GENERALIZED SPIN REPRESENTATIONS.

PART 1: REDUCTIVE FINITE-DIMENSIONAL QUOTIENTS OF MAXIMAL COMPACT SUBALGEBRAS OF KAC–MOODY ALGEBRAS

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Abstract. We introduce the notion of a generalized spin representation of the maximal compact subalgebra \( \mathfrak{k} \) of a symmetrizable Kac–Moody algebra \( \mathfrak{g} \) in order to show that, if defined over a formally real field, every such \( \mathfrak{k} \) has a non-trivial reductive finite-dimensional quotient.

1. Introduction

During the last decade the family of Kac–Moody algebras of type \( E_n(\mathbb{R}) \) has received considerable attention because of its importance in M-theory [DB06], [GN95], [KNP07], [Pal08], [Wes01]. By [DKN06a], [DBHP06] the (so-called) maximal compact subalgebra \( \mathfrak{k} = \text{Fix}_\omega \) of the real split Kac–Moody algebra \( \mathfrak{g} = \mathfrak{g}(E_{10})(\mathbb{R}) \) with respect to the Cartan–Chevalley involution \( \omega \) admits a 32-dimensional complex representation which extends the spin representation of its regular subalgebra \( \mathfrak{so}_{10}(\mathbb{R}) \). This implies that the (infinite-dimensional) Lie algebra \( \mathfrak{k} \) has a non-trivial finite-dimensional quotient, in fact a semisimple finite-dimensional quotient (see Theorem 4.11 below). In contrast, maximal compact subalgebras of finite-dimensional simple real Lie algebras are either simple or a direct sum of two isomorphic simple Lie algebras.

In this article we show that the existence of non-trivial finite-dimensional representations is not peculiar to the maximal compact subalgebra of \( \mathfrak{g}(E_{10})(\mathbb{R}) \) but is shared by all maximal compact subalgebras of symmetrizable Kac–Moody algebras over arbitrary fields of characteristic 0. To this end we introduce the notion of a generalized spin representation (Definitions 4.4 and 4.10 below), which we inductively show to exist for arbitrary symmetrizable Kac-Moody algebras and which, in the case of formally real fields, affords a compact, hence reductive, and often even a semisimple image (Theorem 4.11 below).

Our results presented in this article are generalizations of the results described in [DKN06a], [DBHP06]. They are suitable as the foundation for answering a group-theoretic question relevant to M-theory by Damour and Hillmann raised in [DH09, Section 3.5, p. 24]. This question has been answered by Ghatei, Horn, Weiß, and the second author based on this article.

Note that the terminology of maximal compact subalgebra is misleading. For one, in the infinite-dimensional situation there is no compact group associated to a maximal compact subalgebra. Rather, over the real numbers, the maximal compact subalgebra is related to the group \( K \) studied in [KP85], [DMGH09]. This group naturally carries a non-locally compact non-metrizable \( k_- \)-topology (cf. [HKM13]). Moreover, our construction only involves the Cartan–Chevalley involution and no field involution. Therefore, over the complex numbers, what we call a maximal compact subalgebra is not even anisotropic.

However, this terminology does not lead to serious ambiguities as our main focus lies on Lie algebras over formally real fields. Our main structure-theoretic results in Section 4 below will consequently be obtained over formally real fields; the main future application of our result is over the real numbers.
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2. Preliminaries

In this section we collect several basic facts about Kac–Moody algebras. We refer the reader to [Kac90, chapter 1] and [Kum02, chapter 1] for proofs and further details.

2.1. Kac–Moody algebras. Let $k$ be a field of characteristic 0, let $A = (a_{ij}) \in \mathbb{Z}^{n \times n}$ be a generalized Cartan matrix and let $\mathfrak{g} = \mathfrak{g}_A$ denote the corresponding Kac–Moody algebra over $k$. This means that $a_{ii} = 2$, $a_{ij} \leq 0$ and $a_{ij} = 0 \Leftrightarrow a_{ji} = 0$, while $\mathfrak{g}$ is the quotient of the free Lie algebra over $k$ generated by $e_i, f_i, h_i, i = 1, \ldots, n$, subject to the relations

$$[h_i, h_j] = 0, \quad [h_i, e_j] = a_{ij} e_j, \quad [h_i, f_j] = -a_{ij} f_j,$$

$$[e_i, f_j] = 0, \quad [e_i, h_j] = a_{ij} h_j, \quad (ad e_i)^{-a_{ij}+1}(e_j) = 0, \quad (ad f_i)^{-a_{ij}+1}(f_j) = 0 \text{ for } i \neq j.$$

A generalized Cartan matrix is called simply laced if the off-diagonal entries of $A$ are either 0 or $-1$; it is called symmetrizable if there exists a diagonal matrix $\Lambda$ such that $\Lambda A$ is symmetric. By abuse of terminology, we will say that $\mathfrak{g}$ is simply laced, resp. symmetrizable if its generalized Cartan matrix is simply laced, resp. symmetrizable.

Let $\mathfrak{h} := \langle h_1, \ldots, h_n \rangle$, $\mathfrak{n} := \langle e_1, \ldots, e_n \rangle$ and $\mathfrak{n} := \langle f_1, \ldots, f_n \rangle$ denote the standard subalgebras of $\mathfrak{g}$. Then there is a decomposition as vector spaces

$$\mathfrak{g} = \mathfrak{n}_- \oplus \mathfrak{h} \oplus \mathfrak{n}_+ (\text{see } [\text{Kum02, Theorem 1.2.1(a)}] \text{ or } [\text{Kac90, §1.3, p. 7}]).$$

The defining relations of $\mathfrak{g}$ imply that $\mathfrak{h}$ is $n$-dimensional abelian and normalizes $\mathfrak{n}_+$ and $\mathfrak{n}_-$. In fact, it acts by linear transformations on these vector spaces. Therefore, for each element $\alpha \in \mathfrak{h}^*$ of the dual space it is meaningful to define the eigenspaces

$$\mathfrak{g}_\alpha := \{ x \in \mathfrak{g} \mid \forall h \in \mathfrak{h} : [h, x] = \alpha(h)x \}.$$

The relations $[h_i, e_j] = a_{ij} e_j, 1 \leq i, j \leq n$, imply that each $e_j$ is contained in such an eigenspace, which we denote by $\mathfrak{g}_\alpha$; the corresponding element of $\mathfrak{h}^*$ is denoted by $\alpha_j$. (Cf. [Kum02, Definition 1.1.2] or [Kac90, §1.1].) Note that $\mathfrak{g}_{-\alpha}$ contains $f_j$.

The diagram of a simply laced Kac–Moody algebra $\mathfrak{g}_A$ is the graph $D = (V, E)$ on vertices $\alpha_1, \ldots, \alpha_n$ with $\alpha_i$ and $\alpha_j$ connected by an edge if and only if $a_{ij} = -1$.

Let $Q := \oplus_{i=1}^n \mathbb{Z} \alpha_i$ denote a free $\mathbb{Z}$-module of rank $n$ and $Q_+ := \oplus_{i=1}^n \mathbb{Z}_+ \alpha_i$, where the latter denotes the set of non-negative integral linear combinations. By [Kum02, Theorem 1.2.1(b)], [Kac90, Theorem 1.2(d), Exercise 1.2]

$$\mathfrak{g} = \bigoplus_{\alpha \in Q} \mathfrak{g}_\alpha = \mathfrak{h} \oplus \bigoplus_{\alpha \in Q \setminus \{0\}} \mathfrak{g}_\alpha = \bigoplus_{\alpha \in Q_+ \setminus \{0\}} \mathfrak{g}_{-\alpha} \oplus \mathfrak{h} \oplus \bigoplus_{\alpha \in Q_+ \setminus \{0\}} \mathfrak{g}_\alpha.$$

Therefore, $\mathfrak{g}$ has a $Q$-grading by declaring

$$\deg h_i := 0, \quad \deg e_i := \alpha_i, \quad \deg f_i := -\alpha_i.$$
for $i = 1, \ldots, n$, i.e.,

$$g = \bigoplus_{\alpha \in Q} g_\alpha \quad \text{and} \quad [g_\alpha, g_\beta] \subseteq g_{\alpha + \beta}.$$ 

Let $\Delta := \{\alpha \in Q \setminus \{0\} \mid g_\alpha \neq 0\}$. Then $\Delta = \Delta_+ \cup \Delta_-$, where $\Delta_+ := \Delta \cap (Q^+ \setminus \{0\})$ and $\Delta_- := -\Delta_+$. An element $\alpha \in \Delta$ is called a root and $g_\alpha$ a root space. A root $\alpha \in \Delta$ is called positive if it belongs to $\Delta_+$, otherwise negative. A root of the form $\alpha = \pm \alpha_i$ is called simple.

The extended Weyl group $W^* \leq \text{Aut} g$ is defined as $W^* := \langle s_i^* \mid i = 1, \ldots, n \rangle$, where $s_i^* := \exp \text{ad} f_i \cdot \exp \text{ad} (-e_i) \cdot \exp \text{ad} f_i$ (cf. [Kac90, §3.8], also [Kum02, Definition 1.3.2]). For $\alpha \in \Delta$ and $w \in W^*$ there exists a unique $w \cdot \alpha \in \Delta$ such that $w(g_\alpha) = g_{w \cdot \alpha}$, by [Kac90, Lemma 3.8(a)]. A root $\alpha$ is called real if there is a $w \in W$ such that $w \cdot \alpha$ is simple, otherwise it is called imaginary. Let $\Delta^{\text{re}}$ denote the set of real roots and $\Delta^{\text{im}}$ the set of imaginary roots.

For $\alpha = \sum_{i=1}^n a_i \alpha_i \in \Delta$, the height of $\alpha$ is defined as $\text{ht} \alpha := \left| \sum_{i=1}^n a_i \right|$. For $n \in \mathbb{N}$ let

$$(n_+)_{n} := \bigoplus_{\text{ht} \alpha = n} g_\alpha.$$ 

This is a $\mathbb{Z}$-grading of $n_+$ and, by assigning negative height to elements of $n_-$, can be extended to a $\mathbb{Z}$-grading of $g$, the principal grading (cf. [Kum02, Definition 1.2.2], [Kac90, §1.5]).

### 2.2. The maximal compact subalgebra

Let $g$ be a Kac–Moody algebra over a field $k$ of characteristic 0. Let $\omega \in \text{Aut}(g)$ denote the Cartan–Chevalley involution characterized by $\omega(e_i) = -f_i$, $\omega(f_i) = -e_i$, and $\omega(h_i) = -h_i$. (Cl. [Kum02, Definition 1.1.2], [Kac90, Equation 1.3.4].) Observe that $\omega(g_\alpha) = g_{-\alpha}$.

Let $t := t(g) := \{X \in g \mid \omega(X) = X\}$ denote the fixed point subalgebra, which — in analogy to the situation of finite-dimensional semisimple split real Lie algebras — is called the maximal compact subalgebra of $g$. For example, if $g = \mathfrak{sl}_n(\mathbb{R})$, then $\omega(A) = -A^T$ and $t = \mathfrak{so}_n(\mathbb{R})$. In this case, $\mathfrak{so}_n(\mathbb{R})$ is the Lie algebra of the maximal compact subgroup $\text{SO}_n(\mathbb{R})$ of $\text{SL}_n(\mathbb{R})$. See also [Kna02, Section IV.4].

Over non-real closed fields, especially over the complex numbers, this terminology is a bit unfortunate and misleading. However, our main results in Section 4 below and future applications are over real closed fields.

A theorem of Berman, who calls the Lie algebras $t$ involutory subalgebras, allows one to give a presentation of these.

**Theorem 2.1** (cf. [Ber89, Theorem 1.31]). Let $k$ be a field of characteristic 0. Let $A \in \mathbb{Z}^{n \times n}$ be a simply laced generalized Cartan matrix, let $g_A$ denote the corresponding Kac–Moody algebra and let $t$ denote the maximal compact subalgebra of $g$.

Then $t$ is isomorphic to the quotient of the free Lie algebra over $k$ generated by $X_1, \ldots, X_n$ subject to the relations

$$[X_i, [X_i, X_j]] = -X_j, \quad \text{if the vertices } v_i, v_j \text{ are connected by an edge},$$

$$[X_i, X_j] = 0, \quad \text{otherwise},$$

via the map $X_i \mapsto e_i - f_i$.

**Proof.** Let $\eta \in \text{Aut } g$ denote the involution characterized by

$$(\eta(e_i) = f_i, \eta(f_i) = e_i, \text{ and } \eta(h_i) = -h_i).$$
and let $I := \text{Fix} \eta$ denote the subalgebra of fixed points of $\eta$. By [Ber89, Theorem 1.31], the Lie algebra $I$ is isomorphic to the quotient of the free Lie algebra over $k$ generated by $Y_1, \ldots, Y_n$ subject to the relations

$[Y_i, [Y_i, Y_j]] = Y_j, \quad \text{if the vertices } v_i, v_j \text{ are connected by an edge},$

$[Y_i, Y_j] = 0, \quad \text{otherwise},$

via the map $Y_i \mapsto e_i + f_i$.

Let $I := \sqrt{-1}$ denote a square root of $-1$ and let $L := k(I)$, $g_L := g \otimes_k L$. There is a Lie algebra automorphism $\varphi \in \text{Aut}(g_L)$ determined by

$e_i \mapsto I \cdot e_i, \quad f_i \mapsto -I \cdot f_i, \quad \text{and } h_i \mapsto h_i.$

This automorphism $\varphi$ conjugates $\eta$ to $\omega$, i.e. $\omega = \varphi^{-1} \circ \eta \circ \varphi$, and hence the subalgebras $\text{Fix} \eta$ and $\text{Fix} \omega$ are isomorphic over $L$. As $X_i$ is mapped to $I \cdot Y_i$ under this isomorphism, the claim follows. □

Remark 2.2. Suppose $k = \mathbb{C}$. We can exponentiate the subalgebra of $g$ spanned by $e_i, f_i, h_i$ to a subgroup $G_i$ of $\text{Aut} g$ which is isomorphic to $\text{SL}_2(\mathbb{C})$ or $\text{PSL}_2(\mathbb{C})$. Then $X_i$ identifies with

$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

in $\mathfrak{s}l_2$ and therefore $\exp(\xi X_i)$ is equal to the image of $\begin{pmatrix} \cos \xi & \sin \xi \\ -\sin \xi & \cos \xi \end{pmatrix}$ in $G_i$. In particular, $\exp(-\frac{\pi}{2} X_i)$ is sent to $s_i^*$. It follows that $s_i^*$ and $\omega$ are commuting automorphisms of $g$.

For the case of an arbitrary ground field, $\omega$ induces a Cartan–Chevalley involution on the standard type $A_1$ subgroup $G_1$ of $\text{Aut} g$ whose Lie algebra is spanned by $e_i, f_i, h_i$. The fixed point subgroup of $G_1$ for the Cartan–Chevalley involution is either $SO_2(k)$ or $SO_2(k)/\{\pm I_2\}$, depending on whether $G_1$ is isomorphic to $\text{SL}_2$ or $\text{PSL}_2$. Since this subgroup clearly contains $s_i^*$, it follows that $s_i^*$ commutes with $\omega$.

2.3. Rank 2 Kac–Moody algebras. Let $g$ be the Kac–Moody algebra with Cartan matrix

$\begin{pmatrix} 2 & -r \\ -s & 2 \end{pmatrix}$

where $r, s \in \mathbb{N}$. We map $g$ into a simply laced Kac–Moody algebra as follows: Let $D$ be a complete bipartite graph on $r$ and $s$ vertices, labelled $\alpha_1^{(i)}$ and $\alpha_2^{(j)}$ with $1 \leq i \leq r$, $1 \leq j \leq s$. Let $\widehat{g}$ be a Kac–Moody Lie algebra with simply laced diagram $D$ and label the generators correspondingly: $e_1^{(i)}, f_1^{(i)}, h_1^{(i)}$ and $e_2^{(j)}, f_2^{(j)}, h_2^{(j)}$. We remark that there is an action of $\text{Sym}(r)$ (resp. $\text{Sym}(s)$) on $\widehat{g}$ by permuting the roots $\alpha_1^{(i)}$ (resp. $\alpha_2^{(j)}$). Let

$E_1 = \sum_{i=1}^{r} e_1^{(i)}, \quad F_1 = \sum_{i=1}^{s} f_1^{(i)}, \quad H_1 = [E_1, F_1], \quad E_2 = \sum_{j=1}^{r} e_2^{(j)}, \quad F_2 = \sum_{j=1}^{s} f_2^{(j)}, \quad H_2 = [E_2, F_2].$

Then it is straightforward to check that $[E_1, F_2] = 0 = [E_2, F_1] = [H_1, H_2]$, $(\text{ad} E_1)^{r+1}(E_1) = 0 = (\text{ad} E_2)^{s+1}(E_2)$, and $(\text{ad} F_1)^{r+1}(F_1) = (\text{ad} F_2)^{s+1}(F_2) = 0$. Thus there is a well-defined Lie algebra homomorphism $\widehat{\varphi}$ from $g$ to $\widehat{g}$, sending each of $e_1, e_2, f_1, f_2, h_1, h_2$ to their upper-case letters. Since $g$ has no non-zero ideals intersecting trivially with $\widehat{g}$, it follows that $\widehat{\varphi}$ is injective.

It is clear from the definitions that $\widehat{\varphi}$ induces an injective homomorphism from the extended Weyl group of $g$ to that of $\widehat{g}$ by sending $s_i^*$ to $(s_1^{(1)})^* \cdots (s_r^{(r)})^*$ and similarly for $s_j^*$. Let $\widehat{\omega}$ (resp. $\omega$) denote the Cartan–Chevalley involution on $\widehat{g}$ (resp. $g$). Clearly $\widehat{\varphi} \circ \omega = \widehat{\omega} \circ \widehat{\varphi}$, so $\widehat{\varphi}$ induces a homomorphism from $\mathfrak{k} = \mathfrak{k}(g)$ to $\mathfrak{k} = \mathfrak{k}(\widehat{g})$. Following the proof of Theorem 2.1, let $Y_1 = e_1 + f_1$, $Y_2 = e_2 + f_2$, $Y_1^{(i)} = e_1^{(i)} + f_1^{(i)}$ and $Y_2^{(j)} = e_2^{(j)} + f_2^{(j)}$ for $1 \leq i \leq r, 1 \leq j \leq s$.

Then $\widehat{\varphi}(Y_1) = \sum_i \widehat{Y}_1^{(i)}$ and similarly for $Y_2$.

Since $\alpha_1^{(i)}$ and $\alpha_2^{(j)}$ are connected by a simple edge, we have $((\text{ad} Y_1^{(i)})^2 - 1)(Y_2^{(j)}) = 0$. Now the space spanned by $Y_1^{(i)}$ for $1 \leq i \leq r$ is conjugate to the subspace of $h$ spanned by $h_1^{(i)}$ for
Lemma 2.3. For an arbitrary symmetrizable Kac–Moody Lie algebra \( \mathfrak{g} \) with \( n \times n \) generalized Cartan matrix \( A = (a_{ij})_{1 \leq i, j \leq n} \), its maximal compact subalgebra \( \mathfrak{k} \) has generators \( X_1, \ldots, X_n \) and relations:

\[
(P_{-a_{ij}}(ad X_i))(X_j) = 0
\]

for any \( 1 \leq i \neq j \leq n \), where

\[
P_m(t) = \begin{cases} (t^2 + m^2)(t^2 + (m - 2)^2) \cdots (t^2 + 1), & \text{if } m \text { odd,} \\ (t^2 + m^2)(t^2 + (m - 2)^2) \cdots (t^2 + 4)t, & \text{if } m \text { is even.} \end{cases}
\]

Proof. The proof is exactly the same as that of Theorem 2.1, by restricting to the rank two subsystems and using Berman’s Theorem [Ber89, Theorem 1.31]. \( \square \)

Remark 2.4. Suppose \( A = \begin{pmatrix} 2 & -r \\ -s & 2 \end{pmatrix} \). It is easy to see that if we quotient \( \mathfrak{k} \) by the ideal generated by \([X_1, [X_1, X_2]] + r^2X_2\) and \([X_2, [X_2, X_1]] + s^2X_1 \) then we obtain an epimorphism \( \mathfrak{k} \to \mathfrak{so}_3 \). This corresponds to repeatedly applying Construction 3.5(a) below to the complete bipartite graph to obtain a diagram of type \( A_2 \).

2.4. The general symmetrizable case. Now suppose \( \mathfrak{g} \) is an arbitrary symmetrizable Kac–Moody algebra. Suppose for simplicity that the generalized Cartan matrix \( A \) is indecomposable. Then there is a well-defined, unique up to scalar multiplication length function \( | \cdot | \) on the simple roots such that \( \frac{a_{ii}}{a_{ji}} = |\alpha_i|^2 |\alpha_j|^{-2} \) whenever \( a_{ij} \neq 0 \). After scaling we may assume that \( |\alpha_i|^2 \in \mathbb{N} \) for any \( i \), and that the square lengths \( |\alpha_i|^2 \) have no common factor.

Definition 2.5. A simply laced cover diagram of \( \mathfrak{g} \) (or just a cover diagram for short) is a simply laced diagram \( D \) with \( n_i \) vertices \( \alpha_i^{(1)}, \ldots, \alpha_i^{(n_i)} \) for each simple root \( \alpha_i \) of \( \mathfrak{g} \) (where \( n_i \) are some positive integers), and such that each \( \alpha_i^{(k)} \) is connected to exactly \( |a_{ij}| \) of the vertices \( \alpha_j^{(l)} \) for \( j \neq i \) and to none of the other vertices \( \alpha_i^{(l)} \).

We remark that the \( n_i \) are related by the formula \( \frac{a_{ii}}{n_i} = \frac{a_{ii}}{n_j} \) whenever \( a_{ij} \neq 0 \), hence \( n_i = \frac{M}{|\alpha_i|^2} \) for some constant \( M \). It follows that \( M \) is divisible by all \( |\alpha_i|^2 \). Moreover, each \( n_i \) must be divisible by any non-zero value \( |a_{ij}| \), so that \( M \) is divisible by \( \text{lcm}_{j \neq k, a_{jk} \neq 0}(|\alpha_j|^2 \cdot |a_{jk}|) \). In the special case that \( M = \text{lcm}_{j \neq k, a_{jk} \neq 0}(|\alpha_j|^2 \cdot |a_{jk}|) \) we call the diagram to be of minimal rank.

Clearly, one can construct a minimal rank simply laced cover diagram for \( \mathfrak{g} \) by setting

\[
n_i = \frac{\text{lcm}_{j \neq k, a_{jk} \neq 0}(|\alpha_j|^2 \cdot |a_{jk}|)}{|\alpha_i|^2}
\]

for all \( i \) and for each pair \( (i, j) \) with \( a_{ij} < 0 \), arbitrarily dividing the vertices \( \alpha_i^{(1)} , \ldots, \alpha_i^{(n_i)} \) (resp. \( \alpha_j^{(1)}, \ldots, \alpha_j^{(n_j)} \)) into \( m = n_i / |a_{ij}| = n_j / |a_{ji}| \) subsets \( S_1, \ldots, S_m \) (resp. \( S'_1, \ldots, S'_m \)) of \( |a_{ij}| \) (resp. \( |a_{ji}| \)) vertices with every vertex in \( S_k \) joined to every vertex in \( S'_k \).

As the following examples show, not every connected cover diagram is minimal rank, and two minimal rank cover diagrams need not be isomorphic.
Example 2.6.  (a) The hyperbolic Kac–Moody algebra which has generalized Cartan matrix
\[
\begin{pmatrix}
2 & -1 & -1 \\
-2 & 2 & -2 \\
-2 & 2 & 2
\end{pmatrix}
\]
has (at least) the following two simply laced cover diagrams:

\[
\begin{tikzpicture}
\draw (0,0) -- (1,1) -- (2,0) -- (0,0);
\draw (1,1) -- (2,2);
\draw (0,0) -- (1,-1) -- (2,0);
\node at (0,0) {c};
\node at (1,1) {b};
\node at (2,0) {a};
\node at (1,-1) {d};
\end{tikzpicture}
\]

(b) If \( \mathfrak{g} \) has symmetrizable Cartan matrix
\[
\begin{pmatrix}
2 & -3 & -6 \\
-5 & 2 & -5 \\
-2 & -1 & 2
\end{pmatrix}
\]
then under the assumptions above we have \( |\alpha_1|^2 = 5 \), \( |\alpha_2|^2 = 3 \) and \( |\alpha_3|^2 = 15 \). Thus \( \text{lcm}_{j\neq k: a_{jk} \neq 0}(|\alpha_j|^2 \cdot |a_{jk}|) = 30 \) and therefore \( n_1 = 6 \), \( n_2 = 10 \), \( n_3 = 2 \). Note that \( \alpha_3^{(1)} \) and \( \alpha_3^{(2)} \) are connected to all of the vertices \( \alpha_1^{(1)}, \ldots, \alpha_1^{(6)} \), but each to only half of \( \alpha_2^{(1)}, \ldots, \alpha_2^{(10)} \). Similarly, the vertices \( \alpha_2^{(i)} \) also divide into two groups of five, each connecting to three of the vertices \( \alpha_1^{(1)}, \ldots, \alpha_1^{(6)} \). After renumbering we may assume that \( \alpha_1^{(1)}, \alpha_1^{(2)}, \alpha_1^{(3)} \) are connected to all of \( \alpha_2^{(1)}, \ldots, \alpha_2^{(5)} \). It is not hard to see that there are three isomorphism classes of minimal rank cover diagrams for \( \mathfrak{g} \), given by diagrams in which \( \alpha_3^{(1)} \) connects to 0, 1 or 2 of the vertices \( \alpha_2^{(1)}, \ldots, \alpha_2^{(5)} \).

Remark 2.7. If \( \mathfrak{g} \) is of finite (resp. affine) type then there is a unique choice of connected simply laced cover diagram for \( \mathfrak{g} \), which is also finite (resp. affine). Specifically, for the finite type Lie algebras of type \( B_n, C_n, F_4 \) and \( G_2 \) one obtains simply laced cover diagrams of type \( D_{n+1}, A_{2n-1}, E_6 \) and \( D_4 \), and similarly for the corresponding (untwisted) affine types. The twisted affine types all have simply laced cover diagrams which are of affine type \( D \) except for the dual of affine \( F_4 \), which has simply laced cover \( E_7^+ \). If \( \mathfrak{g} \) is an arbitrary Kac–Moody Lie algebra of rank two then there exists a unique choice of simply laced cover diagram, constructed in Section 2.3.

If the generalized Cartan matrix of \( \mathfrak{g} \) is not indecomposable then a minimal rank simply laced cover diagram for \( \mathfrak{g} \) is one which has the smallest possible number of vertices. Such a diagram can be constructed as the union of the (minimal rank) simply laced cover diagrams for the simple summands of \( \mathfrak{g} \).

Let \( \mathfrak{g} \) be an arbitrary symmetrizable Kac–Moody algebra and let \( \mathfrak{g}^{\natural} \) be the Kac–Moody algebra associated to some simply laced cover diagram for \( \mathfrak{g} \). Let \( e_i^{(k)}, f_i^{(k)}, h_i^{(k)} \) be the simple root elements corresponding to the vertex \( \alpha_i^{(k)} \), for \( 1 \leq k \leq n_i \). As in the rank 2 case there is a natural embedding \( \varphi : \mathfrak{g} \to \mathfrak{g}^{\natural} \) which sends \( e_i \) (resp. \( f_i \)) to \( \sum_{k=1}^{n_i} e_i^{(k)} \) (resp. \( \sum_{k=1}^{n_i} f_i^{(k)} \)) and which induces a map from the extended Weyl group of \( \mathfrak{g} \) to that of \( \mathfrak{g}^{\natural} \). Clearly, there is also a corresponding embedding \( \mathfrak{t} \to \mathfrak{t}^{\natural} \).
In this section we collect some consequences of Berman’s presentation of the maximal compact subalgebra of a Kac–Moody algebra.

3.1. Automorphisms. For $i = 1, \ldots, n$ let $\varepsilon_i \in \{ \pm 1 \}$. Then there is an automorphism $\varphi_\varepsilon$ of $\mathfrak{k}$ characterized by $\varphi(X_i) = \varepsilon_i X_i$, called a sign automorphism.

If $\pi \in \text{Sym}(n)$ is a permutation which preserves the generalized Cartan matrix of $\mathfrak{g}$ (i.e. $a_{\pi(i)\pi(j)} = a_{ij}$ for all $i, j$) then there is an induced automorphism $\varphi_\pi$ of $\mathfrak{k}$ satisfying $\varphi_\pi(X_i) = X_{\pi(i)}$. Such an automorphism is called a graph automorphism. (In the simply laced case $\pi$ corresponds exactly to an automorphism of the diagram of $\mathfrak{g}$, i.e. a permutation of the vertices which preserves adjacency.)

Lemma 3.1. Let $\mathfrak{g}$ be a Kac–Moody algebra over a field $k$ of characteristic 0.

(a) For $i = 1, \ldots, n$, the element $s_i^* \in W^*$ commutes with $\omega$.
(b) Every $w \in W^*$ induces an automorphism $\pi(w)$ of $\mathfrak{g}$.
(c) If the Kac–Moody algebra $\mathfrak{g}$ is simply laced, the automorphism $\pi(s_i^*)$ induced by $s_i^*$ via the isomorphism given in Theorem 2.1 satisfies

$$X_i \mapsto X_j, \quad X_j \mapsto X_i, \text{ if } (i, j) \notin E,$$

and

$$X_j \mapsto [X_i, X_j], \text{ if } (i, j) \in E.$$

Proof. Statement (a) has been proved in Remark 2.2. By (a), each $s_i^*$ stabilizes $\mathfrak{t}$. Statement (b) therefore follows immediately from [Kac90, Lemma 3.8(b)].

Concerning (c), a calculation in $\mathfrak{sl}_2(k)$ shows that $s_i^*(e_i) = -f_i$. A calculation in $\mathfrak{sl}_2(k)$ shows $s_i^*(e_i) = [e_i, e_i]$, if $(i, j) \in E$, and a calculation in $\mathfrak{sl}_2(k) \oplus \mathfrak{sl}_2(k)$ shows $s_i^*(e_i) = e_i$, if $(i, j) \notin E$. More calculations — or use of assertion (a) — show, furthermore, $s_i^*(f_i) = -e_i$ and $s_i^*(f_j) = -[f_i, f_j]$, if $(i, j) \in E$, and $s_i^*(f_j) = f_j$, if $(i, j) \notin E$. In particular,

$$s_i^*(e_i - f_i) = s_i^*(e_j) - s_i^*(f_j) = [e_i, e_j] + [f_i, f_j] = [e_i - f_i, e_j - f_j].$$

Statement (c) follows. □

For $w \in W^*$, the induced automorphism $\pi(w) \in \text{Aut} \mathfrak{k}$ is called a Weyl group automorphism.

Remark 3.2. (a) Let $\varphi_+: n_+ \to \mathfrak{t} : x \mapsto x + \omega(x)$ denote the canonical $k$-linear bijection (cf. [Ber89, p. 3169]), and write $\mathfrak{t}_\alpha := \varphi_+(\mathfrak{g}_\alpha)$. Observe that for the analogous $k$-linear bijection $\varphi_- : n_- \to \mathfrak{t} : x \mapsto x + \omega(x)$ one has $\mathfrak{t}_\alpha = \varphi_+(\mathfrak{g}_\alpha) = \varphi_-(\mathfrak{g}_{-\alpha}) = \mathfrak{t}_{-\alpha}$.

It follows from Lemma 3.1(a) that $\pi(s)(\mathfrak{t}_\alpha) = \mathfrak{t}_{-\alpha}$. Hence, by induction and by the definition of the set of real roots, for any positive real root $\alpha \in \Delta_+$ there is a Weyl group automorphism $\pi(w)$ and a positive simple root $\alpha_i$ such that $\pi(w)(\mathfrak{t}_\alpha) = \mathfrak{t}_{\alpha_i} = kX_i$.

(b) The set of subspaces $\{ \mathfrak{t}_\alpha \mid \gamma \in \Delta^r \cap \Delta_+ \}$ is invariant under the action of the group of Weyl group automorphisms. It can be identified with the walls of the Coxeter complex of the Weyl group $W$. (Cf. [Kac90, Remark 3.8].)

Remark 3.3. If $\mathfrak{g}$ is simply laced then for $i, j$ in the same connected component of the diagram of $\mathfrak{t}$ there is an automorphism such that $\varphi(X_i) = X_j$. This is because, if $(i, j)$ is an edge, then

$$\pi(s_i^*s_j^*)(X_i) \overset{\Delta_1}{=} \pi(s_i^*)([X_j, X_i]) = [\pi(s_i^*)(X_j), \pi(s_i^*)(X_i)] \overset{\Delta_1}{=} [[X_i, X_j], X_i] \overset{\Delta_1}{=} X_j;$$

thus, the claim follows by induction.
This can be used as follows: Let \( \mathfrak{k} \) be the maximal compact subalgebra of a Kac–Moody algebra of type \( AE_2 \) (see Section 5). Then the generator \( X_4 \) is contained in a subalgebra isomorphic to the maximal compact subalgebra of a Kac–Moody algebra of type \( A_2^+ \). Indeed, let \( \varphi \) be a Weyl group automorphism such that \( \varphi(X_3) = X_4 \). Then \( \varphi(X_1, X_2, X_3) \) is as required, as by Theorem 2.1 the Lie algebra \( \langle X_1, X_2, X_3 \rangle \) equals the maximal compact subalgebra of the Kac–Moody algebra with positive simple roots \( \alpha_1, \alpha_2, \alpha_3 \).

3.2. A contraction of \( \mathfrak{k} \). Let \( \mathfrak{g} \) be a symmetrizable Kac–Moody algebra over \( \mathbb{R} \) with Chevalley generators \( e_i, f_i, h_i, i = 1, \ldots, n \). For \( \varepsilon > 0 \) define \( \omega_\varepsilon \) to be the Lie algebra automorphism satisfying

\[
\omega_\varepsilon(e_i) = -\varepsilon f_i, \quad \omega_\varepsilon(f_i) = -\frac{1}{\varepsilon} e_i, \quad \omega_\varepsilon(h_i) = -h_i;
\]

moreover, set \( \mathfrak{k}_\varepsilon := \text{Fix} \, \omega_\varepsilon \). Observe that \( \mathfrak{k}_1 = \mathfrak{k} \), and that \( X_\varepsilon^i := e_i - \varepsilon f_i \in \mathfrak{k}_\varepsilon \) for \( i = 1, \ldots, n \). Moreover, the automorphism \( \theta_\varepsilon \) of \( \mathfrak{g} \) given by \( e_i \mapsto \frac{1}{\sqrt{\varepsilon}} e_i \) and \( f_i \mapsto \sqrt{\varepsilon} f_i \) for all \( i \) satisfies

\[
\theta_\varepsilon(X_i) = \frac{1}{\sqrt{\varepsilon}} X_\varepsilon^i, \quad \omega_\varepsilon = \theta_\varepsilon^2 \circ \omega = \theta_\varepsilon \circ \omega \circ \theta_\varepsilon^{-1}.
\]

Thus \( \theta_\varepsilon \) maps \( \mathfrak{k} \) isomorphically onto \( \mathfrak{k}_\varepsilon \). By applying \( \theta_\varepsilon \) to \( P_{-a_{ij}}(\text{ad} \, X_i)(X_j) \) (in the notation of Theorem 2.3), we obtain the relations:

\[
P_{-a_{ij}}^\varepsilon(\text{ad} \, X_i^\varepsilon)(X_j^\varepsilon) = 0 \quad \text{where} \quad P_m^\varepsilon(t) = \varepsilon \frac{m^2}{2} P_m \left( \frac{t}{\sqrt{\varepsilon}} \right)
\]

that is, \( P_m^\varepsilon(t) = (t^2 + m^2 \varepsilon) \cdots (t^2 + \varepsilon) \) for \( m \) odd, and \( P_m^\varepsilon(t) = (t^2 + m^2 \varepsilon) \cdots (t^2 + 4 \varepsilon) t \) for \( m \) even. In particular, \( [X_i^\varepsilon, [X_j^\varepsilon, X_k^\varepsilon]] = -\varepsilon X_j^\varepsilon \) if \( a_{ij} = -1 \).

Since \( \theta_\varepsilon \) maps \( \mathfrak{k} \) isomorphically onto \( \mathfrak{k}_\varepsilon \), we have:

**Proposition 3.4.** The subalgebra \( \mathfrak{k}_\varepsilon \) is isomorphic to the quotient of the free Lie algebra over \( k \), generated by \( X_1, \ldots, X_n \), subject to the relations

\[
P_{-a_{ij}}^\varepsilon(\text{ad} \, X_i)(X_j) = 0
\]

via the map \( X_i \mapsto e_i - \varepsilon f_i \).

Note that, if we set \( \varepsilon = 0 \) in the above presentation, the resulting algebra is isomorphic to \( \mathfrak{n}_+ \) [Kac90, Theorem 9.11]. This means that \( \mathfrak{n}_+ \) is a contraction of the maximal compact subalgebra \( \mathfrak{k} = \mathfrak{t} \) in the sense of [FdM06].

3.3. Quotients. Let \( k \) be a field of characteristic 0 and \( \mathfrak{g} \) a Kac–Moody algebra over \( k \) with simply laced diagram \( D \). Due to the Coxeter-like presentation of the maximal compact subalgebra \( \mathfrak{k} \) it is possible to exhibit quotients of \( \mathfrak{k} \) if \( D \) has a certain shape.

For a graph \( D \), let \( \mathfrak{k}(D) \) denote the maximal compact subalgebra of the Kac–Moody algebra \( \mathfrak{g} \) over \( k \) with diagram \( D \).

**Construction 3.5.** Suppose that there are distinct vertices \( v_i, v_j \) of the diagram \( D \) such that any vertex \( v_r \) distinct from \( v_i, v_j \) is connected to \( v_i \) if and only if \( v_r \) is connected to \( v_j \).

(a) If \( v_i \) and \( v_j \) are not connected by an edge, let \( D' \) be the diagram obtained from \( D \) by deleting the vertex \( v_j \). Let \( \mathfrak{k}' := \mathfrak{k}(D') \) and \( X'_1, \ldots, X'_n \) its Berman generators. Then there is a well-defined epimorphism of Lie algebras \( \varphi: \mathfrak{k} \to \mathfrak{k}' \) determined by \( \varphi(X_r) := X'_r \) for \( r \neq j \) and \( \varphi(X_j) := X'_j \).

(b) If \( v_i \) and \( v_j \) are connected by an edge, let \( D' \) be the diagram obtained from \( D \) by deleting all edges emanating from \( v_j \) except for the edge \((v_i, v_j)\). As above, let \( \mathfrak{k}' := \mathfrak{k}(D') \) and \( X'_1, \ldots, X'_n \) its Berman generators. Then there is a well-defined epimorphism of Lie algebras \( \varphi: \mathfrak{k} \to \mathfrak{k}' \) determined by \( \varphi(X_r) := X'_r \) for \( r \neq j \) and \( \varphi(X_j) := [X'_i, X'_j] \).
This can be checked by using the Weyl automorphisms introduced in Lemma 3.1. For instance, for all \( r \neq i, j \) with \((v_r, v_j) \in E_D\) (which is equivalent to \((v_r, v_i) \in E_D\)), one has
\[
[\varphi(X_j), [\varphi(X_j), \varphi(X_r)]] = [[X_j', X'_j], [X_r', X'_r]]
\]
and
\[
\begin{align*}
3.1 & \quad -\pi(s^*_j)(X'_r) = \pi(s^*_j)X'_r \]
& \quad = \pi(s^*_j)[X'_r, [X'_r, X'_r]] \\
2.1 & \quad \varphi(-X_r) = \varphi(X_r) \\
2.1 & \quad \varphi[X_j, [X_j, X_r]].
\end{align*}
\]

Case (a) (resp. (b)) of Construction 3.5 corresponds to quotienting \( \mathfrak{k} \) by the ideal generated by \((X_i - X_j)\) (resp. by all terms of the form \([X_r, [X_i, X_j]]\)) where \( r \neq i, j \).

**Example 3.6.** (a) The preceding discussion gives a sequence of epimorphisms of real Lie algebras \( \mathfrak{k}(D_4^+) \to \mathfrak{k}(D_4) \to \mathfrak{k}(A_3) = \mathfrak{so}_4(\mathbb{R}) \to \mathfrak{k}(A_2) = \mathfrak{so}_3(\mathbb{R}) \).

\[
\begin{array}{cccc}
\bullet & \bullet & \bullet & \rightarrow \bullet \quad \bullet \quad \bullet \quad \rightarrow \quad \bullet \quad \bullet \quad \rightarrow \\
\bullet
\end{array}
\]

\( \mathfrak{k}(D_4^+) \quad \mathfrak{k}(D_4) \quad \mathfrak{k}(A_3) = \mathfrak{so}_4(\mathbb{R}) \quad \mathfrak{k}(A_2) = \mathfrak{so}_3(\mathbb{R}) \)

This sequence can be extended further: Let \( \Gamma_n = (\{1, \ldots, n\}, \{(1, k) \mid 2 \leq k \leq n\}) \) denote the star diagram on \( n \) vertices and let \( \mathfrak{t}_n \) denote the maximal compact subalgebra of the Kac-Moody algebra \( \mathfrak{g}_n \) with Dynkin diagram \( \Gamma_n \). Then there are epimorphisms \( \mathfrak{t}_n \rightarrow \mathfrak{t}_{n-1} \).

(b) Denoting by \( K_4 \) the complete graph on four vertices, there similarly is a sequence of epimorphisms \( \mathfrak{k}(K_4) \to \mathfrak{k}(AE_2) \to \mathfrak{k}(A_4) \).

4. **Generalized spin representations**

4.1. **Generalized spin representations of** \( \mathfrak{k}(E_{10}(\mathbb{R})) \). Let us recall the extension of the spin representation of \( \mathfrak{k}(\mathfrak{sl}_{10}(\mathbb{R})) \) to \( \mathfrak{k}(E_{10}(\mathbb{R})) \) as described by [DKN06a], [DBHP06], [Keu04].

**Example 4.1.** Let \( V \) be a \( k \)-vector space and \( q: V \to k \) a quadratic form with associated bilinear form \( b \). Then the **Clifford algebra** \( C := C(V, q) \) is defined as \( C := T(V) / \langle vw + wv - b(v, w) \rangle \) where \( T(V) \) is the tensor algebra of \( V \).

Now let \( V = \mathbb{R}^{10} \) with standard basis vectors \( v_i \), let \( q = x_1^2 + \cdots + x_{10}^2 \) and let \( C = C(V, q) \). Then in \( C \) we have
\[
v_i^2 = 1 \text{ and } v_i v_j = -v_j v_i.
\]
Since \( C \) is an associative algebra, it becomes a Lie algebra by setting \([A, B] := AB - BA \). Let the diagram of \( \mathfrak{g}(E_{10})(\mathbb{R}) \) be labelled as
and define a Lie algebra homomorphism $\rho : \mathfrak{k} \to C$ using these labels, i.e., via

$$
\begin{align*}
X_1 &\mapsto \frac{1}{2} v_1 v_2, & X_2 &\mapsto \frac{1}{2} v_1 v_2 v_3, & X_3 &\mapsto \frac{1}{2} v_2 v_3, \\
X_4 &\mapsto \frac{1}{2} v_3 v_4, & X_5 &\mapsto \frac{1}{2} v_4 v_5, & X_6 &\mapsto \frac{1}{2} v_5 v_6, \\
X_7 &\mapsto \frac{1}{2} v_6 v_7, & X_8 &\mapsto \frac{1}{2} v_7 v_8, & X_9 &\mapsto \frac{1}{2} v_8 v_9, \\
X_{10} &\mapsto \frac{1}{2} v_9 v_{10},
\end{align*}
$$

where $X_i$ denotes the Berman generator corresponding to the root $\alpha_i$, enumerated in Bourbaki style as in Section 5. Observe that each $A_i := \rho(X_i)$ satisfies $A_i^2 = -\frac{1}{4} \text{id}$. Here we would like to remark that $(v_1 v_2 v_3)^2 = (v_2 v_3)^2 = -1$ depends on $v_1^2 = 1$; for parity reasons, this would not be true in the Clifford algebra $C(V, -q)$, as then $(v_1 v_2 v_3)^2 = -(v_2 v_3)^2 = 1$.

Using the criterion established in Remark 4.5 below, one checks easily that $\rho$ indeed is a Lie algebra homomorphism, i.e., that the defining relations of $\mathfrak{k}$ from Theorem 2.1 are respected. Indeed, one just needs to establish

(i) $A_i^2 = -\frac{1}{4} \cdot \text{id}$,  
(ii) $A_i A_j = A_j A_i$, if $(i, j) \notin E$, 
(iii) $A_i A_j = -A_j A_i$, if $(i, j) \in E$.

We have already observed (i). Assertions (ii) and (iii) are obvious for $i, j \neq 2$. Moreover, one quickly computes $(v_1 v_2 v_3)(v_3 v_4) = -(v_3 v_4)(v_1 v_2 v_3)$ and $(v_1 v_2 v_3)(v_k, v_{k_2}) = (v_k, v_{k_2})(v_1 v_2 v_3)$, if \{\{k, k_2\}\} is a set of two elements that is either a subset of \{1, 2, 3\} or disjoint from \{1, 2, 3\}. Assertions (ii) and (iii) follow.

By [FH91, Lemma 20.9], [Mei13, Proposition 2.4] the Clifford algebra $C$ splits over $\mathbb{C}$ as $C \otimes_{\mathbb{R}} \mathbb{C} \cong \mathbb{C}^{32 \times 32}$. Hence $\rho$ affords a 32-dimensional complex representation of $\mathfrak{k}(E_{10})(\mathbb{R})$. The restriction of this representation to the maximal compact subalgebra of the $A_9$-subdiagram, $\mathfrak{t}(A_9)(\mathbb{R}) = \mathfrak{so}_{10}(\mathbb{R})$, coincides with the spin representation of $\mathfrak{so}_{10}$ (see e.g. [FH91, Chapter 20]), i.e., $\rho$ extends the classical spin representation.

Let $\iota \in \text{Aut} C$ denote the involution induced by $v \mapsto -v$. Let $C_0 := \text{Fix} \iota$ and $C_1 := \{w \in C \mid \iota(w) = -w\}$ denote the even and the odd part of $C$. Then $C_0$ and $C_1$ are invariant subspaces under the spin representation of $\mathfrak{so}_{10}$ since $\text{im} \rho \subseteq C_0$ (multiplication with a product of the $v_i$ of even length does not change the parity) and these subspaces are irreducible non-isomorphic representations of $\mathfrak{so}_{10}$ ([FH91, Chapter 20]).

The remaining Berman generator $X_2$ of $\mathfrak{k}(E_{10})$ is sent to an element which interchanges $C_0$ and $C_1$.

**Remark 4.2.** A calculation shows that $\text{im} \rho$ is the linear span of all elements of the form $v_{i_1} \cdots v_{i_k}$, where $\{i_1, \ldots, i_k\} = I \subseteq \{1, \ldots, 10\}$ with $|I| \in \{2, 3, 6, 7, 10\}$. Therefore, $\dim \text{im} \rho = 45 + 120 + 210 + 120 + 1 = 496$. Since $\text{im} \rho \subseteq \mathbb{R}^{32 \times 32}$ by [Mei13, Section 2.2.3] and since $\text{im} \rho$ is compact and semisimple by Theorem 4.11 below, this dimension $\dim \text{im} \rho = 496$ implies $\text{im} \rho \cong \mathfrak{so}_{32}(\mathbb{R})$ (see also [DKN06b]).
Remark 4.3. Let $\rho: \mathfrak{so}_{10}(\mathbb{R}) \to \mathbb{C}^{n \times n}$ be a representation. To extend $\rho$ to a representation of $\mathfrak{t}(E_{10})$, it suffices to find a matrix $X \in \mathbb{C}^{n \times n}$ such that for $A_i := \rho(X_i)$, $1 \leq i \leq 10$, $i \neq 2, 4$, the following equations are satisfied (where we again use the labelling of the diagram $E_{10}$ as given in Section 5):

$$
[A_i, X] = 0 \quad \text{for} \ 1 \leq i \leq 10, \ i \neq 2, 4,
$$

$$
[A_4, [A_4, X]] = -X,
$$

$$
[X, [X, A_4]] = -A_4.
$$

Theorem 2.1 then implies that $\rho$ can be extended to $\mathfrak{t}(E_{10})$ by setting $\rho(X_2) := X$.

The first two sets of equations define a linear subspace, the third set of equations yields a family of quadratic equations. With the help of a Gröbner basis one can compute that in case $A$ representation $\rho$ of $\mathfrak{so}_{10}(\mathbb{R})$, let $k$ be a field of characteristic 0, let $g$ be a Kac–Moody algebra over $k$ with simply laced diagram and let $\mathfrak{t}$ be its maximal compact subalgebra.

Let $L := k(I)$, where $I$ is a square root of $-1$ and denote by $id_s \in L^{s \times s}$ the identity matrix.

Definition 4.4. A representation $\rho: \mathfrak{t} \to \text{End}(L^s)$ is called a \textit{generalized spin representation} if the images of the Berman generators from Theorem 2.1 satisfy

$$
\rho(X_i)^2 = -\frac{1}{4} \cdot id_s \quad \text{for} \ i = 1, \ldots, n.
$$

Remark 4.5. (a) Since $\rho$ is assumed to be a representation, it follows from the defining relations that $\rho(X_i)$ and $\rho(X_j)$ commute if $(i, j) \notin E$. On the other hand, if $(i, j) \in E$, then $A := \rho(X_i)$ and $B := \rho(X_j)$ anticommute. Indeed, we have

$$
-B \stackrel{2 \text{ or } 1}{=} [A, [A, B]] = A^2 B - 2ABA + BA^2 = -\frac{1}{2} B - 2ABA
$$

from which the claim follows after multiplying with $A^{-1} = -4A \iff A^2 = -\frac{1}{4} \cdot id_s$.

(b) Conversely, suppose that there are matrices $A_i \in L^{s \times s}$ satisfying

(i) $A^2 = -\frac{1}{4} \cdot id_s$,

(ii) $A_i A_j = A_j A_i$ if $(i, j) \notin E$,

(iii) $A_i A_j = -A_j A_i$ if $(i, j) \in E$.

Then, by reversing the argument in the above computation, the assignment $X_i \mapsto A_i$ gives rise to a representation of $\mathfrak{t}$.

Remark 4.6. Let $\rho$ be a generalized spin representation of $\mathfrak{t}$ and set $S_i := 2I \cdot \rho(X_i)$. Let $W$ be the Coxeter group defined by the presentation

$$
W = \langle s_1, \ldots, s_n \mid (s_i s_j)^{m_{ij}} = 1 \rangle,
$$

where $m_{ii} = 1$ and $m_{ij} = 2$ if $(i, j) \notin E$, while $m_{ij} = 4$ if $(i, j) \in E$. Then the assignment $s_i \mapsto S_i$ gives a representation of $W$.

Write $\mathfrak{t}_{\leq r} := \langle X_1, \ldots, X_r \rangle$.

Theorem 4.7. Let $1 \leq r < n$. Let $\rho: \mathfrak{t}_{\leq r} \to \text{End}(L^s)$ be a generalized spin representation.

(a) If $X_{r+1}$ centralizes $\mathfrak{t}_{\leq r}$, then $\rho$ can be extended to a generalized spin representation $\rho': \mathfrak{t}_{\leq r+1} \to \text{End}(L^s)$ by setting $\rho'(X_{r+1}) := \frac{1}{2} I \cdot id_s$.
Proof. \( \text{Up to a change of labelling the set of generalized (basic) spin representations is possible for any (simply laced) Coxeter group.} \) That by a combination of the methods of [Maa10] and of the present article, a similar construction for a generalized spin representation is possible for any (simply laced) Coxeter group.

An inductive construction of the basic spin representations of the symmetric group similar to the one in Theorem 4.7 has independently been obtained by Maas [Maa10]. It is likely that by a combination of the methods of [Maa10] and of the present article, a similar construction of generalized (basic) spin representations is possible for any (simply laced) Coxeter group.

Corollary 4.8. Let \( n \) be the cardinality of the diagram of \( \mathfrak{g} \) and let \( r \) be the size of a maximal clique of that diagram. Then there exists a \( 2^{n+r}- \)dimensional generalized spin representation of \( \mathfrak{k} \). Furthermore, if the diagram is irreducible, then there exists a \( 2^{n-1} \)-dimensional maximal generalized spin representation of \( \mathfrak{k} \).

Proof. \( \text{Up to a change of labelling the set } M := \{ \alpha_1, \ldots, \alpha_r \} \text{ forms a maximal clique. The map } \rho : \mathfrak{k}_{\leq r} \rightarrow \text{End}(L^1) : \alpha_i \mapsto \frac{1}{2} I \text{ is a generalized spin representation. By Theorem 4.7, the representation } \rho \text{ can be extended inductively to a generalized spin representation of } \mathfrak{k} \text{; the dimension doubles at each step because } M \text{ was assumed to be a maximal clique.} \)

Remark 4.9. An inductive construction of the basic spin representations of the symmetric group similar to the one in Theorem 4.7 has independently been obtained by Maas [Maa10]. It is likely that by a combination of the methods of [Maa10] and of the present article, a similar construction of generalized (basic) spin representations is possible for any (simply laced) Coxeter group.

4.3. Generalized spin representations for symmetrizable Kac–Moody algebras. In this section let \( \mathfrak{g} \) be an arbitrary symmetrizable Kac–Moody Lie algebra with maximal compact subalgebra \( \mathfrak{k} \), and let \( n_i \) be the number of vertices associated to the root \( \alpha_i \) in a minimal rank simply laced cover diagram for \( \mathfrak{g} \). As above, we assume the ground field \( k \) has characteristic zero.

Definition 4.10. A generalized spin representation for \( \mathfrak{k} \) is a Lie algebra homomorphism \( \rho : \mathfrak{k} \rightarrow \text{End}(L^s) \) such that each of the Berman generators \( X_i \) (see Lemma 3.2) satisfies:

\[
\left( \rho(X_i)^2 + \frac{n_i^2}{4} \text{id}_s \right) \left( \rho(X_i)^2 + \frac{(n_i-2)^2}{4} \text{id}_s \right) \ldots \left( \rho(X_i)^2 + \text{id}_s \right) \rho(X_i) = 0, \quad \text{if } n_i \text{ is even},
\]

\[
\left( \rho(X_i)^2 + \frac{n_i^2}{4} \text{id}_s \right) \left( \rho(X_i)^2 + \frac{(n_i-2)^2}{4} \text{id}_s \right) \ldots \left( \rho(X_i)^2 + \frac{1}{4} \text{id}_s \right) = 0, \quad \text{if } n_i \text{ is odd},
\]

i.e. \( P_{\mathfrak{k}}^X(\rho(X_i)) = 0 \) (in the notation of Proposition 3.4).

Another way of saying this is that \( \rho(X_i) \) is semisimple with eigenvalues belonging to the set \( \{ \frac{(n_i-2j)^2}{4} : 0 \leq j \leq n_i \} \). When the generalized Cartan matrix of \( \mathfrak{g} \) is simply laced, this definition clearly coincides with Definition 4.4.
Theorem 4.11. Let $L = k(I)$ where $I^2 = -1$. Let $g$ be an arbitrary symmetrizable Kac–Moody Lie algebra with maximal compact subalgebra $t$. Then there exists a generalized spin representation $\rho : t \to \text{End}(L^s)$.

Moreover, if $k$ is formally real, then $\rho$ can be considered as a representation $t \to \text{End}(k^{2s})$ with $\text{im} \rho$ compact and, therefore, reductive. Furthermore, in this case $\text{im} \rho$ is semisimple, if for all $i$ there exists $j \neq i$ such that $a_{ji}$ is odd. Finally, in this case $t \cong \ker \rho \oplus \text{im} \rho$.

Note that the condition in the next-to-final sentence of the theorem is satisfied if, for example, $g$ has a simply laced diagram which has no isolated nodes.

Proof. To see that $t$ has a generalized spin representation, let $\tilde{g}$ be the Kac–Moody algebra associated to some minimal rank simply laced cover diagram for $g$ and let $\tilde{\varphi} : g \to \tilde{g}$ be the Lie algebra embedding described in Section 2.4. Then it is clear from the earlier discussion that, if $\tilde{\rho} : \tilde{t} \to \text{End}(L^s)$ is a generalized spin representation for $\tilde{t}$, then $\rho = \tilde{\rho} \circ \tilde{\varphi}|_t$ is a generalized spin representation for $t$. (It is, however, not clear that any generalized spin representation for $t$ arises in this way.) Thus the first statement follows immediately from Corollary 4.8.

For the second statement it will suffice to prove that there exists a generalized spin representation $\rho : t \to \text{End}(L^s)$ such that, with respect to an appropriate choice of $k$-basis for $L^s$, each of the images $\rho(X_i)$ is a skew-symmetric $2s \times 2s$ matrix over $k$ and, thus, $\rho$ can be interpreted as a homomorphism $t \to \mathfrak{so}_{2s}(k)$. Since we can construct generalized spin representations for $t$ by restricting from those for the Lie algebra associated to a simply laced cover diagram, it will clearly suffice to show that the representation constructed in Theorem 4.7 can be realized by using skew-symmetric matrices only. For the extension of the representation in part (a) of Theorem 4.7 this is obvious, as $L \cong \{ \begin{pmatrix} a & b \\ -b & a \end{pmatrix} | a, b \in k \}$ as $k$-algebras, whence $I$ is represented by the skew-symmetric matrix $\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$. For the extension of the representation in part (b) of Theorem 4.7, observe that

$$\begin{pmatrix} 1 & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -I \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

so that after a change of basis we have instead $\rho'(X_{r+1}) = \frac{1}{2} \text{id}_s \otimes \begin{pmatrix} 0 & 1 \\ 0 & -1 \end{pmatrix}$ (while $\rho'|_{t_{\perp r}}$ remains unchanged). Therefore, if the representation of $t|_{t_{\perp r}}$ consists of skew-symmetric matrices over $k$, one can ensure that the representation of $t|_{t_{\perp r}}$ also consists of skew-symmetric matrices over $k$. Thus $\text{im} \rho$ is compact, whence reductive.

For the statement concerning semisimplicity observe that $t$ is perfect. Indeed, by hypothesis, for each generator $X_i$ of $t$, there is some $j$ such that $a_{ji}$ is odd, and therefore the constant term in the polynomial $P_{-a_{ji}}$ is non-zero. Since $P_{-a_{ji}}(\text{ad} X_j)(X_i) = 0$ by Lemma 2.3, it follows that $X_i$ is contained in the linear span of $(\text{ad} X_j)^\ell(X_i)$, $\ell \geq 1$. Thus, the image $\text{im} \rho$ is perfect and, by the above, reductive. The claim is now obvious, as a perfect direct sum of a semisimple and an abelian Lie algebra necessarily is semisimple.

For the final statement observe that $t$ is anisotropic and so $(\ker \rho)^\perp \cong \text{im} \rho$ is an ideal of $t$, where $\perp$ denotes the orthogonality relation with respect to the Killing form of $t$. □

Let $C$ denote the class of all generalized spin representation of $t$. We check some closure properties of $C$.

Proposition 4.12. (a) $C$ is closed under direct sums, quotients, duals and taking subrepresentations.
(b) If the generalized Cartan matrix of $\mathfrak{g}$ is simply laced and $\rho_1, \rho_2, \rho_3 \in \mathcal{C}$, then so is $\rho: X_i \mapsto 4\rho_1(X_i) \otimes \rho_2(X_i) \otimes \rho_3(X_i)$.

(c) More generally, if the generalized Cartan matrix of $\mathfrak{g}$ is simply laced and $\rho_1, \rho_2 \in \mathcal{C}$, then so is $\rho := 2I\rho_1 \otimes \rho_2$. (M. Horn, personal communication.)

(d) If $\rho \in \mathcal{C}$ and $\varphi$ is either a sign, graph or Weyl group automorphism of $\mathfrak{t}$, then $\rho \circ \varphi \in \mathcal{C}$.

Proof. The first three assertions can be easily verified. The fourth assertion is clear if $\varphi$ is a graph or a sign automorphism. The remaining claim follows from Remark 2.2, since if $\rho(X_j)$ has eigenvalues $\frac{rI}{2}, \frac{(r-2)I}{2}, \ldots, -\frac{rI}{2}$ then so does $\rho(\exp(\xi \text{ad} X_i)(X_j)) = \exp(\xi \rho(X_i))(\rho(X_j))$. □

5. Some Dynkin diagrams

We give the list of relevant Dynkin diagrams we use in the main text.

\begin{align*}
A_n^+ & \quad 1 \quad 2 \quad \ldots \quad n-1 \quad n \\
D_n^+ & \quad 1 \quad 2 \quad 3 \quad \ldots \quad n-1 \quad n \\
E_6^+ & \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \\
E_7^+ & \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \\
E_8^+ & \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \\
E_8^{++} & \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \\
\end{align*}
\[ A_{n+2} = AE_{n+1} \]

References


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