Integral Structures on $H$-type Lie Algebras

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Abstract. In this paper we prove that every $H$-type Lie algebra possesses a basis with respect to which the structure constants are integers. Existence of such an integral basis implies via the Mal’cev criterion that all simply connected $H$-type Lie groups contain co-compact lattices. Since the Campbell-Hausdorff formula is very simple for two-step nilpotent Lie groups we can actually avoid invoking the Mal’cev criterion and exhibit our lattices in an explicit way. As an application, we calculate the isoperimetric dimensions of $H$-type groups.

1. Introduction

In this paper we prove that every $H$-type Lie algebra $[7, 8, 9]$ possesses a basis with respect to which the structure constants are integers. We are going to call such a basis an integral basis. Existence of an integral basis implies via the Mal’cev criterion that all simply connected $H$-type Lie groups contain co-compact lattices. Since the Campbell-Hausdorff formula is very simple for two-step nilpotent Lie groups we can actually avoid invoking the Mal’cev criterion and exhibit our lattices in an explicit way.

The theory of $H$-type Lie algebras is related very closely to the theory of Clifford algebras and Clifford modules (cf. [4, 10]) and we are going to use the classification of Clifford modules in our construction.

We briefly recall the definition of $H$-type Lie algebras and establish notation and conventions for the sequel. Let $\mathcal{U}$ and $\mathcal{V}$ be two finite-dimensional inner product spaces over $\mathbb{R}$ of dimensions $m$ and $n$ respectively. Let $J : \mathcal{U} \rightarrow \text{End}(\mathcal{V})$, $z \mapsto J_z$, be a linear mapping satisfying

\begin{align}
|J_z(v)| &= |z| |v| \\
J_z \cdot J_z(v) &= -|z|^2 v
\end{align}

for all $z \in \mathcal{U}$ and $v \in \mathcal{V}$. Such a mapping $J$ is called an orthogonal multiplication. Because of (2), by the universal property of Clifford algebras [10, Proposition 1.1, Chapter 1], $J$ extends to an algebra homomorphism $\phi$ of the Clifford algebra

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$C(U)$ into End($V$) so that $V$ acquires the structure of a module over $C(U)$. We will often write $\phi(\alpha)v = \alpha v$ and call $\alpha v$ the Clifford product of $\alpha$ and $v$.

After squaring, polarization of (1) yields

$$
(J_{z_1}(v), J_{z_2}(v)) = (z_1, z_2) |v|^2
$$

(3)

$$
(J_{v_1}(v), J_{v_2}(v)) = |v|^2 (v_1, v_2)
$$

(4)

holding for all $z, z_1, z_2 \in U$ and $v, v_1, v_2 \in V$. In order not to complicate notation, we use the same notation for norms and inner products in $U$ and $V$. It follows immediately that

$$
(J_z(v_1), v_2) = -(v_1, J_z(v_2)),
$$

(5)

i.e. $J_z(v)$ is a skew-adjoint endomorphism of $V$, $J_z^* = -J_z$. Now the Lie algebra structure is defined on $N = U \oplus V$ by requiring that $U$ be contained in the center and that the bracket of two elements of $V$ belong to $U$ and satisfy

$$
(z, [v_1, v_2]) = (J_z(v_1), v_2).
$$

In this way, $N$ becomes a two-step nilpotent Lie algebra which is referred to as a Heisenberg-type or $H$-type Lie algebra. Orthonormal bases $z_1, \ldots, z_m$ and $v_1, \ldots, v_n$ of $U$ and $V$ respectively give rise to the basis $z_1, \ldots, z_m, v_1, \ldots, v_n$ of $N$ which is orthonormal. The only nonzero structure constants for $N$ with respect to this basis occur among numbers $A_{i,j,k}^k$ defined by

$$
[v_i, v_j] = A_{i,j,k}^k z_k.
$$

(6)

We are now ready to state our main result.

**Theorem 1.1.** For every $H$-type Lie algebra $N = U \oplus V$ as above there exist orthonormal bases $z_1, \ldots, z_m$ and $v_1, \ldots, v_n$ of $U$ and $V$ respectively so that the structure constants $A_{i,j,k}^k$ of the Lie algebra $N$ with respect to the basis $z_1, \ldots, z_m, v_1, \ldots, v_n$ are integers and in fact take values $0, 1, -1$.

The numbers $A_{i,j,k}^k$ are clearly equal to $(J_{z_k}(v_i), v_j) = (z_k v_i, v_j)$, i.e. depend only on the Clifford module structure and the inner product of $V$. According to [10, Proposition 5.16], every Clifford module, i.e. a finite dimensional module over $C(U)$, admits an inner product such that the Clifford multiplication by elements of $U \subset C(U)$ is an orthogonal multiplication. We remark that the Clifford multiplication is orthogonal if and only if elements of $U$ act by skew-adjoint transformations, i.e. if and only if (5) holds.

Thus every Clifford module gives rise to an $H$-type Lie algebra and Theorem 1.1 can be reformulated as a statement about Clifford modules as follows.

**Theorem 1.2.** Given an inner product space $U$ with an orthonormal basis $z_1, \ldots, z_m$ and a module $V$ over the Clifford algebra $C(U)$ there exists an inner product $(\cdot, \cdot)$ on $V$ and an orthonormal basis $v_1, \ldots, v_n$ of $V = (V, (\cdot, \cdot))$ so that the Clifford multiplication $J_z(v) = z v$ by elements of $U$ satisfies (1) and (2) and $(z_i v_p, v_q)$ is equal to $0, 1$ or $-1$ for all $i, p, q$. 
We will say that the choice of an inner product and a basis for \( V \) as above is an\textit{ integral structure} and that \( V \) with this additional structure is an \textit{integral Clifford module}. Observe that the fact that the values of \((e_i v_p, v_q)\) are 0, 1, -1 is equivalent to the assertion that each of the generators \(e_i\) acts on the basis \(v_1, v_2, \ldots, v_n\) by a permutation and, possibly, some changes of sign.

"From now on we will abandon the notational distinction between an inner product space \( U \) and the underlying vector space \( U \).

2. Proof of Theorem 1.2

Since Clifford modules are completely reducible [10, p. 31], it suffices to prove Theorem 1.2 for irreducible Clifford modules. Suppose \( \dim U = k \) and let \( e_1, \ldots, e_k \) be an orthonormal basis of \( U \). We are going to identify \( U \) with \( \mathbb{R}^k \) and \( C(U) \) with the algebra \( C_k \) generated over \( \mathbb{R} \) by \( e_1, \ldots, e_k \) subject to relations

\[
e_i e_j = -e_j e_i, \quad e_i^2 = -1. \tag{7}
\]

According to the classification of irreducible Clifford modules, for every \( k \neq 3 \) (mod 4) there exists only one isomorphism class of irreducible modules over \( C_k \). If \( k = 3 \) (mod 4) there are two such classes, but the dimensions as vector spaces over \( \mathbb{R} \) of non-isomorphic modules are equal and the \( H \)-type groups associated to them are isomorphic. We will denote an irreducible module over \( C_k \) by \( V_k \).

Classification of irreducible Clifford modules proceeds by induction on \( k \), cf. [10, p. 33], and we shall retrace this induction proving at every stage existence of an integral basis. It will be convenient to first classify \( \mathbb{Z}_2 \)-graded Clifford modules. We briefly recall their definition. Denote by \( C_k^0 \) the subspace generated by products of even numbers of generators \( e_1, \ldots, e_k \) and by \( C_k^1 \) the subspace generated by products of an odd number of generators. Then \( C_k^0 \) is a subalgebra, \( C_k^0 \oplus C_k^1 = C_k \), and

\[
C_k^i \cdot C_k^j \subset C_k^{i+j}
\]

for \( i, j \in \mathbb{Z}_2 \). A finite dimensional space \( W \) over \( \mathbb{R} \) is a \( \mathbb{Z}_2 \)-graded Clifford module if \( W = W^0 \oplus W^1 \) and

\[
C_k^i \cdot W^j \subset W^{i+j}
\]

with \( i, j \in \mathbb{Z}_2 \).

We need to define an analog of integral structure on \( \mathbb{Z}_2 \)-graded Clifford modules (we use definitions and notation of [4, Chapter 11, Sections 4,6] regarding \( \mathbb{Z}_2 \)-graded tensor products of Clifford algebras and Clifford modules).

\textbf{Definition 2.1.} Suppose \( W^0 \) is a module over \( C_k^0 \). A choice of inner product \((\cdot, \cdot)\) on \( W^0 \) and an orthonormal basis \( w_1, \ldots, w_m \) with respect to this inner product is called \textit{integral} if the basis elements are permuted with a possible change in sign by Clifford multiplication by all double products \( e_i e_j \) and

\[
(z e_k w, z e_k w) = |z|^2 |w|^2
\]

for all \( w \in W^0 \) and \( z \in \mathbb{R}^k \). We will call \( W^0 \) with the inner product and a basis satisfying the conditions above\textit{ integral}.
If $W^0$ is the 0-component of a $\mathbb{Z}_2$-graded Clifford module $W$ then multiplication by $e_k$ is an isomorphism of $W^0$ onto $W^1$. Therefore we can transfer the inner product on $W^0$ to $W^1$ and define the inner product on $W^0 \oplus W^1 = W$ by requiring the two summands to be orthogonal. A simple calculation then shows that the Clifford multiplication by elements of $\mathbb{R}^k$ is an orthogonal multiplication and the elements of the basis $w_1, \ldots, w_m, e_kw_1, \ldots e_kw_m$ are permuted by Clifford multiplication by every $e_i$ with a possible change in sign. In particular, Theorem 1.2 holds for $W$. In the sequel we are only going to use inner products such that $W^0 \perp W^1$ and the multiplication by $e_k$ maps $W^0$ onto $W^1$ isometrically.

Our proof of Theorem 1.2 will be carried out by showing that for every $k$ there exists an irreducible $\mathbb{Z}_2$-graded Clifford module $W_k$ with an integral structure. This will imply that every (ungraded) irreducible Clifford module is integral. It will follow a posteriori that all $\mathbb{Z}_2$-graded Clifford modules are integral. The main fact in the classification of Clifford modules is that if $W_k$ and $W_8$ are irreducible $\mathbb{Z}_2$-graded modules over $C_k$ and $C_8$ respectively, then $W_k \otimes W_8$ is an irreducible $\mathbb{Z}_2$-graded module over $C_k \otimes C_8 \simeq C_{k+8}$. Our proof of Theorem 1.2 will consist of exhibiting an integral irreducible $\mathbb{Z}_2$-graded Clifford module $W_k$ for $k = 1, \ldots, 8$ and then showing that $W_k \otimes W_8$ is integral if $W_k$ carried an integral structure. To handle the low dimensional cases we need the following general lemma.

**Lemma 2.2.** Suppose $V$ is an integral module over the algebra $C_k^0$. Then $W = C_k \otimes C_k^0 V$ is a $\mathbb{Z}_2$-graded module over $C_k$ with the $\mathbb{Z}_2$-grading given by $W^0 = 1 \otimes V$ and $W^1 = e_k \otimes V$. Thus $W^0$ has integral structure transferred from $V$ via the isomorphism $v \mapsto 1 \otimes v$. In addition, if $V$ is irreducible as a $C_k^0$-module then $W$ is irreducible as a $\mathbb{Z}_2$-graded module over $C_k$.

**Proof.** This is obvious (see [4, Chapter 11, Proposition 6.3]).

Our next task is to describe integral structures on Clifford modules over $C_k$ for $k \leq 8$. For $k \leq 7$, we refer to the description of (ungraded) Clifford modules given in [1].

**Case $k = 1$.** $\mathbb{R} \simeq i\mathbb{R}$ is acting on $\mathbb{C}$ by complex multiplication. The real and imaginary parts are 0- and 1-components of $\mathbb{Z}_2$-grading respectively and the standard inner product together with 1 as the basis of the 0-component give the integral structure.

**Case $k = 2$.** Consider the space of quaternions $\mathbb{H}$ equipped with the standard inner product. Identify $\mathbb{R}^2$ with the span of $i, j$ and let it act on $\mathbb{H}$ by quaternion multiplication. This makes $\mathbb{H}$ into an irreducible module over $C_2$. In addition, the decomposition $\mathbb{H} = \text{span} \{1, k\} \oplus \text{span} \{i, j\}$ is a $\mathbb{Z}_2$-grading and an integral structure is given by the basis $1, k, i, j$.

**Case $k = 3$.** In this case the space of quaternions becomes a module over the Clifford algebra $C_3$ represented in the algebra of endomorphisms of $\mathbb{H}$ as the subalgebra generated by quaternion multiplications by $i$, $j$, and $k$. Clearly, the standard basis $1, i, j, k$ is permuted with possibly a change in sign by these
endomorphisms so that $\mathbb{H}$ as a module over $C_3$ carries an integral structure. However, this module does not have a natural $\mathbb{Z}_2$-graded structure. We regard $\mathbb{H}$ as a module over $C_3^0 \subset C_3$ and apply Lemma 2.2 to create an integral $\mathbb{Z}_2$-graded irreducible $C_3$-module structure on $C_3 \otimes C_3^0 \mathbb{H}$.

To cover the remaining low-dimensional cases we will use the algebra of octonions $\mathbb{O}$ with its standard generators $1, i_1, \ldots i_7$ and multiplication table given in [5, Page 448] with $c = -1$.

**Case $k = 4$.** This is analogous to the case $k = 2$. $\mathbb{R}^4$ is identified with span$\{i_1, i_2, i_3, i_4\}$ which acts on $\mathbb{O}$ by octonion multiplication. The resulting Clifford module is $\mathbb{Z}_2$-graded with the 0-component equal to span$\{1, i_5, i_6, i_7\}$ and the 1-component span$\{i_1, i_2, i_3, i_4\}$. These bases are orthonormal with respect to the standard inner product and give rise to an integral structure. This follows from inspection of the multiplication table.

**Case $k = 5, 6, 7$.** We treat these three cases simultaneously. The Clifford algebra $C_k$ can be represented as an algebra of endomorphisms of $\mathbb{O}$ generated by transformations of octonion multiplications by $i_j, 1 \leq j \leq k$. The resulting Clifford module $V_k$ is irreducible but not $\mathbb{Z}_2$-graded. As above, we regard it as a module over $C_k^0$ which allows us to create an irreducible, $\mathbb{Z}_2$-graded, integral Clifford module $W_k = C_k \otimes C_k^0 \mathbb{O}$ using Lemma 2.2.

**Case $k = 8$.** This uses the isomorphism, for every $k \geq 2$, $\phi : C_{k-1} \longrightarrow C_k^0$ defined as follows [4, Chapter 11, Section 6]. Let $x = x_0 + x_1$ be the decomposition of $x \in C_k$ into its 0 and 1 components. Then $\phi(x) = x_0 + e_k x_1$ where, given standard generators $e_1, \ldots, e_k$ of $C_k$, we regard $C_{k-1}$ as the subalgebra generated by $e_1, \ldots, e_{k-1}$. The octonions are a module over $C_7$ as above (we relabel $i_j$ as $e_j$) which allows us to regard $\mathbb{O}$ as a module over $C_8^0$ by defining the multiplication $x_0$ as $\phi^{-1}(x_0)$. Since $\phi^{-1}(e_j) = e_j$ and $\phi^{-1}(e_i e_j) = e_j$ for $j \leq 7$ and $\mathbb{O}$ was integral as a module over $C_7$, the resulting module over $C_8^0$ is integral. Applying Lemma 2.2 we obtain an integral, irreducible, $\mathbb{Z}_2$-graded module $W_8 = C_8 \otimes C_8^0 \mathbb{O}$. We remark that $W_8$ is irreducible as an ungraded Clifford module as well. This is because $W_8^0$ is irreducible as a module over $C_8^0$ (since the pair $(W_8^0, C_8^0)$ is isomorphic to $(V_7, C_7)$ and $V_7$ is irreducible as a module over $C_7$).

We are now ready for the inductive step in the argument. Suppose $W_k$ and $W_l$ are integral, $\mathbb{Z}_2$-graded Clifford modules over $C_k$ and $C_l$ respectively. Let $e_1, \ldots, e_k$ and $f_1, \ldots, f_l$ be the standard generators of $C_k$ and $C_l$. Suppose $W_k^0$ and $W_l^0$ are equipped with inner products and integral bases $v_1, \ldots, v_m$ and $w_1, \ldots, w_n$ respectively. Recall that as a vector space $W_k \otimes W_l$ is isomorphic to $W_k \otimes W_l^o$ so that we can equip $W_k \otimes W_l$ with an inner product by requiring that

$$(x_1 \otimes y_1, x_2 \otimes y_2) = (x_1, x_2) \cdot (y_1, y_2).$$

In particular, different components $W_k^i \otimes W_l^j$ for $(i, j) \in \mathbb{Z}_2 \times \mathbb{Z}_2$ are orthogonal. Under the isomorphism $C_k \otimes C_l \simeq C_{k+l}$, cf. [4, Corollary 4.8] note that our
notation differs from the notation in [4] since we use the symbol $\otimes$ instead of $\otimes$ to denote the tensor product of $\mathbb{Z}_2$-graded algebras), the standard generators of $C_{k+l}$ correspond to $e_1 \otimes 1, \ldots, e_k \otimes 1, 1 \otimes f_1, \ldots 1 \otimes f_l$. To exhibit an integral structure we need a basis of $(W_k \otimes W_i)^0 = (W_k^0 \otimes W_i^0) \oplus (W_k^1 \otimes W_i^1)$ in addition. The basis that we are going to use is

$$\{ v_i \otimes w_j, e_kv_i \otimes f_lw_j \mid 1 \leq i \leq m, 1 \leq j \leq n \}. \quad (8)$$

**Lemma 2.3.** The bases described above give rise to an integral structure on $(W_k \otimes W_i)^0$ and, consequently, on $W_k \otimes W_i$.

**Proof.** We first verify that the Clifford multiplication by elements of the space $U$ spanned by the generators of $C_k \otimes C_l$ is orthogonal. Recall that it suffices to verify that each element $z \in U$ acts on $W_k \otimes W_i$ as a skew-symmetric endomorphism. We abuse the notation and write $z$ for an endomorphism associated with $z$. Clearly,

$$(e_i \otimes 1)^* = e_i^* \otimes 1 = -e_i \otimes 1$$

$$(1 \otimes f_j)^* = 1 \otimes f_j^* = -1 \otimes f_j$$

since Clifford multiplications on $W_k$ and $W_i$ are orthogonal. Since every element of $U$ is a linear combination of such products, our assertion follows.

To verify properties of the integral structure, it suffices to show that elements of the basis (8) are permuted up to sign by the double products of generators. There are three cases to consider $(e_i \otimes 1) \cdot (e_j \otimes 1) = e_ie_j \otimes 1$, $(1 \otimes f_i) \cdot (1 \otimes f_j) = 1 \otimes f_if_j$, and $(e_i \otimes 1) \cdot (1 \otimes f_j) = (e_i \otimes f_j^*)$. In the first two cases the action is as desired since the multiplication by $e_p$'s permutes $v_1, \ldots, v_m$ up to sign and the multiplication by $f_q$'s acts the same way on $w_1, \ldots, w_n$. To treat the third case, note that $e_p = \pm e_ke_pe_k$ and $f_q = \pm f_qf_q^*$. Thus, up to signs,

$$(e_p \otimes f_q) \cdot (v_i \otimes w_j) = e_ke_pe_kv_i \otimes f_qf_qf_lw_j = e_kv_i \otimes f_lw_j$$

since double products of generators of $C_k$ and $C_l$ permute up to sign the distinguished bases of $W_k^0$ and $W_l^0$ respectively. Similarly,

$$(e_p \otimes f_q) \cdot (e_kv_i \otimes f_lw_j) = e_pe_kv_i \otimes f_qf_lw_j = e_kv_i \otimes f_lw_j.$$  

This proves the lemma.

**Corollary 2.4.** Suppose that $W_k$ is an irreducible, integral, $\mathbb{Z}_2$-graded module over $C_k$. Then $W_k \otimes W_8$ is an irreducible, integral, $\mathbb{Z}_2$-graded module over $C_k \otimes C_8 \cong C_{k+8}$ with the integral structure described above.

**Proof.** All assertions except irreducibility are contained in the lemma above. By [4, Chapter 11, 6.5] $\dim_k W_k \otimes W_8 = \dim_k W_k \cdot \dim_k W_8 = 16 \dim_k W_k$ is equal to the dimension of an irreducible, $\mathbb{Z}_2$-graded Clifford module over $C_{k+8}$. It follows immediately that $W_k \otimes W_8$ is irreducible.
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Table 1: Dimensions of irreducible Clifford modules

An easy induction using the explicit description of irreducible, $\mathbb{Z}_2$-graded Clifford modules over $C_k$, $1 \leq k \leq 8$ and the lemma above yields existence of an irreducible, $\mathbb{Z}_2$-graded Clifford module $W_k$ over $C_k$ for every $k$.

Some additional work is required to show that every (ungraded) Clifford module has an integral structure. Let $a_k$ be the dimension of an irreducible Clifford module over $C_k$, and let $b_k$ denote the dimension of an irreducible, $\mathbb{Z}_2$-graded module over $C_k$. It follows from [4, Propositions 6.2 and 6.3, Chapter 11] that $a_k = b_{k+1}/2$. From basic periodicity [4, 6.5, Chapter 11], $a_{k+8} = 16a_k$ and $b_{k+8} = 16b_k$. All values of $a_k$ and $b_k$ can now be computed from Table 1, which summarizes some of the information about Clifford modules of low dimensions.

Recall now (cf. [4, Chapter 6]) that if $k = 1, 2, 4, 8 \pmod{8}$ then the dimensions over $\mathbb{R}$ of an irreducible Clifford module and an irreducible $\mathbb{Z}_2$-graded Clifford module are equal. Thus $\mathbb{Z}_2$-graded Clifford modules $W_k$ constructed above are irreducible as (ungraded) Clifford modules. The classification also says that for these values of $k$ there exists exactly one isomorphism class of Clifford modules over $C_k$ which proves Theorem 1.2 for $k = 1, 2, 4, 8 \pmod{8}$.

Next consider the case $k = 3 \pmod{4}$. According to the classification there are two non-isomorphic Clifford modules over $C_k$. We are going to show that their direct sum is isomorphic as an ungraded Clifford module to $W_k$ and that the integral structure of $W_k$ induces integral structures on the two modules. The key role in the proof of this fact is played by the “volume element” $\omega = e_1e_2\ldots e_k$. $\omega$ belongs to the center of $C_k$ and satisfies $\omega^2 = 1$, cf. [10, Proposition 3.3, Chapter 1]. In addition, the multiplication by $\omega$ is a symmetric operator on every orthogonal Clifford module. This can be seen as follows. If $k = 4l + 3$, then

$$
\omega^* = e_k^* e_{k-1}^* \ldots e_1^* = (-1)^{4l+3} e_k e_{k-1} \ldots e_1 = - (-1)^{(4l+3)/2} e_1 e_2 \ldots e_k = \omega,
$$

since multiplications by $e_p$‘s are skew-symmetric and $e_p$‘s anti-commute. Now define $\phi_+$ and $\phi_-$ to be multiplications by central elements $(1+\omega)/2$ and $(1-\omega)/2$ respectively. $\phi_\pm$ are self-adjoint and satisfy $\phi_\pm^2 = \phi_\pm$, i.e. they are orthogonal projections onto their images. Since $(1+\omega)(1-\omega) = 0$ and $\phi_+ + \phi_- = 1$ the ranges of these projections are perpendicular. Since $1 \pm \omega$ are central, they are in fact (ungraded) Clifford submodules $V_+$ and $V_-$ of $W_k$. Since $\omega W_k^0 = W_k^1$, $\phi_\pm$ is injective on $W_k^0$. A count of dimensions shows that $W_k = \phi_+ W_k^0 \oplus \phi_- W_k^0$ is an orthogonal direct decomposition of $W_k$ into two Clifford submodules. $\omega$ acts on $V_\pm$ by multiplication by $\pm 1$ so that the two modules are non-isomorphic. To conclude our analysis we exhibit integral bases of the two modules. We do the
argument for $V_+$ since the argument for $V_-$ is identical after $1 + \omega$ is replaced by $1 - \omega$. Let $w_1, \ldots, w_m$ be an integral basis of $W_0$, i.e. an orthonormal basis which is permuted up to sign by multiplications by double products $e_i e_j$. Let

$$v_p = \frac{1}{\sqrt{2}}(1 + \omega)w_p \in V_+$$

for $p = 1, \ldots, m$. Since $\omega W_k^0 = W_k^1$ is perpendicular to $W_k^0$, the Pythagorean theorem insures that this is an orthonormal basis. For a generator $e_i$ of $C_k$ we calculate

$$(e_i v_p, v_q) = (e_i w_p + e_i \omega w_p, w_q + \omega w_q)/2.$$ 

Observe that $e_i \omega w_p$ and $w_q$ belong to $W_k^0$ while $e_i w_p$ and $\omega w_q$ are in $W_k^1$. Therefore the inner product above simplifies to

$$( (e_i w_p, \omega w_q) + (e_i \omega w_p, w_q) )/2 = (e_i w_p, \omega w_q),$$

since $\omega$ is central and self-adjoint. Now $\omega w_q$ can be expressed as a product of $e_i$ times a product of an even number of generators of $C_k$. It therefore follows from the definition of an integral basis that $e_i \omega w_q$ is up to sign equal to $e_i w_{q'}$ so that, finally

$$(e_i v_p, e_i v_{q'}) = (v_p, v_{q'}) = \delta_{p, q'},$$

which proves that the basis $v_1, \ldots, v_m$ is integral.

The remaining two cases of Theorem 1.2 are $k = 5, 6$ (mod 8) say $k = 8l + r$, with $r$ equal to 5 or 6. By the classification, in either case there is only one isomorphism class of irreducible modules over $C_k$ and the dimension over $\mathbb{R}$ of an irreducible module in this class is equal to the dimension of the Clifford module $V_+$ over $C_{4l+7}$ constructed above. Clearly, $C_k$ can be regarded as the subalgebra of $C_{4l+7}$ generated by the first $k$ generators so that $V_+ = V_k$ becomes a module over $C_k$. It is irreducible since its dimension is that of an irreducible module and, trivially, integral. Theorem 1.2 is proved.

We conclude this section with a very simple proof, available now, of the fact that two non-isomorphic Clifford modules over $C_k$, $k = 3$ (mod 4) give rise to isomorphic $\textbf{H}$-type algebras. This is very well known, cf. [11], but we give the proof for completeness. The structure constants of the $\textbf{H}$-type Lie algebra $U \oplus V_+$ associated to the Clifford module $V_+$ have been computed above and are equal to

$$(e_i v_p, v_q) = (e_i w_p, \omega w_q)$$

(here $U = \text{span}\{e_1, \ldots, e_k\}$). In the analogous calculation for $V_-$, $\omega$ is replaced by $-\omega$ so that the corresponding structure constants for the Lie algebra $U \oplus V_-$ (with respect to the basis $e_1, \ldots, e_k, v'_1, \ldots, v'_m$ where $v'_p = (1/\sqrt{2})(1 - \omega)w_p$ are negatives of the structure constants for $U \oplus V_+$ if we choose the obvious correspondence between bases of $V_+$ and $V_-$. However, if we deploy the set $-e_1, \ldots, -e_k, v'_1, \ldots, v'_m$ as the basis for $U \oplus V_-$ instead, the structure constants for the two Lie algebras are equal so that the algebras are isomorphic.

3. Examples and applications

In this section we show that every simply connected Lie group of Heisenberg type contains a co-compact lattice. We are also going to calculate the isoperimetric dimension of such groups.
We choose and fix an integral basis as in Theorem 1.1. Since $H$-type Lie algebras are two-step nilpotent (in particular nilpotent) the exponential mapping is a global diffeomorphism of the Lie algebra and the group. We will therefore use it to identify the two. In addition the Campbell-Hausdorff formula that expresses the group multiplication in terms of the Lie bracket takes a particularly simple form

$$X \cdot Y = X + Y + \frac{1}{2}[X, Y] \tag{9}$$

where $X, Y \in N = U \oplus V$ as in the Introduction. Let $U_Z$ be the abelian subgroup of $U$ consisting of linear combination with integer coefficients of the generators $e_1, \ldots, e_k$ of $C(U) \simeq C_k$. Let $V_Z$ be the lattice in $V$ generated by elements of an integral basis. Since $[V_Z, V_Z] \subset U_Z$ our candidate for the lattice $L$ in the group $(N, \cdot)$ is the subset

$$L = \frac{1}{2}U_Z \oplus V_Z.$$

Verification of this claim is straightforward after first checking that $-X$ is the inverse of $X$ with respect to the group operation. Thus $L$ is a subgroup of $N$ and it is obviously discrete. The product of an arbitrary element $u + v$ of $N$ with $w \in V$ is equal to $u + (1/2)[v, w] + v + w$ and has $u + (1/2)[v, w]$ as its $U$ component and $v + w$ as the component in $V$. Given $v$ we can choose $w \in V_2$ so that $v + w$ has all coefficients in the interval $[0, 1]$ when expanded with respect to the distinguished basis of $V$. We can then act on $u + (1/2)[v, w]$ by elements $u_1$ of $(1/2)U_Z$. Since this action is by ordinary translation ($U_Z$ is contained in the center of $N$) we can easily achieve that $u + v + (1/2)[v, w] + u_1$ has its coefficients with respect to the basis $e_1, \ldots, e_k$ in the interval $[0, 1/2]$. Hence all coefficients in the expansion of

$$(u + v) \cdot (u_1 + w) = u + u_1 + \frac{1}{2}[v, w] + v + w$$

with respect to the integral basis chosen lie in $[0, 1]$, which proves that $L$ is co-compact.

To calculate the isoperimetric dimension of $N$ we will need to calculate the ranks of groups in the lower central series of $L$. Using our explicit description of the product in $N$ one verifies very easily that the bracket operation of the Lie algebra coincides with the commutator operation in the group. We therefore have $[L, L] = [V_Z, V_Z] = U_Z$. The second equality requires a proof. Observe first that

$$|(z, [v, w])| = |(zv, w)| \leq |z| \cdot |v| \cdot |w|$$

if $z \in U$, $v, w \in V$. It follows that

$$|[v, w]| \leq |v| \cdot |w|.$$ 

Now let $e_i$ be one of the generators of $C_k$. Then $e_i$ induces a permutation of the basis vectors of $V$ with a possible change in sign. Thus given $v_p$, $e_k v_p = \pm v_q$ for some $q$. It follows that $|(e_i, [v_p, v_q])| = |(e_i v_p, v_q)| = 1$ so that $e_i = \pm [v_p, v_q]$. Thus each of the generators $e_i$ is a commutator which proves the claim. We see therefore that

$$L/[L, L] \simeq (\frac{1}{2}U_Z/U_Z) \oplus V_Z \simeq \mathbb{Z}_2 \oplus V_Z.$$
We remark that there is no ambiguity in the interpretation of the quotient above since \([L, L] \subset U\) and the group multiplication by \(u \in U\) amounts to the translation by \(u\) because of (9).

A theorem of Bass [2] gives the estimate of growth of \(L\) in the word metric with respect to a finite set of generators. In our case we can take for example the generating set \(S\) given by the vectors of an integral basis and their negatives. The lower central series of \(L\) reduces to \(L_0 = L \supset L_1 = [L, L] \supset L_2 = 0\). The ranks of successive quotients are therefore equal to \(\dim V\) and \(\dim U\). If \(d = \dim V + 2\dim U\) then by Bass’ theorem \(L\) has polynomial growth of degree \(d\), i.e. the number \(g(R)\) of distinct elements of \(L\) in the metric ball of radius \(R\) in \(L\) satisfies
\[ g(R) \geq cR^d. \]

where the constant \(c\) depends on the choice of the generating set. A result of Coulhon and Saloff-Coste [3] asserts that the Cayley graph of a group of polynomial growth of degree \(d\) satisfies a \(d\)-dimensional isoperimetric inequality. Since every Lie group has bounded geometry we can invoke Kanai’s theorem [6] to conclude that the \(H\)-type group under consideration satisfies an isoperimetric inequality of the same kind. More precisely we have the following.

**Theorem 3.1.** Suppose \(N = U \oplus V\) is an \(H\)-type group equipped with a left-invariant metric. There exists a positive constant \(c\) such that for every relatively compact subset \(F\) of \(N\) with smooth boundary \(\partial F\) we have
\[ \frac{A(\partial F)}{\nu(F)^{1/d}} \geq c, \]

where \(A(\partial F)\) and \(\nu(F)\) denote the \(n-1\)-dimensional volume of the boundary of \(F\) and \(\nu(F)\) stands for the volume of \(F\).

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