BASIC STRUCTURE OF COXETER GROUPS

These are class notes from the first month of Math 665, taught at the University of Michigan, Fall 2017. Class taught by David E Speyer; class notes edited by David and written by the students: Elizabeth Collins-Wildman, Deshin Finlay, Haoyang Guo, Alana Huszar, Gracie Ingermanson, Zhi Jiang and Robert Walker. Thanks also to the Fall 2019 class, Anna Brosowsky, Shelby Cox, Will Dana, Will Newman, RuiLin Shi and Danny Stoll for their comments and suggestions. Further comments and corrections are welcome!

Contents

1. Introduction 2
2. Arrangements of hyperplanes 3
3. Classification of positive definite Cartan matrices 4
4. Non-orthogonal reflections 8
5. The geometry of two reflections 9
6. Coxeter Groups, Cartan matrices, roots and hyperplanes 12
7. The sign function and length 12
8. A key lemma 13
9. Consequences of the Key Lemma 15
10. Reflections, transpositions and roots 18
11. Finishing the classification of finite reflection groups 18
12. Inversions, reflection sequences and length 20
13. Root sequences 21
14. Parabolic Subgroups 22
15. Crystallographic groups 23
16. Affine symmetries and affine reflection groups 27
17. Positive semidefinite Cartan matrices 28
18. Partial proofs of claims about affine Coxeter groups 29
19. Hyperbolic Coxeter groups 31
This course will study the combinatorics and geometry of Coxeter groups. We start by discussing the finite reflection groups. We are doing this for three reasons:

1. The classification of finite reflection groups is the same as that of finite Coxeter groups, and the structure of finite reflection groups motivates the definition of a Coxeter group.

2. One of my favorite things in math is when someone describes a natural sort of object to study and turns out to be able to give a complete classification. Finite reflection groups is one of those success stories.

3. This will allow us to preview many of the most important examples of Coxeter groups. I’ll also take the opportunity to tell you their standard names.

Today we will, without proof, describe all the finite reflection groups.

Let $V$ be a real vector space with a positive definite symmetric bilinear form $\cdot$ (dot product). Let $\alpha$ be a nonzero vector in $V$. The orthogonal reflection across $\alpha$ is the linear map $x \mapsto x - 2\frac{\alpha \cdot x}{\alpha \cdot \alpha}\alpha$. This fixes the hyperplane $\alpha$ and negates the normal line $R\alpha$. An orthogonal reflection group is a subgroup of $GL(V)$ generated by orthogonal reflections. We will be classifying the finite orthogonal reflection groups.

Let $W_1 \subset GL(V_1)$ and $W_2 \subset GL(V_2)$ be reflection groups. Then we can embed $W_1 \times W_2$ into $GL(V_1 \oplus V_2)$, sending $(w_1, w_2)$ to $\begin{bmatrix} w_1 & 0 \\ 0 & w_2 \end{bmatrix}$. We call a reflection group irreducible if we can not write it as a product in this way. We will now begin describing all of the irreducible orthogonal reflection groups.

The trivial group: Take $V = \mathbb{R}$ and $W = \{1\}$.

The group of order 2: Take $V = \mathbb{R}$ and $W = \{\pm 1\}$. This group can be called $A_1$ or $B_1$.

The dihedral group: Let $m$ be a positive integer and consider the group of symmetries of regular $m$-gon in $\mathbb{R}^2$. This is generated by reflections across two hyperplanes with angle $\pi/m$ between them. Calling these reflections $\sigma$ and $\tau$, we have $\sigma^2 = \tau^2 = (\sigma\tau)^m = 1$. This dihedral group has order $2m$ and can be called $I_2(m)$. We note a general rule of naming conventions – the subscript is always the dimension of $V$.

The symmetric group: Consider the group $S_n$ acting on $\mathbb{R}^n$ by permutation matrices. The transposition $(ij)$ is the reflection across $(e_i - e_j)^\perp$. This breaks down as $\mathbb{R}(1,1,\ldots,1) \oplus (1,1,\ldots,1)^\perp$. So the irreducible reflection group is $S_n$ acting on $(1,1,\ldots,1)^\perp$. This is called $A_{n-1}$.

The group $S_n \ltimes \{\pm 1\}^n$: Consider the subgroup of $GL_n(\mathbb{R})$ consisting of matrices which are like permutation matrices, but with a $\pm 1$ in the nonzero positions. This is a reflection group, generated by the reflections over $(e_i - e_j)^\perp$, $(e_i + e_j)^\perp$ and $e_i^\perp$. We give example matrices for $n = 3$ below:

\[
\begin{bmatrix}
0 & 1 & 0 \\
1 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
0 & -1 & 0 \\
-1 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
-1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

reflection across $(e_1 - e_2)^\perp$, $(e_1 + e_2)^\perp$, $e_1^\perp$.

For reasons we will get to eventually, this is both called $B_n$ and $C_n$. 
The group $S_n \ltimes \{\pm 1\}^{n-1}$: Consider the subgroup of the previous group where the product of the non-zero entries in the matrix is 1. This is an index two subgroup of $B_n$, generated by the reflections across $(e_i \pm e_j)$. It is called $D_n$.

Collisions of names: We have $A_1 \cong B_1$, $D_1 \cong \{1\}$, $A_1 \times D_1 \cong I_2(1)$, $A_1 \times A_1 \cong D_2 \cong I_2(2)$, $A_2 \cong I_2(3)$, $B_2 \cong I_2(4)$ and $A_3 \cong D_3$. (The last is not obvious.) Some authors will claim that some of these notations are not defined, but if you define them in the obvious ways, this is what you have. Also, $I_2(6)$ has another name, $G_2$.

We have now listed all but finitely many of the finite orthogonal reflection groups. The remaining cases are probably best understood after we start proving the classification, but we'll try to say something about them. Their names are $E_6$, $E_7$, $E_8$, $F_4$, $H_3$ and $H_4$.

Sporadic regular solids: $H_3$ is the symmetry group of the dodecahedron and its dual the icosahedron. $F_4$ is the symmetry group of a regular 4-dimensional polytope called the 24-cell, $H_4$ is the symmetry group of two regular 4-dimensional polytopes: the 120-cell and the 600-cell. We'll discuss this further in Section 14.

Symmetries of lattices: $F_3$ is the group of symmetries of the lattice $\mathbb{Z}^4 \cup [\mathbb{Z}^4 + \{\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}\}]$ in $\mathbb{R}^4$. $E_8$ is the group of symmetries of the eight dimensional lattice

$$\left\{(a_1, a_2, \ldots, a_8) \in \mathbb{Z}^8 \cup [\mathbb{Z}^8 + \{\frac{1}{2}, \frac{1}{2}, \ldots, \frac{1}{2}\}] : \sum a_i \in 2\mathbb{Z}\right\}.$$  

$E_7$ is the subgroup of this stabilizing $(1, 1, 1, 1, 1, 1, 1)$; $E_6$ is the subgroup of $E_7$ stabilizing $(0, 0, 0, 0, 0, 0, 1, 1)$. A reflection group which stabilizes a full rank lattice (it need not be the full stabilizer of that lattice) is called \textit{crystallographic}. The crystallographic finite reflection groups are types $A_n$, $B_n = C_n$, $D_n$, $E_6$, $E_7$, $E_8$, $F_4$ and $G_2$.

2. Arrangements of hyperplanes

Let $V$ be a finite dimensional $\mathbb{R}$-vector space and let $H_1, H_2, \ldots, H_N$ be finitely many hyperplanes in $V$. Let $H_i = \beta_i^\perp$ for some vectors $\beta_i \in V^\vee$. The $H_i$ divide $V$ up into finitely many polyhedral cones.

Choose some $\rho$ not in any $H_i$. Let $D^\circ$ be the open polyhedral cone it lies in and let $D$ be the closure of $D^\circ$. We'll choose our normal vectors $\beta_i$ such that $\langle \beta_i, \rho \rangle > 0$. Observe: There can be no linear relation between the $\beta_i$'s of the form $\sum c_i \beta_i = 0$ with $c_i \geq 0$ (except $c_1 = c_2 = \cdots = c_N = 0$) since then $\sum c_i \langle \beta_i, \rho \rangle = 0$.

We will call $\beta_i$ \textbf{simple} if $\beta_i$ is \textbf{not} of the form $\sum c_j \beta_j$ with $c_j \geq 0$. So

$$D = \{\sigma : \langle \beta_i, \sigma \rangle \geq 0, 1 \leq i \leq n\} = \{\sigma : \langle \beta_i, \sigma \rangle \geq 0, \beta_i \text{ simple}\}.$$  

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Our running example of a hyperplane arrangement}
\end{figure}
In Figure 1, $\beta_1$ and $\beta_2$ are simple and $\beta_3$ is not.

Now let $V$ have an inner product and let $H_i$ be the reflecting hyperplanes of some finite orthogonal reflection group. Let $\rho$, $D^0$, $D$, $H_i$ and $\beta_i$ be as before. Call the $\beta_i$ “positive roots”. Let $\alpha_1, \ldots, \alpha_k$ be the simple roots.

**Example.** Consider $A_{n-1}$ (the symmetric group $S_n$) acting on $\mathbb{R}^n$. The reflections are the transpositions $(ij)$; the hyperplanes are $x_i = x_j$ with normal vectors $e_i - e_j$. If we take $\rho = (1, 2, \cdots, n)$, then the positive roots are $e_i - e_j$ for $(i > j)$.

The simple roots are $e_{i+1} - e_i =: \alpha_i$. All the other roots are positive combinations of these, since $e_j - e_i = (e_j - e_{j-1}) + (e_{j-1} - e_{j-2}) + \cdots + (e_{i+1} - e_i)$. So $D = \{(x_1, x_2, \cdots, x_n) : x_1 \leq x_2 \leq \cdots \leq x_n\}$.

Let’s review basic linear algebra by computing the angles between these simple roots. Since $\langle \alpha_1, \alpha_3 \rangle = 0$, the angle between $\alpha_1$ and $\alpha_3$ is $\frac{1}{2}\pi$. What’s the angle between $\alpha_1$ and $\alpha_2$? We have $\alpha_1 \cdot \alpha_1 = \alpha_2 \cdot \alpha_2 = (1)^2 + (-1)^2 = 2$, so $|\alpha_1| = |\alpha_2| = \sqrt{2}$ and $\alpha_1 \cdot \alpha_2 = (e_2 - e_1) \cdot (e_3 - e_2) = -1$, so the angle is $\cos^{-1} \frac{1}{\sqrt{2} \cdot \sqrt{2}} = \frac{\pi}{2}$. These are examples of the lemma we will prove next.

**Lemma.** In any finite reflection group with $\alpha_1, \ldots, \alpha_k$ as before, the angle between $\alpha_i$ and $\alpha_j$ is of the form $\pi(1 - \frac{1}{m_{ij}})$, $m_{ij} \in \{2, 3, 4, \cdots \}$. Letting $s_i$ be the reflection over $\alpha_i^\perp$, the integer $m_{ij}$ is the order of $s_is_j$.

**Proof.** Let $\theta$ be the angle between $\alpha_i$ and $\alpha_j$. Then $s_is_j$ is rotation by $\theta$ around the axis $\alpha_i^\perp \cap \alpha_j^\perp$. Letting $m$ be order of $s_is_j$, we see $\theta$ must be of the form $\frac{\pi}{m}$, where GCD($i, m) = 1$. So $s_i, s_j$ generate a copy of the dihedral group of order $2m$. The $m$ reflections in that subgroup are in mirrors $\frac{\pi}{m}$ apart. So the corresponding positive roots look like this: $\begin{array}{c}
\begin{array}{c}
\pi \\
\frac{m}{m} \\
\end{array}
\end{array}$

The simple roots $\alpha_i$ and $\alpha_j$ must be the two at the ends, as the other roots aren’t simple. $\square$

**Corollary.** For $i \neq j$, $\langle \alpha_i, \alpha_j \rangle \leq 0$.

**Proof.** We have $\cos \pi(1 - \frac{1}{m}) \leq 0$ for $m \geq 2$. $\square$

**Lemma.** The simple roots $\alpha_1, \alpha_2, \cdots, \alpha_k$ are linearly independent.

**Proof.** Suppose $\sum c_i \alpha_i = 0$. We already know we can’t have all $c_i \geq 0$. We also can’t have all $c_i \leq 0$.

Let $I = \{i : c_i > 0\}$, and define $J = \{j : c_j < 0\}$ analogously. Rewrite the proposed relation as $\sum_{i \in I} c_i \alpha_i = \sum_{j \in J} (-c_j) \alpha_j$, and call this sum $\gamma$. But then $\gamma \cdot \gamma = \sum_{i \in I, j \in J} c_i(-c_j) \langle \alpha_i, \alpha_j \rangle \leq 0$. So $\gamma = 0$. But we already showed that there is no nontrivial relationship $\sum c_i \alpha_i = 0$ with all $c_i \geq 0$ or all $c_j \leq 0$. $\square$

3. Classification of positive definite Cartan matrices

Let’s summarize what we accomplished last time. Let $V$ be a finite dimensional vector space with an inner product. Let $W \subseteq GL(V)$ be a finite orthogonal reflection group and $H_1, \ldots, H_n$ be the hyperplanes corresponding to the reflections in $W$. Choose $\rho \in V - \bigcup H_i$. Let $\beta_i$ be normal to $H_i$ such that $\langle \beta_i, \rho \rangle > 0$ and we let $\alpha_1, \ldots, \alpha_k$ be the simple roots. Let $s_i$ be
the reflection in $\alpha_i^\perp$. We showed that the $\alpha_i$ are linearly independent and the angle between $\alpha_i$ and $\alpha_j$ is $\pi \left(1 - \frac{1}{m_{ij}}\right)$, where $m_{ij}$ is the order of $s_is_j$.

**Main Idea:** Today, we will forget about the reflection group and look at sets of vectors with these properties. It turns out that this is a very limited set.

We begin by normalizing $|\alpha_i|$ to $\sqrt{2}$ so $\langle \alpha_i, \alpha_j \rangle = 2 \cos \left[\pi \left(1 - \frac{1}{m_{ij}}\right)\right] = -2 \cos \frac{\pi}{m_{ij}}$. We call this $A_{ij}$. We also have $A_{ii} = \langle \alpha_i, \alpha_i \rangle = 2$. The $A_{ij}$ form a symmetric matrix, which we call $A$.

**Example.** Let $W = S_n = A_{n-1}$. So $\alpha_i = e_i - e_{i+1}$ for $1 \leq i \leq n - 1$. We have

$$A = \begin{bmatrix}
2 & -1 & 0 & 0 & 0 & 0 \\
-1 & 2 & -1 & \cdots & 0 & 0 \\
0 & -1 & 2 & 0 & 0 & 0 \\
\vdots & \ddots & \ddots & \vdots & \ddots & \ddots & & & & & \\
0 & 0 & 0 & 2 & -1 & 0 \\
0 & 0 & 0 & \cdots & -1 & 2 & -1 \\
0 & 0 & 0 & 0 & -1 & 2
\end{bmatrix}.$$  

**Proposition.** $A$ is positive definite.

**Proof.** Let $\vec{c} \in \mathbb{R}^k_{\neq 0}$. Then, $\vec{c}^T A \vec{c} = \sum_{i,j} c_i c_j \langle \alpha_i, \alpha_j \rangle = \left(\sum_i c_i \alpha_i, \sum_j c_j \alpha_j \right) \geq 0$. There is equality here if and only if $\sum c_i \alpha_i = 0$, but as the $\alpha_i$ are linearly independent and $\vec{c} \neq 0$, this doesn’t happen. Thus, $\vec{c}^T A \vec{c} > 0$.

We encode $A$ in a graph $\Gamma$: The vertices are $1, \ldots, k$ and we include an edge $(i, j)$ if $m_{ij} \geq 3$ (so $A_{ij} < 0$) and we label those edges with $m_{ij}$ if $m_{ij} > 3$. These are called **Coxeter diagrams**. We’ll classify the connected Coxeter diagrams.

Before we begin, we remind the reader of a few key values:

<table>
<thead>
<tr>
<th>$m_{ij}$</th>
<th>$A_{ij}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
</tr>
<tr>
<td>4</td>
<td>$-\sqrt{2} \approx -1.41$</td>
</tr>
<tr>
<td>5</td>
<td>$\frac{-1 + \sqrt{5}}{2} \approx -1.62$</td>
</tr>
<tr>
<td>6</td>
<td>$-\sqrt{3} \approx -1.73$</td>
</tr>
</tbody>
</table>

Since positive definite matrices have all submatrices positive definite, $\Gamma$ cannot contain an induced subgraph corresponding to a non-positive definite matrix. We will thus begin to list non-positive definite graphs. To do this, we use the following convention: If a matrix $A$ isn’t positive definite, there is a nonzero vector $c$ such that $c^T Ac \leq 0$. We will label the vertex $i$ with $c_i$ in the below graphs to illustrate why each graph is not positive definite, and write the value of $c^T Ac$ to the right of these graphs.

Observe that, in each of our examples, the vector we have used has positive coordinates. This means that any submatrix whose entries are termwise dominated by those of these graphs is also not positive definite. In particular, these graphs are excluded not only as induced subgraphs, but as subgraphs altogether.
Since $\Gamma$ cannot contain this subgraph, $\Gamma$ is a tree.

Since $\Gamma$ cannot contain these subgraphs or any graph whose edge labels dominate them, $\Gamma$ has no vertices of degree $\geq 4$, and at most one of degree 3.

Since $\Gamma$ cannot contain this subgraph or any graph whose edge labels dominate this, $\Gamma$ has at most one edge with $m_{ij} \geq 4$.

Since $\Gamma$ cannot contain this subgraph or any graph whose edge labels dominate this, $\Gamma$ does not have both an edge with $m_{ij} \geq 4$ and a vertex of degree 3.

At this point, we know that $\Gamma$ is either

1. Three paths with a common endpoint, and all edges with $m_{ij} = 3$ or
2. A single path, with at most one edge having $m_{ij} > 3$.

The following excluded graphs rule out all but finitely many three path cases:

The following excluded graphs rule out all but finitely many single path cases.
Remark. Almost all of the graphs above are positive semidefinite, meaning that we can achieve \( c^T A c = 0 \) but not \( c^T A c < 0 \). Moreover, their kernel is one dimensional. Thus, we are forced to use the precise weights shown here. The exceptions are 1 2 5 2 1 and 3 5 4 3 2 1. In these cases, the matrix has signature ++ +− and + + + + −, and the weights given were chosen by rounding the eigenvector of negative eigenvalue to the nearest integer vector and checking that the resulting \( c \) worked.

Although I say that there is no choice as to what weights I use in the positive semidefinite case, that is a little misleading. I chose to normalize \(|\alpha| = \sqrt{2}\) which means, in the vocabulary of the next section, that \( \alpha = \alpha^\vee \). If I allow myself the more general setting where \( \alpha \) and \( \alpha^\vee \) are proportional but not equal, I gain the freedom to choose their ratio, and I could use that freedom to remove the square roots from the figures above.

The surviving graphs are the (connected) Coxeter diagrams! We list them in Table 1.

There are some collisions of names. Some books have fixed conventions about which one of these names to use in each case, but I see no reason not to have two names for the same object.

\[
\begin{array}{cccc}
2 & 4 & 3\sqrt{2} & 2\sqrt{2} \\
1 & 2 & 5 & 2 \\
3 & 5 & 4 & 3 \\
\sqrt{3} & 6 & 2 & 1 \\
\end{array}
\]

\[c^T A c = 0\]

\[c^T A c = 8 - 4\sqrt{5} < 0\]

\[c^T A c = 26 - 12\sqrt{5} < 0\]

\[c^T A c = 0\]

\[B_n = C_n\]

\[A_2 = I_2(3)\]

\[B_2 = I_2(4)\]

\[G_2 = I_2(6)\]

\[A_3 = D_3.\]

Reversing the Process: We have now shown that every reflection group generates one of these Coxeter diagrams, but in order to conclude that this is a classification, we need to show that this process can be reversed and is a bijection. It is clear that we can go from the graph \( \Gamma \) to the matrix \( A \). Then, we have the following:

**Theorem.** For any positive definite symmetric matrix \( A \), there exist vectors \( \alpha_1, \alpha_2, \ldots, \alpha_n \) that are linearly independent such that \( \langle \alpha_i, \alpha_j \rangle = A_{ij} \).

**Proof.** Write \( A = U^T D U \) with \( U \) orthogonal, \( D \) diagonal. Then, \( D = \text{diag}(\lambda_1, \ldots, \lambda_n) \).

Let \( X = \text{diag}(\sqrt{\lambda_1}, \ldots, \sqrt{\lambda_n}) U \). Then, \( A = X^T X \) and the columns of \( X \) have the desired property. \( \square \)

We can thus go from \( A \) to some \( \alpha_1, \ldots, \alpha_k \), with corresponding reflections \( s_i(x) = x - 2\frac{\langle \alpha_i, x \rangle}{\langle \alpha_i, \alpha_i \rangle} \alpha_i \). These then generate some group \( W_{\text{output}} \).

**However:** The following issues still remain

1. Is \( W_{\text{output}} \) necessarily finite?
2. If we start with a group \( W_{\text{input}} \), run the first algorithm to get a graph \( \Gamma \) and then run it backwards to get \( W_{\text{output}} \), does \( W_{\text{output}} = W_{\text{input}} \)? As a special case, if \( \Gamma = \Gamma_1 \sqcup \Gamma_2 \), then \( W_{\text{output}}(\Gamma) \) is clearly the product of \( W_{\text{output}}(\Gamma_1) \) and \( W_{\text{output}}(\Gamma_2) \), but it isn’t clear that the input group decomposes as a product. So addressing this issue will justify our choice to focus on connected graphs.
3. If we change \( \rho \), do we always get the same Coxeter diagram \( \Gamma \)?
4. If we start with \( \alpha_1, \ldots, \alpha_k \), build \( W_{\text{output}} \) and take a \( \rho \) with \( \langle \rho, \alpha_i \rangle > 0 \), will \( \alpha_i, \ldots, \alpha_k \) be the simples we get?
We will show in Section 11 that the answer to all these questions is yes. However, before we answer these questions, we will build up the vocabulary to study infinite Coxeter groups, so that we can prove more general theorems which address these questions in the finite case.

4. Non-orthogonal reflections

Let $V$ be a finite dimensional real vector space and let $V^\vee$ be its dual. We call an element $\sigma \in \text{GL}(V)$ a reflection if $\sigma^2 = \text{Id}$ and $V^\sigma$ is of codimension one. Then reflections look like $\sigma(x) = x - \langle \alpha^\vee, x \rangle \alpha$ for some $\alpha \in V$, $\alpha^\vee \in V^\vee$ with $\langle \alpha^\vee, \alpha \rangle = 2$. Note that this formula negates $\mathbb{R}\alpha$ and fixes $(\alpha^\vee)^\perp$.

The vectors $\alpha$ and $\alpha^\vee$ are determined by $\sigma$ up to rescaling of the form

$$\alpha \mapsto c\alpha, \quad \alpha^\vee \mapsto c^{-1}\alpha^\vee.$$ 

If $V$ is equipped with a nondegenerate symmetric bilinear form, giving an identification $V \cong V^\vee$, then $\sigma$ is orthogonal if and only if $\alpha$ and $\alpha^\vee$ are proportional. In that case, we will have $\alpha^\vee = \frac{2\alpha}{\langle \alpha, \alpha \rangle}$. 

A reflection group is defined as a subgroup of $\text{GL}(V)$ generated by reflections.

Lemma. If $G$ is a finite subgroup of $\text{GL}(V)$, then $G$ preserves a positive definite symmetric bilinear form.
Proof. Take any positive-definite bilinear form $(, )$. Set
\[
\langle \vec{v}, \vec{w} \rangle := \frac{1}{G} \sum_{g \in G} (g\vec{v}, g\vec{w}).
\]
Then $(,)$ is positive definite and $G$-invariant. \qed

So all finite reflection groups are orthogonal; we will only get interesting new examples in the infinite case.

Remark. Allowing $\alpha$ and $\alpha^\vee$ to be distinct can simplify formulas even in the positive definite case. In the conventions of the last section, the roots of $B_n$ are $\pm e_i \pm e_j$ and $\pm \sqrt{2} e_k$. If we instead take the roots to be $\{\pm e_i \pm e_j, \pm e_k\}$ and the co-roots to be $\{\pm e_i \pm e_j, \pm 2e_k\}$, then we can compute in $B_n$ without any square roots of 2. Indeed, well chosen scalings can remove the square roots in all the crystallographic cases: $A, B, C, D, E, F$ and $G$.

This explains why we have the double name $B_n = C_n$; we could have chosen the roots to be $\{\pm e_i \pm e_j, \pm 2e_k\}$ and the co-roots to be $\{\pm e_i \pm e_j, \pm e_k\}$ instead. The former choice is $B_n$ and the latter is $C_n$.

Cartan originally chose these names when classifying simple Lie algebras, and in that context we get specific roots and coroots, with $A_{ij}$ always integral. The Lie algebras $B_n$ and $C_n$ are honestly different, but they have the same associated reflection group. This explains why $G_2$ gets a special name: It showed up in Cartan’s classification, whereas $I_2(m)$ for $m \notin \{2, 3, 4, 6\}$ did not, because for those other values of $m$ we cannot make $A_{ij}$ integral. This is also why $H$ and $I$ are at the end of the list; they were added later.

5. The geometry of two reflections

Let $\sigma$ and $\tau$ be two reflections with
\[
\sigma(x) = x - \langle \alpha^\vee, x \rangle \alpha, \quad \tau(x) = x - \langle \beta^\vee, x \rangle \beta,
\]
and $\langle \alpha^\vee, \alpha \rangle = \langle \beta^\vee, \beta \rangle = 2$. Let $K$ be the cone $\{x \in V^\vee : \langle \alpha, x \rangle, \langle \beta, x \rangle > 0\}$.

The key fact that we will need is the following:

Theorem. Suppose that $\langle \beta^\vee, \alpha \rangle, \langle \alpha^\vee, \beta \rangle \leq 0$ and $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle$ is either of the form $4 \cos^2 \frac{\pi}{m}$, or else is $\geq 4$. If $\alpha$ and $\beta$ are not proportional, then the images of $K$ under the subgroup generated by $\sigma$ and $\tau$ are disjoint.

If $\alpha$ and $\beta$ are proportional, then they must point in opposite directions, since $\langle \alpha^\vee, \alpha \rangle$ and $\langle \alpha^\vee, \beta \rangle$ have different signs. So, in this case, $K$ is empty.

The case where $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle = 4$ is a bit annoying, so postpone that one until the end.

The vectors $(\alpha^\vee, \beta^\vee)$ and $(\alpha, \beta)$ pair by $\begin{pmatrix} 2 & \langle \alpha^\vee, \beta \rangle \\ \langle \beta^\vee, \alpha \rangle & 2 \end{pmatrix}$, which is nonsingular since we assume $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle \neq 4$. So $V$ decomposes as $\text{Span}(\alpha, \beta) \oplus \text{Span}(\alpha^\vee, \beta^\vee)^\perp$. The action on the second summand is trivial, so we consider the action on $\text{Span}(\alpha, \beta)$. In the $(\alpha, \beta)$-basis, we have
\[
\sigma = \begin{bmatrix} -1 & -\langle \alpha^\vee, \beta \rangle \\ 0 & 1 \end{bmatrix}, \quad \tau = \begin{bmatrix} 1 & 0 \\ -\langle \beta^\vee, \alpha \rangle & -1 \end{bmatrix}
\]
and
\[
\sigma \tau = \begin{bmatrix} -1 + \langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle & \langle \alpha^\vee, \beta \rangle \\ -\langle \beta^\vee, \alpha \rangle & -1 \end{bmatrix}
\]
We thus see that $\sigma \tau$ has determinant 1 and trace $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle - 2$. 

Case 0: If $\langle \alpha^\vee, \beta \rangle = \langle \beta^\vee, \alpha \rangle = 0$, then $\sigma$ and $\tau$ act on $\alpha$ and $\beta$ by $[1 \ 0 \ 0] \text{ and } [\ 0 \ 1 \ 1]$ respectively, so $\sigma$ and $\tau$ commute and generate a copy of the $I_2(2) = A_1 \times A_1$ hyperplane arrangement.

Case I: Suppose that $0 < \langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle < 4$; put $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle = 4 \cos^2 \theta$ for some $\theta \in (0, \pi/2)$. So $\text{Tr}(\sigma \tau) = 4 \cos^2 \theta - 2 = 2 \cos(2\theta)$. We see that the characteristic polynomial of $\sigma \tau$ is $(\lambda - e^{i2\theta})(\lambda - e^{-i2\theta})$. Since $e^{i2\theta} \neq e^{-i2\theta}$, we know that $\sigma \tau$ is conjugate to a rotation by $2\theta$.

If $\theta = \frac{2\pi}{m}$ with $\text{GCD}(\ell, m) = 1$, then $\sigma$ and $\tau$ generate a dihedral group of order $2m$; if $\theta/\pi$ is irrational, then $\sigma$ and $\tau$ generate an infinite group. In particular, if $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle = 4 \cos^2 \frac{\pi}{m}$, then $\sigma \tau$ is a rotation by $2\pi/m$, the wedge $K$ has central angle $\pi/m$ and the group $\langle \sigma, \tau \rangle$ permutes $2m$ copies of this wedge.

For future reference note that, if $m$ is even, then the orbits of $\alpha$ and $\beta$ under $\langle \sigma, \tau \rangle$ each have $m$ elements, and the vectors in the $\alpha$ orbit are not proportional to those in the $\beta$ orbit. If $m$ is odd, the orbits of each of $\alpha$ and $\beta$ have $2m$ vectors, and the vectors in the $\beta$ orbit are proportional to the vectors in the $\alpha$ orbit. The ratio of proportionality is $\sqrt{\frac{\langle \alpha^\vee, \beta \rangle}{\langle \beta^\vee, \alpha \rangle}}$.

Case II: Suppose that $4 < \langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle$. Put $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle = 4 \cosh^2 \phi$. (Recall that the hyperbolic cosine is $\cosh \phi = \frac{e^\phi + e^{-\phi}}{2}$.) So $\text{Tr}(\sigma \tau) = 2 \cosh(2\phi)$. So the eigenvalues of $\sigma \tau$ are $e^{\pm 2\phi}$, and thus $\sigma \tau$ has infinite order. More specifically, the eigenspaces of $\sigma \tau$ divide $\text{Span}(\alpha, \beta)$ into 4-cones. The $\langle \sigma, \tau \rangle$ orbit of $K$ covers one of these cones, dividing it into infinitely many non-overlapping wedges. The reader who has studied relativity will recognize $[\cosh \tau \ \sinh \tau \ \sinh \tau \ \cosh \tau]$ as the matrix of a Poincare transformation; the analogue of a rotation in one space and one time dimension.

Case III: We finally turn back to the case where $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle = 4$.

If $\alpha$ and $\beta$ are linearly independent, then $\sigma \tau$ acts on the $\alpha$, $\beta$ basis by a matrix of the form $[\begin{array}{cc} 3 & 2 \\ -2 & 1 \end{array}]$, hence of Jordan form $[\begin{array}{cc} 1 & 1 \\ 0 & 1 \end{array}]$. The translates of $K$ form adjacent cones, filling up a half space. □

We close with some pictures. The actions of $\sigma$ and $\tau$ are depicted by the red and blue arrows, and the reflecting hyperplanes are shown in black. In Figure 2, we have $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle = 2 = 4 \cos^2 \frac{\pi}{4}$. In Figure 3, we have $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle = 9$.

Figure 2. The reflecting hyperplanes for the dihedral group $I_2(4)$

We draw several figures in the affine case, when $\langle \alpha^\vee, \beta \rangle \langle \beta^\vee, \alpha \rangle = 4$. First, suppose that $\alpha$ and $\beta$ are not proportional, but $\alpha^\vee$ and $\beta^\vee$ are. In this case, the action in $V$ looks like the left hand side of Figure 4 and the action in $V^\vee$ looks like the right hand side.
If neither $\alpha$, $\beta$ nor $\alpha^\vee$, $\beta^\vee$ are proportional, then $\dim V$ must be at least 3. The action of $\langle \sigma, \tau \rangle$ preserves planes parallel to $\text{Span}(\alpha, \beta)$. Figure 5 depicts the action on such an affine plane.

**Figure 3.** The reflecting hyperplanes for a hyperbolic infinite dihedral group

**Figure 4.** An affine infinite dihedral group, acting on $V$ and $V^\vee$

**Figure 5.** An affine slice through a three dimensional representation of the infinite dihedral group
6. Coxeter Groups, Cartan matrices, roots and hyperplanes

The combinatorial data to give a Coxeter group is a collection of integers \( m_{ij} \) for \( 1 \leq i, j \leq n \), with \( m_{ii} = 1 \) and \( m_{ij} = m_{ji} \geq 2 \). The Coxeter group \( W \) is the group with generators \( s_i \) for \( 1 \leq i \leq n \) and relations \( (s_i s_j)^{m_{ij}} = 1 \). In particular, each \( s_i \) has order 2.

A Cartan matrix \( A \), for our Coxeter group \( W \), is an \( n \times n \) matrix satisfying

\[
\begin{align*}
A_{ii} &= 2, \\
A_{ij} &= 0 \quad \text{if } m_{ij} = 2, \\
A_{ij}A_{ji} &= 4 \cos^2 \frac{\pi}{m_{ij}}, \quad A_{ij}, A_{ji} < 0 \quad \text{if } 3 \leq m_{ij} < \infty, \text{ and} \\
A_{ij}A_{ji} &\geq 4, \quad A_{ij}, A_{ji} < 0 \quad \text{if } m_{ij} = \infty.
\end{align*}
\]

If \( V \) and \( V^\vee \) are dual vector spaces with \( \alpha_1, \alpha_2, \ldots, \alpha_k \in V \) and \( \alpha_1^\vee, \alpha_2^\vee, \ldots, \alpha_k^\vee \in V^\vee \), we say that the pair by \( A \) if \( \langle \alpha_i^\vee, \alpha_j \rangle = A_{ij} \). In this case, we get actions of \( W \) on both \( V \) and \( V^\vee \) with \( s_i(x) = x - \langle \alpha_i^\vee, x \rangle \alpha_i \), and \( s_i(x^\vee) = x^\vee - \langle x^\vee, \alpha_i \rangle \alpha_i^\vee \). The \( \alpha_i \) and \( \alpha_i^\vee \) are called the simple roots and simple coroots.

Let \( D = \{ x^\vee \in V^\vee | \langle x^\vee, \alpha_i \rangle \geq 0 \} \), and \( D^\circ = \{ x^\vee \in V^\vee | \langle x^\vee, \alpha_i \rangle > 0 \} \). We will almost always impose that \( D^\circ \) is non-empty.

The set of roots is defined by \( \Phi = W \cdot \{ \alpha_1, \alpha_2, \ldots, \alpha_k \} \subset V \).

We write \( T \) for the set of elements of \( W \) of the form \( ws_i w^{-1} \). (Think \( T \) for “transposition”.) Each \( t \) in \( T \) acts on \( V \) by a reflection; if \( t = ws_i w^{-1} \) then \( t \) acts by \( x \mapsto x - \langle \beta_i^\vee, x \rangle \beta_i \) where \( \beta_i = w \alpha_i \) and \( \beta_i^\vee = w \alpha_i^\vee \). Later, we will see that every element of \( W \) which acts by a reflection on \( V \) is in \( T \).

Remark. We have set up our vocabulary in such a general manner that \( \beta \) and \( c \beta \) could both be roots, for some \( c > 1 \). Also, for this reason, the notations \( \beta_i \) and \( \beta_i^\vee \) should only be considered up to scalar. In most practical cases, this issue doesn’t come up. The precise criterion is the following: Suppose that, whenever \( m_{ij} \) is a finite odd integer, we have \( A_{ij} = A_{ji} \). Then, if \( \beta_1 \) and \( \beta_2 \) are proportional roots, we must have \( \beta_1 = \pm \beta_2 \). We’ll be ready to prove this in Section 13.

In the mean time, note that if our goal is to study Coxeter groups rather than root systems, we can just choose to take \( A_{ij} = A_{ji} \) and be safe. If we further assume that the \( \alpha_i \) are a basis of \( V \), there is an easy proof: Define an inner product on \( V \) by \( \alpha_i \cdot \alpha_j = A_{ij} \). Since we assumed \( A_{ij} = A_{ji} \), this is a symmetric bilinear form. It is easy to check that \( W \) preserves \( \cdot \). Since \( \alpha_i \cdot \alpha_i = 2 \), we have \( \beta \cdot \beta = 2 \) for any \( \beta \in \Phi \), and thus, if \( \beta_1 \) and \( \beta_2 \) are proportional, then \( \beta_1 = \pm \beta_2 \).

7. The sign function and length

Let \( W \) be a Coxeter group, and continue to use the notations from the previous section.

Lemma. There is a homomorphism \( sgn : W \longrightarrow \pm 1 \) given by:

\[
s_i \mapsto -1.
\]

Proof. Recall \( W = \langle s_i | (s_i s_j)^{m_{ij}} = 1 \rangle \). All relations are sent to 1 if we send \( s_i \) to \(-1\). □

Proof (alternate). Choose a Cartan matrix, roots, and coroots. This gives us:
For $w \in W$, define $\ell(w)$ to be the minimal $\ell \in \mathbb{Z}_{\geq 0}$ such that we can write $w = s_{i_1}s_{i_2}\ldots s_{i_\ell}$ for some sequence of simple reflections. Notice $\ell(w) = 0$ if and only if $w = \text{Id}$. Note also that $\text{sgn}(w) = (-1)^{\ell(w)}$.

We define a word $(s_{i_1}, s_{i_2}, \ldots, s_{i_\ell})$ to be reduced if $\ell = \ell(s_{i_1}s_{i_2}\ldots s_{i_\ell})$. A (consecutive) subword of a reduced word is reduced, i.e. if $s_1s_2\ldots s_\ell$ is reduced, $s_is_{i+1}\ldots s_{i+j}$ is reduced.

**Lemma.** For $w \in W$ and any simple generator $s_i$, $\ell(s_iw) = \ell(w) + 1$ and $\ell(ws_i) = \ell(w) + 1$.

**Proof.** We have $\ell(s_iw) \leq \ell(w) + 1$ and $\ell(ws_i) \leq \ell(w) + 1$. So, $\ell(s_iw) - \ell(w) \in \{-1, 0, 1\}$. We also have

$$(-1)^{\ell(w)} = \text{sgn}(w) = -\text{sgn}(s_iw) = -(-1)^{\ell(s_iw)},$$

so $\ell(w) \equiv \ell(s_iw) + 1 \mod 2$. $\square$

We will say $s_i$ is a **left ascent/descent** of $w$ according to whether:

$$\ell(s_iw) = \ell(w) + 1 \text{ (left ascent), or}$$

$$\ell(s_iw) = \ell(w) - 1 \text{ (left descent).}$$

We also define

$$\ell(ws_i) = \ell(w) + 1 \text{ (right ascent), and}$$

$$\ell(ws_i) = \ell(w) - 1 \text{ (right descent).}$$

Any $w$ other than the identity has some left descent and some right descent.

As an exercise, in $S_n$ we have

$$\ell(w) = \#\{(i, j)\mid 1 \leq i < j \leq n, w(i) > w(j)\}.$$ 

The pairs $(i, j)$ in this formula are called the **inversions** of $w$. So $s_i$ is a left ascent if $w^{-1}(i) < w^{-1}(i + 1)$, and is a right ascent if $w(i) < w(i + 1)$.

**Example.** Let $231$ be $2 \mapsto 1, 3 \mapsto 2, 1 \mapsto 3$. Then,

- $s_2$ is a right descent of $231$, because positions 2 and 3 are out of order, and
- $s_2$ is a left ascent of $231$, because numbers 2 and 3 are in order.

If you find writing $231$ to denote $2 \mapsto 1, 3 \mapsto 2, 1 \mapsto 3$ confusing, you have my sympathies. It is, however, reasonably standard and has the advantage of working nicely with labeling the hyperplane arrangement. Specifically, $\{x_1 \leq x_2 \leq x_3\}, \{x_1 \leq x_3 \leq x_2\}, \{x_2 \leq x_3 \leq x_1\}$ are consecutive regions of the hyperplane arrangement, given by $D, s_2D$ and $s_2s_1D$. We would like to abbreviate $\{x_2 \leq x_3 \leq x_1\}$ to $231$, so we want $s_2s_1$ to be $231$. But $s_2(s_1(1)) = s_2(2) = 3$, $s_2(s_1(2)) = s_2(1) = 1$ and $s_2(s_1(3)) = s_2(3) = 2$, so $s_2s_1$ is $1 \mapsto 3, 2 \mapsto 1, 3 \mapsto 2$.

8. **A Key Lemma**

Let $W$ be a Coxeter group and $A$ a Cartan matrix for $W$. Let $\alpha_i$ in $V$ and $\alpha_i^\vee$ in $V^\vee$ with $\alpha_i^\vee \alpha_j = A_{ij}$. We set $D = \{x^\vee \in V^\vee \mid \langle x^\vee, \alpha_i \rangle \geq 0\}$ and $D^0 = \{x^\vee \in V^\vee \mid \langle x^\vee, \alpha_i \rangle > 0\}$.

We assume $D^0 \neq \emptyset$. 

\[
\begin{align*}
W & \longrightarrow GL(V) \\
\downarrow \text{sgn} & \quad \downarrow \text{det} \\
\{\pm 1\} & \longrightarrow \mathbb{R}^* \\
\end{align*}
\]
Remark. Many sources assume that the $\alpha_i$ are linearly independent; we don’t need that. However, we note that $\alpha_i$ and $\alpha_j$ are not proportional: We can’t have $\alpha_i \in \mathbb{R}_{>0} \alpha_j$ as $\langle \alpha_i^\vee, \alpha_i \rangle = 2$ and $\langle \alpha_i^\vee, \alpha_j \rangle \leq 0$, and we can’t have $\alpha_i \in \mathbb{R}_{<0} \alpha_j$ as that would make $D^0 = \emptyset$.

Today’s goal is the following key lemma:

Lemma. For $w \in W$ and $s_i$ a simple reflection:

- If $s_i$ is a left ascent of $w$, then $\langle , \alpha_i \rangle \geq 0$ on $wD$ and
- If $s_i$ is a left descent of $w$, then $\langle , \alpha_i \rangle \leq 0$ on $wD$.

We depict the Lemma in Figure 6: We have $\langle , \alpha_1 \rangle \geq 0$ on the right hand half of the figure and $\langle , \alpha_1 \rangle \leq 0$ on the left.

Example. Let’s see what this means for the symmetric group $S_n$. Recall that $(\sigma x)_i = x_{\sigma^{-1}(i)}$ where $\sigma \in S_n$ and $x \in \mathbb{R}^n$. So $x \in \sigma D \iff \sigma^{-1} x \in D \iff (\sigma^{-1} x)_i$ is increasing $\iff x_{\sigma(1)} \leq x_{\sigma(2)} \leq \ldots \leq x_{\sigma(n)}$.

The lemma says that $(i, i+1)$ is a left ascent of $\sigma$ $\iff \langle e_{i+1} - e_i, x \rangle \geq 0$ for $x \in \sigma D$. By the above equivalences, this will happen if and only if $\sigma^{-1}(i) \leq \sigma^{-1}(i+1)$.

**Figure 6.** We have $\langle , \alpha_1 \rangle \geq 0$ on the right side of the figure and $\leq 0$ on the left.

Proof. We proceed by induction on $\ell(w)$.

**Base case:** $\ell(w) = 0$ so $w = 1$. We want to show $\langle , \alpha_i \rangle \geq 0$ on $D$. This is true by the definition of $D$.

**Case I:** $s_i$ is a left descent of $w$ so $\ell(s_i w) = \ell(w) - 1$. Inductively, $\langle x, \alpha_i \rangle \geq 0$ for $x \in s_i wD$, so $\langle s_i y, \alpha_i \rangle \geq 0$ for $y \in wD$. But $\langle s_i y, \alpha_i \rangle = \langle y, s_i \alpha_i \rangle = -\langle y, \alpha_i \rangle$ so $\langle y, \alpha_i \rangle \leq 0$ for $y \in wD$.

**Case II:** $s_i$ is a left ascent of $w$, but $\ell(w) > 0$. This is the key case. Since $w \neq 1$, there is some left descent $s_j$ of $w$. Choose a reduced word for $w$ of the form $uv$ where $u$ is in the subgroup generated by $s_i$ and $s_j$ and $u$ is as long as possible. Then $u$ and $v$ are reduced and $\ell(u) + \ell(v) = \ell(w)$.

Since we chose $u$ maximal, $v$ doesn’t have reduced words with first letter $s_i$ or $s_j$. So $s_i$ and $s_j$ are both left ascents of $v$. And $\ell(v) = \ell(w) - \ell(u) < \ell(w)$. So, inductively, $\langle , \alpha_i \rangle \geq 0$ and $\langle , \alpha_j \rangle \geq 0$ on $vD$. Geometrically, $vD$ is somewhere in the dark gray cone of Figure 7.
We know \( u \) doesn’t start with \( s_i \) since \( s_i \) is a left ascent for \( w \), so \( u = s_js_js_is_i\ldots s_i \) or \( j \) We claim that \( 1 \leq \ell(u) \leq m_{ij} - 1 \). If \( \ell(u) = 0 \) then \( s_j \) is not a descent of \( w \), contradiction. No element of \( \langle s_i, s_j \rangle \) has length greater than \( m_{ij} \). Finally, is if \( \ell(u) = m_{ij} \) then \( u \) could be rewritten as \( s_is_j\ldots \) with \( m_{ij} \) terms, which contradicts \( s_i \) being a left ascent of \( w \). So the claim is proven. Geometrically, we have shown that \( uD \) is one of the blue triangles in Figure 7.

![Figure 7. The proof of the Key Lemma](image)

By our computations in Section 5, and the result of the previous paragraph regarding \( u \), we know that \( u \) maps the region \( \{ x : \langle \alpha_i, x \rangle, \langle \alpha_j, x \rangle \geq 0 \} \) into the half space \( \{ x : \langle \alpha_i, x \rangle \geq 0 \} \). (This half space is shaded in Figure 7.) So \( uvD = wD \) lies in \( \{ x : \langle \alpha_i, x \rangle \geq 0 \} \), as desired. □

**Corollary.** If \( w \in W \) is not 1 then \( wD^0 \cap D^0 = \emptyset \).

**Proof.** Let \( s_i \) be a descent of \( w \). We have \( \langle \alpha_i, \rangle < 0 \) on \( wD^0 \) and \( \langle \alpha_i, \rangle > 0 \) on \( D^0 \). □

**Corollary.** \( W \to GL(V^\vee) \) is injective. \( W \to GL(V) \) is also injective.

**Remark.** Remember that \( W \) is defined abstractly by generators and relations. Even in type \( A_{n-1} \), it is not obvious that these relations are enough to quotient down to the group \( S_n \), but we have shown this must be true, because \( S_n \) is clearly the image of \( W \) in \( GL_n(\mathbb{R}) \).

## 9. Consequences of the Key Lemma

We continue to impose that \( D^0 \neq \emptyset \).

Last time, we proved the Key Lemma:

**Lemma.** We have \( \langle \alpha_i, \rangle \geq 0 \) on \( wD \) if \( s_i \) is a left ascent of \( w \) and we have \( \langle \alpha_i, \rangle \leq 0 \) on \( wD \) if \( s_i \) is a left descent of \( w \).

**Corollary.** For any \( w \in W \) other than the identity, we have \( wD^0 \cap D^0 = \emptyset \).

**Proof.** Let \( s_i \) be a descent of \( w \). Then \( \alpha_i^+ \) separates \( D^0 \) and \( wD^0 \). □

**Corollary.** For \( u, v \in W \), with \( u \neq v \), we have \( uD^0 \cap vD^0 = \emptyset \).

**Proof.** We have \( uD^0 \cap vD^0 = u(D^0 \cap u^{-1}vD^0) \).

So all \( wD^0 \) are disjoint.
Corollary. The maps $W \to GL(V)$ and $W \to GL(V^\vee)$ are injective.

We define $\Phi$ to be $\Phi = W \cdot \{\alpha_1, \alpha_2, ..., \alpha_n\} \subset V$.

Corollary. For any $\beta \in \Phi$ and $w \in W$, the cone $wD$ lies entirely to one side of $\beta^\perp$.

Proof. Let $\beta = u\alpha_i$. We can reduce to $\alpha_i$ and $u^{-1}wD$ and use the Key Lemma. \hfill $\Box$

Corollary. Each $wD^\circ$ is a connected component of $V \setminus \cup_{\beta \in \Phi} \beta^\perp$.

Proof. It's enough to show the claim for $D^\circ$. We know $D^\circ$ lies entirely to one side of each $\beta^\perp$, and it is connected, so $D^\circ$ lies in some connected component $E$ of $V \setminus \cup_{\beta \in \Phi} \beta^\perp$. Suppose for contradiction, there is some $x \in E \setminus D^\circ$. Since $x \in E$, for each $\alpha_i$, we have $\langle x, \alpha_i \rangle \neq 0$. Moreover, since $x \not\in D^\circ$, for some $\alpha_j$, we have $\langle x, \alpha_i \rangle < 0$. Then $\alpha_j^\perp$ separates $x$ from $D^\circ$. \hfill $\Box$

We now know that, for any $\beta \in \Phi$ and $w \in W$, the cone $wD$ is entirely to one side of $\beta^\perp$. In particular, for any $\beta \in \Phi$, we have either $\langle \ , \beta \rangle \geq 0$ or $\langle \ , \beta \rangle \leq 0$ on $D$. So we can write $\Phi = \Phi^+ \cup \Phi^-$, where $\Phi^+ = \{\beta \in \Phi | \langle \Phi, \beta \rangle > 0\}$ are the positive roots, and $\Phi^- = \{\beta \in \Phi | \langle \Phi, \beta \rangle < 0\}$ are the negative roots. We earlier described positive and negative roots using a particular $\rho \in D^\circ$; we now see that the choice of $\rho$ is irrelevant.

We now describe how to see positive and negative roots in $V$ rather than in terms of their pairing with the dual space $V^\vee$. See Figure 8 for a graphical depiction.

![Figure 8](image)

Figure 8. $D$ lying on the positive side of $\beta^\perp$ is dual to $\beta$ being in the positive span of the $\alpha_i$.

Lemma. If $\beta \in \Phi^+$, then $\beta$ can be written as $\sum c_i\alpha_i$ with $c_i \geq 0$.

Proof. Suppose not. Let $R = \{\sum c_i\alpha_i | c_i \geq 0\}$, so $R$ is a closed convex set in $V$ and $\beta \not\in R$. By the Farkas lemma, there is some $\gamma \in V^\vee$, with $\langle \gamma, \ \rangle \geq 0$ on $R$, and $\langle \gamma, \ \rangle < 0$ on $\beta$. But then $\gamma \in D$, and $\langle \gamma, \beta \rangle < 0$, so $\beta$ is not in $\Phi^+$ after all. \hfill $\Box$

Lemma. Choose an index $i$. There exists an $\theta \in D$, such that $\langle \theta, \alpha_i \rangle = 0$ and $\langle \theta, \alpha_j \rangle > 0$ for $i \neq j$.

Proof. Consider the line segment joining $\rho \in D^\circ$ and $-\alpha_i^\perp$. At $\rho$, all $\langle \ , \alpha_j \rangle > 0$, and at $-\alpha_i^\perp$, we have $\langle \ , \alpha_i \rangle = -2$ and $\langle \ , \alpha_j \rangle \geq 0$ for $i \neq j$. So $\theta$ has this property. \hfill $\Box$

Corollary. $\alpha_i \not\in \text{Span}_{\mathbb{R}^+}\{\alpha_j : j \neq i\}$

Proof. Let $\alpha_i = \sum_{j \neq i} c_j\alpha_j$, pair with $\theta$ in the previous lemma. \hfill $\Box$

Corollary. There is a nonempty open set of $\alpha_i^\perp$ contained in $D \cap s_iD$
Proof. Let $U$ be a small enough neighborhood of $\theta$ in $\alpha_i^\perp$. Then all other $\langle \cdot, \alpha_j \rangle > 0$ on $U$ and $\langle \cdot, \alpha_i \rangle = 0$ on $U$, so $U \subset D \cap \alpha_i^\perp$. But $s_i D \cap \alpha_i^\perp = s_i (D \cap \alpha_i^\perp) = D \cap \alpha_i^\perp$ since $s_i$ fixes $\alpha_i^\perp$. □

Figure 9. $D$ and $s_i D$ border along a codimension 1 wall

This shows that $D$ and $s_i D$ border along a codimension 1 wall, as shown in Figure 9. Thus, for any $v$, the cones $vD$ and $vs_i D$ border along a codimension 1 wall. This raises the following application, which will return next class. Consider a word $s_i s_{i_2} \cdots s_{i_k}$ with product $w$. Set $v_k = s_i s_{i_2} \cdots s_{i_k}$. Then $v_k D$ and $v_k D = v_{k-1} s_{i_k} D$ border along a codimension one wall. So the sequence of cones $D = v_0 D$, $v_1 D$, $v_2 D$, $\ldots$, $v_\ell D = w D$ each border along codimension one walls, as in Figure 10.

Figure 10. A word in $W$ gives a walk through the chambers $w D$

The region $\bigcup_{w \in W} w D$ is called the Tits cone and denoted Tits($W$). The above argument shows that it is connected in codimension one. We can reverse the description of the previous paragraph, using the following lemma:

**Proposition.** For any $\beta \in \Phi$, $\beta$ not a multiple of $\alpha_i$, the cones $D$ and $s_i D$ are on the same side of $\beta^\perp$.

*Proof.* If $D$ and $s_i D$ are on opposite sides of $\beta^\perp$, then $\langle \beta, \cdot \rangle = 0$ on $D \cap s_i D$. Then Span($D \cap s_i D$) = $\alpha_i^\perp$ so $\langle \beta, \cdot \rangle$ can be 0 on it only if $\beta \in \mathbb{R} \alpha_i$. □

So the chambers bordering $D$ are precisely the chambers $s_i D$. So the chambers bordering $u D$ are $us_i D$. Thus, if we have a sequence of adjacent chambers $D$, $v_1 D$, $v_2 D$, $\ldots$, $v_\ell D$, we must have $v_k = v_{k-1} s_{i_k}$ for some sequence $s_{i_1}, \ldots, s_{i_\ell}$.

We point out a useful corollary for later:

**Proposition.** For any $\beta \in \Phi^+$, $\beta$ not a multiple of $\alpha_i$, the root $s_i \beta$ is in $\Phi^+$.

*Proof.* Since $\beta$ is positive, we have $\langle \beta, \cdot \rangle > 0$ on $D$. So we also have $\langle \beta, \cdot \rangle > 0$ on $s_i D$, and thus $\langle s_i \beta, \cdot \rangle > 0$ on $D$. □
10. Reflections, transpositions and roots

We continue to assume $D^\circ \neq \emptyset$.

We can now clear up a few details. We defined $T = \{us_iu^{-1} : u \in W, \; i = 1, \ldots, n\}$, and we defined an element $t$ of $GL(V)$ to be a reflection if $t^2 = 1$ and $t$ fixes a linear space of codimension 1. It is clear that the elements of $T$ are reflections, but it is not clear that every reflection is in $T$. Indeed, until we knew that $W \to GL(V)$ was injective, we had no hope of proving this since, if $g$ is in the kernel of this map and $t \in T$, then $gt$ is also a reflection. Now we can address this issue.

**Proposition.** Let $t \in W$ act on $V$ by a reflection. Then $t \in T$.

**Proof.** Let $H$ be the fixed plane of $t$. Choose a word $s_i s_{i_2} \cdots s_{i_k}$ for $t$, and define $v_k = s_i s_{i_2} \cdots s_{i_k}$ as before. Then $D$, $v_1 D$, $v_2 D$, $\ldots$, $v_{\ell} D = tD$ is a walk through the Tits cone. Since $D$ and $tD$ are on opposite sides of the Tits cone, this walk must cross it somewhere. There are two cases:

1. **Case 1:** The hyperplane $H$ passes through the interior of some $v_k D$. But then $tv_k D^\circ \cap v_k D^\circ$ is nonempty, contradicting that the $v D^\circ$ are disjoint.

2. **Case 2:** For some index $k$, the hyperplane $H$ separates $v_{k-1} D$ and $v_k D$. Then $tv_{k-1} D^\circ \cap v_k D^\circ$ is nonempty, so $tv_{k-1} = v_k$. We deduce that $t = v_{k-1} s_k v_k^{-1}$. $\square$

We often describe a reflection by pointing to the hyperplane it fixes. The next Proposition justifies this:

**Proposition.** If $t_1$ and $t_2 \in T$ reflect over the same hyperplane, then $t_1 = t_2$.

**Proof.** Let $t_1 = u_1 s_1 u_1^{-1}$ and $t_2 = u_2 s_2 u_2^{-1}$. Consider $t_2 \cdot u_1 D$. Points of $u_1 D^\circ$ very near the $(u_1 \alpha_1)^\perp$ wall would be mapped by $t_2$ into $t_1 u_1 D^\circ$. Since the interiors of the chambers are disjoint, $t_2 u_1 = t_1 u_1$ and hence $t_2 = t_1$. $\square$

**Remark.** This need not be true when $D = \emptyset$, see the left hand side of Figure 4.

If $t = us_i u^{-1}$, then $t(x) = x - \langle \beta^\vee, x \rangle\beta$, where $\beta = u \alpha_i$ and $\beta^\vee = u \alpha_i^\perp$.

We have now shown that we have bijections between $T$, reflections and reflecting hyperplanes. Reflecting hyperplanes correspond to $\Phi$ modulo scaling, so these things all correspond to $\Phi$ modulo scaling. Unfortunately, we still don’t have quite enough tools to address the scaling issue that we discussed in Section 6.

11. Finishing the classification of finite reflection groups

In Section 3, we classified positive definite Cartan matrices. Prior to doing that, we discussed one procedure which starts with a finite orthogonal reflection group and produces a positive definite Cartan matrix, and another which starts with a positive definite Cartan matrix and produces an orthogonal reflection group. We did not show that these procedures were inverse, so we don’t know that our classification of Cartan matrices corresponds to a classification of finite reflection groups. (We did note that every finite reflection group is orthogonal, see Section 4.)

**Algorithm 1:** Start with $W$ a finite orthogonal reflection group. Take

$$\Phi = \{\text{normals to hyperplanes}\}.$$ 

Choose $\rho$ not in any $\beta^\perp$; this splits $\Phi = \Phi^+ \sqcup \Phi^-$. Let $\alpha_1, \ldots, \alpha_k$ be simple roots in $\Phi^+$ with reflections $s_1, \ldots, s_k$. The $\alpha_i$ will be linearly independent, and the angle between $\alpha_i$ and $\alpha_j$
is $\pi(1 - 1/m_{ij})$ where $m_{ij}$ is the order of $s_is_j$. We get a positive-definite Cartan matrix $A$ with entries $A_{ij} = \alpha_i \cdot \alpha_j$.

**Algorithm 2:** Start with positive-definite Cartan matrix with entries $A_{ij}$. Find $\alpha_1, \ldots, \alpha_k \in V$ and $\alpha_1^\vee, \ldots, \alpha_k^\vee \in V^\vee$ such that $\langle \alpha_i^\vee, \alpha_j \rangle = A_{ij}$. Note that the $\alpha_j$’s will be linearly independent: indeed, if $\sum_i c_i \alpha_i = 0$, then $\langle \sum_i c_i \alpha_i^\vee, \sum_j c_j \alpha_j \rangle = 0$. However, the latter value can be expressed as $\langle \Sigma, \Sigma \rangle = c^T A c$ and $A$ is positive definite, yielding a contradiction.

We can define an inner product on $V$ (so $V \cong V^\vee$) and can think of $V = V^\vee$. The $s_i$, given by $s_i(x) = x - \langle \alpha_i^\vee, x \rangle \alpha_i$, generate some subgroup $W \subseteq \text{GL}(V)$.

**Claim 1:** The output of Algorithm 2 is finite when $A$ is positive definite.

**Proof of Claim 1.** Let $\Sigma$ be the unit sphere in $V$ and let $\Delta = \Sigma \cap D$. We equip $\Sigma$ with a Riemannian metric by restricting the inner product from $V$, so we can talk about volumes of subsets of $V$. All of the $w\Delta$ have disjoint interiors in $\Sigma$. So

$$\text{Vol}(\Sigma) \geq \sum_{w \in W} \text{Vol}(w\Delta) = |W| \text{Vol}(\Delta)$$

where the equality is because $W$ preserves the inner product on $V$ and hence preserves the metric on $\Sigma$. Thus

$$|W| \leq \frac{\text{Vol}(\Sigma)}{\text{Vol}(\Delta)}.$$  

**Remark.** In Section 12, we will show that, if $W$ is finite, then $V = \bigcup wD$. So, in fact, $\Sigma = \bigcup w\Delta$ and $|W| = \frac{\text{Vol}(\Sigma)}{\text{Vol}(\Delta)}$ in this case.

We now know that it makes sense to compose the algorithms in either order. We first consider the composition

$$W_{in} \xrightarrow{\text{Alg 1}} A \xrightarrow{\text{Alg 2}} W_{out}. $$

That is, $W_{in}$ is sent to $A$ by Algorithm 1, and $A$ in turn is sent to $W_{out}$ by Algorithm 2.

**Claim 2:** $W_{in}$ is isomorphic to $W_{out}$.

**Proof of Claim 2.** By definition, $W_{out}$ is generated by $s_1^{out}, \ldots, s_k^{out}$ obeying $(s_i^{out} s_j^{out})^{m_{ij}} = 1$. Meanwhile, the elements $s_1^{in}, \ldots, s_k^{in}$ in $W_{in}$ obey $(s_i^{in} s_j^{in})^{m_{ij}} = 1$. So we have a group homomorphism $W_{out} \to W_{in} \subseteq \text{GL}(V)$.

We showed $W_{out} \to \text{GL}(V)$ is injective, so $W_{out} \subseteq W_{in}$. The group $W_{in}$ is generated by reflections, so it is enough to check every reflection $t$ in $W_{in}$ is in the image of $W_{out}$. Suppose that $H = \text{Fix}(t)$ and that $H = \beta^\perp$ for some $\beta \in \Phi_{in}$. If $H = \beta^\perp$ for some $\beta \in \Phi_{out}$, then $t$ is the orthogonal reflection over $\beta^\perp$ and $t \in W_{out}$. If not, $H$ passes through $wD^\circ$ for some $w \in W_{out}$. Up to replacing $t$ by $w^{-1}tw$, we may assume $H$ passes through $D^\circ$. Then $\beta \not\in \text{Span}_R(\alpha_1, \ldots, \alpha_k) \cup - \text{Span}_R(\alpha_1, \ldots, \alpha_k)$.

But that means we failed to take the correct simples in Algorithm 1, a contradiction.  

Now we compose in the opposite order. Suppose we start with a positive-definite Cartan matrix $A_{in}$ and we construct

$$A_{in} \xrightarrow{\text{Alg 2}} W \xrightarrow{\text{Alg 1}} A_{out}. $$

Under Algorithm 2 we consider the following data: $\alpha_1^{in}, \ldots, \alpha_k^{in} \in V$ and a positive-definite inner product on $V$ with $(s_i^{in}) = W$. Under Algorithm 1 we consider the following data: $\Phi = \Phi^+ \cup \Phi^-$, where $\alpha_1^{out}, \ldots, \alpha_k^{out} \in \Phi^+$ are the simples of $\Phi^+$. We want to verify that:
• \langle \alpha_i^{\text{out}}, \alpha_j^{\text{out}} \rangle = \langle \alpha_i^{\text{in}}, \alpha_j^{\text{in}} \rangle.

• If \rho is such that \langle \rho, \alpha_i^{\text{in}} \rangle > 0, then \{\alpha_i^{\text{in}}\} = \{\alpha_j^{\text{out}}\}.

First of all, what if we choose \rho such that \langle \alpha_i^{\text{in}}, \rho \rangle > 0?

Thus \Phi^+, as defined by \langle \rho, \cdot \rangle, will be positive combinations of the \alpha_j^{\text{in}}'s; the latter will be the simple roots.

What about some other \rho? That \rho must lie in \wD^o for some \w \in W, so \w^{-1}\rho \in D^o. The positive roots for \rho are \w \cdot \{\text{positive roots for } D^o\} = \{\w \cdot \alpha_i^{\text{in}} : i = 1, \ldots, k\}.

12. Inversions, Reflection Sequences and Length

Last time, we defined \wT = \{us_i\w^{-1} : i = 1, \ldots, n, u \in W\}, the set of conjugates of simple generators. We saw the bijection:

\[
\begin{align*}
T & \quad \longleftrightarrow \quad \{\beta^\perp : \beta \in \Phi\} \\
t & \quad \longleftrightarrow \quad \text{Fix}(t) \\
w_i s_i w_i^{-1} & \quad \longleftrightarrow \quad (w_i \alpha_i)^\perp.
\end{align*}
\]

Given a word \si \cdot s_i \cdots s_i, we defined a sequence \vk = s_i \cdot s_i \cdots s_i and \tk = s_i \cdot s_i \cdots s_i \cdot s_i, \si. The chambers \D = v_0D, v_1D, \ldots, v_{\ell}D form a walk through the Tits cone, and \vk D and \vk D are separated by the hyperplane \text{Fix}(\tk). We call \ti, \tj, \ldots, \tl the reflection sequence of \si \cdot s_i \cdots s_i.

Suppose we have two words for \w. By the definition of \w as generators and relations, we can turn one word into the other by

• Inserting or deleting \si^2 and
• Replacing \si s_i \cdots s_i \cdots s_i \cdots s_i \cdots s_i, \si by \j \cdot s_i \cdots s_i \cdots s_i \cdots s_i, \si, where these two blocks are of length \mij.

This latter operation is called a braid move for \mij \geq 3, and a commutation move for \mij = 2. These two operations effect the reflection sequence as follows:

• Inserting \si^2 in positions \ki and \ki + 1 inserts two copies of the same reflection in positions (\ki, \ki + 1).
• Performing a braid or commutation move in positions (\ki + 1, \ki + 2, \ldots, \ki + \mij) reverses the reflection sequence in those positions.

We thus see that, for any reflection \t, the parity of the number of times \t occurs in the reflection sequence is independent of the choice of reduced word. For \w \in W, we define \t to be an inversion of \w if \t occurs an odd number of times in words for \w, and write \text{inv}(\w) for the set of inversions of \w. Geometrically, we see that

\text{inv}(\w) = \{t \in T : \text{Fix}(t) \text{ separates } D \text{ and } wD\}.

It is clear that |\text{inv}(\w)| \equiv \ell(\w) \mod 2 and |\text{inv}(\w)| \leq \ell(\w). We will soon show something better:

**Proposition.** For any \w \in W, we have |\text{inv}(\w)| = \ell(\w).

**Corollary.** A word for \w is reduced if and only if no reflection occurs twice in the reflection sequence.

Before we prove this, it is worth making a more general definition: for \x \in V^\vee - \bigcup_{\beta \in \Phi} \beta^\perp, set

\[
I(\x) = \{t \in T : \text{Fix}(t) \text{ separates } D \text{ and } \x\}.
\]

So \text{inv}(\w) = I(\w) for \x \in wD^o.
Proposition. For $x$ as above and $s_i$ a simple reflection, we have $I(s_ix) = s_iI(x) \triangleleft \{s_i\}$, where $\triangle$ is symmetric difference.

Proof. It is clear that $x$ and $s_ix$ are on opposite sides of $\alpha_i^\perp$, so $s_i \in I(x)$ if and only if $s_i \notin I(s_ix)$. For any reflection $t$ other than $s_i$, let $\beta$ be a corresponding positive root. Then $s_i\beta$ is also a positive root. We have $\langle \beta, x \rangle > 0$ if and only if $\langle s_i\beta, s_ix \rangle > 0$.

We now show that $|\text{inv}(w)| = \ell(w)$, as claimed above, and something more.

Proposition. Let $x \in V^\perp - \bigcup_{\beta \in \Phi} \beta^\perp$ and suppose that $I(x)$ is finite. Then $x \in wD$ for some $w$ with $\ell(w) = |I(x)|$.

Proof. Our proof is by induction on $|I(x)|$. If $|I(x)| = 0$, then $\langle \alpha, x \rangle > 0$ for every simple root $\alpha_i$, so $x \in D$ and we take $w = e$.

Now, suppose that $I(x) \neq \emptyset$ so $x \notin D$. Then some $\langle \alpha_i, x \rangle < 0$ and $s_i \in I(x)$. Then $|I(s_ix)| = |I(x)| - 1$ so, by induction, we have $s_ix \in w'D$ for some $w'$ with $\ell(w') = |I(x)| - 1$. Then $x \in s_ixw'D$. Moreover, since $\langle \alpha_i, x \rangle > 0$ on $w'D$, we know that $s_i$ is a left-ascent of $w'$, so $\ell(s_ixw') = \ell(w') + 1$. Taking $w = s_ixw'$, we are done.

We have now established that the number of inversions of $w$ is the length of $w$. There are also some other useful corollaries of this result:

Corollary. Let $x \in V^\perp - \bigcup_{\beta \in \Phi} \beta^\perp$. Then $x \in \text{Tits}$ if and only if $I(x)$ is finite.

Corollary. Let $x \in V^\perp$. Then $x \in \text{Tits}$ if and only if $\{t \in T : \langle \beta_i, x \rangle < 0\}$ is finite.

From this we can deduce:

Corollary. We have $\text{Tits} = V^\perp$ if and only if $W$ is finite, if and only if $-D \subseteq \text{Tits}$.

If $W$ is finite, then there must be some $w_0$ with $w_0D = -D$. We have $\text{inv}(w_0) = T$, so $w_0$ is the longest element of $W$. The element $w_0$ is called the long word or the longest word of $W$.

13. Root sequences

Last time, given a word $s_{i_1}s_{i_2} \cdots s_{i_t}$, we defined a sequence $v_k = s_{i_1}s_{i_2} \cdots s_{i_k}$ and $t_k = s_{i_1}s_{i_2} \cdots s_{i_k} \cdots s_{i_2}s_{i_1}$. Put $\beta_k^\perp = s_{i_1}s_{i_2} \cdots s_{i_k} - 1$. So $\beta_k^\perp$ is the fixed space of $t_k$. We call $\beta_1, \ldots, \beta_t$ the root sequence.

When we walk from $t_{k-1}D$ to $t_kD$, we cross from the side where $\langle \beta_k, \cdot \rangle$ is positive to where it is negative. This has the following easy consequences:

Proposition. Fix a reflecting hyperplane $H$. Then vectors normal to $H$ occur in the reflection sequence with alternately positive and negative sign, starting with positive.

Corollary. The word $s_{i_1}s_{i_2} \cdots s_{i_k}$ is reduced if and only if all the $\beta_k$ are positive.

This is a practical condition to use to test whether a word is reduced.

Finally, we have the tools to address the annoying issue of proportional positive roots. As we noted way back in Section 5, if $m_{ij}$ is odd and $A_{ij} \neq A_{ji}$, then $(s_is_j)^{(m-1)/2} = \sqrt{\frac{A_{ij}}{A_{ji}}}\alpha_i$. We therefore make the hypothesis that, if $m_{ij}$ is odd, then $A_{ij} = A_{ji}$.

With this hypothesis in place, we analyze the effect of changing the word $s_{i_1} \cdots s_{i_k}$ on the reflection sequence.
Proposition. Inserting $s_i^2$ in positions $k$ and $k + 1$ inserts a $\beta$ and a $-\beta$ in position $(k, k+1)$.

Proof. Put $u = s_{i_1} \cdots s_{i_{k-1}}$. We are considering the roots $u\alpha_i$ and $us_i\alpha_i$. Clearly, $us_i\alpha_i = u(-\alpha_i) = -u\alpha_i$. \hfill \Box

Proposition. With the hypothesis that, if $m_{ij}$ is odd, then $A_{ij} = A_{ji}$, performing a braid or commutation move on $s_i$ and $s_j$ in positions $(k+1, k+2, \ldots, k + m_{ij})$ reverses the root sequence in those positions.

Proof. Put $u = s_{i_1} \cdots s_{i_k}$. We want to consider, on the one hand, $(u\alpha_i, us_i\alpha_j, us_is_j\alpha_i, \cdots)$ and, on the other hand, $(u\alpha_j, us_j\alpha_i, us_j\alpha_j, \cdots)$. We observed in Section 5 that the sequences $(\alpha_i, s_i\alpha_j, s_is_j\alpha_i, \cdots)$ and $(\alpha_j, s_j\alpha_i, s_j\alpha_j, \cdots)$ are reversals of each other, and acting on everything by $u$ doesn’t change that. \hfill \Box

Corollary. Consider any root $\beta \in \Phi$. The elements in the reflection sequence of the form $\pm \beta$ appear alternately, starting with the positive root. If $\beta$ occurs an odd number of times in the reflection sequence for one word, then it also occurs an odd number of times in the reflection sequence for any other word.

We are finally ready to address the nuisance issue. The importance of this result is much smaller than the amount of time it has taken up; it just keeps coming up when we want to state things carefully:

Theorem. Suppose that if $m_{ij}$ is odd, then $A_{ij} = A_{ji}$, and that $D^o \neq \emptyset$. Let $u\alpha_i$ and $v\alpha_j$ be proportional roots. Then $u\alpha_i = \pm v\alpha_j$.

Proof. Since $u\alpha_i$ and $v\alpha_j$ are proportional, $us_iu^{-1}$ and $vs_jv^{-1}$ are reflections over the same hyperplane and thus $us_iu^{-1} = vs_jv^{-1}$. We rearrange this equation as $(v^{-1}u)s_i = s_j(v^{-1}u)$, and put $w = v^{-1}u$.

We first make some preliminary clean up: The hypotheses and desired conclusion are unchanged by replacing $u$ by $us_i$ and/or replacing $v$ by $vs_j$. These have the effect of replacing $w$ by $ws_i$, $s_jw$ or $s_jws_i$. We may therefore assume that $s_i$ is a right ascent, and $s_j$ a left ascent, of $w$. (This reduction is the place where the ± comes from. Once we have made this reduction, we can show the sign is +.)

Choose a reduced word $s_{k_1} \cdots s_{k_r}$ for $w$. By our reduction in the previous paragraph, the words $s_{k_1} \cdots s_{k_r}s_i$ and $s_js_{k_1} \cdots s_{k_r}$ are reduced as well. So there is only one root in the reflection sequence of $s_{k_1} \cdots s_{k_r}$ which is proportional to $\alpha_j$, namely the $\alpha_j$ in the first position. But then $\alpha_j$ must occur in the reflection sequence of $s_{k_1} \cdots s_{k_r}s_i$ and, since that word is reduced as well, it must occur in the last position. We deduce that $\alpha_j = s_{k_1} \cdots s_{k_r}\alpha_i = w\alpha_i$. So $\alpha_j = w\alpha_i = v^{-1}u\alpha_i$, and we have $u\alpha_i = u\alpha_j$ as desired. \hfill \Box

14. Parabolic Subgroups

Let $I$ be a subset of the vertices of the Dynkin diagram. The standard parabolic subgroup $W_I$ is the subgroup of $W$ generated by $s_i$ for $i \in I$.

We choose a Cartan matrix $A$, roots and coroots $\alpha_i$ and $\alpha_i^\vee$ as usual, such that $D^o$ is nonempty. Let $A_I$ be the submatrix of $A$ with rows and columns indexed by $I$. Then $\{\alpha_i\}_{i \in I}$ and $\{\alpha_i^\vee\}_{i \in I}$ pair by $A_I$. Setting $D^o_I = \{x \in V^\vee : \langle x, \alpha_i \rangle > 0 \ i \in I\}$, we have $D^o_I \supseteq D^o$ and in particular is nonempty. Thus, all of our results apply to $\{\alpha_i\}_{i \in I}$ and $\{\alpha_i^\vee\}_{i \in I}$, and we get to deduce that the group $W_I$ is the Coxeter group for the generators $\{s_i\}_{i \in I}$, with relations coming from $m_{ij}$ with $i, j \in I$. 
Put $L = \{x \in V^\vee : \langle x, \alpha_i \rangle \in I \}$. So we have built a hyperplane arrangement for $W_I$ in $V^\vee$ where all the hyperplanes contain the linear space $L$. The Tits cone for $W_I$ contains the Tits cone of $W$, so every cone $wD^\circ$ for $w \in W$ is contained in $w_I D^\circ_I$ for a unique $w_I \in W_I$. We can characterize $w_I$ alternately by saying that the inversions of $w_I$ are $\text{inv}(w) \cap W_I$.

If we write $w$ as $w_I^T w$, then we have with $\ell(w) = \ell(w_I) + \ell(I w)$. We note that we have $w_I = e$, and equivalently $w$ is of the form $I(\ )$, if and only if $s_i$ is a left ascent of $w$ for $i \in I$.

We have previously seen that $W$ has trivial stabilizer on the points in $D^\circ$. We are now ready to describe what happens on the boundary. Let $x \in D$ and let $I$ be the set of indices $i$ for which $\langle x, \alpha_i \rangle = 0$.

**Theorem.** With the above notation, the stabilizer of $x$ is $W_I$. More strongly, $wx \in D$, if and only if $w \in W_I$.

**Proof.** Clearly, $W_I$ stabilizes $x$ and also, clearly, if $w$ stabilizes $x$, then $wx \in D$. Thus, the nontrivial fact is that, if $wx \in D$, then $w \in W_I$.

So, let $wx \in D$ or, equivalently, $x \in w^{-1} D$. We abbreviate $(w^{-1})_I$ as $u^{-1}$ and $I(w^{-1})$ as $v^{-1}$, so $w = vu$. Since $u \in W_I$, we have $wx = vx$. We may thus replace $w$ by $v$. Having made this replacement, our goal will be to show that $v = e$.

If $v \neq e$, then it has a right descent $s_j$, and so $s_j$ is a left descent of $v^{-1}$. Since $v^{-1}$ is of the form $I(\ )$, we know that $s_j$ is a left ascent of $v^{-1}$ for all $i \in I$, so we must have $j \not\in I$.

Since $s_j$ is a left descent of $v^{-1}$, by the key lemma, $\langle \alpha_j, y \rangle \leq 0$ for $y \in v^{-1} D$, and in particular $\langle \alpha_j, x \rangle \leq 0$. But also $x \in D$, so $\langle \alpha_j, x \rangle \geq 0$. We conclude that $\langle \alpha_j, x \rangle = 0$, and thus $j$ is in $I$ after all, a contradiction.

**Corollary.** For each $y$ in the Tits cone, there is precisely one point in the orbit of $y$ that lies in $D$.

If $w^{-1} y \in D$, then use $w^{-1} y$ to define $I$ as above.

**Corollary.** With the above notation, the stabilizer of $y$ is $wW_I w^{-1}$.

It is interesting to consider the classification of regular polytopes, also known as platonic solids, from this perspective. A **regular polytope** is a polytope in $\mathbb{R}^n$ whose symmetry group acts transitively on chains (vertex, edge, two face, . . . , facet). They correspond to the ways to put edges on the path of length $n$ to make a finite Coxeter diagram. Specifically, the symmetry group of a regular polytope is always a finite reflection group. The centers of the $k$-dimensional faces have stabilizers conjugate to $W_{\{1,2,\ldots,k,k+2,\ldots,n\}}$. In Table 2, the vertices of the path are numbered from left to right. There are three infinite families in this table: The simplex is the convex hull of the standard basis vectors $e_j$ in $\mathbb{R}^n$; the hypercube is the convex hull of the $2^n$ vectors $\pm e_1 \pm e_2 \cdots \pm e_n$, and the cross polytope is the convex hull of the $2n$ vectors $\pm e_i$.

**Remark.** Be warned that, while “simplex” and “hypertetrahedon” are synonyms, “hyper-simplex” means something else. The hypersimplex is the convex hull of the $\binom{n}{k}$ vectors given as the $S_n$ orbit of $e_1 + e_2 + \cdots + e_k \in \mathbb{R}^n$. This has symmetry group $S_n$ (or $S_n \times \{\pm 1\}$ when $k = n/2$), but is not a regular polytope except in the cases $k = 1$, $k = n - 1$ and $(k, n) = (2, 4)$.

15. Crystallographic groups

We have built our Coxeter groups to act on a vector space $V$. We now discuss when $W$ fixes some lattice in $V$. We start by recalling the basic linear algebra of lattices.
Definition. Let $V$ be a vector space. Then, $\Lambda \subseteq V$ is called a lattice if it is a discrete additive subgroup of $V$ which spans $V$ as a vector space.

Theorem. Let $\Lambda$ be a lattice in $V$. Then we can choose a basis of $V$ as a real vector space which is also a basis of $\Lambda$ as a free $\mathbb{Z}$-module.

Proof sketch: By induction on $n$; the base case $n = 0$ is vacuously true.

Now, suppose that $n > 0$. Choose a nonzero vector $w_n \in \Lambda$ such that $\frac{1}{k} w_n \notin \Lambda$ for integers $k > 1$. We can always do this by discreteness. Then $\Lambda/\mathbb{Z} w_n$ injects in $V/\mathbb{R} w_n$, call the image $\overline{\Lambda}$. Then $\overline{\Lambda}$ is again a lattice (details left to the reader), so choose a basis $\overline{w}_1, \ldots, \overline{w}_{n-1}$ of $\overline{\Lambda}$ as required. Lift $\overline{w}_j$ to $w_j \in \Lambda$. Then $w_1, \ldots, w_{n-1}, w_n$ has the required properties (details left to reader).

If $\Lambda_1 \subseteq \Lambda_2$ are two lattices, then the lattices between $\Lambda_1$ and $\Lambda_2$ are in bijection with the subgroups of $\Lambda_2/\Lambda_1$.

Definition. For a lattice $\Lambda$ in $V$, the dual lattice $\Lambda^\vee \subseteq V^\vee$ is

$$\Lambda^\vee := \{ x \in V^\vee : \langle x, \beta \rangle \in \mathbb{Z} \text{ for all } \beta \in \Lambda \}.$$ 

Note that $\Lambda_1 \subseteq \Lambda_2$ if and only if $\Lambda_1^\vee \supseteq \Lambda_2^\vee$.

Definition. For $W$ acting on $V$, we say that $W$ preserves $\Lambda$ iff $w(\Lambda) = \Lambda$ for all $w \in W$.

Note that if $W$ preserves $\Lambda$ then $W$ also preserves $\Lambda^\vee$ (acting via the dual action).

We will show that, roughly, if $W$ is a Coxeter group, $W$ preserves some lattice in $V$ iff $A_{ij} \in \mathbb{Z}$. More specifically, we have the following two main theorems:

Theorem. If all $A_{ij} \in \mathbb{Z}$ and $\mathbb{Z} \langle \alpha_i \rangle$ and $\mathbb{Z} \langle \alpha_j^\vee \rangle$ are lattices, then $W$ preserves them and preserves any lattice $\Lambda$ between them.

Proof. Recall $s_i(\alpha_j) = \alpha_j - A_{ij} \alpha_i$ so if all $A_{ij} \in \mathbb{Z}$, then $s_i$ acts on $\mathbb{Z} \alpha_j$ by an integer matrix and $W$ preserves $\mathbb{Z} \alpha_j$. Likewise $W$ preserves $(\mathbb{Z} \alpha_i^\vee)^\vee$.

To show $W$ preserves any $\Lambda$ between these, it is enough to show that $W$ acts trivially on $(\mathbb{Z} \alpha_i^\vee)^\vee/\mathbb{Z} \alpha_i$. Let $v \in (\mathbb{Z} \alpha_i^\vee)^\vee$. Then, $s_i(v) = v - \langle \alpha_i^\vee, v \rangle \alpha_i \equiv v \mod \mathbb{Z} \alpha_i$. \qed
Theorem. If $W$ preserves a lattice in $V$, then we can choose positive real scalars $c_i$ so that, after replacing the $\alpha_i$ by $c_i\alpha_i$ and the $\alpha_i^\vee$ by $c_i^{-1}\alpha_i^\vee$, we have $\mathbb{Z}\langle\alpha_i\rangle \subseteq \Lambda \subseteq (\mathbb{Z}\langle\alpha_i^\vee\rangle)^\vee$ and $\mathbb{Z}\langle\alpha_i^\vee\rangle \subseteq \Lambda^\vee \subseteq (\mathbb{Z}\langle\alpha_i\rangle)^\vee$. With this rescaling, the $A_{ij}$ are integers.

Proof. Let $W$ preserve $\Lambda$. Then, we claim that $R\alpha_i \cap \Lambda = \{0\}$. To see this, note that $\Lambda$ spans $V$, so it contains $\lambda \notin (\alpha_i^\vee)^\perp$. Then, $s_i(\lambda) = \lambda + c\alpha_i$ for some $c \notin 0$, so $c\alpha_i \in \Lambda$. Thus, the claim holds.

Since the lattice is discrete, $R\alpha_i \cap \Lambda = \mathbb{Z} \cdot (c\alpha_i)$ for some $c \in \mathbb{R}_{\neq 0}$. Rescale so $c = 1$. Now, $\mathbb{Z}\langle\alpha_i\rangle_{i=1,\ldots,n} \subseteq \Lambda$. Then, $s_i(\alpha_j) = \alpha_j - A_{ij}\alpha_i \in \Lambda$, so $A_{ij}\alpha_i \in \Lambda$ and $A_{ij} \in \mathbb{Z}$.

Finally, for any $\lambda \in \Lambda$, $s_i(\lambda) = \lambda - \langle\alpha_i^\vee,\lambda\rangle\alpha_i \in \Lambda$ so $\langle\alpha_i^\vee,\lambda\rangle\alpha_i \in \Lambda$, which means that $\langle\alpha_i^\vee,\lambda\rangle \in \mathbb{Z}$. Thus, we have shown that $\Lambda \subseteq (\mathbb{Z}\langle\alpha^\vee\rangle)^\vee$. \qed

We use the following terminology, inspired by ideas from Lie groups: $\mathbb{Z}\langle\alpha\rangle$ is the root lattice and $\mathbb{Z}\langle\alpha^\vee\rangle^\vee$ is the weight lattice. The corresponding lattices in $V^\vee$ are the coroot lattice and the coweight lattice.

Note that, if $A$ is a crystallographic Cartan matrix with $\alpha_i$ a basis for $V$, then the abelian group $(\mathbb{Z}\langle\alpha^\vee\rangle)^\vee / \mathbb{Z}\langle\alpha\rangle$ is isomorphic to the cokernel of $A$. Here are the values of the cokernel for the finite connected crystallographic groups.

<table>
<thead>
<tr>
<th>$(\mathbb{Z}\alpha_i^\vee)^\vee / \mathbb{Z}\alpha_i$</th>
<th>$A_n$</th>
<th>$B_n$</th>
<th>$C_n$</th>
<th>$D_n$, $n$ even</th>
<th>$D_n$, $n$ odd</th>
<th>$E_6$</th>
<th>$E_7$</th>
<th>$E_8$</th>
<th>$F_4$</th>
<th>$G_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbb{Z}_{n+1}$</td>
<td>$\mathbb{Z}_2$</td>
<td>$\mathbb{Z}_2$</td>
<td>$\mathbb{Z}_2 \times \mathbb{Z}_2$</td>
<td>$\mathbb{Z}_4$</td>
<td>$\mathbb{Z}_3$</td>
<td>$\mathbb{Z}_2$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

We conclude by discussing examples. We begin with the rank two examples. In the following diagrams, the origin is at the center. The black circles are the roots, and thus the generators of the root lattice $\mathbb{Z}\langle\alpha\rangle$. The lines are where pairing with some $\alpha_i^\vee$ gives an integer and the open circles are the weight lattice $\mathbb{Z}\langle\alpha^\vee\rangle^\vee$.

![Figure 11. The $A_2$ roots and weight lattice](image-url)
B_n = C_n has Coxeter diagram $\bullet \cdots \bullet$. Thus, we have $A_{12}A_{21} = 2$, we have $A_{i,i+1}A_{i+1,i} = 1$ for $i > 1$ and $A_{ij} = 0$ for $|i - j| > 1$. If we also impose that the $A_{ij}$ are integers then we must have $A_{i,i+1}A_{i+1,i} = -1$ for $i > 1$, and we either have $A_{12} = -2, A_{21} = -1$ or vice versa. The former case is $B_n$ and the latter is $C_n$.

We can realize $B_n$ in coordinates as $\Phi = \{\pm e_k, \pm e_i \pm e_j\}$ and $\Phi^\vee = \{\pm 2e_k, \pm e_i \pm e_j\}$. In $C_n$, the roles of $\Phi$ and $\Phi^\vee$ are reversed. For $B_n$, we have $\mathbb{Z}\langle \alpha_i \rangle = \mathbb{Z}^n$, while $\mathbb{Z}\langle \alpha^\vee \rangle^\vee = \mathbb{Z}^n + \mathbb{Z}\{\frac{1}{2}, \frac{1}{2}, \ldots, \frac{1}{2}\}$. For $C_n$, we have $\mathbb{Z}\langle \alpha \rangle = \{(a_1, \ldots, a_n) \in \mathbb{Z}^n : \sum a_i \equiv 0 \pmod{2}\}$, while $\mathbb{Z}\langle \alpha^\vee \rangle^\vee = \mathbb{Z}^n$.
16. Affine symmetries and affine reflection groups

Let $V_0$ be a real vector space. Let $V_1$ be a principal homogenous space (also called affine space) for $V_0$, meaning that $V_0$ acts freely and transitively on $V_1$. Concretely, if we choose a base point $z$ in $V_1$, then $\vec{v} \mapsto z + \vec{v}$ identifies $V_0$ with $V_1$. The affine symmetry group $AGL(V_1)$ of $V_1$ can be identified with $GL(V_0) \ltimes V_0$. We note that the maps $V_0 \to AGL(V_1)$ and $AGL(V_1) \to GL(V_0)$ are completely natural, whereas the choice of right splitting $AGL(V_1) \to GL(V_0)$ corresponds to choosing a base point in $V_1$ to be fixed by the image of $GL(V_0)$.

If $V_0$ has an inner product, then the Euclidean symmetry group $Euc(V_1)$ is the subgroup $O(V_0) \ltimes V_0$ of $AGL(V_1)$. Classical Euclidean geometry studies properties of $\mathbb{R}^2$ and $\mathbb{R}^3$ which are preserved by the Euclidean symmetry group.

From this perspective, reflection over an affine hyperplane is an element of $GL(V_0) \ltimes V_0$ of the form $(\sigma, \vec{v})$ where $\sigma$ is a reflection and $\sigma(\vec{v}) = -\vec{v}$. This reflection is orthogonal if $\sigma$ is orthogonal.

There is a standard trick to embed all these ideas into ordinary linear algebra in one more dimension. Let $V = V_0 \oplus \mathbb{R}$. Then $GL(V_0) \ltimes V_0$ embeds in $GL(V)$ as $(g, \vec{v}) \mapsto \begin{bmatrix} g & \vec{v} \\ 0 & 1 \end{bmatrix}$. We can think of $V_1$ as the set of pairs $(x, 1) \in V_0 \oplus \mathbb{R}$.

Taking account of the inner product is slightly trickier. Let’s assume that $\theta_0$ is a non-degenerate symmetric bilinear form on $V_0$, so we can (and will) identify $V_0$ and $V_0^\vee$. Let $V = V_0 \oplus \mathbb{R}$ with degenerate bilinear form $(\vec{x}, a) \cdot (\vec{y}, b) = \vec{x} \cdot_0 \vec{y}$. The full symmetry group of this bilinear form is $\begin{bmatrix} O(V_0) & 0 \\ V_0^\vee & \mathbb{R}_{\neq 0} \end{bmatrix}$. The corresponding dual action on $V^\vee$ is $\begin{bmatrix} O(V_0) & V_0 \\ 0 & \mathbb{R}_{\neq 0} \end{bmatrix}$. The Euclidean symmetry group thus embeds in $GL(V^\vee)$ as $\begin{bmatrix} O(V_0) & V_0 \\ 0 & \mathbb{R}_{\neq 0} \end{bmatrix}$. If we put $\delta = (\vec{0}, 1) \in V$, then we can identify $V_1$ with the affine hyperplane $\{x : \langle \delta, x \rangle = 1\}$ in $V^\vee$.

This trick is reversible. Let $V$ be a real vector space equipped with a symmetric bilinear form $\cdot$ that has 1-dimensional kernel $\mathbb{R}\delta$. Put $V_0 = V/\mathbb{R}\delta$. Then $\cdot$ descends to a non-degenerate symmetric bilinear form $\cdot_0$ on $V_0$. Put $V_1 = \{x : \langle \delta, x \rangle = 1\}$ in $V^\vee$. Then $V_1$ is a principal homogenous space for $V_0$. The group of symmetries of $V$ preserving $\cdot$ and $\delta$ is the Euclidean symmetry group of $V_1$.

Suppose that $G_0 \subset GL(V_0)$ is a reflection group preserving a lattice $\Lambda$, and consider the group $G = G_0 \ltimes \Lambda$ inside the affine symmetry group. Let $R \subseteq \Lambda$ be the lattice generated by those $\vec{v} \in \Lambda$ which are $(-1)$-eigenvectors of some reflection in $G_0$. Clearly, $R$ is $G_0$-invariant.

We claim that the subgroup of $GL(V_0) \ltimes V_0$ generated by affine reflections $(\sigma, v) \in G_0$ and $\vec{v} \in \Lambda$ is precisely $G_0 \ltimes R$. Indeed,

$$(\sigma_1, v_1)(\sigma_2, v_2) \cdots (\sigma_k, v_k) = (\sigma_1\sigma_2 \cdots \sigma_k, \sum_{j=1}^k \sigma_1\sigma_2 \cdots \sigma_{j-1} v_j)$$

which is plainly in $G_0 \ltimes R$. Conversely, pairs $(\sigma, 0)$ generate $G_0$ (since $G_0$ is a reflection group) and $(\sigma, v)(\sigma, 0) = (e, v)$ for any reflection $\sigma$ and $(-1)$-eigenvector $\vec{v}$ of $\sigma$. Combining these, we see that the group generated by the $(\sigma, v)$ contains $G_0$ and contains $R$, so it contains $G_0 \ltimes R$.

Thus, in particular, if $W_0$ is a crystallographic Coxeter group, then $W_0 \ltimes \mathbb{Z}\langle \alpha \rangle$ and $W_0 \ltimes \mathbb{Z}\langle \alpha^\vee \rangle$ are reflection groups. The reflecting hyperplanes of $W_0 \ltimes \mathbb{Z}\langle \alpha \rangle$ are of the form $\{x \in V_0 : \langle \beta^\vee, x \rangle = k\}$ for $\beta^\vee \in \Phi^\vee$ and $k \in \mathbb{Z}$.

1If we don’t have $\sigma(\vec{v}) = -\vec{v}$, then $(\sigma, v)$ is a “glide reflection”, and has infinite order.
17. Positive semidefinite Cartan matrices

At the start of the class, we classified positive definite Cartan matrices, showed they are in bijection with finite reflection groups, and that all of them are Coxeter groups. We have a similar situation with positive semidefinite Cartan matrices. We’ll only sketch the proofs this time.

Recall that a symmetric $n \times n$ matrix $A$ is called positive semidefinite if $\bar{x}^T A \bar{x} \geq 0$ for all $\bar{x} \in \mathbb{R}^n$. We note that, for $A$ positive semidefinite, we have $A \bar{x} = 0$ if and only if $\bar{x}^T A \bar{x} = 0$.

We will also abuse language and say that $A$ is positive semidefinite if there are $d_i > 0$ such that $d_i A_{ij} = d_j A_{ji}$ and the symmetric matrix $d_i A_{ij}$ is positive semidefinite. (We will make the same abuse for “positive definite”.)

As usual, given an $n \times n$ Cartan matrix $A$, we define the Coxeter diagram $\Gamma$ to be the graph with vertices $\{1, 2, \ldots, n\}$ and an edge $(i, j)$ if and only if $A_{ij} \neq 0$. We know that, if a Coxeter graph is disconnected then the corresponding Coxeter group $W$ decomposes as a product $W_1 \times W_2$ and the corresponding reflection representation of $V$ of $W$ decomposes as a direct sum $V_1 \oplus V_2$. So we focus on the connected Coxeter diagrams.

**Lemma.** Suppose that $A$ is a positive semidefinite, but not positive definite, Cartan matrix for which $\Gamma$ is connected. Then the kernel of $A$ is one dimensional and all the entries of its generator have the same sign.

Define the matrix $B_{ij} = d_i A_{ij}$, so $B$ is symmetric. We note that $B = DA$ where $D$ is the diagonal matrix with entries $d_i$, so $\text{Ker}(A) = \text{Ker}(B)$.

**Proof.** It is enough to show that, if $B \bar{c} = 0$ then all entries of $\bar{c}$ have the same sign, since, in any vector space of dimension $\geq 2$, there is some vector with entries of different signs. Thus, let $\bar{c}$ be a nonzero vector with $B \bar{c} = 0$. Let $I_+, I_0$ and $I_-$ be the sets of indices where $c_i$ is $> 0$, $= 0$ and $< 0$ respectively. Put $\bar{c}_+ = \sum_{i \in I_+} c_i e_i$ and $\bar{c}_- = - \sum_{i \in I_-} c_i e_i$, so $\bar{c} = \bar{c}_+ - \bar{c}_-$. Expanding $\bar{c}^T B \bar{c} = 0$, we get

$$\bar{c}_+^T B \bar{c}_+ + \bar{c}_-^T B \bar{c}_- = 2 \bar{c}_+^T B \bar{c}_-.$$

Since $B$ is positive semidefinite, the left hand side is $\geq 0$. But the right hand side is $2 \sum_{i \in I_+, j \in I_0} c_i c_j B_{ij}$, and every term of this sum is $\leq 0$. Comparing the two, we deduce that $B \bar{c}_+ = B \bar{c}_- = 0$.

What we want to show is that one of $I_+$ and $I_-$ is all of $\{1, 2, \ldots, n\}$ and the other is $\emptyset$. Without loss of generality, suppose that $I_+$ is nonempty and suppose for the sake of contradiction that $I_+ \neq \{1, 2, \ldots, n\}$. Since $\Gamma$ is connected, there is some $i \in I_+$ that borders $j \not\in I_+$. But then the $j$-th component of $B \bar{c}_+$ is $< 0$, a contradiction. $\square$

Let $A$ be a connected positive semidefinite (but not definite) Cartan matrix and let $\text{Ker}(A) = \mathbb{R} \delta$ with all $\delta_j > 0$. Put $V_0 = V/\mathbb{R} \delta$, so the positive semidefinite inner product on $V$ descends to a positive definite inner product on $V_0$. Then any reflection in $V$ with respect to this Cartan matrix fixes the vector $\delta$. So we can think of the corresponding Coxeter group as a subgroup of the Euclidean symmetry group of $V_0$.

Here are the main results:

**Theorem.** The following are in bijection:

1. Cartan matrices where each component of $\Gamma$ corresponds to a positive semidefinite, but not definite, submatrix, up to the equivalence of replacing $A_{ij}$ by $\frac{\delta_i}{\delta_j} A_{ij}$.
(2) Reflection subgroups of Euclidean symmetry groups whose hyperplanes divide $V_0$ into bounded polytopes of positive volume.

**Theorem.** If $A$ is a Cartan matrix as above, then $A$ is crystallographic. Moreover, there is positive definite crystallographic Cartan matrix such that, for the corresponding group $W_0$, we have $W \cong W_0 \rtimes \mathbb{Z}<\alpha_i>$ and, for any positive definite crystallographic Cartan matrix, the group $W_0 \rtimes \mathbb{Z}<\alpha_i>$ is as above.

The Coxeter groups corresponding to connected positive definite crystallographic Cartan matrices are called *affine groups*.

We list the connected positive definite crystallographic Cartan matrices in Table 3. The kernel vector $\delta$ is shown (up to some issues discussed below) as numbers on the vertices. In each diagram, one vertex is boxed; the parabolic subgroup generated by the unboxed simple generators is $W_0$. Note that “the subscript acts before the tilde”, so $\bar{E}_8$ has 9 vertices.

We note that $\bar{B}_n$ and $\bar{C}_n$ are genuinely different groups for $n > 2$. The group $\bar{C}_n$ is generated by reflections over mirrors of the forms $x_j \pm x_k = a$ and $x_j = b$ for $a$ and $b \in \mathbb{Z}$, which $\bar{B}_n$ is the subgroup where we only reflect over $x_j = 2b$.

A final technical point: this is a classification of Coxeter groups inside Euclidean symmetry groups, not a classification of positive semidefinite crystallographic Cartan matrices. Different positive semidefinite crystallographic Cartan matrices can be equivalent under $A_{ij} \mapsto c^i_j A_{ij}$ and hence give the same affine reflection group. For example, $\begin{bmatrix} 2 & -2 \\ -2 & 2 \end{bmatrix}$ and $\begin{bmatrix} 2 & -4 \\ -1 & 2 \end{bmatrix}$ both give rise to $\bar{A}_1$, which is the infinite dihedral group, and they give isomorphic reflection representations. We note that this changes the kernel vector $\delta$ from $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ to $\begin{bmatrix} 2 \\ 1 \end{bmatrix}$; we have made one particular choice of $\delta$ in each diagram above.

The matrices $\begin{bmatrix} 2 & -2 \\ -2 & 2 \end{bmatrix}$ and $\begin{bmatrix} 2 & -4 \\ -1 & 2 \end{bmatrix}$ give non-isomorphic root systems and, for those interested in applications to cluster algebras, to quiver representations or to Kac-Moody Lie algebras/groups/quantum groups, it is important to distinguish them. If you need to refer to positive semidefinite crystallographic Cartan matrices, there are standard notations for them which you can find in Kac’s Chapter Four of book *Infinite Dimensional Lie Algebras* (Cambridge University Press, 1990). Macdonald’s “Affine root systems and Dedekind’s $\eta$-function” (*Inventiones*, 1972) also classifies positive semidefinite crystallographic Cartan matrices and uses what Professor Speyer considers much better notation, but his notation sadly hasn’t caught on.

18. **PARTIAL PROOFS OF CLAIMS ABOUT AFFINE COXETER GROUPS**

We now sketch the proofs of the main theorems from the last section. We want to show

**Theorem.** The following are in bijection:

1. Cartan matrices where each component of $\Gamma$ corresponds to a positive semidefinite, but not definite, submatrix, up to the equivalence of replacing $A_{ij}$ by $\frac{c^i_j}{c^j_i} A_{ij}$.

2. Reflection subgroups of Euclidean symmetry groups whose hyperplanes divide $V_0$ into bounded polytopes of positive volume.

Let’s start with a reflection subgroup $W$ of $\text{Euc}(V_1)$. Let $W_0$ be the image of $W$ under $\text{Euc}(V_1) \to O(V_0)$ and let $P = W \cap V_0$ be the group of translations. We note that we have not yet chosen a splitting $\text{Euc}(V_1) \leftarrow O(V_0)$, but these definitions do not need such a choice. Let $D^0_1$ be one of the regions that result from removing the reflecting hyperplanes from $V_1$; note that all other connected components of the complement are isomorphic to $D^0_1$. 
We claim that there are only finitely many parallelism classes of hyperplanes our reflection arrangement. Proof: If not, there would be a sequence of pairs of nonparallel hyperplanes $H_1^i, H_2^j$ where the angle between $H_1^i$ and $H_2^j$ approaches 0. But then there is some region of the reflection arrangement which borders $H_1^i \cap H_2^j$ and is in the acute angle between them, so the angle is bounded below by the smallest angle between adjacent walls of any region, and all the regions are isomorphic to $D_1$. 

Table 3. The affine Coxeter groups
Thus, the reflection group $W_0$ has finitely many hyperplanes and preserves a positive definite form on $V_0$, so $W_0$ is a finite reflection group.

Also, since $D_1$ is bounded, the lattice $P$ has full rank in $V_0$. So $W_0$ is a group which preserves a lattice, and is thus crystallographic. Since $W$ is a reflection group, $P$ must be $\mathbb{Z}$-spanned by the $(-1)$-eigenvectors it contains, so we can rescale to arrange that $P$ is the root lattice. We now know that $W = W_0 \ltimes \mathbb{Z}\langle \alpha_i \rangle$ for some crystallographic Cartan matrix, but it isn’t clear yet that this is a Coxeter group. We claim that is the Coxeter group on the hyperplanes bounding $D_1$.

**Lemma.** Let $H_i$ and $H_j$ be two hyperplanes bounding $D_1$. The angle between $H_i$ and $H_j$, measured on the side containing $D_1$ is of the form $\frac{\pi}{m_{ij}}$, where we take $m_{ij} = \infty$ when $H_i$ and $H_j$ are parallel.

**Proof.** If $H_i$ and $H_j$ are parallel, we are done. If not, let them meet at some point $x \in V_1$. If the angle is not of the form $\frac{\pi}{m}$, then the reflection subgroup generated by the reflections over $H_i$ and $H_j$ contains some hyperplane which passes through $x$ on the $D_1$ side of $H_1$ and $H_2$. But then this hyperplane cuts $D_1$, a contradiction. \hfill \Box

We will show that $W$ is the Coxeter group for these $m_{ij}$; let’s temporarily call this group $G$. Let the hyperplanes bounding $D_1$ be of the form $\{x : \langle x, \beta_i \rangle = k_i\}$ for $\beta_i^{\vee}$ in the coroot system of $W_0$ and $k_i \in \mathbb{R}$. Let $\alpha_i^{\vee}$ and $\alpha_i$ be the vectors $(\beta_i, k_i) \in V_0 \oplus \mathbb{R}\delta$ and $(\beta_i^{\vee}, k_i)$. With respect to the degenerate bilinear form on $V_0 \oplus \mathbb{R}\delta$, we have $\alpha_i^{\vee} \cdot \alpha_j = -2 \cos \frac{\pi}{m_{ij}}$. So these vectors pair by a Cartan matrix for $G$, and the group these reflections generate is $G$. We now have $G \subset W$; the proof of equality is similar to the earlier proof that $W_{out}$ is all of $W_{in}$.

**Now start with a Cartan matrix as stated** We can reduce immediately to the case that the Coxeter diagram is connected. The Cartan matrix $A$ gives a positive semidefinite inner product on $V$; let $\delta$ span its kernel. Define $V_1 \subset V^{\vee}$ to be the hyperplane $\{x : \langle x, \delta \rangle = 1\}$ and define the other notations related to Euclidean symmetry groups as before. The Coxeter group $W$ coming from our Coxeter diagram fixes $\delta$ and fixes the inner product on $V_0$, so it is a reflection subgroup of Euc($V_1$). A fundamental domain for the action of $W$ on Euc($V_1$) is

$$\{x : \langle x, \alpha_i \rangle \geq 0 \text{ and } \langle x, \delta \rangle = 1\}.$$

Using that $\delta$ is a positive linear combination of the $\alpha_i$, this is bounded.

### 19. Hyperbolic Coxeter groups

Here is a summary of the different types of Coxeter groups that give pretty pictures:

- Positive definite bilinear forms correspond to finite Coxeter groups which look like triangulations of the sphere $S^{n-1}$.
- Positive semi-definite bilinear forms correspond to affine Coxeter groups which look like triangulations of the affine space $\mathbb{R}^{n-1}$.
- Bilinear forms with signature $(+\ldots+) \leftrightarrow$ correspond to hyperbolic Coxeter groups which look like triangulations of the hyperbolic space $\mathbb{H}^{n-1}$.

We’ve seen two of these, and we now sketch the third.

**Hyperbolic geometry:** Let $V$ be an $n$-dimensional real vector space with a symmetric bilinear form, the dot product $\cdot$ with signature $(+\ldots-)$. Let $Q = \{\vec{v} \in V : \vec{v} \cdot \vec{v} = -1\}$. This is a hyperboloid of two sheets. Call this hyperboloid $Q$ and denote its sheets by $Q_+$ and $Q_-$ respectively. Each sheet, as a manifold, is an open ball of dimension $n-1$. 

Figure 14. The hyperboloid $Q = Q_+ \cup Q_-$

For $\vec{v} \in Q_+$, we have the tangent space $T_{\vec{v}}Q_+ = \{ \vec{x} \in V : \vec{v} \cdot \vec{x} = 0 \} = \vec{v}^\perp$. Restricting $\cdot$ to $T_{\vec{v}}Q$ gives a positive definite dot product on $T_{\vec{v}}Q$ (because $V = \mathbb{R}\vec{v} \oplus (\vec{v})^\perp$). So $Q_+$ is naturally a Riemannian manifold, commonly called the hyperbolic plane/space/disk.

Given $\vec{v} \in V$ with $\vec{v} \cdot \vec{v} > 0$, we can reflect over $\vec{v}^\perp$ in the following way:

$$\vec{x} \mapsto \vec{x} - 2 \frac{\vec{v} \cdot \vec{x}}{\vec{v} \cdot \vec{v}} \vec{v}.$$

This takes $Q_+$ to itself. Thus, we can talk about hyperbolic reflection groups, which are order two isometries fixing hyperplanes in hyperbolic space.

If $n = 3$ then $Q_+$ is a two dimensional disc. There are two standard ways of explicitly identifying $Q_+$ with the unit disc in $\mathbb{R}^2$.

**The Klein model** Take an affine plane, $K$, separating the origin from $Q_+$. Plot $\vec{x} \in Q_+$ at the intersection of $\mathbb{R}\vec{x}$ with $K$. See Figure 15. The picture will be contained within an open ball and hyperplanes are represented as affine hyperplanes in the open ball.

**Poincare model** Choose $\vec{v} \in Q_+$. Plot $\vec{x} \in Q_+$ at the intersection of the line through $-\vec{v}$ and $\vec{x}$ with $T_{\vec{v}}Q_+$. See Figure 16. In the Poincare model, lines are arcs of circles perpendicular to the boundary of the disk. The Poincare model is conformal, meaning that angles are correct. It also puts things nearer to the center of the disk, so the diagram can render more detail.
**Example.** Consider the Cartan matrix and reflection group given as follows:

\[
A = \begin{bmatrix} 2 & -2 & -2 \\ -2 & 2 & -2 \\ -2 & -2 & 2 \end{bmatrix} \quad W = \langle s_1, s_2, s_3 | s_1^2 = s_2^2 = s_3^2 = 1 \rangle
\]

The left and right sides of Figure 17 draw this arrangement in the Klein and Poincare models.

If we have \(\alpha_1, \ldots, \alpha_n \in V\) with \(\alpha_i \cdot \alpha_i = 2\) and \(\alpha_i \cdot \alpha_j \in \{-2 \cos \frac{\pi}{m} : m \geq 2\} \cup (-\infty, -2]\) and \(\{x : \alpha_i \cdot x > 0\} \neq \emptyset\) we’ll get a Coxeter group acting on \(Q_+\). We can do this if \(A\) is symmetric with signature \((+ + \ldots + -)\). Take \(V\) to be the vector space on basis \(\{\alpha_i\}\) and define \(\cdot\) by \(\alpha_i \cdot \alpha_j = A_{ij}\).

**Example.** If we want \(m_{12} = m_{13} = m_{23} = 4\) (i.e. triangles with all angles equal to \(\frac{\pi}{4}\)) then use the Cartan matrix

\[
\begin{bmatrix} 2 & -\sqrt{2} & -\sqrt{2} \\ -\sqrt{2} & 2 & -\sqrt{2} \\ -\sqrt{2} & -\sqrt{2} & 2 \end{bmatrix}
\]
We can also get hyperbolic tilings by polytopes other than simplices. Suppose that $A$ is a symmetric Cartan matrix with signature $^{+n-1}0r^-$. Then we can find $n + r$ vector in $V$ which pair by $A$, and thus get a polytope in hyperbolic $n - 1$ space with $n + r$ facets.

**Example.** Suppose we want to tile the disk with pentagons whose angles are all $\frac{\pi}{2}$. Then we need $m_{12} = m_{23} = \ldots = m_{51} = 2$ and $m_{13} = m_{24} = \ldots = \infty$. So our Cartan matrix should be of the form

$$A = \begin{bmatrix}
2 & 0 & -\alpha & -\alpha & 0 \\
0 & 2 & 0 & -\alpha & -\alpha \\
-\alpha & 0 & 2 & 0 & -\alpha \\
-\alpha & -\alpha & 0 & 2 & 0 \\
0 & -\alpha & -\alpha & 0 & 2
\end{bmatrix} \text{ with } \alpha \geq 2$$

We can achieve signature $++00-$ if we take $\alpha = 1 + \sqrt{5}$. (More generally, we could choose 5 distinct values for off diagonal terms, constrained to make this matrix have rank 3, and get hyperbolic pentagons with angles $\frac{\pi}{2}$ and sides of different lengths.) Here is the resulting tiling.

However, there is a technical point to worry about. How will $D$ relate to $Q_+^+$? In all our examples so far, $\cdot$ is $\leq 0$ on $D$ and Tits$(W)$ filled up the cone $\mathbb{R}_{\geq 0}Q_+^+$.

Here is the answer: We always have $\mathbb{R}_{\geq 0}Q_+^+ \subseteq$ Tits$(W)$. The domain $D \setminus \{0\}$ is in the interior of $\mathbb{R}_{\geq 0}Q_+^+$ if and only if the $(n - 1) \times (n - 1)$ principal minors are positive definite or, equivalently, if the parabolic subgroups are finite. The domain $D$ is in the closure of $\mathbb{R}_{\geq 0}Q_+^+$ if and only if the $(n - 1) \times (n - 1)$ principal minors are positive semidefinite or, equivalently, if the parabolic subgroups are finite or affine.

If some of these principal minors have $-$ part to their signature, then $D$ sticks out of the outside of $Q_+^+$.

**Example.** Let $A = \begin{bmatrix}
2 & -2 & -2 & -2 & 2 \\
-2 & 2 & -2 & -2 & 2 \\
-2 & -2 & 2 & -2 & 2 \\
-2 & -2 & -2 & 2 & 2 \\
-2 & -2 & -2 & 2 & 2
\end{bmatrix}$. The corresponding Coxeter has $m_{12} = m_{13} = m_{23} = \infty$, just as in Figure 17. Figure 18 depicts this example in the Klein model. There is no natural way to draw this picture in the Poincare model, because the Poincare model has no natural place to draw points not coming from $Q_+^+$. 
Figure 18. Klein model for an example with negative signature

Notational warning: A Coxeter group is only called \textit{hyperbolic} if $D$ does not stick out of $\mathbb{R}_{\geq 0}\mathbb{Q}_+$. The hyperbolic Coxeter groups have been classified, but the list is quite long.