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A CONSTRUCTION OF THE SHEPHARD-TODD GROUP G_{32} THROUGH THE WEYL GROUP OF TYPE E_6

by

CÉDRIC BONNAFÉ

Abstract. — It is well-known that the quotient of the derived subgroup of the Shephard-Todd complex reflection group G_{32} (which has rank 4) by its center is isomorphic to the derived subgroup of the Weyl group of type E_6 . We show that this isomorphism can be realized through the second exterior power, and take the opportunity to propose an alternative construction of the group G_{32} .

Let G_{32} denote the complex reflection group constructed by Shephard-Todd [ShTo] and let E_6 be a Weyl group of type E_6 (which is denoted by G_{35} in the Shephard-Todd classification). Let $\mathbf{Sp}_4(\mathbb{F}_3)$ (resp. $\mathbf{SO}_5(\mathbb{F}_3)$) denote the symplectic (resp. orthogonal) group of dimension 4 (resp. 5) over the finite field with three elements \mathbb{F}_3 . Let $\Omega_5(\mathbb{F}_3)$ be the image of $\mathbf{Sp}_4(\mathbb{F}_3)$ in $\mathbf{SO}_5(\mathbb{F}_3)$ through the natural morphism $\mathbf{Sp}_4(\mathbb{F}_3) \rightarrow \mathbf{SO}_5(\mathbb{F}_3)$: this is the normal subgroup of index 2 of $\mathbf{SO}_5(\mathbb{F}_3)$. Finally, if G is a group, let $D(G)$ and $Z(G)$ denote respectively its derived subgroup and its center and, if d is a non-zero natural number, let μ_d be the group of d -th roots of unity in \mathbb{C} .

It is shown in [LeTa, théo. 8.43 et 8.54] that $G_{32} \simeq \mu_3 \times \mathbf{Sp}_4(\mathbb{F}_3)$ and that $E_6 \simeq \mathbf{SO}_5(\mathbb{F}_3)$. In particular,

$$(*) \quad D(G_{32})/\mu_2 \simeq \Omega_5(\mathbb{F}_3) \simeq D(E_6).$$

The purpose of this note is to present a direct elementary explanation of the isomorphism $D(G_{32})/\mu_2 \simeq D(E_6)$, which in fact allows us to construct the the complex reflection group G_{32} from the rational reflection group E_6 . This construction uses the classical morphism $\mathbf{SL}_4(\mathbb{C}) \rightarrow \mathbf{SO}_6(\mathbb{C})$, and follows the same lines as our previous paper [Bon] (in which we constructed the complex reflection group G_{31} from the Weyl group of type B_6).

This note does not pretend to prove a deep result: it is just a nice example of the application of the classical theory of reflection groups (invariants, Springer theory,...).

Remark. It is shown in [LeTa, Theo. 8.53] that $G_{33} \simeq \mu_2 \times \Omega_5(\mathbb{F}_3)$. In particular, this gives an indirect isomorphism $D(G_{33}) \simeq D(E_6)$. However, we do not know of any construction of this isomorphism which would be in the same spirit as above.

1. The morphism $\mathbf{SL}_4(\mathbb{C}) \rightarrow \mathbf{SO}_6(\mathbb{C})$

We recall here the construction of this morphism, using some notation from [Bon]. Let us fix a complex vector space V of dimension 4 and let

$$\begin{aligned} \Lambda : \mathbf{GL}(V) &\longrightarrow \mathbf{GL}(\wedge^2 V) \\ g &\longmapsto \wedge^2 g \end{aligned}$$

be the natural morphism of algebraic groups. Note that $\wedge^2 V$ has dimension 6 and that

$$(1.1) \quad \text{Ker } \Lambda \simeq \mu_2 = \{\pm \text{Id}_V\}.$$

The lists of eigenvalues of elements of $\mathbf{GL}(V)$ or $\mathbf{GL}(\wedge^2 V)$ will always be given with multiplicities. If $g \in \mathbf{GL}(V)$ admits a, b, c and d as eigenvalues, then

$$(1.2) \quad \Lambda(g) \text{ admits } ab, ac, ad, bc, bd \text{ and } cd \text{ as eigenvalues.}$$

In particular,

$$(1.3) \quad \det \Lambda(g) = (\det g)^3.$$

Let us fix now a generator ε of the one-dimensional vector space $\wedge^4 V$. The choice of this generator allows to identify \mathbb{C} and $\wedge^4 V$ and to define a bilinear form

$$\begin{aligned} \beta_\wedge : \wedge^2 V \times \wedge^2 V &\longrightarrow \mathbb{C} \\ (x, y) &\longmapsto x \wedge y. \end{aligned}$$

This bilinear form is symmetric and non-degenerate. By definition of the determinant,

$$(1.4) \quad \beta_\wedge(\Lambda(g)(x), \Lambda(g)(y)) = (\det g)\beta_\wedge(x, y)$$

for all $g \in \mathbf{GL}(V)$ and $x, y \in \wedge^2 V$. For dimension and connectedness reasons, the image of $\mathbf{GL}(V)$ through Λ is the neutral component $\mathbf{CO}(\wedge^2 V)^\circ$ of the conformal orthogonal group $\mathbf{CO}(\wedge^2 V) = \mathbf{CO}(\wedge^2 V, \beta_\wedge)$ and Λ induces an isomorphism of algebraic groups

$$(1.5) \quad \mathbf{SL}(V)/\mu_2 \simeq \mathbf{SO}(\wedge^2 V).$$

The next elementary lemma will be useful (in this paper, we denote by j a primitive third root of unity).

Lemma 1.6. — *Let $g \in \mathbf{SO}(\wedge^2 V)$ having j, j, j, j^2, j^2 and j^2 as eigenvalues. Then there exists a unique element $\tilde{g} \in \mathbf{SL}(V)$, having $1, j, j$ and j as eigenvalues, and such that*

$$\Lambda^{-1}(\{g, g^{-1}\}) = \{\pm \tilde{g}, \pm \tilde{g}^{-1}\}.$$

Proof. — Let $h \in \mathbf{SL}(V)$ be such that $\Lambda(h) = g$. Then $\Lambda^{-1}(\{g, g^{-1}\}) = \{\pm h, \pm h^{-1}\}$. Let a, b, c and d be the eigenvalues of h . By (1.2), by reordering if necessary the eigenvalues of h , we may assume that $ab = ac = j$. In particular, $b = c$. So $bd = cd$, which implies that $bd = cd = j^2$ (for otherwise j would be an eigenvalue of g with multiplicity ≥ 4). Still by (1.2), $(ad, bc) = (j, j^2)$ or $(ad, bc) = (j^2, j)$.

If $(ad, bc) = (j, j^2)$, then $b = c = d$ and $b^2 = j^2$, so $b = c = d = \eta j$ and $a = \eta$, for some $\eta \in \{\pm 1\}$. By replacing h by $-h$ if necessary, the eigenvalues of h are then $1, j, j, j$ and so h is indeed the unique element of $\Lambda^{-1}(\{g, g^{-1}\})$ admitting this list of eigenvalues.

If $(ad, bc) = (j^2, j)$, then $d = jb = jc$ and $b^2 = j$, which implies that $a = b = c = \eta j^2$ and $d = \eta$, for some $\eta \in \{\pm 1\}$. By replacing h by $-h$ if necessary, the eigenvalues of h are then $1, j^2, j^2, j^2$ and so h^{-1} is indeed the unique element of $\Lambda^{-1}(\{g, g^{-1}\})$ admitting $1, j, j, j$ as list of eigenvalues. \square

Corollary 1.7. — *Let $g \in \mathbf{SO}(\wedge^2 V)$ having j, j, j, j^2, j^2 and j^2 as eigenvalues. Then g and g^{-1} are not conjugate in $\mathbf{SO}(\wedge^2 V)$.*

Proof. — Assume that we have found $w \in \mathbf{SO}(\wedge^2 V)$ such that $wgw^{-1} = g^{-1}$. Let ω and γ be respective preimages of w and g in $\mathbf{SL}(V)$. Then $\Lambda(\omega\gamma\omega^{-1}) = g^{-1} = \Lambda(\gamma^{-1})$. This shows that γ^{-1} is conjugate to γ or to $-\gamma$, which is impossible by examining the possible lists of eigenvalues of γ obtained in the proof of Lemma 1.6. \square

2. Construction of G_{32}

Let us see E_6 as a finite subgroup of $\mathbf{O}(\wedge^2 V)$ generated by reflections. Set

$$\mathbf{jSO}(\wedge^2 V) = \langle \mathbf{SO}(\wedge^2 V), j \text{Id}_{\wedge^2 V} \rangle$$

and $\sqrt[3]{\mathbf{SL}}(V) = \{g \in \mathbf{GL}(V) \mid \det(g)^3 = 1\} = \langle \mathbf{SL}(V), j \text{Id}_V \rangle$.

Then

$$(2.1) \quad \Lambda^{-1}(\mathbf{jSO}(\wedge^2 V)) = \sqrt[3]{\mathbf{SL}}(V).$$

We then define

$$W = \Lambda^{-1}(\langle \mathbf{D}(E_6), j \text{Id}_{\wedge^2 V} \rangle).$$

It is a subgroup of $\sqrt[3]{\mathbf{SL}}(V)$. The aim of this note is to show that W is isomorphic to the complex reflection group G_{32} of Shephard-Todd. Note first that

$$(2.2) \quad \mu_6 \subset W.$$

2.A. Reflections in W . — The list of degrees E_6 is 2, 5, 6, 8, 9, 12 while its list of codegrees is 0, 3, 4, 6, 7, 10 (see [Bro, Table A.3]). In particular, exactly 3 of the degrees are divisible by 3, which shows [Spr, Theo. 3.4] that E_6 contains an element w_3 admitting the eigenvalue j with multiplicity 3. We will denote by C_3 the conjugacy class of w_3 in W . Since also exactly 3 of the codegrees are divisible by 3, this implies, for instance by [LeMi, Theo. 1.2], that w_3 is regular in the sense of Springer [Spr, §4] (that is, admits an eigenvector for the eigenvalue j whose stabilizer in E_6 is trivial). Since E_6 is a rational group, w_3 also admits j^2 as an eigenvalue with multiplicity 3. Hence, the eigenvalues of w_3 are j, j, j, j^2, j^2 and j^2 . In particular, $\det w_3 = 1$ and so

$$w_3 \in \mathbf{D}(E_6) = E_6 \cap \mathbf{SO}(\wedge^2 V).$$

By [Spr, Theo. 4.2(iii)], the centralizer of w_3 in E_6 has order $6 \cdot 9 \cdot 12$, which shows that

$$(2.3) \quad |C_3| = 2 \cdot 5 \cdot 8 = 80.$$

Moreover [Spr, Theo. 4.2(iii)], if $w \in E_6$, then

$$(2.4) \quad w \in C_3 \text{ if and only if } \dim \text{Ker}(w - j \text{Id}_V) = 3.$$

Hence, if $w \in C_3$, then $w^{-1} \in C_3$ but w^{-1} is not conjugate to w in $\mathbf{D}(E_6)$ (by Corollary 1.7).

Now, let $\text{Ref}(W)$ denote the set of reflections of W . If $s \in \text{Ref}(W)$, the eigenvalues $\Lambda(s)$ are $1, 1, 1, \det(s), \det(s), \det(s)$. Since $\det(s) \in \{j, j^2\}$, the eigenvalues of $\det(s)\Lambda(s)$ are then j, j, j, j^2, j^2, j^2 . It follows from (2.4) that $\det(s)\Lambda(s) \in C_3$. This defines a map

$$\begin{aligned} \lambda : \text{Ref}(W) &\longrightarrow C_3 \\ s &\longmapsto \det(s)\Lambda(s). \end{aligned}$$

The next result will be very useful:

Lemma 2.5. — *The map λ is bijective.*

Proof. — First, if $\lambda(s) = \lambda(s')$, then there exists $\xi \in \mathbb{C}^\times$ such that $s' = \xi s$. Since s and s' are reflections, this is possible only if $\xi = 1$, and so $s = s'$. This shows that λ is injective.

Let us now show the surjectivity. Let $w \in C_3$. By Corollary 1.7, there exists a unique $\tilde{w} \in \Lambda^{-1}(\{w, w^{-1}\})$ admitting $1, j, j, j$ as eigenvalues. Then $j^2\tilde{w}$ and $j\tilde{w}^{-1}$ are reflections satisfying

$$\lambda(j^2\tilde{w}) = \det(j^2\tilde{w})\Lambda(j^2\tilde{w}) = j^8 \cdot j^4\Lambda(\tilde{w}) = \Lambda(\tilde{w})$$

$$\text{and} \quad \lambda(j\tilde{w}^{-1}) = \det(j\tilde{w}^{-1})\Lambda(j\tilde{w}^{-1}) = j^4 \cdot j^2\Lambda(\tilde{w}^{-1}) = \Lambda(\tilde{w})^{-1}.$$

So $w \in \{\lambda(j^2\tilde{w}), \lambda(j\tilde{w}^{-1})\}$, which shows that λ is surjective. \square

We then deduce from (2.3) and Lemma 2.5 that

$$(2.6) \quad |\text{Ref}(W)| = 80.$$

2.B. Structure of W . — Our main result is Theorem 2.7 below: the proof we propose here uses neither known properties of the group G_{32} nor the classification of complex reflection groups and so might be viewed as an alternative construction of G_{32} starting from E_6 (however, note that we use properties of E_6).

Theorem 2.7. — *The group W :*

- (a) *has order 155 520;*
- (b) *is generated by reflections of order 3;*
- (c) *is irreducible and primitive;*
- (d) *admits 12, 18, 24, 30 as list of degrees.*

Proof. — Set $E_6^\# = \langle D(E_6), j \text{Id}_{\wedge^2 V} \rangle$ and $W^+ = W \cap \mathbf{SL}(V)$. Recall that $|E_6| = 51\,840$. So

$$(2.8) \quad |D(E_6)| = 25\,920, \quad |E_6^\#| = 77\,760, \quad |W| = 155\,520 \quad \text{and} \quad |W^+| = 51\,840.$$

This shows (a). Moreover,

$$(2.9) \quad Z(W) = \mu_6 \quad \text{and} \quad W/\mu_6 \simeq D(E_6).$$

Let $\mathcal{R} = \{\det(s)^{-1}s \mid s \in \text{Ref}(W)\}$. Set

$$G = \langle \text{Ref}(W) \rangle \quad \text{and} \quad H = \langle \mathcal{R} \rangle.$$

The statement (b) is equivalent to the following one

$$(\#) \quad W = G.$$

First, $\Lambda(\mathcal{R}) = C_3$ and so $\Lambda(H) = D(E_6)$ (as this last group is simple and C_3 is a conjugacy class). In particular, $W = H \cdot \mu_6$ and so, since $H \subset G \cdot \mu_3$, we obtain

$$W = G \cdot \mu_6,$$

which is almost the expected result (#). Before showing (#), note that, since $\Lambda(H) = D(E_6)$, we have that H (and so G) acts irreducibly on V . Moreover, if G is not primitive, then G (and so H) would be monomial [LeTa, Lem. 2.12], which would imply that $\Lambda(H) = D(E_6)$ is monomial, which is false. So

(♣) G is irreducible and primitive.

Statement (c) follows.

Let us conclude this proof by showing simultaneously (b) et (d). Let d_1, d_2, d_3, d_4 be the degrees of G . It follows from (2.6) and for instance from [Bro, Theo. 4.1] that

$$(\diamond) \quad \begin{cases} d_1 d_2 d_3 d_4 = |G|, \\ d_1 + d_2 + d_3 + d_4 = 84. \end{cases}$$

The morphism $\det : G \rightarrow \mu_3$ is surjective (since $\det(s) \in \{j, j^2\}$ for any $s \in \text{Ref}(W)$), and this implies that $\mu_3 \subset G$ (because $G/(G \cap \mu_6) \simeq D(E_6)$ is simple). It remains to show that $|G| \neq |W|/2 = 77\,760$.

So assume that $|G| = 77\,760$. Since $\mu_3 \subset G$, all the d_i 's are divisible by 3 and, since $\mu_6 \not\subset G$, at least one of them (say d_4) is not divisible by 6. Write $e_i = d_i/3$. Then

$$\begin{cases} e_1 e_2 e_3 e_4 = 960 = 2^6 \cdot 3 \cdot 5, \\ e_1 + e_2 + e_3 + e_4 = 28, \\ e_4 \text{ is odd.} \end{cases}$$

From the second equality, we deduce that at least one of the e_i 's (say e_3) is odd. From the first equality, we deduce that at least one of the e_i 's (say e_2) is even and so e_1 is also even. The first equality shows that e_1 or e_2 (say e_2) is divisible by 8. So $e_2 \in \{8, 16, 24\}$. A quick inspection of the possibilities shows that $e_1 = 4, e_2 = 16$ and $\{e_3, e_4\} = \{3, 5\}$. The degrees of G are then 9, 12, 15 and 48. Since 16 divides one of the degrees, it then follows from [Spr, théo. 3.4(i)] that $G = H \times \mu_3$ contains an element of order 16 and so H contains an element of order 16. Therefore, $D(E_6) = \Lambda(H)$ contains an element of order 8, which is impossible (see Remark 2.11 below for a proof of this fact based only on Springer theory). This contradicts the fact that $|G| = 77\,760$. So we have shown (#), that is,

$$W = \langle \text{Ref}(W) \rangle = G.$$

This is statement (b). In particular, $\mu_6 \subset W$ and so all the d_i 's are divisible by 6. Set $a_i = d_i/6$. Then (\diamond) implies that

$$\begin{cases} a_1 a_2 a_3 a_4 = 120 = 2^3 \cdot 3 \cdot 5, \\ a_1 + a_2 + a_3 + a_4 = 14, \end{cases}$$

By the same argument as before, since $\mu_{12} \not\subset W$, we may assume that a_3 and a_4 are odd and that a_1 and a_2 are even. A quick inspection of the possibilities shows that $\{a_1, a_2\} = \{2, 4\}$ and $\{e_3, e_4\} = \{3, 5\}$. This concludes the proof of (d). \square

Corollary 2.10. — *The group W is isomorphic to the reflection group G_{32} of Shephard-Todd.*

Proof. — This follows from Theorem 2.7 and from the classification of complex reflection groups [ShTo]. \square

Hence, Corollary 2.10 gives an explanation for the fact, mentioned in the introduction, that $D(G_{32})/\mu_2 \simeq D(E_6)$: the isomorphism is realized by Λ .

Remarque 2.11. — In the proof of Theorem 2.7, we have used the fact that $D(E_6)$ does not contain any element of order 8. This fact can be easily obtained by a computer calculation for instance, but we propose here a proof using only Springer theory. Let $w \in E_6$ be an element of order 8. Then w necessarily admits an eigenvalue which is a primitive 8-th root of unity ζ . As only one of the degrees of E_6 and only one of the codegrees of E_6 is divisible by 8, this implies that w is a regular element in the sense of Springer [LeMi, Theo. 1.2]. Then [Spr, Theo. 4.2(v)] the list of eigenvalues of w is $\zeta^{-1}, \zeta^{-4}, \zeta^{-5}, \zeta^{-7}, \zeta^{-8}, \zeta^{-11}$, and so $\det(w) = \zeta^{-36} = -1$. So $w \notin D(E_6)$.

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