4. Nilpotent Lie algebras with infinitely many non-isomorphic rational forms

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In this section we propose a construction which can provide a series of nilpotent Lie algebras with infinitely many isomorphism classes of rational forms.

4.1 Basic lemma

Let

$$\mathfrak{h} = \bigoplus_{i=1}^{c} \mathfrak{h}_i = \mathfrak{h}(\mathbf{Q})$$

be a graded Lie algebra over $\mathbf{Q}$ generated by $\mathfrak{h}_1$. Let $\mathbf{K}$ be a number field, $\dim_{\mathbf{Q}} \mathbf{K} = d$, of type (s, t), that is, there are s real and $2t$ complex embeddings of $\mathbf{K}$ in $\mathbf{C}$ $(d = s + 2t)$ whence there exists an isomorphism of $\mathbf{R}$-algebras

$$\mathbf{K} \otimes_{\mathbf{Q}} \mathbf{R} \cong \bigoplus_{k=1}^{s} \mathbf{R} \oplus \bigoplus_{l=1}^{t} \mathbf{C}.$$

More generally one can take a finite-dimensional commutative associative algebra $\mathbf{A}$ over $\mathbf{Q}$ instead of $\mathbf{K}$. We consider the Lie algebra $\mathfrak{h}(\mathbf{K}) = \mathfrak{h} \otimes_{\mathbf{Q}} \mathbf{K}$ as a Lie algebra over $\mathbf{Q}$. This algebra has two important properties. Firstly,

$$\mathfrak{h}(\mathbf{K}) \otimes_{\mathbf{Q}} \mathbf{R} \cong (\mathfrak{h} \otimes_{\mathbf{Q}} \mathbf{K}) \otimes_{\mathbf{Q}} \mathbf{R} \cong \mathfrak{h} \otimes_{\mathbf{Q}} (\mathbf{K} \otimes_{\mathbf{Q}} \mathbf{R}) \cong \bigoplus_{k=1}^{s} \mathfrak{h}(\mathbf{R}) \oplus \bigoplus_{l=1}^{t} \mathfrak{h}(\mathbf{C}),$$

i.e., $\mathfrak{h}(\mathbf{K})$ is a $\mathbf{Q}$-form of the last Lie algebra for any number field $\mathbf{K}$ of type (s, t). Secondly, there is an embedding $R\colon \mathbf{K}^* \to \mathrm{Aut}_{\mathbf{Q}}(\mathfrak{h}(\mathbf{K}))$ of the multiplicative group $\mathbf{K}^*$ such that $R(k)(h_i \otimes k_1) = h_i \otimes \tilde{k}k^i$ where $h_i \in \mathfrak{h}_i$ is homogenenous of degree i. The following lemma is straightforward.

Lemma 4.1. *Let $\mathbf{K} \neq \mathbf{K}'$ be two distinct number fields of the same type. If there is no injection of $\mathbf{K}^*$ into $\mathrm{Aut}_{\mathbf{Q}}(\mathfrak{h}(\mathbf{K}'))$ then two $\mathbf{Q}$-forms $\mathfrak{h}(\mathbf{K})$ and $\mathfrak{h}(\mathbf{K}')$ are not isomorphic.*

4.2 Proof of Theorem 2

We start with the class of nilpotence $c = 2$. Let $\mathbf{K} = \mathbf{Q}(\sqrt{m})$ and $\mathbf{K}' = \mathbf{Q}(\sqrt{n})$, where $m \neq n$ are two positive (resp. negative) square-free integers. Consider the automorphism $A = R(\sqrt{m})$ of $\mathfrak{h}(\mathbf{K}) = \mathfrak{f}_2(p, \mathbf{K})$. One immediately checks that

1) A^2 acts on $\mathfrak{h}(\mathbf{K})/[\mathfrak{h}(\mathbf{K}), \mathfrak{h}(\mathbf{K})]$ as $m \cdot Id$;

2) the restriction

$$A|_{[\mathfrak{h}(\mathbf{K}), \mathfrak{h}(\mathbf{K})]} = m \cdot Id.$$

By Lemma 4.1 we must prove that there is no such automorphism for $\mathfrak{h}(\mathbf{K}') = \mathfrak{h}(\mathbf{Q}(\sqrt{n}))$. We choose the following basis of $\mathfrak{h}(\mathbf{K}')$ over $\mathbf{Q}$:

$$X_i = x_i \otimes 1, \quad Y_i = x_i \otimes \sqrt{n}, \quad C_{ij} = c_{ij} \otimes 1, \quad Z_{ij} = c_{ij} \otimes \sqrt{n},$$

$x_1, \dots, x_p, c_{ij} = [x_i, x_j]$ being the standard basis of $\mathfrak{f}_2(p, \mathbf{Q})$.

Suppose that there exists an automorphism A' with two above properties. First of all, let us show that $[X_i, A'(X_i)] = 0$. On the one hand,

$$A'[X_i, A'(X_i)] = [A'(X_i), mX_i] = -m[X_i, A'(X_i)].$$

On the other hand,

$$A'[X_i, A'(X_i)] = m[X_i, A'(X_i)].$$

Since the centralizer of X_i is generated modulo the centre by X_i, Y_i it follows that

$$A'(X_i) = p_i X_i + q_i Y_i + \varepsilon = x_i \otimes (p_i + q_i\sqrt{n}) + \varepsilon, \quad q_i \neq 0.$$

Here ε stands for a central element which plays no role below.

Consider now $[X_i, A'(X_j)] = c_{ij} \otimes (p_j + q_j\sqrt{n})$. On the one hand,

$$A'[X_i, A'(X_j)] = [A'(X_i), mX_j] = c_{ij} \otimes m(p_i + q_i\sqrt{n}).$$

On the other hand,

$$A'[X_i, A'(X_i)] = m[X_i, A'(X_j)] = c_{ij} \otimes m(p_j + q_j\sqrt{n}),$$

whence

$$p_i + q_i\sqrt{n} = p_j + q_j\sqrt{n} = p + q\sqrt{n} \notin \mathbf{Q} \ \forall i, j.$$

Finally, we apply A' to $[A'(X_i), A'(X_j)] = c_{ij} \otimes (p + q\sqrt{n})^2$. On the one hand,

$$A'[A'(X_i), A'(X_j)] = [mX_i, mX_j] = c_{ij} \otimes m^2.$$

On the other hand,

$$A'[A'(X_i), A'(X_i)] = m[A'(X_i), A'(X_j)] = c_{ij} \otimes m(p + q\sqrt{n})^2.$$

It follows that $m = (p + q\sqrt{n})^2$. We have obtained a contradiction since $q \neq 0$. Thus, there are infinitely many non-isomorphic rational forms of $\mathfrak{f}_2(p, \mathbf{R}) \oplus \mathfrak{f}_2(p, \mathbf{R})$ and of $\mathfrak{f}_2(p, \mathbf{C})$.

More generally let $\mathfrak{g} = \mathfrak{f}_c(p, \mathbf{R})$ be a free nilpotent Lie algebra of class $c \geq 3$ on p generators. Then $\mathfrak{g} \oplus \mathfrak{g}$ and $\mathfrak{g} \otimes_{\mathbf{R}} \mathbf{C} = \mathfrak{f}_c(p, \mathbf{C})$ (as a Lie algebra over $\mathbf{R}$) also have infinitely many non-isomorphic rational forms. Consider the automorphism A as above and note that it respects the descending central series. Any isomorphism between $\mathfrak{f}_c(p, \mathbf{K})$ and $\mathfrak{f}_c(p, \mathbf{K}')$ must respect it, too. Then we can take the free nilpotent quotients of class 2 of both algebras and obtain a contradiction just like in the first part of the proof. □

Thus, the case of a free nilpotent Lie algebra $\mathfrak{f}_c(p, \mathbf{C})$ (as a Lie algebra over $\mathbf{R}$) on p generators differs from the case 2.2.

REMARK. All rational forms of $\mathfrak{f}_2(2, \mathbf{C}) = \mathfrak{hei}_3(\mathbf{C})$ and $\mathfrak{f}_2(2, \mathbf{R}) \oplus \mathfrak{f}_2(2, \mathbf{R}) = \mathfrak{hei}_3(\mathbf{R}) \oplus \mathfrak{hei}_3(\mathbf{R})$ are listed in Theorem 3.

COROLLARY 4.2. *There are infinitely many non-commensurable (in any sense) lattices in the Lie groups of type $F_c(p, \mathbf{R}) \times F_c(p, \mathbf{R})$ where $F_c(p, \mathbf{R})$ is the free nilpotent Lie group on p free generators.*

4.3 CLASSIFICATION OF RATIONAL FORMS FOR SOME 6-DIMENSIONAL LIE ALGEBRAS

Let m be a rational number and $A_m = \mathbf{Q}[x]/(x^2 - m)$. A_m is a 2-dimensional commutative algebra over $\mathbf{Q}$ which depends only on m modulo square factors. Thus there are four types of A_m :

1) if $m = 1$ then $A_m \cong \mathbf{Q} \oplus \mathbf{Q}$;
2) if $m > 1$ is a positive square-free integer then $A_m \cong \mathbf{Q}(\sqrt{m})$ is a real quadratic field over $\mathbf{Q}$;
3) if $m = 0$ then A_0 is the algebra of dual numbers over $\mathbf{Q}$;
4) if m is a negative square-free integer then $A_m \cong \mathbf{Q}(\sqrt{m})$ is an imaginary quadratic field over $\mathbf{Q}$.

Let $\mathfrak{hei}_3(A_m)$ be a Heisenberg algebra over A_m considered over $\mathbf{Q}$. Then $\mathfrak{hei}_3(A_m)$ is a rational form of either $\mathfrak{hei}_3(\mathbf{R}) \oplus \mathfrak{hei}_3(\mathbf{R})$, or $\mathfrak{hei}_3(\mathbf{R}[x]/(x^2))$, or $\mathfrak{hei}_3(\mathbf{C})$. More precisely,

THEOREM 3. *Let $\mathfrak{h}$ be a 6-dimensional nilpotent Lie algebra of class 2 over $\mathbf{Q}$. Suppose that $[\mathfrak{h}, \mathfrak{h}]$ coincides with the 2-dimensional centre of $\mathfrak{h}$. Then $\mathfrak{h} \cong \mathfrak{hei}_3(A_m)$ for some $m \in \mathbf{Q}$ as above.*

Moreover,

1) $\mathfrak{h} \otimes_{\mathbf{Q}} \mathbf{R} \cong \mathfrak{hei}_3(\mathbf{R}) \oplus \mathfrak{hei}_3(\mathbf{R}) = \mathfrak{g}_+$ *iff* $m > 0$,
2) $\mathfrak{h} \otimes_{\mathbf{Q}} \mathbf{R} \cong \mathfrak{hei}_3(\mathbf{R}[x]/(x^2)) = \mathfrak{g}_0$ *iff* $m = 0$,
3) $\mathfrak{h} \otimes_{\mathbf{Q}} \mathbf{R} \cong \mathfrak{hei}_3(\mathbf{C}) = \mathfrak{g}_-$ *iff* $m < 0$,

and up to isomorphism there are no more rational forms for $\mathfrak{g}_-$, $\mathfrak{g}_0$, $\mathfrak{g}_+$. The Lie algebras $\mathfrak{hei}_3(A_m)$ and $\mathfrak{hei}_3(A_n)$ are isomorphic over $\mathbf{Q}$ if and only if A_m and A_n are isomorphic.

Proof. Take some $\mathbf{Q}$-basis $x_1,\dots,x_6$ of $\mathfrak{h}$. First of all, we may suppose that $[x_1,x_2]=x_5$ (possibly after a change of basis). Thus x_5 is central. We have to deal with two cases.

CASE 1. All brackets $[x_1,x_j]$, $[x_2,x_j]$ $(j\geq 3)$ are multiples of x_5. If $[x_1,x_j]=a_jx_5$, $[x_2,x_j]=b_jx_5$ then we set $X_j=x_j-a_jx_2+b_jx_1$ whence $[x_1,X_j]=[x_2,X_j]=0$.

Since $[\mathfrak{h},\mathfrak{h}]$ is 2-dimensional we conclude that some commutator, say $[x_3,x_4]$, is not a multiple of x_5 (for convenience, we use lower-case 'x' instead of 'X'). Consider

$$[x_3,x_4]=ax_1+bx_2+cx_3+dx_4+ex_5+fx_6\,. \tag{4.1}$$

Commuting $[x_3,x_4]$ with x_1, x_2 we obtain that $a=b=0$. Let us suppose that $f=0$. Then

$$[x_3,x_4]=cx_3+dx_4+ex_5\,. \tag{4.2}$$

Recall that x_5 and $[x_3,x_4]$ in the form (4.2) span the 2-dimensional centre. Commuting $cx_3+dx_4+ex_5$ from (4.2) with x_3, x_4 we get $c=d=0$ and a contradiction. Thus $f\neq 0$. We may assume that $[x_3,x_4]=x_6$ where x_6 is central. Hence, we have the following multiplication table for $\mathfrak{h}$: $[x_1,x_2]=x_5$, $[x_3,x_4]=x_6$, other brackets being equal to 0. Consequently,

$$\mathfrak{h}=\langle x_1,x_2,x_5\rangle\oplus\langle x_3,x_4,x_6\rangle\cong\mathfrak{hei}_3(\mathbf{Q})\oplus\mathfrak{hei}_3(\mathbf{Q})\,.$$

CASE 2. Among the brackets $[x_1,x_j]$, $[x_2,x_j]$ $(j\geq 3)$ there is at least one which is not a multiple of x_5. In this case we may suppose (changing indices if necessary) that this bracket is $[x_1,x_3]$. Let

$$[x_1,x_3]=ax_1+bx_2+cx_3+dx_4+ex_5+fx_6 \quad . \tag{4.3}$$

and let us suppose that $d=f=0$. Then

$$[x_1,x_3]=ax_1+bx_2+cx_3+ex_5\,. \tag{4.4}$$

Commuting the right-hand term of (4.4) with x_1 we get

$$0=[x_1,[x_1,x_3]]=bx_5+c[x_1,x_3]=cax_1+cbx_2+c^2x_3+(ce+b)x_5\,.$$

Hence $c=b=0$. By virtue of this $a=0$ and we obtain a contradiction if we commute both sides of (4.4) with x_2. It follows that either $d\neq 0$ or $f\neq 0$. In other words, we may suppose that $[x_1,x_3]$ is equal to x_6.

Now

$$[x_1, x_2] = x_5, \quad [x_1, x_3] = x_6 \tag{4.5}$$

where x_5, x_6 span $[\mathfrak{h}, \mathfrak{h}]$. Suppose that $[x_2, x_3] = ax_5 + bx_6$. Adding if necessary some multiples of x_1 to x_2 and x_3 we obtain $[x_2, x_3] = 0$. In the same way we may suppose that $[x_1, x_4] = 0$. Adding to x_4 some multiple of x_1 we also obtain a relation $[x_2, x_4] = Cx_6$. Moreover, after scaling x_4 we get $C = 0$ or $C = 1$. Thus, $\mathfrak{h}$ has a basis in which the *non-trivial* brackets are the following:

$$\begin{aligned} &[x_1, x_2] = x_5, & &[x_1, x_3] = x_6, \\ &[x_2, x_4] = Cx_6 \quad (C = 0 \text{ or } C = 1), & &[x_3, x_4] = Ax_5 + Bx_6. \end{aligned} \tag{4.6}$$

In any case $A^2 + B^2 + C^2 \neq 0$ because x_4 cannot belong to the 2-dimensional centre of $\mathfrak{h}$.

We will show that we can always make $C = 1$ and $B = 0$ in (4.6).

SUBCASE 2.1. If $C = 0$ then the following basis transformation

$$\begin{aligned} &X_1 = x_1, & &X_2 = ax_2 + x_3, \\ &X_3 = Ax_2 + Bx_3, & &X_4 = x_4, \end{aligned} \tag{4.7}$$

yields (a is any constant such that $aB \neq A$)

$$\begin{aligned} &[X_1, X_2] = ax_5 + x_6 = X_5, & &[X_1, X_3] = Ax_5 + Bx_6 = X_6, \\ &[X_2, X_4] = Ax_5 + Bx_6 = X_6, & &[X_3, X_4] = B(Ax_5 + Bx_6) = BX_6. \end{aligned} \tag{4.8}$$

From now on we may suppose that $C = 1$ in (4.6) and we arrive at

SUBCASE 2.2: $C = 1$, $A = 0$. Let

$$\begin{aligned} &X_1 = x_1 + ax_4, & &X_2 = x_2 - ax_3, \\ &X_3 = x_2 + dx_3, & &X_4 = -x_1 + dx_4, \end{aligned} \tag{4.9}$$

where $a, d, a + d \neq 0$, $aB \neq 1$, $dB \neq -1$. Hence

$$\begin{aligned} &[X_1, X_2] = x_5 + (a^2B - 2a)x_6 = X_5, \\ &[X_1, X_3] = x_5 + (d - a - adB)x_6 = X_6, \\ &[X_2, X_4] = x_5 + (d - a - adB)x_6 = X_6, \\ &[X_3, X_4] = x_5 + (d^2B + 2d)x_6 = \lambda X_5 + (1 - \lambda)X_6. \end{aligned} \tag{4.10}$$

Since a, d and $a + d$ are all non-zero, X_5 and X_6 are linearly independent. Straightforward computations yield

$$\lambda = \frac{dB + 1}{aB - 1} \neq 0, \ 1.$$

Thus we have the following alternative.

SUBCASE 2.3.1: $C = 1$; A, B, $4A + B^2 \neq 0$. Let now

$$X_1 = x_1 + tx_4, \quad X_2 = x_2 - tx_3, \qquad (4.11)$$
$$X_3 = x_3, \quad X_4 = x_4,$$

where $t = -B/2A$. Hence

$$\begin{aligned}
[X_1, X_2] &= (1 + t^2 A)x_5 + (t^2 B - 2t)x_6 = X_5, \\
[X_1, X_3] &= -tAx_5 + (1 - tB)x_6 = X_6, \\
[X_2, X_4] &= -tAx_5 + (1 - tB)x_6 = X_6, \\
[X_3, X_4] &= Ax_5 + Bx_6 = \alpha X_5 = \tfrac{4A^2}{4A+B^2} X_5.
\end{aligned} \qquad (4.12)$$

SUBCASE 2.3.2: $C = 1$; $A, B \neq 0$, $4A + B^2 = 0$. The same transformation (4.11) yields

$$\begin{aligned}
[X_1, X_2] &= 0, \\
[X_1, X_3] &= -tAx_5 + (1 - tB)x_6 = X_6, \\
[X_2, X_4] &= -tAx_5 + (1 - tB)x_6 = X_6, \\
[X_3, X_4] &= Ax_5 + Bx_6 = X_5
\end{aligned} \qquad (4.13)$$

and, after the transformation $x_1 = X_3$, $x_2 = X_4$, $x_3 = X_1$, $x_4 = X_2$, $x_5 = X_5$, $x_6 = -X_6$, we obtain (4.12) with $\alpha = 0$. Anyway, we obtain the desired form of $\mathfrak{h}$

$$[x_1, x_2] = x_5, \quad [x_1, x_3] = x_6, \quad [x_2, x_4] = x_6, \quad [x_3, x_4] = Ax_5. \qquad (4.14)$$

Scaling x_3, x_4 by $\lambda \neq 0$ we may suppose that $A = m$ where m is a square-free integer as above.

In order to conclude the proof of the first part of the theorem we point out an isomorphism $\rho\colon \mathfrak{h} \to \mathfrak{hei}_3(A_m)$. Recall that A_m has a basis 1, x over $\mathbf{Q}$ such that $x^2 = m$. Here are the matrices representing $\rho(x_i)$ if $m \neq 1$ (the case $m = 1$ is left to the reader as an easy exercise):

$$\rho(x_1) = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \rho(x_2) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}, \quad \rho(x_5) = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$
$$\rho(x_3) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & x \\ 0 & 0 & 0 \end{pmatrix}, \quad \rho(x_4) = \begin{pmatrix} 0 & -x & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \rho(x_6) = \begin{pmatrix} 0 & 0 & x \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \qquad (4.15)$$

Now it is evident that $\mathfrak{h} \otimes_{\mathbf{Q}} \mathbf{R}$ is isomorphic to either $\mathfrak{hei}_3(\mathbf{R}) \oplus \mathfrak{hei}_3(\mathbf{R})$, or $\mathfrak{hei}_3(\mathbf{R}[x]/(x^2))$, or $\mathfrak{hei}_3(\mathbf{C})$ depending on the sign of m. Thus, we have classified up to $\mathbf{Q}$-isomorphism all rational forms for these 3 real Lie algebras. By Theorem 2 these forms are non-isomorphic. The proof of the theorem is complete. □

REMARK. It is worth mentioning that the above three real Lie algebras are not pairwise isomorphic over $\mathbf{R}$. Indeed, the centralizer of any element in $\mathfrak{g}_- = \mathfrak{hei}_3(\mathbf{C})$ is even dimensional over $\mathbf{R}$ since this algebra can be viewed as a complex Lie algebra, whereas in both $\mathfrak{g}_+ = \mathfrak{hei}_3(\mathbf{R}) \oplus \mathfrak{hei}_3(\mathbf{R})$ and $\mathfrak{g}_0 = \mathfrak{hei}_3(\mathbf{R}[x]/(x^2))$ there are elements with 5-dimensional centralizers. In order to show that the last two algebras are not isomorphic we need some more information about elements with 5-dimensional centralizers.

The centralizer $C(x)$ will not be changed if we scale x by any $\lambda \neq 0$ or add to x any central element. This means that dimension of the centralizer is a well-defined function on the projective space $\mathbf{P}(\mathfrak{g}/[\mathfrak{g},\mathfrak{g}])$ where $\mathfrak{g}$ is either $\mathfrak{g}_+$ or $\mathfrak{g}_0$. Straightforward computations show that in $\mathbf{P}(\mathfrak{g}_0/[\mathfrak{g}_0,\mathfrak{g}_0])$ all points with 5-dimensional centralizer belong to a unique line whereas in $\mathbf{P}(\mathfrak{g}_+/[\mathfrak{g}_+,\mathfrak{g}_+])$ the points under consideration form two disjoint lines.

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