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<tr>
<td>Author(s)</td>
<td>Mimura, Yoshio</td>
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<tr>
<td>Citation</td>
<td>数理解析研究所講究録 (2006), 1476: 105-110</td>
</tr>
<tr>
<td>Issue Date</td>
<td>2006-03</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/2433/48210">http://hdl.handle.net/2433/48210</a></td>
</tr>
<tr>
<td>Type</td>
<td>Departmental Bulletin Paper</td>
</tr>
<tr>
<td>Textversion</td>
<td>publisher</td>
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Kyoto University
A Construction of Unimodular Lattices
Without Non-Trivial Automorphisms
(A survey)

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1. Introduction

Let $V$ be a positive definite quadratic space over $\mathbb{Q}$ with its bilinear symmetric form $B$ and associated quadratic form $Q: Q(x) = B(x, x), 2B(x, y) = Q(x+y) - Q(x) - Q(y)$. Let $L$ be a lattice in $V$, that is, a finitely generated $\mathbb{Z}$-module in $V$. The orthogonal group of $V$ is defined as follows:

$$O(V) = \{ \sigma \in GL(V) | Q(\sigma x) = Q(x) \text{ for } \forall x \in V \}$$

The automorphism group (unit group) of $L$ is:

$$O(L) = \{ \sigma \in O(V) | \sigma(L) = L \}.$$

Note that $O(L)$ is a finite group and $\pm 1_v \in O(L)$.

Problem:

Can the group $O(L)$ be trivial (i.e., $O(L) = \{ \pm 1_v \}$)?

In 1975 O.T. O'Meara gives a method to construct such a lattice starting from any given lattice. But the discriminant is big!

In 1981 J. Biermann proved that there is such a lattice of any rank with sufficiently big discriminant.

A lattice $L$ is a free $\mathbb{Z}$-module, hence it can be written as

$$L = \mathbb{Z}x_1 + \mathbb{Z}x_2 + \cdots + \mathbb{Z}x_n$$

with a suitable basis $x_1, x_2, \ldots, x_n$. For this basis we consider the matrix

$$A = \begin{bmatrix}
B(x_1, x_1) & B(x_1, x_2) & \cdots & B(x_1, x_n) \\
B(x_2, x_1) & B(x_2, x_2) & \cdots & B(x_2, x_n) \\
\vdots & \vdots & \ddots & \vdots \\
B(x_n, x_1) & B(x_n, x_2) & \cdots & B(x_n, x_n)
\end{bmatrix}$$
and we represent $L$ by using the matrix $A$. The discriminant $d(L)$ of $L$ is defined by $d(L) = \det A$. It is independent of the choice of basis, and note that $d(L) > 0$. The scale $s(L)$ and the norm $n(L)$ of $L$ are defined as follows:

$s(L)$ is the ideal generated by $\{B(x, y) \mid x, y \in L\}$,

$n(L)$ is the ideal generated by $\{Q(x) \mid x \in L\}$.

In the following we assume that $s(L) = \mathbb{Z}$, hence $n(L) = \mathbb{Z}$ or $n(L) = 2\mathbb{Z}$. $L$ is said to be odd when $n(L) = \mathbb{Z}$, and $L$ is said to be even when $n(L) = 2\mathbb{Z}$. And we say that $L$ is unimodular if $s(L) = \mathbb{Z}$ and $d(L) = 1$.

Consider the lattice $M_n$ of rank $n$:

$$M_n \cong \begin{bmatrix} 3 & 1 & 0 & 0 & \ldots & 0 & 0 & 0 \\ 1 & 3 & 1 & 0 & \ldots & 0 & 0 & 0 \\ 0 & 1 & 3 & 1 & \ldots & 0 & 0 & 0 \\ 0 & 0 & 1 & 3 & \ldots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \ldots & 3 & 1 & 0 \\ 0 & 0 & 0 & 0 & \ldots & 1 & 3 & 1 \\ 0 & 0 & 0 & 0 & \ldots & 0 & 1 & 4 \end{bmatrix}$$

Then it is clear that $O(L)$ is trivial, but the discriminant is big as $n$ is big.

We list up all binary lattices $L \cong \begin{bmatrix} a & c \\ c & b \end{bmatrix}$ $(0 < a \leq b, 0 \leq c \leq a/2)$.

$L \cong \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}$, $\#O(L) = 12$, $d(L) = 3$. $L \cong \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\#O(L) = 8$, $d(L) = 1$.

$L \cong \begin{bmatrix} a & c \\ c & a \end{bmatrix}$, $\#O(L) = 4$ $(0 < c < a/2)$. $L \cong \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}$, $\#O(L) = 4$ $(0 < a < b)$.

$L \cong \begin{bmatrix} a & c \\ c & b \end{bmatrix}$, $\#O(L) = 4$ $(0 < a < b, a = 2c)$.

$L \cong \begin{bmatrix} a & c \\ c & b \end{bmatrix}$, $\#O(L) = 2$ $(0 < a < b, 0 < c < a/2)$.

We may say "$\#O(L) = 2$ for almost all binary lattices $L$!!".

From now on we assume that $L$ is an odd or even unimodular lattice. It is known that there is at least an odd unimodular lattice of any rank. We know that there is an even unimodular lattice if and only if the rank is divisible by 8. We list up the orders of $O(L)$ for unimodular lattices $L$ of low rank.

If rank$(L) = n \leq 7$ then $L$ is odd and
\[ L = I_n \cong [1] \perp [1] \perp \cdots \perp [1]. \text{ #}O(L) = 2^n \times n! \]

If rank \( L \) = 8 then \( L \) is \( I_8 \) (odd) or \( E_8 \) (even):
\[ L = I_8 \cong [1] \perp [1] \perp \cdots \perp [1]. \text{ #}O(L) = 2^8 \times 8! \]
\[ L = E_8 \cong \begin{bmatrix} 2 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 2 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 2 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 2 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 2 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 2 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 2 \end{bmatrix} \]
\[ \text{#}O(L) = 2^{14} \times 3^5 \times 5^2 \times 7 = 696729600. \]

If rank \( L \) = \( n \) (\( n = 9, 10, 11 \)), then we have:
\[ L = I_n. \text{ #}O(L) = 2^n \times n! \]
\[ L = I_{n-8} \perp E_8. \text{ #}O(L) = 2^{n-8}(n-8)! \times \text{#}O(E_8) \]


In the above book you can see all quadratic lattices of rank \( \leq 24 \), and they have non-trivial automorphism group except the trivial case \( I_1 \).

Remark. It is known that if the automorphism group of a unimodular lattice is trivial, then the rank \( \geq 28 \) (odd case) and the rank \( \geq 32 \) (even case). Recently it was proved that the rank \( \geq 29 \) in odd case.

2. Results of Etsuko Bannai (1988)

She proved:

There is an odd unimodular lattice with the trivial automorphism group of any rank \( \geq 43 \), and there is an even unimodular lattice with the trivial automorphism group of any rank \( \geq 144 \)
in her paper Positive definite unimodular lattices with the trivial automorphism groups (Diss, The Ohio State Univ). But any explicit examples of such a lattice was not known.

3. Examples of Y. Mimura (1990)

Among the unimodular lattices with the trivial automorphism groups, Mimura gives two examples of odd unimodular lattices of rank 36, 40, one example of even unimodular lattices of rank 64.

3-1. Construction of unimodular lattices (by using Kneser's neighbouring).

Kneser's neighbouring is a simple way of constructing many lattices in the given genus of lattices.

1. Initial lattice: \( I = I_n = \mathbb{Z}e_1 + \cdots + \mathbb{Z}e_n \cong [1] \perp \cdots \perp [1] \)
2. Take a positive integer \( q \) and a vector \( v \in q^{-1}I \) such that \( Q(x) \in \mathbb{Z} \).
3. Neighbouring: \( L = I[v] = \mathbb{Z}v + \{ u \in I \mid \langle u, v \rangle \in \mathbb{Z} \} \).

(detail)
a) \( L \) is unimodular. Especially, \( L \) is odd if \( q \) is odd.

b) Let \( v = q^{-1} \sum_{i=1}^{n} c_i e_i, \quad c_i \in \mathbb{Z} \).

Then a vector \( x \in L \) is written as
\[
x = \pm \left( cv + \sum_{i=1}^{n} a_i e_i \right), \quad c \in \mathbb{Z}, \quad a_i \in \mathbb{Z}, \quad 0 \leq c \leq q/2, \quad \sum_{i=1}^{n} c_i a_i \equiv 0 \pmod{q}
\]

c) \( Q(x) = q^{-2} \sum_{i=1}^{n} (cc_i + qa_i)^2 \)

Remark.
i) If \( L = J \perp K \ (J, K \neq \{0\}) \), then \( \pm 1_L \neq 1_J \perp (-1_K) \in O(L) \), i.e., \( O(L) \) is not trivial.
ii) If there is a vector \( x \in L \) with \( Q(x) = 1 \), then \( L = [1] \perp L' \).
iii) If there is a vector \( x \in L \) with \( Q(x) = 2 \), then \( \pm 1_L \neq \tau_x \in O(L) \), i.e., \( O(L) \) is not trivial. Here the symmetry \( \tau_x \) w.r.t. \( x \) is defined by
\[
\tau_x(y) = y - \frac{2\langle x, y \rangle}{Q(x)}x \quad \text{for} \quad y \in L.
\]
iv) Hence we must choose a vector \( v \) so that
a) \( c_i \not\equiv 0 \pmod{q} \) \((1 \leq i \leq n) \) by (i) and (ii)
b) \( c_i \not\equiv c_j \pmod{q} \) \((1 \leq i < j \leq n) \) by (iii)
c) \[ \sum_{i=1}^{n} R(cc_i)^2 \geq 2q^2 \] \((1 \leq c \leq q/2) \) by (iii)
where \( R(a) \) is defined by \( R(a) \equiv a \pmod{q} \) and \(|R(a)| \leq q/2 \)
3-2. Proof of the triviality of $O(L)$

Let $m$ be a positive integer. Put

$$X = \{x \in L \mid Q(x) = m\}, \quad \overline{X} = X / \pm 1.$$ 

We consider a graph $G$ with the vertex set $\overline{X}$,

where $\pm x$ and $\pm y$ are adjacent $\iff B(x, y) \neq 0$

Then the group $O(L)$ induces a subgroup $H$ of the automorphism group of $G$.

Proposition. The automorphism group $O(L)$ is trivial if

(P1) $H = \{1\}$,
(P2) $G$ is connected,
(P3) $V$ is generated by $X$ over $\mathbb{Q}$.

Proof. Take any $\sigma \in O(L)$. By (P1) we see that $\sigma x \in \{x, -x\}$ for all $x \in X$. Take a vector $x_0 \in X$. We may suppose that $\sigma x_0 = x_0$ (Replace $\sigma$ by $-\sigma$ if necessary.) Thus we have $\sigma y = y$ for any $y \in X$ with $B(x_0, y) \neq 0$. Hence, by (P2), we have $\sigma x = x$ for any $x \in X$. Finally, by (P3), we have $\sigma = 1_V$. \qed

3-3. Explicit Examples

(1) Odd unimodular lattice of rank 40.

$n = 48, \quad q = 97, \quad 97v = \sum_{j \in J} je_j, \quad Q(v) = 4,$

where $J = \{j \in \mathbb{Z} \mid 6 \leq j \leq 48, j \neq 8, 10, 13\}$.

$I_{48}[v] = I_8 \perp L, \quad X = \{x \in L \mid Q(x) = 3\}.$

The elements of $\overline{X}$ are

$$\pm(e_i + e_j + e_k), \text{ with } i, j, k \in J, i < j < k, i + j + k = 97,$$

$$\pm(e_i + e_j - e_k), \text{ with } i, j, k \in J, i < j < k, i + j = k.$$ 

We see $\#\overline{X} = 163 + 249 = 412$.

The degree of a vertex of $G$ is one of 81, 82, ..., 94.

Hence $\overline{X} = \overline{X}_{81} \cup \cdots \cup \overline{X}_{94}$ (disjoint), where $\overline{X}_t = \{\pm x \in \overline{X} \mid \deg(\pm x) = t\}$

Each set $\overline{X}_t$ is invariant under $O(L)$. Consider the function $\delta_t$ of $\overline{X}$:

$$\delta_t(\pm x) = \#\{\pm y \in \overline{X}_t \mid \pm x \text{ and } \pm y \text{ are adjacent}\}.$$ 

We can prove: $\pm x = \pm y \iff \delta_t(\pm x) = \delta_t(\pm y)$ for all $t$.

(P1) is satisfied since $\delta_t(\pm x) = \delta_t(\sigma(\pm x))$ for all $\sigma \in O(L)$. By a direct computation, we can see that (P2) and (P3) are valid. \qed
(2) Odd unimodular lattice of rank 36.
\[ n = 38, \quad q = 79, \quad 79v = \sum_{j \in J} je_j, \quad Q(v) = 3, \]
where \( J = \{ j \in \mathbb{Z} | 1 \leq j \leq 38, j \neq 10, 14 \} \).
\[ I_{38}[v] = I_2 \perp L, \quad X = \{ x \in L | Q(x) = 3 \}. \]
In this case we have \( X = \overline{X}_{91} \cup \overline{X}_{93} \cup \overline{X}_{95} \) (disjoint). This is a disjoint sum of 400 subsets which are \( O(L) \)-invariant.

(3) Even unimodular lattice of rank 64.
\[ n = 129, \quad q = 270, \quad 270v = \sum_{j \in J} j' e_j, \quad Q(v) = 6, \]
where \( J = \{ j \in \mathbb{Z} | 1 \leq j \leq 129, j \neq 5, j : \text{odd} \} \), \( j' = j \) if \( j \neq 3 \), and \( 3' = -267 \).
\[ I_{129}[v] = I_{65} \perp L, \quad X = \{ x \in L | Q(x) = 4 \}. \]

4. Results of Roland Bacher (1993)

Using the same method of Mimura, R. Bacher presented:
- an odd unimodular lattice of rank 29 and
- an even unimodular lattice of rank 32
among the unimodular lattices with the trivial automorphism groups.

(1) Odd unimodular lattice of rank 29 : \( I_{29}[v] \)
\[ n = 29, \quad q = 71, \quad 71v = \sum_{j=1}^{29} c_j e_j, \quad Q(v) = 14, \]
where \( c_j \)'s are 5, 7, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31, 33, 35

(2) Even unimodular lattice of rank 32 : \( I_{32}[v] \)
\[ n = 32, \quad q = 142, \quad 142v = \sum_{j=1}^{32} c_j e_j, \quad Q(v) = 4, \]
where \( c_j \)'s are 3, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31, 33, 35, -105, 39,
41, 43, 45, -95, 49, 53, 55, -85, 59, -81, -79, 65, 67, -73

There was an open problem : Is there a unimodular lattice (of rank 28) with the trivial automorphism group? This was solved : No. So his explicit examples are ones of the smallest rank.