

A coroot calculation

April 28, 2023

Abstract

An informal account of the proof of the lemmas
`is_root_system.coroot_symmetry_apply_eq` and `is_root_system.coroot_span_eq_top`.

1 The coroot of the reflection of a root

Recall our definition of the (pre)symmetry associated to a pair:

Definition 1.1. *Let k be a field of characteristic zero and V a vector space over k . Given a vector $x \in V$ and a linear form $f \in V^*$ the **pre-symmetry** associated to the pair (x, f) is the linear endomorphism of V :*

$$s_{x,f} : y \mapsto y - f(y)x.$$

*If the condition $f(x) = 2$ holds then $s_{x,f}$ is invertible, satisfies $s_{x,f}^{-1} = s_{x,f}$, and we call it a **symmetry**.*

Recall the uniqueness lemma:

Lemma 1.2. *Let k be a field of characteristic zero, V a vector space over k , and $\Phi \subseteq V$ a finite subset which spans V . Given a vector $x \in V$ and two linear forms $f, g \in V^*$ such that:*

- $f(x) = 2$ and $s_{x,f}(\Phi) \subseteq \Phi$,
- $g(x) = 2$ and $s_{x,g}(\Phi) \subseteq \Phi$,

then $f = g$.

Recall the definition of a root system:

Definition 1.3. *Let k be a field of characteristic zero, V a vector space over k , and $\Phi \subseteq V$. Then we say Φ is a **root system** in V over k if:*

- Φ is finite,
- Φ spans V ,
- for all $\alpha \in \Phi$, there exists $f \in V^*$ such that $f(\alpha) = 2$ and $s_{\alpha,f}(\Phi) \subseteq \Phi$,
- for all $\alpha \in \Phi$ and $f \in V^*$ such that $f(\alpha) = 2$ and $s_{\alpha,f}(\Phi) \subseteq \Phi$, we have $f(\Phi) \subseteq \mathbb{Z} \subseteq k$.

We call the elements of $\alpha \in \Phi$ **roots**.

Recall the definition of the coroot and symmetry of a root:

Definition 1.4. Let Φ be a root system in V over k and let $\alpha \in \Phi$ be a root. We define the **coroot** $\alpha^* \in V^*$ to be the unique linear form such that:

- $\alpha^*(\alpha) = 2$,
- $s_{\alpha,\alpha^*}(\Phi) \subseteq \Phi$.

We emphasise that uniqueness follows from lemma 1.2. Furthermore we write:

$$s_\alpha = s_{\alpha,\alpha^*},$$

and speak of the **symmetry** of a root.

Now if α and β are two roots of some root system then $s_\alpha(\beta) \in \Phi$ is another root and thus has a coroot $(s_\alpha(\beta))^*$. In order to show that the set of coroots form a root system in V^* we need to calculate this coroot in terms of the coroots α^* and β^* . The following lemma gives the answer:

Lemma 1.5 (`is_root_system.coroot_symmetry_apply_eq`). Let Φ be a root system for V over k and let $\alpha, \beta \in \Phi$ be a roots, then:

$$(s_\alpha(\beta))^* = \beta^* - (\beta^*(\alpha))\alpha^*.$$

Proof. Let $\gamma = s_\alpha(\beta)$ and $g = \beta^* - (\beta^*(\alpha))\alpha^*$. By the uniqueness lemma 1.2 it is sufficient to show that:

- (i) $g(\gamma) = 2$,
- (ii) $s_{\gamma,g}(\Phi) \subseteq \Phi$.

We did the proof of (i) together on Wednesday: you just unfold all definitions, expand brackets, and use $\alpha^*(\alpha) = \beta^*(\beta) = 2$.

To prove (ii), since s_α and s_β both preserve Φ , it is sufficient to show that:

$$s_{\gamma,g} = s_\alpha \circ s_\beta \circ s_\alpha.$$

To prove this we just pick any vector $v \in V$ and unfold the left and right hand sides applied to v and observe that they are equal. \square

2 The span of the coroots

Definition 2.1. Let V a vector space over a field k , G a finite group, and:

$$\rho : G \rightarrow GL(k, V)$$

a group homomorphism (aka a representation of G on V). Given a bilinear form:

$$B : V \times V \rightarrow k,$$

we define a new bilinear form B_ρ as follows:

$$\begin{aligned} B_\rho : V \times V &\rightarrow k \\ (v, w) &\mapsto \sum_g B(g \cdot v, g \cdot w) \end{aligned} \tag{1}$$

where the notation $g \cdot v$ means $\rho(g)(v)$.

Lemma 2.2. In the notation of definition 2.1, the form B_ρ is G -invariant, i.e.,

$$B_\rho(g \cdot v, g \cdot w) = B_\rho(v, w),$$

for all v, w in V and g in G . Furthermore if k is an ordered field and B is symmetric and positive definite, then so is B_ρ .

Proof. These are just calculations using formula (1). \square

Corollary 2.1. Let ρ be a representation of a finite group G on a finite-dimensional vector space V over an ordered field k . There exists a G -invariant symmetric positive definite bilinear form on V .

Proof. Pick any symmetric positive definite bilinear form¹ and apply lemma 2.2 to obtain an invariant form. \square

Corollary 2.2. Let Φ be a root system in a vector space V over an ordered field k and let:

$$\rho : W \rightarrow GL(k, V)$$

be the corresponding representation of the Weyl group. There exists a W -invariant symmetric positive definite bilinear form on V . Note that the map ρ is an inclusion map because W is a subgroup of $GL(k, V)$.

¹E.g., choose a basis and define the form to be the dot product of coordinates.

Proof. This follows from lemma 2.1 because the Weyl group is finite. \square

Lemma 2.3 (`is_root_system.coroot_span_eq_top`). *Let Φ be a root system in a vector space V over an ordered field k . The coroots span V^* .*

Proof. It is sufficient to show that for any v in V :

$$(\alpha^*(v) = 0 \text{ for all } \alpha \in \Phi) \implies v = 0. \quad (2)$$

(Since a non-zero v satisfying (2) would define a non-zero linear form vanishing on the span of the α^* .)

Thus let v be a vector satisfying the hypothesis of (2). Note that we have:

$$s_\alpha(v) = v \text{ for all } \alpha \in \Phi.$$

Using corollary 2.2 let B be a Weyl-group-invariant non-singular bilinear form on V . Let $\alpha \in \Phi$ and calculate:

$$\begin{aligned} B(v, \alpha) &= B(s_\alpha(v), s_\alpha(\alpha)) \\ &= B(v, -\alpha) \\ &= -B(v, \alpha). \end{aligned}$$

and so:

$$B(v, \alpha) = 0,$$

for all $\alpha \in \Phi$.

Since the roots span V and B is non-singular, we must have $v = 0$ as required. \square

3 Bilinear forms

Definition 3.1. *A root system Φ in a vector space V over a field k , induces a bilinear form on V as follows:*

$$\begin{aligned} B_\Phi : V \times V &\rightarrow k, \\ (v, w) &\mapsto \sum_{\alpha \in \Phi} \alpha^*(v) \alpha^*(w). \end{aligned}$$

Lemma 3.2. *Let B_Φ be the bilinear form associated to a root system Φ in a vector space V over an ordered field k . Then B_Φ has the following properties:*

(i) *it is symmetric,*

- (ii) it is positive definite,
- (iii) it is invariant under the group of symmetries of the root system,
- (iv) given $\alpha \in \Phi$:

$$\langle \alpha \rangle^\perp = \ker \alpha^*,$$

where $\langle \alpha \rangle^\perp$ is the orthogonal complement of α wrt B_Φ .

Proof. Claim (i) is clear.

Claim (ii) follows because the coroots span V^* . More precisely, since they span, given any non-zero v in V , there must exist some $\beta \in \Phi$ such that:

$$\beta^*(v) \neq 0.$$

We then have:

$$\begin{aligned} 0 &< \beta^*(v)^2 \\ &\leq \sum_{\alpha \in \Phi} (\alpha^*(v))^2 \\ &= B_\Phi(v, v) \end{aligned}$$

as required.

For claim (iii), let $u : V \rightarrow V$ be a linear automorphism preserving Φ . Note that for any $\alpha \in \Phi$ we have the following generalisation of lemma 1.5 (this is essentially `is_root_system.coroot_apply_of_mem_symmetries` in the Lean code except with u^{-1} instead of u):

$$u^*(\alpha^*) = (u^{-1}(\alpha))^*,$$

where $u^* : V^* \rightarrow V^*$ is the transpose of $u : V \rightarrow V$. Given any v, w in V we thus calculate:

$$\begin{aligned} B_\Phi(u(v), u(w)) &= \sum_{\alpha \in \Phi} \alpha^*(u(v)) \alpha^*(u(w)) \\ &= \sum_{\alpha \in \Phi} (u^*(\alpha^*))(v) (u^*(\alpha^*))(w) \\ &= \sum_{\alpha \in \Phi} (u^{-1}(\alpha))^*(v) (u^{-1}(\alpha))^*(w) \\ &= \sum_{\alpha \in u^{-1}(\Phi)} \alpha^*(v) \alpha^*(w) \\ &= \sum_{\alpha \in \Phi} \alpha^*(v) \alpha^*(w) \\ &= B_\Phi(v, w) \end{aligned}$$

as required.

For claim (iv) note that by taking $u = s_\alpha$ in part (iii), for any v in V we have:

$$\begin{aligned} B_\Phi(\alpha, v) &= B_\Phi(s_\alpha(\alpha), s_\alpha(v)) \\ &= B_\Phi(-\alpha, v - \alpha^*(v)\alpha) \\ &= -B_\Phi(\alpha, v) + \alpha^*(v)B_\Phi(\alpha, \alpha) \end{aligned}$$

And thus:

$$\alpha^*(v) = 2 \frac{B_\Phi(\alpha, v)}{B_\Phi(\alpha, \alpha)},$$

from which the claim follows. □