On Maximal Finite Irreducible Subgroups of $GL(n, \mathbb{Z})$

I. The Five and Seven Dimensional Cases

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Abstract. General methods for the determination of maximal finite absolutely irreducible subgroups of $GL(n, \mathbb{Z})$ are described. For $n = 5, 7$ all these groups are computed up to $\mathbb{Z}$-equivalence.

1. Introduction. By the Jordan-Zassenhaus Theorem [5], [14] there is only a finite number of conjugacy classes of finite subgroups of $GL(n, \mathbb{Z})$, the group of all integral $n \times n$ matrices with determinant $\pm 1$. For $n = 2, 3$ they were already classified in the last century. They are used for describing symmetry properties of crystals. Recently, the groups in four dimensions were determined in two steps. Firstly, E. C. Dade [6] found the maximal finite subgroups of $GL(4, \mathbb{Z})$ in 1965. Then R. Bülow, J. Neubüser, and H. Wondratschek [2] computed all finite subgroups by means of electronic computation. Later on the maximal finite subgroups of $GL(5, \mathbb{Z})$ were determined independently by S. S. Ryškov [11], [12] and R. Bülow [1]. Our aim is to give a list of the maximal finite irreducible subgroups of $GL(7, \mathbb{Z})$ which can be found in Section 6, Theorem (6.6). We also give a short derivation of the corresponding groups in five dimensions in Section 7. Other dimensions, e.g. $n = 6$, will follow later on.

Prior to the exposition of our method we remark:

(1) Let $\Delta$ be an irreducible integral representation of a finite group $G$. If the degree of $\Delta$ is an odd prime number, $\Delta$ is irreducible over $\mathbb{Z}$ if and only if $\Delta$ is irreducible over $\mathbb{C}$, i.e. every irreducible representation is absolutely irreducible [5]. Unless otherwise stated, irreducibility means always absolute irreducibility in the following.

(2) Every finite subgroup $G$ of $GL(n, \mathbb{Z})$ fixes a positive definite integral $n \times n$ matrix $X$: $g^TXg = X$ for all $g \in G$. For instance, $X := \sum_{g \in G} g^Tg$ will do. By Schur's Lemma $X$ is uniquely determined up to scalar multiples in case $G$ is irreducible, i.e. its natural representation $\Delta: G \rightarrow GL(n, \mathbb{Z})$: $g \mapsto g$ is irreducible. On the other hand, the $\mathbb{Z}$-automorph of an integral positive definite matrix $X$ is finite since it is a discrete subgroup of the compact $\mathbb{R}$-automorph. Hence the irreducible maximal finite subgroups $G$ of $GL(n, \mathbb{Z})$ are the $\mathbb{Z}$-automorphs of each integral positive definite $n \times n$ matrix which is fixed by $G$, and $G$ is uniquely determined by each of its irreducible subgroups.

Received February 16, 1976.


Key words and phrases. Integral matrix groups.

*This paper originated from joint work at the California Institute of Technology under grants awarded by the Studienstiftung des deutschen Volkes and the Deutsche Forschungsgemeinschaft.

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MAXIMAL FINITE IRREDUCIBLE SUBGROUPS. 1

Therefore, we proceed in the following manner. We derive all minimal irreducible subgroups of $GL(n, \mathbb{Z})$ up to rational equivalence. So we must look for all finite groups which have a rational irreducible faithful representation of degree $n = 7$ such that this representation becomes reducible for every nontrivial subgroup. Next we compute the integral equivalence classes into which the rational equivalence classes of these representations are divided. This is done by means of the centering algorithm [10] which will be described in the next section. Together with the representations the fixed forms are computed also. In a last step we obtain the maximal irreducible subgroups of $GL(n, \mathbb{Z})$ as the $\mathbb{Z}$-automorphs of those forms.

We find seven groups up to integral equivalence. They are listed in Section 6.

All computations were carried out on the IBM 370/158 at the California Institute of Technology in Pasadena. We herewith want to thank the Mathematics Department for the generous grant to finance this project. In particular, we thank Professor H. J. Zassenhaus and Professor D. B. Wales for valuable suggestions.

2. The Centering Algorithm. The algorithm was developed in [10] to find all integral classes into which the rational class of a given irreducible $\mathbb{Z}$-representation splits. We give a brief account of part of the results and describe the corresponding computer program.

Let $G$ be a finite group and $L$ a $\mathbb{Z}G$-representation module, i.e. a $\mathbb{Z}G$-module which is also a free abelian additive group of finite rank. By a centering of $L$ we mean a $\mathbb{Z}G$-submodule of $L$ of finite index in $L$ or, equivalently, of the same rank as $L$. Two $\mathbb{Z}G$-modules say $L, L'$ are called $\mathbb{Z}$-equivalent ($\mathbb{Q}$-equivalent), if $L$ and $L'$ are $\mathbb{Z}$-isomorphic ($\mathbb{Q}L$ and $\mathbb{Q}L'$ are $\mathbb{Q}G$-isomorphic) [5]. Hence every centering of $L$ is $\mathbb{Q}$-equivalent to $L$. If two $\mathbb{Z}G$-modules $L$ and $L'$ are $\mathbb{Q}$-equivalent, then there exists a centering $L''$ of $L$ such that $L'$ and $L''$ are $\mathbb{Z}$-equivalent. For let $\psi: \mathbb{Q}L' \to \mathbb{Q}L$ be a $\mathbb{Q}G$-isomorphism. Because $L$ is of finite rank there is a natural number $k$ such that $k\psi(L') \subseteq L$. Clearly, $\psi: L' \to k\phi(L')$: $l \mapsto k\phi(l)$ is a $\mathbb{Z}G$-isomorphism and $k\phi(L')$ is a centering of $L$. The $\mathbb{Q}$-equivalence class of a $\mathbb{Z}G$-module $L$ splits into a finite number of $\mathbb{Z}$-equivalence classes (Jordan-Zassenhaus Theorem, [5], [14]). By our remarks a set of representatives of the $\mathbb{Z}$-classes can be chosen from the centerings of $L$.

To find such a set of representatives we define a partial ordering on the set $\mathfrak{Z}(L)$ of all centerings of $L$: for $M, N \in \mathfrak{Z}(L)$ let $M < N$, if there is a natural number $k$ with $kN = M$. If $M < N$ for $M, N \in \mathfrak{Z}(L)$, then $M$ and $N$ are $\mathbb{Z}$-equivalent. Every centering of $L$ is contained in a uniquely determined $\prec$-maximal centering. For a proof let $M \in \mathfrak{Z}(L)$ and $e_1, \ldots, e_n$ and $\alpha_1 e_1, \ldots, \alpha_n e_n$ a pair of compatible $\mathbb{Z}$-bases of $L, M$, respectively ($\alpha_i \in \mathbb{Z}, i = 1, \ldots, n; \alpha_i | \alpha_{i+1}, i = 1, \ldots, n - 1$). The $\prec$-maximal centering $\overline{M}$, $M < \overline{M}$, is given by $\overline{M} = \alpha_1^{-1}M$. Note, that $M$ is itself $\prec$-maximal if and only if $\alpha_1 = \pm 1$. This also implies the uniqueness. We always consider $L$ itself to be $\prec$-maximal.

(2.1) Theorem. Let $L$ be an (absolutely) irreducible $\mathbb{Z}G$-representation module. Then the $\prec$-maximal centerings of $L$ form a set of representatives of the $\mathbb{Z}$-classes contained in the $\mathbb{Q}$-class of $L$.

Proof. By our remarks it suffices to show that two $\prec$-maximal centerings
cannot be \( Z \)-equivalent. Let, therefore, \( \overline{M} \) and \( \overline{N} \) be two \(<\)-maximal centerings of \( L \) and \( \varphi: \overline{M} \rightarrow \overline{N} \) a \( ZG \)-isomorphism. For all \( g \in G \) and all \( m \in \overline{M} \) we have \( \varphi(gm) = g\varphi(m) \). Since \( L \) is an irreducible \( ZG \)-module, there exists an \( r \in \mathbb{Q}\setminus\{0\} \), \( \varphi(m) = rm \) by Schur's Lemma. This implies \( N = rM \subseteq L \). From the \(<\)-maximality of \( M \) we derive \( r \in \mathbb{Z} \) by choosing a pair of consistent bases for \( M \) and \( L \). But then \( r \) has to be \( \pm 1 \) because otherwise \( N \) would not be \(<\)-maximal. Q.E.D.

Now let \( \mathcal{M} \) be a centering of \( L \). Then the \( ZG \)-composition factors of \( L/\mathcal{M} \) are irreducible \( ZpG \)-representation modules for prime numbers \( p \) dividing the index of \( \mathcal{M} \) in \( L \). Let

\[
0 = \mathcal{M}_0/\mathcal{M} \subset \mathcal{M}_1/\mathcal{M} \subset \cdots \subset \mathcal{M}_{k-1}/\mathcal{M} \subset \mathcal{M}_k/\mathcal{M} \quad (k \in \mathbb{N}, \mathcal{M}_0 = \mathcal{M}, \mathcal{M}_k = L)
\]
a \( G \)-composition series of \( L/\mathcal{M} \). Then the \( \mathcal{M}_i \) \((i = 1, \ldots, k - 1)\) are also centerings of \( L \). In our algorithm we will obtain \( \mathcal{M}_{i-1} \) from \( \mathcal{M}_i \) \((i = k, k - 1, \ldots, 1)\) as the kernel of a \( ZG \)-epimorphism of \( \mathcal{M}_i \) onto an irreducible \( ZpG \)-module for suitable \( p \). Which irreducible \( ZpG \)-modules can actually occur as such composition factors?

Let \( p_1, \ldots, p_s \) \((s \in \mathbb{N})\) be the different prime numbers dividing the index of \( \mathcal{M} \) in \( L \).

(2.2) **Lemma.** The irreducible \( Z_pG \)-composition factors \((p \in \{p_1, \ldots, p_s\})\) of \( L/\mathcal{M} \) occur already as \( Z_pG \)-composition factors of \( L/pL \).

**Proof.** Let \( \mathcal{K} \) be an arbitrary centering of \( L \). By a theorem of Brauer and Nesbitt [5, p. 585] the irreducible \( Z_qG \)-composition factors of \( L/qL \) and \( K/qK \) are the same for every prime number \( q \). Let \( \mathcal{M}_i/M_{i-1} \) be a composition factor of \( L/M \) \((1 \leq i \leq k)\) and \( p|\mathcal{M}_i/M_{i-1} \) \((p \in \{p_1, \ldots, p_s\})\). Then \( \mathcal{M}_i/M_{i-1} \) is also a composition factor of \( \mathcal{M}_i/p\mathcal{M}_i \), hence of \( L/pL \). Q.E.D.

(2.3) **Lemma.** If \( M \) is a \( <\)-maximal centering of \( L \), then the irreducible \( Z_pG \)-composition factors of \( L/M \) have a \( Z_p \)-rank which is smaller than the \( Z \)-rank of \( L \) \((p \in \{p_1, \ldots, p_s\})\).

**Proof.** Assume \( \mathcal{M}_i/M_{i-1} \) is a \( Z_pG \)-composition factor of \( L/M \) of \( Z_p \)-rank equal to the \( Z \)-rank of \( L \) \((i \in \{1, \ldots, k\}, p \in \{p_1, \ldots, p_s\})\). Hence \( p^{-1}\mathcal{M}_{i-1} = \mathcal{M}_i \subseteq L \), implying \( p^{-1}\mathcal{M} \subseteq L \). But this is a contradiction to the \(<\)-maximality of \( M \). Q.E.D.

Therefore, the index of a \(<\>-maximal centering \( M \) of \( L \) is divisible at most by those prime numbers \( p \) for which \( L/pL \) is reducible. A useful criterion for the irreducibility of \( L/pL \) is given in [5]:

(2.4) **Lemma.** Let \( p \) be a prime number. If the order of the \( p \)-Sylow group of \( G \) divides the \( Z \)-rank of \( L \), then \( L/pL \) is an irreducible \( Z_pG \)-module.

Hence in order to find the \(<\>-maximal centerings of \( L \), we need only consider those prime numbers which divide the order of \( G \).

The centering algorithm works as follows. By \( M \) we always denote the \(<\>-maximal centering of our given irreducible \( ZG \)-representation module \( L \).

(a) Let \( \mathcal{M} = L \).

(b) By solving systems of linear equations compute all centerings \( \mathcal{M}_i \) of \( L \) with the following properties:

(i) \( \mathcal{M}_i \subseteq \mathcal{M} \),

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(ii) $M_i$ is $<_\text{-maximal}$ in $M$.

(iii) $M_i$ is maximal in $M$.

This step requires the knowledge of the $G$-composition factors of $L/p_iL$ for each prime number $p$ dividing the order of $G$.

(γ) For each $M_i$ obtained in (β) check whether $M_i$ is $<_\text{-maximal}$ in $L$. In this case store $M_i$. If $M_i$ is not $<_\text{-maximal}$ in $L$, look for the previously obtained $<_\text{-maximal}$ centering of $L$ which is equal to $p^{-1}M_i$ where $p$ is the unique prime number dividing the index of $M_i$ in $M$.

(δ) Take the next centering out of the storage for which (β) was not yet carried out, call it $M_i$, and go back to (β). If no such $M_i$ is available, the algorithm terminates.

Now let us describe the details necessary for the execution of the algorithm.

Let $G = \langle g_1, \ldots, g_r \rangle$ and $\Delta: G \twoheadrightarrow GL(n, \mathbb{Z})$ be an irreducible representation of $G$ with the corresponding $\mathbb{Z}G$-representation module $L = \mathbb{Z}^n \times 1$. Let $p_1, \ldots, p_k$ be all prime numbers for which $L/p_iL$ becomes reducible ($i = 1, \ldots, k$). By $\Delta_{ij}$ we denote the irreducible $\mathbb{Z}_{p_i}$-constituents of the representation belonging to $L/p_iL$ with $j$ running from 1 to $s(i)$. The corresponding degrees $n_{ij}$ are smaller than $n$.

As input data we have

$$n, r, \Delta(g_1), \Delta(g_2), \ldots, \Delta(g_r);$$

for $i = 1, \ldots, k$: $p_i$, $s(i)$, $n_{ij}$, $\Delta_{ij}(g_1)$, $\Delta_{ij}(g_2)$, $\ldots$, $\Delta_{ij}(g_r)$ ($1 \leq j \leq s(i)$).

The output consists of bases of all $<_\text{-maximal}$ centerings $M_i$ of $L$ (expressed in the standard basis of $L$) in the form of an integral $n \times n$-matrix $U_i$ of $L$ (expressed in the standard basis of $L$) in the form of an integral $n \times n$-matrix $U_i$ of $L$, further of $U_i^{-1}$, the invariant factors of $U_i$, and $\Delta_{ij}(g_{\mu}) := U_i^{-1} \Delta_{ij}(g_{\mu})U_i$ ($\mu = 1, \ldots, r$) with $\Delta_{ij}$ denoting the integral representation of $G$ belonging to $M_i$. (The $\Delta_{ij}$ form a full set of representatives of all integral representations of $G$ which are $\mathbb{Q}$-equivalent to $\Delta$.) $\nu$ runs from 1 to $h = h(\Delta)$, the class number of $\Delta$. The output also provides the lattice of centerings.

The computer program is composed of the following steps:

(2.5) (1) $M = L$, $\Delta_M = \Delta$, store $L$ (i.e. $I_n$, the unit matrix representing a basis of $L$).

(2) for every prime number $p_i$ ($i = 1, \ldots, k$) and the corresponding constituents $\Delta_{ij}$ ($j = 1, \ldots, s(i)$) proceed as follows.

(3) Determine all solutions $\phi \in (\mathbb{Z}_{p_i})^{n_{ij} \times n}$ of the system of linear equations $\phi \Delta_{ij}(g_{\mu}) = \Delta_{ij}(g_{\mu})\phi$ ($\mu = 1, \ldots, r$). Each nontrivial solution represents a $G$-epimorphism from $M$ onto an irreducible finite $G$-module, the kernel of which is a maximal centering of $M$. If two nontrivial solutions are linearly dependent, they yield the same centering. If there is no nontrivial solution, go back to (2).

(4) Choose one vector $\phi \neq 0$ out of every one dimensional subspace of the space of all solutions of (2) and go on.

(5) Compute a $\mathbb{Z}$-basis of the centering $N$ of all $x \in \mathbb{Z}^n \times 1$ satisfying $\phi x = 0$, express it in terms of the basis of $L$, and determine the invariant factors of the attached matrix.

(6) If the greatest common divisor of the invariant factors is greater than one, go to (8).
(7) Check, whether the computed new centering $N$ is identical to one already stored. If it is not, store it. Go back to (4).

(8) Determine the stored $\prec$-maximal centering which is $Z$-equivalent to $N$ that is identical to $p_i^{-1}N$. Go back to (4).

(9) Take the next centering $M$ (that is the matrix $U$ of its basis) out of the storage, for which (2) was not yet carried out. Compute $\Delta_M(g_\mu) = U^{-1}\Delta(g_\mu)U$ ($\mu = 1, \ldots, r$) and go back to (2). If no centering $M$ is left, the program terminates.

Remarks. (2.6) If some constituent $A_\mu$ of the modular representation belonging to $L/p_iL$ is not absolutely irreducible, the algorithm can be shortened at step (4). Instead of choosing a vector $\varphi \neq 0$ out of every one dimensional subspace it suffices to choose one out of certain $m_\mu$-dimensional subspaces with trivial intersections, where $m_\mu$ denotes the dimension of the commuting algebra of $\Delta_\mu$.

(2.7) Clearly, every $\prec$-maximal centering of $L$ is the intersection of uniquely determined centerings with prime power index in $L$. This can be used to modify the algorithm in the way that one computes the $\prec$-maximal centerings of prime power index for each prime $p_i$ ($i = 1, \ldots, k$) separately and forms the intersections afterwards.

(2.8) As we mentioned in the introduction, we are also interested in the quadratic forms which are fixed by $A(G)$, i.e. we compute the symmetric matrices $X_\nu \in \mathbb{Z}^{n \times n}$ satisfying $\Delta(g)^TX_\nu\Delta(g) = X_\nu$ for all $g \in G$ and $1 \leq \nu \leq h(\Delta)$. Since $X_\nu$ is unique up to scalar multiples, it suffices to determine one $X_\nu$ for every $\nu = 1, \ldots, h(\Delta)$. Let $\Delta_1 = \Delta$, then $X_\nu = U_\nu^{-1}X_1U_\nu$. This computation can easily be implemented into the computer program.

3. Preliminary Considerations About Integral Representations. Since we want to determine the minimal irreducible finite subgroups of $GL(n, \mathbb{Z})$ up to rational equivalence for certain $n$ the following version of Clifford's Theorem [5] will be useful.

(3.1) Theorem. Let $G$ be a finite group, $\Delta: G \rightarrow GL(n, \mathbb{Z})$ be an irreducible (not necessarily absolutely irreducible) representation of $G$, and $N$ a normal subgroup of $G$.

(1) There exist natural numbers $k, r, m$ with $n = krm$ and $r$ rationally inequivalent $Q$-irreducible integral representations $\Delta_1, \ldots, \Delta_r$ of $N$, all of the same degree $m$, which satisfy $\Delta_1(N) = \cdots = \Delta_r(N)$; and the restriction $\Delta|_N$ is rationally equivalent to $k_1\Delta_1 \oplus \cdots \oplus \Delta_r$.

(2) There exists a representation $\Delta'$ of $G$, which is rationally equivalent to $\Delta$, and $\Delta'|_N = \Gamma_1 \oplus \cdots \oplus \Gamma_r$, where $\Gamma_1, \ldots, \Gamma_r$ are integral representations of $N$ satisfying $\Gamma_\nu \sim_Q k_\nu \Delta_\nu$ ($i = 1, \ldots, r$) and $\Gamma_1(N) = \cdots = \Gamma_r(N)$.

Proof. (1) This is essentially Clifford's Theorem on the restriction of irreducible representations to normal subgroups. That the $\Delta_i$ ($i = 1, \ldots, r$) can be chosen integral follows from [5, Theorem 73.5].

(2) Let $V$ be a $QG$-representation module belonging to $\Delta$ and $U$ the inertia group of $\Delta_1, U := \{g \in G| \Delta_1^g \sim_Q \Delta_1\}$, where $\Delta_1^g: G \rightarrow GL(m, \mathbb{Z}): h \mapsto \Delta_1(ghg^{-1})$. Let $V$ be an irreducible $QU$-submodule of $V$. If $g_1, \ldots, g_r$ form a system of (right) representatives of $U$ in $G$, then $V = g_1V \oplus \cdots \oplus g_rV$ is a direct sum of the irreduc-
ible \( \mathbb{Q} \)-modules \( g_i \tilde{V} \) (\( i = 1, \ldots, r \)) by Clifford's theory. By [5, Theorem 73.5] \( \tilde{V} \) contains a \( \mathbb{Z} \)-module \( \tilde{V} \) with \( \mathbb{Q} \tilde{V} = \tilde{V} \). Clearly, \( g_1 \tilde{V} \oplus \cdots \oplus g_r \tilde{V} \) is a \( \mathbb{Z} \)-representation module. Let \( \Delta' \) be the corresponding integral representation of \( G \). Then \( \Delta' \cong_{\mathbb{Z}} \Delta \) holds and \( \Delta'\mid_{\mathbb{N}} = \Gamma_1 \oplus \cdots \oplus \Gamma_r \) where the \( \mathbb{Z} \)-module for \( \Gamma_i \) is given by \( g_i \tilde{V} \) for \( i = 1, \ldots, r \). Q.E.D.

The \( \mathbb{Z} \)-automorph of the unit matrix \( I_n \) is called the full monomial group \( H_n \) of degree \( n \). Clearly, \( H_n \) is irreducible and, therefore, a maximal finite irreducible subgroup of \( GL(n, \mathbb{Z}) \). To determine certain minimal irreducible subgroups of \( H_n \) the following theorem is useful:

(3.2) Theorem. Let \( G \) be a minimal irreducible subgroup of \( H_n \) with natural representation \( \Delta \), and \( \varphi: G \to \tilde{S}_n \) \( (g_i) \to (\bar{g}_i) \) a homomorphism of \( G \) into the group \( \tilde{S}_n \) of all permutation matrices of degree \( n \). If \( \Delta \mid_{\ker \varphi} = \Delta_1 \oplus \cdots \oplus \Delta_n \) with pairwise inequivalent representations \( \Delta_i \) (\( i = 1, \ldots, n \)), \( \varphi(G) \) yields a minimal transitive permutation group of degree \( n \), that is a transitive permutation group which has no proper transitive subgroups. If \( G \) splits over \( \ker \varphi \), then \( \ker \varphi \) is characterized by the following three properties:

(i) \( \ker \varphi \subseteq \{ \text{diag}(a_1, \ldots, a_n) | a_i = \pm 1 \ (i = 1, \ldots, n) \} \), and \( \ker \varphi \) is invariant under conjugation by \( \varphi(G) \).

(ii) The projections \( \Delta_i: \ker \varphi \to \{ \pm 1 \}: \text{diag}(a_1, \ldots, a_n) \to a_i \ (i = 1, \ldots, n) \) are pairwise unequal.

(iii) \( \ker \varphi \) is minimal with the properties (i) and (ii).

Proof. Since the \( \Delta_i \) (\( i = 1, \ldots, n \)) are pairwise inequivalent, \( \Delta \) is irreducible if and only if \( \varphi(G) \) is transitive. Hence, if \( G \) is minimal irreducible, \( \varphi(G) \) is minimal transitive. For \( g \in G \) and \( a_i = \pm 1 \ (i = 1, \ldots, n) \) we have \( g \cdot \text{diag}(a_1, \ldots, a_n)g^{-1} = \varphi(g)\text{diag}(a_1, \ldots, a_n)\varphi(g)^{-1} \). The characterization of \( \ker \varphi \) follows immediately. Q.E.D.

4. The Minimal Irreducible Finite Subgroups of \( GL(7, \mathbb{Z}) \). First we consider the solvable case.

(4.1) Theorem. Let \( G \) be a minimal irreducible finite subgroup of \( GL(7, \mathbb{Z}) \). If \( G \) is solvable, \( G \) is \( \mathbb{Q} \)-equivalent to

\[
G_1 = \left< g_1 = \begin{pmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} , g_2 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} \right>.
\]

\( G \) is isomorphic to \( A(1, 8) \) the full affine group on \( \mathbb{F}_8 \), the galois field of eight elements.

Proof. Let \( N \) be a maximal abelian normal subgroup of \( G \) and \( \Delta \) the natural
representation of $G$. Applying Theorem (3.1), we get three natural numbers $k$, $r$, $m$, $7 = krm$ and a decomposition of $\Delta$ in the form $\Delta|_N = \Gamma_1 + \cdots + \Gamma_r$ (w.l.o.g. $\Delta = \Delta'$). The assumption $m = 7$ leads to a contradiction:

In this case $N = \Delta(N)$ is an irreducible abelian group. Then the enveloping algebra $E(N)$ of $N$ is a simple commutative $\mathbb{Q}$-algebra. By Wedderburn's theorem $E(N)$ is a field. Because $N$ is finite, $E(N)$ is a cyclotomic field of degree 7 over $\mathbb{Q}$. But the degrees of the cyclotomic fields are given by the values of the Euler-\(\varphi\)-function which are even or equal to 1. Therefore, $m$ has to be 1. The assumption $k = 7$ also leads to a contradiction: $k = 7$ implies $N = \langle I_7 \rangle$ or $N = \langle -I_7 \rangle$, hence $N$ is contained in the center of $G$. So $N$ cannot be a maximal abelian subgroup since $G$ is solvable. Thus, $\Delta|_N = \Gamma_1 + \cdots + \Gamma_7 = \Delta_1 + \cdots + \Delta_7$ with pairwise inequivalent representations $\Delta_i$ ($i = 1, \ldots, 7$), and the premises of Theorem (3.2) are fulfilled. As a minimal transitive permutation group we can choose $\langle (1 \ 2 \ 3 \ 4 \ 5 \ 6 \ 7) \rangle$, which is the only one up to equivalence by Sylow's theorem, and get $\varphi(G) = \langle g_2 \rangle$. $\varphi(G)$ operates on $D := \{ \mathrm{diag}(a_1, \ldots, a_7) \mid a_i = \pm 1 \ (i = 1, \ldots, 7) \}$ by conjugation. $D$ is a $\mathbb{Z}_2$-vector space, and $g_2$ induces a linear transformation with the characteristic polynomial $x^7 - 1 = (x + 1)(x^3 + x^2 + 1)(x^3 + x + 1)$. The corresponding decomposition of $D$ as a $\varphi(G)$-module is given by $D = N_1 \oplus N_2 \oplus N_3$ with irreducible $\mathbb{Z}_2\varphi(G)$-modules

$$N_1 = \langle \mathrm{diag}(-1, -1, -1, -1, -1, -1, -1) \rangle,$$
$$N_2 = \langle \mathrm{diag}(-1, -1, -1, -1, 1, 1, 1), \mathrm{diag}(1, -1, -1, 1, -1, 1, 1), \rangle$$
$$\mathrm{diag}(1, 1, -1, -1, -1, 1, 1),$$
$$N_3 = \langle \mathrm{diag}(-1, -1, -1, -1, 1, 1), \mathrm{diag}(1, -1, 1, -1, -1, 1, 1), \rangle$$
$$\mathrm{diag}(1, 1, -1, 1, -1, -1, -1),$$

Hence we find $\ker \varphi$ is equal to $N_2$ or $N_3$.

By the Schur-Zassenhaus Theorem $N$ has a complement in $G$ which can be chosen to be generated by $g_2$ (after conjugation by a monomial matrix). So we get two groups $\langle N_2, g_2 \rangle$, $\langle N_3, g_2 \rangle$, which turn out to be rationally equivalent. Indeed, an easy computation shows that both groups are isomorphic to the full affine group on $\mathbb{F}_8$, which has only one irreducible representation of degree 7. Q.E.D.

For the derivation of the nonsolvable groups the following lemma is useful.

(4.2) Lemma. Let $G$ be a minimal irreducible finite subgroup of $\mathrm{GL}(n, \mathbb{Z})$, $n$ odd. Then $G$ is already contained in $\mathrm{SL}(n, \mathbb{Z})$. In particular, the center of $G$ is trivial.

Proof. This is an easy application of Clifford’s theory. The last statement then follows from Schur’s Lemma and $\det(-I_n) = -1$ for odd $n$. Q.E.D.

(4.3) Theorem. The minimal irreducible finite subgroups $G$ of $\mathrm{GL}(7, \mathbb{Z})$, which are imprimitive as subgroups of $\mathrm{GL}(7, \mathbb{C})$, are solvable or isomorphic to $\mathrm{PSL}(2, 7)$, which in fact is isomorphic to a subgroup of $H_7$.

Proof. Because 7 is a prime number $G$ is $\mathbb{C}$-equivalent to a complex monomial group. Let $G$ be given in this form, and let
be the associated permutation representation of the natural representation \( \Delta \) of \( G \). The restriction of \( \Delta \) to \( \ker \varphi \) decomposes into seven one dimensional representations: 
\[ \Delta |_{\ker \varphi} = \Delta_1 + \cdots + \Delta_7. \]
By Clifford's theory the \( \Delta_i \) (\( i = 1, \ldots, 7 \)) are either all pairwise inequivalent or all equal. In the first case we conclude as in (3.2) and (4.1) that \( \varphi(G) \) is isomorphic to the cyclic group of order 7 and hence \( G \) is solvable. In the second case \( \ker \varphi \leq \langle -\mathbf{I}_7 \rangle \) holds, but because of (4.2) \( \varphi \) has to be injective and so \( G \) is isomorphic to a transitive permutation group of degree 7. The transitive permutation groups of degree 7 are either solvable or isomorphic to one of the groups \( \text{PSL}(2, 7) \), \( A_7 \), or \( S_7 \). Among these only \( \text{PSL}(2, 7) \) has an irreducible representation of degree 7. The corresponding linear group can be chosen as a subgroup of \( H_7 \). Since the orders of the proper subgroups of \( \text{PSL}(2, 7) \) are smaller than 50, it is a minimal irreducible group. Q.E.D.

The primitive finite subgroups of \( \text{SL}(7, \mathbb{C}) \) were determined by D. B. Wales in [13]. From his results we conclude

(4.4) Theorem. There are no minimal irreducible finite subgroups \( G \) of \( \text{GL}(7, \mathbb{Z}) \) which are primitive (as subgroups of \( \text{GL}(7, \mathbb{C}) \)).

Proof. Because of (4.2) all groups \( G \), which we are interested in, must be contained in Wales' list. By a result of Minkowski [9] the order of a finite subgroup of \( \text{GL}(7, \mathbb{Z}) \) divides \( 2^{11} 3^4 5 \cdot 7 \). Thus \( G \) must be isomorphic to one of the following five isomorphism types:

(I) \( \text{PSL}(2, 8) \), (II) \( A_8 \), (III) \( \text{PSL}(2, 7) \), (IV) \( \text{PSU}(3, 9) \), (V) \( S_6(2) \).

Ad(I). \( \text{PSL}(2, 8) \) contains \( A(1, 8) \), the affine group on \( \mathbb{F}_8 \). \( A(1, 8) \) has exactly one faithful representation of degree 7, and this representation is irreducible ((4.1)). Hence there is no minimal irreducible finite subgroup of \( \text{GL}(7, \mathbb{Z}) \) isomorphic to \( \text{PSL}(2, 8) \).

Ad(II). In this case the same argument as in (I) applies.

Ad(III). Compare Theorem (4.3).

Ad(IV). \( \text{PSU}(3, 9) \) has three irreducible representations of degree 7, only one of them can be made rational. (For a character table see [7].) From the representation theory of \( \text{PSL}(2, 7) \) one can easily conclude that \( \text{PSU}(3, 9) \) has a subgroup which is isomorphic to \( \text{PSL}(2, 7) \). An inspection of the character tables of both groups shows that \( G (\cong \text{PSU}(3, 9)) \) is not minimal irreducible.

Ad(V). In Section 6 we shall see that the group \( S_6(2) \) has a subgroup, which is isomorphic to the symmetric group \( S_6 \). This subgroup has only two faithful representations of degree 7 both being irreducible. Hence similar to (I) we conclude, that \( G (\cong S_6(2)) \) is not minimal irreducible. Q.E.D.

5. Computation of the \( \mathbb{Z} \)-Classes. We proved in the last section that there are exactly two minimal irreducible finite subgroups of \( \text{GL}(7, \mathbb{Z}) \) up to rational equivalence. As representatives, we choose \( G_1 \cong A(1, 8) \), given in (4.1), and \( G_2 \cong \text{PSL}(2, 7) \), given
in the form

\[
G_2 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

\[
g_1 = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & -1 & 0 & 0 & 0 \\
\end{bmatrix}
\]

An isomorphism of \(G_2\) onto \(PSL(2, 7)\) is:

\[
g_1 \mapsto \pm \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, \quad g_3 \mapsto \pm \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}.
\]

The form fixed by \(G_1\) and \(G_2\) is the unit form in seven variables. As input data we also need the modular constituents of the natural representations \(\Delta_1, \Delta_2\) of \(G_1, G_2\), respectively. Both representations become reducible only modulo 2. For \(G_1\) the 2-modular constituents of \(\Delta_1\) are:

\[
\Delta_{11}: G_1 \twoheadrightarrow \mathbb{Z}_2^x: g \mapsto 1; \\
\Delta_{12}: G_1 \twoheadrightarrow GL(3, \mathbb{Z}_2): g_2 \mapsto \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad g_1 \mapsto \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \\
\Delta_{13}: G_1 \twoheadrightarrow GL(3, \mathbb{Z}_2): g_2 \mapsto \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix}, \quad g_1 \mapsto \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}.
\]

(Note: \(\Delta_{12}, \Delta_{13}\) are not absolutely irreducible.)

For \(G_2\) and \(\Delta_2\) we get:

\[
\Delta_{21}: G_2 \twoheadrightarrow \mathbb{Z}_2^x: g \mapsto 1, \\
\Delta_{22}: G_2 \twoheadrightarrow GL(3, \mathbb{Z}_2): g_1 \mapsto \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad g_3 \mapsto \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}; \\
\Delta_{23}: G_2 \twoheadrightarrow GL(3, \mathbb{Z}_2): g_1 \mapsto \begin{bmatrix} 1 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \quad g_3 \mapsto \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}.
\]

The lattice of centerings for \(G_1\) has the form
The bases of the centerings $M_p, N_i$ expressed in the basis of $M_1, N_1$, respectively, are the columns of the following matrices $A_p, B_i$. They are ordered according to the corresponding forms $\lambda A_i^T A_i, \lambda B_i^T B_i$, respectively, ($\lambda \in \mathbb{Q}$).

Quadratic form: $F_1 = I_7$.

Bases of corresponding centerings: $A_1 = B_1 = I_7$ and
$B_8 = (x, g_1 x, g_1^2 x, \ldots, g_1^6 x)$ where $x^T = (0, 1, 1, -1, 0, 0, 1)$.

Quadratic form:

$$F_2 = \begin{pmatrix}
2 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 2 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 2 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 2 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 2 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}.$$

Bases of corresponding centerings:

$A_2 = B_2 = (x, g_1 x, \ldots, g_1^5 x, y)$ with $x^T = (1, 1, 0, \ldots, 0)$, $y^T = (0, \ldots, 0, 1, -1)$ and $B_{10} = B_8 B_2$.

Quadratic form:

$$F_3 = \begin{pmatrix}
4 & 0 & 0 & 0 & 0 & 0 & 2 \\
0 & 4 & 0 & 0 & 0 & 0 & 2 \\
0 & 0 & 4 & 0 & 0 & 0 & 2 \\
0 & 0 & 0 & 4 & 0 & 0 & 2 \\
0 & 0 & 0 & 0 & 4 & 0 & 2 \\
0 & 0 & 0 & 0 & 0 & 4 & 2 \\
2 & 2 & 2 & 2 & 2 & 2 & 7
\end{pmatrix}.$$

Bases of corresponding centerings:

$A_7 = B_6 = (x, g_1 x, \ldots, g_1^5 x, y)$ with $x^T = (2, 0, \ldots, 0)$, $y^T = (1, \ldots, 1)$ and $B_5 = \frac{1}{2} B_8 B_6$.

Quadratic form: $F_4 = 8I_7 - J_7$ where $J_7 \in \mathbb{Z}^{7 \times 7}$ has all its entries equal to 1.

Bases of corresponding centerings:

$A_9 = (x, g_1 x, \ldots, g_1^6 x)$ with $x^T = (-1, -1, -1, 1, -1, 1, 1)$ and

$B_9 = (y, g_1 y, \ldots, g_1^6 y)$ with $y^T = (-1, 1, 1, -1, 1, -1, -1)$.

Quadratic form: $F_5 = I_7 + J_7$.

Bases of corresponding centerings:

$A_8 = (x, g_1 x, \ldots, g_1^6 x)$ with $x^T = (1, 0, 0, 1, 1, 1, 0)$ and

$B_7 = (y, g_1 y, \ldots, g_1^6 y)$ with $y^T = (1, 1, 0, 0, 1, 0, 1)$.

Quadratic form:

$$F_6 = \begin{pmatrix}
2 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 2 & 0 & 1 & 0 & 0 & 0 \\
1 & 0 & 2 & 1 & 0 & 0 & 0 \\
0 & 1 & 1 & 2 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 2 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 & 2 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 0
\end{pmatrix}.$$
Bases of corresponding centerings:

\[
B_4 = A_5 = \begin{pmatrix}
2 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 2 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & -1 & -1 & -1 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

and

\[
A_6 = \begin{pmatrix}
2 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

Quadratic form:

\[
F_7 = \begin{pmatrix}
3 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 3 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 3 & 1 & 1 & -1 & 1 \\
1 & 1 & 1 & 3 & 1 & -1 & 1 \\
1 & 1 & 1 & 1 & 3 & -1 & 1 \\
1 & 1 & -1 & -1 & -1 & 3 & -1 \\
1 & 1 & 1 & 1 & 1 & -1 & 3
\end{pmatrix}
\]

Bases of corresponding centerings:

\[
A_3 = B_3 = (x, g_1 x, \ldots, g_4 x, y, g_5 x) \quad \text{with} \quad x^T = (1, 1, 0, 1, 0, 0, 0),
\]

\[
y^T = (0, 1, 0, 0, 0, -1, -1) \quad \text{and} \quad B_4 = (\bar{x}, g_1 \bar{x}, \ldots, g_4 \bar{x}, \bar{y}, g_5 \bar{x}) \quad \text{with}
\]

\[
\bar{x}^T = (1, 0, 1, 1, 0, 0, 0), \quad \bar{y}^T = (0, 0, 0, 1, 0, -1, -1).
\]

6. The Irreducible Maximal Finite Subgroups of GL(7, Z). Let \( \Delta : G \rightarrow GL(n, Z) \) be a representation of the group \( G \). By \( \Delta^{-T} \) we denote the inverse transposed representation of \( \Delta \) defined by \( \Delta^{-T}(g) = \Delta(g^{-1})^T \) for all \( g \in G \). The following elementary theorem will be useful [10]:

(6.1) Theorem. Let \( G \) be a finite group with representation \( \Delta : G \rightarrow GL(n, Z) \). Let \( X \in \mathbb{Q}^{n \times n} \) be symmetric and nonsingular.

(i) \( \Delta^{-T} \) is \( Q \)-equivalent to \( \Delta \).

(ii) \( X \) is fixed by \( \Delta(G) \) if and only if \( X^{-1} \) is fixed by \( \Delta^{-T}(G) \).

(iii) The \( Z \)-automorph of \( X \) is \( Q \)-equivalent to the \( Z \)-automorph of \( X^{-1} \).

Proof. We already remarked in the introduction that there is a symmetric positive definite matrix \( Y \in \mathbb{Z}^{n \times n} \) satisfying \( \Delta(g)^TY\Delta(g) = Y \) for all \( g \in G \). This equation implies \( \Delta^{-T}(g) = Y\Delta(g)^{-1} \) for all \( g \in G \), which proves (i). By inverting both sides of the equation \( \Delta(g)^TX\Delta(g) = X \) (\( g \in G \)) we get (ii). Then (iii) follows immediately. Q.E.D.

Assume that \( M \) is a \( < \)-maximal centering of the irreducible \( ZG \)-representation module \( L \) and that \( \Delta \) is the according representation of \( M \). For the \( < \)-maximal centering of \( L \) belonging to \( \Delta^{-T} \) we write \( M^{\#} \). Clearly, \( (M^{\#})^{\#} = M \).

For the centerings \( M_i \) \((i = 1, \ldots, 9) \) of \( G_1 \) derived in Section 5 an easy computation shows \( M_1^{\#} = M_1, M_2^{\#} = M_7, M_3^{\#} = M_5, M_4^{\#} = M_6, M_8^{\#} = M_9 \). For \( G_2 \) we get \( N_1^{\#} = N_1, N_2^{\#} = N_5, N_3^{\#} = N_4, N_6^{\#} = N_{10}, N_7^{\#} = N_9, N_8^{\#} = N_8 \). Therefore, \( F_1^{-1} \) is...
Z-equivalent to $F_1$, $2F_2^{-1} \sim Z F_3$ ($\det(F_2) = 4$), $8F_4^{-1} \sim Z F_5$ ($\det(F_4) = 8^6$), $2F_6^{-1} \sim Z F_7$ ($\det(F_6) = 2$). Now we can determine all irreducible maximal finite subgroups of $GL(7, \mathbb{Z})$. Namely they are Z-equivalent to the automorphs of one of the quadratic forms $F_1, \ldots, F_7$. We already mentioned that the automorph of $F_1$ is the full monomial group $H_7$ of degree 7. Moreover, the following two theorems hold. They are special cases of (III.6) and (III.3) in [10].

(6.2) Theorem. The automorphs of $F_1, F_2,$ and $F_3$ are $\mathbb{Q}$-equivalent maximal finite subgroups of $GL(7, \mathbb{Z})$.

Proof. By (6.1) the automorphs of $F_2$ and $F_3$ are $\mathbb{Q}$-equivalent. Clearly, 
$$\left\{(a_1, \ldots, a_7)^T | a_i \in \mathbb{Z}, \sum_{i=1}^7 a_i \equiv 0 \mod 2\right\} \leq \mathbb{Z}^{7 \times 1}$$

and 
$$\{(a_1, \ldots, a_7)^T | a_i \in \mathbb{Z}, a_i \equiv a_j \mod 2 (i, j = 1, \ldots, 7)\} \leq \mathbb{Z}^{7 \times 1}$$

are centerings of $H_7$ and correspond to the forms $F_2, F_3$, respectively. Hence $H_7$ is rationally equivalent to subgroups of the automorphs of $F_2, F_3$ which are in fact equal to the automorphs. The last statement follows easily since the vectors of shortest length in the second lattice are of the form $(0, \ldots, 0, \pm 2, 0, \ldots, 0)$. Q.E.D.

(6.3) Theorem. The automorphs of $F_4$ and $F_5$ are $\mathbb{Q}$-equivalent maximal finite subgroups of $GL(7, \mathbb{Z})$. They are isomorphic to $C_2 \times S_8$.

Proof. Define a faithful $\mathbb{Z}S_8$-representation module $L = \bigoplus_{i=1}^8 \mathbb{Z}e_i$ by $\pi e_i = e_{\pi(i)}$ for all $\pi \in S_8$ ($i = 1, \ldots, 8$), which corresponds to the natural permutation representation of $S_8$. Clearly, $L' := \mathbb{Z}(\sum_{i=1}^8 e_i)$ is an invariant submodule and $L/L'$ is a faithful irreducible $\mathbb{Z}S_8$-representation module. We write $\overline{e}_i = e_i + L'$ ($i = 1, \ldots, 8$). $\overline{e}_1, \ldots, \overline{e}_7$ constitute a basis of $L/L'$ and $\sum_{i=1}^8 \overline{e}_i = 0$ holds. The scalar product $\Phi : \Phi(\overline{e}_i, \overline{e}_j) = 8\delta_{ij} - 1$ ($i, j = 1, \ldots, 7$) is invariant under $S_8$. The shortest vectors of this lattice are $\pm \overline{e}_1, \ldots, \pm \overline{e}_8$. This implies that the $\mathbb{Z}$-automorph of $\Phi$ is isomorphic to $(-\text{id}) \times S_8$, and the theorem follows by (6.1). Q.E.D.

In order to deal with the last two forms we need

(6.4) Theorem. The automorphs of $F_6$ and $F_7$ are $\mathbb{Q}$-equivalent maximal finite subgroups of $GL(7, \mathbb{Z})$. They are isomorphic to the Weyl group $W(E_7)$ of order $2^{10} \cdot 3^4 \cdot 5 \cdot 7$.

Proof. The automorphs are $\mathbb{Q}$-equivalent by (6.1). The form $F_6$ can also be derived from the root system $E_7$ [8, p. 66], and the automorph of $F_6$ is equal to the automorphism group of the root system, in this case the Weyl group $W(E_7)$. Q.E.D.

In order to complete the proof of (4.4) we still have to verify the

(6.5) Remark. The Weyl group $W(E_7) \cong C_2 \times S_6(2)$ contains a subgroup isomorphic to $S_8$, hence $S_6(2)$ has a subgroup isomorphic to $S_8$.

Proof. In the terminology of the proof of (6.3) the $K_v = \{ \sum_{i=1}^8 a_i \overline{e}_i | a_i \in \mathbb{Z}, \sum_{i=1}^8 a_i \equiv 0 \mod v \}$ for $v = 1, 2, 4, 8$ are centerings of $L/L'$ ($K_1 = L/L'$). From $K_4$ we obtain the form $F_6$ (from $K_2$ the form $F_7$, from $K_8$ the form $F_8$). Hence the automorph of $F_4$, which is isomorphic to $C_2 \times S_8$, is rationally equivalent to a subgroup of the automorph of $F_6$ (equal to $W(E_7)$). Q.E.D.

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Therefore we have proved:

(6.6) Theorem. There are exactly seven irreducible maximal finite subgroups of 
$GL(7, \mathbb{Z})$ up to $\mathbb{Z}$-equivalence. The automorphs of the quadratic forms $F_1, \ldots, F_7$ as 
given in Section 5 form a full set of representatives. (For a description of these groups 
see Theorems (6.2) to (6.4).)

7. The Maximal Irreducible Finite Subgroups of $GL(5, \mathbb{Z})$. The results for the 
five dimensional case can be obtained very easily by our method. In analogy to (4.1) 
we find only one solvable minimal irreducible finite subgroup $G_1$ of $GL(5, \mathbb{Z})$, up to 
$\mathbb{Q}$-equivalence:

$$G_1 = \left\langle g_1, g_2 \right\rangle,$$

where

$$g_1 = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix}, \quad g_2 = \begin{pmatrix} -1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

By checking R. Brauer's list of the irreducible finite subgroups of $SL(5, \mathbb{C})$ [3] we see 
that there is only one nonsolvable group $G_2$ up to $\mathbb{Q}$-equivalence. (Note that the order 
of such a group has to divide $2^8 \cdot 3^2 \cdot 5$ [9].) $G_2$ is isomorphic to the alternating group 
$A_5$ and is obtained by reduction of the doubly transitive permutation representation 
of $A_5$ of degree 6.

$$G_2 = \left\langle g_1, g_3 \right\rangle,$$

where

$$g_1 = \begin{pmatrix} 1 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & -1 & 0 \end{pmatrix}.$$

An isomorphism of $G_2$ onto $A_5$ is:

$$g_1 \mapsto (1 2 3 4 5), \quad g_2 \mapsto (1 2)(3 4).$$

The forms fixed by $G_1, G_2$ are $I_5, 6I_5 - J_5$, respectively. The natural representations 
$\Delta_1, \Delta_2$ of $G_1, G_2$ have the modular constituents:

$\Delta_1$ becomes reducible only modulo 2:

$\Delta_{11}: G_1 \rightarrow \mathbb{Z}_2^\times: g \mapsto 1$;

$\Delta_{12}: G_1 \rightarrow GL(4, \mathbb{Z}_2): g_1 \mapsto \begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \end{pmatrix}, \quad g_2 \mapsto \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$

$\Delta_2$ becomes reducible modulo 2 and modulo 3:
\[ \Delta_{21}: G_2 \rightarrow \mathbb{Z}_2^X: g \mapsto 1; \]

\[ \Delta_{22}: G_2 \rightarrow GL(4, \mathbb{Z}_2): g_1 \mapsto \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}, \quad g_2 \mapsto \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 \end{pmatrix}; \]

\[ \Delta_{23}: G_2 \rightarrow \mathbb{Z}_3^X: g \mapsto 1; \]

\[ \Delta_{24}: G_2 \rightarrow GL(4, \mathbb{Z}_3): g_1 \mapsto \begin{pmatrix} -1 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}, \quad g_2 \mapsto \begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & -1 & 0 \end{pmatrix}. \]

The lattices of centerings are

In analogy to Section 5 we denote by \( A_i, B_i \) the matrices whose columns are bases of the centerings \( M_i, N_i \) expressed in terms of the basis of \( M_1, N_1 \), respectively. Again they are ordered according to the corresponding forms.

Quadratic form: \( F_1 = I_5 \).

Basis of corresponding centering: \( A_1 = I_5 \).

Quadratic form: \( F_2 = A_2A_2^T \) with basis of corresponding centering

\[ A_2 = (x, g_1x, g_1^2x, g_1^3x, y) \quad \text{and} \quad x^T = (1, 1, 0, 0, 0), \quad y^T = (0, 0, 0, 1, -1). \]

Quadratic form: \( F_3 = A_3A_3^T \) with basis of corresponding centering

\[ A_3 = (x, g_1x, g_1^2x, g_1^3x, y) \quad \text{and} \quad x^T = (2, 0, 0, 0, 0), \quad y^T = (1, 1, 1, 1, 1). \]

Quadratic form: \( F_4 = 6I_5 - J_5 \).

Basis of corresponding centering: \( B_1 = I_5 \).

Quadratic form: \( F_5 = I_5 + J_5 \).

Basis of corresponding centering: \( B_4 = I_5 + J_5 \).

Quadratic form: \( F_6 = B_2(6I_5 - J_5)B_2^T \) with basis of corresponding centering

\[ B_2 = A_2. \]

Quadratic form: \( F_7 = B_3(6I_5 - J_5)B_3^T \) with basis of corresponding centering
An easy consideration shows $M_1^* = M_1$, $M_2^* = M_2$, $N_1^* = N_4$, $N_2^* = N_3$. Now some simple computations yield

(7.1) **Theorem.** There are exactly seven irreducible maximal finite subgroups of $GL(5, \mathbb{Z})$ up to $\mathbb{Z}$-equivalence. The automorphs of the quadratic forms $F_1, \ldots, F_7$ as given in this section form a full set of representatives. The automorphs of $F_1, F_2, F_3$ are rationally equivalent and isomorphic to the wreath product $C_2 \ltimes S_5$. Also, the automorphs of $F_4, F_5, F_6, F_7$ are rationally equivalent and isomorphic to $C_2 \times S_6$. 

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