNode, s := [startLabel, label], m := CoxeterMatrixEntry(
16        matrix, rank, startLabel, label))) do
17      trace := [];
18      k := 1;
19      n := comb.startNode;
20
21      Add(trace, rec(node := n, edge := rec(label := comb.s[1], type := -1)));
22
23      while k < comb.m do
24        e := FindElement(n.inEdges, e -> e.label = comb.s[k mod 2 + 1]);
25        if e = fail then break; fi;
26        n := e.source;
27
28        Add(trace, rec(node := n, edge := e));
29        k := k + 1;
30      od;
31
32      while k > 0 do
33        e := FindElement(n.outEdges, e -> e.label = comb.s[k mod 2 + 1]);
34        if e = fail then break; fi;
35        n := e.target;
36
37        Add(trace, rec(node := n, edge := e));
38        k := k - 1;
39      od;
40
41      if k <> 0 then continue; fi;
42
43      if Length(trace) = 2*comb.m then
44        return rec(result := 0, node := trace[Length(trace)].node, type := trace[
45          comb.m + 1].edge.type, trace := trace);
46      fi;
47
48      if Length(trace) >= 4 then
49        if trace[Length(trace) / 2 + 1].edge.type <> trace[Length(trace) / 2].edge.
50          type then
51          # cannot be equal
52        else
53          if trace[Length(trace)].edge.type = 0 then
54            return rec(result := 0, node := trace[Length(trace)].node, type :=
55              0, trace := trace);
56          else
57            Add(possibleEqualNodes, trace[Length(trace)].node);
58          fi;
59        fi;
60      fi;
61    end;
62  end;

```

```

53         fi;
54     else
55         Add(possibleEqualNodes, trace[Length(trace)].node);
56     fi;
57 od;
58
59     return rec(result := -1, possibleEqualNodes := possibleEqualNodes);
60 end;
61
62 # Calculates the poset Wk(theta).
63 TwistedInvolutionWeakOrdering := function (filename, W, matrix, theta)
64     local persistInfo, maxOrder, nodes, edges, absNodeIndex, absEdgeIndex, prevNode,
65         currNode, newEdge,
66         label, type, deduction, startTime, endTime, S, k, i, s, x, y, n;
67
68     persistInfo := TwistedInvolutionWeakOrderingPersistResultsInit(filename);
69
70     S := GeneratorsOfGroup(W);
71     maxOrder := Minimum([Maximum(Concatenation(matrix, [1])), 5]);
72     nodes := [ [], [ rec(element := One(W), twistedLength := 0, inEdges := [], outEdges
73         := [], absIndex := 1) ] ];
74     edges := [ [], [] ];
75     absNodeIndex := 2;
76     absEdgeIndex := 1;
77     k := 0;
78
79     while Length(nodes[2]) > 0 do
80         if not IsFinite(W) then
81             if k > 200 or absNodeIndex > 10000 then
82                 break;
83             fi;
84         fi;
85
86         for i in [1..Length(nodes[2])] do
87             Print(k, " ", i, " \r");
88
89             prevNode := nodes[2][i];
90             for label in Filtered([1..Length(S)], n -> Position(List(prevNode.inEdges,
91                 e -> e.label), n) = fail) do
92                 deduction := TwistedInvolutionDeduceNodeAndEdgeFromGraph(matrix,
93                     prevNode, label, [1..Length(S)]);
94
95                 if deduction.result = 0 then
96                     type := deduction.type;
97                     currNode := deduction.node;
98                 elif deduction.result = 1 then
99                     type := deduction.type;
100
101                     currNode := rec(element := y, twistedLength := k + 1, inEdges :=
102                         [], outEdges := [], absIndex := absNodeIndex);
103                     Add(nodes[1], currNode);
104
105                     absNodeIndex := absNodeIndex + 1;
106                 else
107                     x := prevNode.element;
108                     s := S[label];
109
110                     type := 1;
111                     y := s^theta*x*s;
112                     if (CoxeterElementsCompare(x, y)) then
113                         y := x * s;

```

```

109         type := 0;
110     fi;
111
112     currNode := FindElement(deduction.possibleEqualNodes, n ->
        CoxeterElementsCompare(n.element, y));
113
114     if currNode = fail then
115         currNode := rec(element := y, twistedLength := k + 1, inEdges
            := [], outEdges := [], absIndex := absNodeIndex);
116         Add(nodes[1], currNode);
117
118         absNodeIndex := absNodeIndex + 1;
119     fi;
120 fi;
121
122 newEdge := rec(source := prevNode, target := currNode, label := label,
    type := type, absIndex := absEdgeIndex);
123
124 Add(edges[1], newEdge);
125 Add(currNode.inEdges, newEdge);
126 Add(prevNode.outEdges, newEdge);
127
128 absEdgeIndex := absEdgeIndex + 1;
129 od;
130 od;
131
132 TwistedInvolutionWeakOrderingPersistResults(persistInfo, nodes[2], edges[2]);
133
134 Add(nodes, [], 1);
135 Add(edges, [], 1);
136 if (Length(nodes) > maxOrder + 1) then
137     for n in nodes[maxOrder + 2] do
138         n.inEdges := [];
139         n.outEdges := [];
140     od;
141     Remove(nodes, maxOrder + 2);
142     Remove(edges, maxOrder + 2);
143 fi;
144 k := k + 1;
145 od;
146
147 TwistedInvolutionWeakOrderingPersistResultsInfo(persistInfo, W, matrix, theta,
    absNodeIndex - 1, k - 1);
148 TwistedInvolutionWeakOrderingPersistResultsClose(persistInfo);
149
150 return rec(numNodes := absNodeIndex - 1, numEdges := absEdgeIndex - 1,
    maxTwistedLength := k - 1);
151 end;
152
153 # Calculates the poset Wk(theta).
154 TwistedInvolutionWeakOrdering1 := function (filename, W, matrix, theta)
155     local persistInfo, maxOrder, nodes, edges, absNodeIndex, absEdgeIndex, prevNode,
        currNode, newEdge,
156     label, type, deduction, startTime, endTime, S, k, i, s, x, y, n;
157
158     persistInfo := TwistedInvolutionWeakOrderingPersistResultsInit(filename);
159
160     S := GeneratorsOfGroup(W);
161     maxOrder := Minimum([Maximum(Concatenation(matrix, [1])), 5]);
162     nodes := [ [], [ rec(element := One(W), twistedLength := 0, inEdges := [], outEdges
        := [], absIndex := 1) ] ];

```

```

163 edges := [ [], [] ];
164 absNodeIndex := 2;
165 absEdgeIndex := 1;
166 k := 0;
167
168 while Length(nodes[2]) > 0 do
169   if not IsFinite(W) then
170     if k > 200 or absNodeIndex > 10000 then
171       break;
172     fi;
173   fi;
174
175   for i in [1..Length(nodes[2])] do
176     Print(k, " ", i, " \r");
177
178     prevNode := nodes[2][i];
179     for label in Filtered([1..Length(S)], n -> Position(List(prevNode.inEdges,
180       e -> e.label), n) = fail) do
181       x := prevNode.element;
182       s := S[label];
183
184       type := 1;
185       y := s^theta*x*s;
186       if (CoxeterElementsCompare(x, y)) then
187         y := x * s;
188         type := 0;
189       fi;
190
191       currNode := FindElement(nodes[1], n -> CoxeterElementsCompare(n.element
192         , y));
193
194       if currNode = fail then
195         currNode := rec(element := y, twistedLength := k + 1, inEdges :=
196           [], outEdges := [], absIndex := absNodeIndex);
197         Add(nodes[1], currNode);
198
199         absNodeIndex := absNodeIndex + 1;
200       fi;
201
202       newEdge := rec(source := prevNode, target := currNode, label := label,
203         type := type, absIndex := absEdgeIndex);
204
205       Add(edges[1], newEdge);
206       Add(currNode.inEdges, newEdge);
207       Add(prevNode.outEdges, newEdge);
208
209       absEdgeIndex := absEdgeIndex + 1;
210     od;
211   od;
212
213   TwistedInvolutionWeakOrderingPersistResults(persistInfo, nodes[2], edges[2]);
214
215   Add(nodes, [], 1);
216   Add(edges, [], 1);
217   if (Length(nodes) > maxOrder + 1) then
218     for n in nodes[maxOrder + 2] do
219       n.inEdges := [];
220       n.outEdges := [];
221     od;
222     Remove(nodes, maxOrder + 2);
223     Remove(edges, maxOrder + 2);

```

---

```

220         fi;
221         k := k + 1;
222     od;
223
224     TwistedInvolutionWeakOrderingPersistResultsInfo(persistInfo, W, matrix, theta,
        absNodeIndex - 1, k - 1);
225     TwistedInvolutionWeakOrderingPersistResultsClose(persistInfo);
226
227     return rec(numNodes := absNodeIndex - 1, numEdges := absEdgeIndex - 1,
        maxTwistedLength := k - 1);
228 end;
229
230 TwistedInvolutionWeakOrderungResiduum := function (vertex, labels)
231     local visited, queue, residuum, current, edge;
232
233     visited := [ vertex ];
234     queue := [ vertex ];
235     residuum := [];
236
237     while Length(queue) > 0 do
238         current := queue[1];
239         Remove(queue, 1);
240         Add(residuum, current);
241
242         for edge in current.outEdges do
243             if edge.label in labels and not edge.target in visited then
244                 Add(visited, edge.target);
245                 Add(queue, edge.target);
246             fi;
247         od;
248     od;
249
250     return residuum;
251 end;
252
253 TwistedInvolutionWeakOrderungLongestWord := function (vertex, labels)
254     local current;
255
256     current := vertex;
257
258     while Length(Filtered(current.outEdges, e -> e.label in labels)) > 0 do
259         current := Filtered(current.outEdges, e -> e.label in labels)[1].target;
260     od;
261
262     return current;
263 end;

```

## B References

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