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Nilpotent Groups of Class Two that Can Appear as Central Quotient Groups.

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In this note we will be concerned with the following question: Suppose $C_p \times C_p = G' \subseteq Z(G)$. What can be said about $G/Z(G)$ if G is isomorphic to some central quotient group $H/Z(H)$ of a group H ? The answer to the corresponding question for $|G'| = p$ is wellknown for a long time; it is $|G/Z(G)| = p^2$ (see for instance Beyl and Tappe [1; p. 233]).

The proof of the answer (Proposition 3) makes use of our knowledge about vector spaces with two alternating bilinear forms. The bounds obtained are strict for odd primes p ; this is shown in the second section. In the third section we give an example of a group G such that

$$G_3 = G^p = 1, \quad |G'| = |Z(G)| = p^n, \quad |G/G'| = p^{2n + \binom{n}{2}}$$

and G is a central quotient. This shows at least quadratic growth for the upper bound of the rank of $G/Z(G)$ with growing rank of G' .

1. The bounds for $|G/Z(G)|$.

In what follows we will have to deal with vector spaces V with two alternating bilinear forms f_1, f_2 which are of a comparatively transparent structure: There are two linear combinations

$$g_1 = af_1 + bf_2 \quad \text{and} \quad g_2 = cf_1 + df_2$$

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and a basis x_1, \dots, x_m of V such that

$$\begin{aligned} g_1(x_{2t-1}, x_{2t}) &= g_2(x_{2t}, x_{2t+1}) = 1, \\ g_1(x_{2t}, x_{2t+1}) &= g_2(x_{2t-1}, x_{2t}) = 0 \quad \text{for all } t \leq \frac{m}{2}, \\ g_1(x_i, x_j) &= g_2(x_i, x_j) = 0 \quad \text{for } |i - j| > 1. \end{aligned}$$

For brevity we will call such a vector space a string with respect to g_1 and g_2 . If $\dim V$ is odd, V is also a string with respect to any two different linear combinations of f_1, f_2 ; on the other hand if $\dim V$ is even, g_1 is fixed and g_2 can be changed to any other linear combination different from g_1 . The reference to the respective bilinear forms will mostly be unnecessary and is then omitted.

A direct sum is called an orthogonal sum, if in addition the summands are orthogonal to each other with respect to all bilinear forms considered.

PROPOSITION 1. If two alternating forms f_1, f_2 are defined on a finite dimensional vector space V , then V is the orthogonal sum

$$V = R \oplus X_1 \oplus X_2 \oplus \dots \oplus X_t,$$

where every linear combination $rf_1 + sf_2 \neq 0$ is nondegenerate on R and X_1, \dots, X_t are strings. Any two such decompositions of V are of the same form.

PROOF. Following Scharlau [2], we can compare the finite dimensional vector space V possessing two alternating forms with a Kronecker module consisting of two spaces and two endomorphisms mapping the first space into the second: for the first space take a subspace which is maximal with respect to both forms reducing to the zero form on it, for the second take the dual of the respective quotient space. Scharlau proves [2; 3.e, Theorem p. 14] that the decomposition of such a vector space into an unrefineable orthogonal sum is unique up to isomorphism. For R we take the sum of such summands with all linear combinations $rf_1 + rf_2$ non-degenerate; the remaining summands correspond to Kronecker modules M_2, L_n, L_n^* as described in [2; p. 16], and these are strings in our sense.

PROPOSITION 2. Denote by V a finite-dimensional vector space with two alternating forms f_1 and f_2 such that every linear combination $rf_1 + sf_2$ is non-degenerate on V . Then

(i) $\dim V$ is even, and at least 4.

(ii) If W is a subspace of V of codimension 1, then $W = T \oplus S$, where every linear combination $rf_1 + sf_2$ is non-degenerate on T while S is a string of odd dimension.

PROOF. Since f_1 is nondegenerate on V , $\dim V$ is even, for $\dim V = 2$ f_1 and f_2 are linearly dependent. On the other hand, $\dim W = \dim V - 1$ is odd, and every linear combination $rf_1 + sf_2$ is degenerate on W , so W is an orthogonal sum with at least one string, and one string of odd dimension. Since every linear combination $rf_1 + sf_2$ is nondegenerate on V , $(rf_1 + sf_2)(x, W) = 0$ has as space of solution a subspace of dimension $\dim V - \dim W = 1$ at most. This shows that there is at most one string, it contains all the solutions mentioned.

In the sequel we make use of the following well known fact: If G is a p -group of nilpotency class 2 and $G' = \langle a \rangle \times \langle b \rangle$ with $a^p = b^p = 1$, then the mapping

$$(x, y) \rightarrow [x, y] = a^{r(x, y)} b^{s(x, y)}$$

induces two alternating bilinear forms on $G/Z(G)$. This allows us to argue from vector spaces to groups and back. This argument can be found operating in Vishnevetskii [3], for instance.

PROPOSITION 3. If G is a finite group such that

$$C_p \times C_p = G' \subseteq Z(G)$$

and there is a group H such that $G = H/Z(H)$, then

$$p^2 < |G/Z(G)| < p^6.$$

PROOF. The first part of the inequality $p^2 < |G/Z(G)|$ is obvious. For the other we begin with some preliminary statements. We assume that G is isomorphic to some quotient $H/Z(H)$ and deduce restrictions on G .

(a) If $G = UV$ and $[U, V] = 1$, then $U' \cap V' = 1$.

If, on the contrary, $G = UV$ with $[U, V] = 1$ and $U' \cap V' \neq 1$ and $G = H/Z(H)$, we choose a basis $u_1, \dots, u_r, v_1, \dots, v_s$ of G such that the elements u_i belong to U and the v_j 's to V . Since $U \cap V \subseteq Z(G)$ we have $\langle u_1, \dots, u_r \rangle Z(G) = UZ(G)$ and $\langle v_1, \dots, v_s \rangle Z(G) = VZ(G)$.

The pre-image of the element x of G with respect to the mapping of H onto $G = H/Z(H)$ shall be denoted by \tilde{x} .

Now

$$[[v_i, v_j], u_k] = [[u_k, v_i], v_j]^{-1} [[v_j, u_k], v_i]^{-1} = 1 \quad \text{for all } i, j, k.$$

The same holds if the roles of U and V are interchanged. Take

$$\prod [u_i, u_j]^{m_{ij}} = \prod [v_i, v_j]^{m_{ij}} = c \neq 1.$$

Then $\tilde{c} \notin Z(H)$ and $[\tilde{c}, \tilde{v}_k] = [\tilde{c}, \tilde{u}_k] = 1$ for all k , a contradiction. So (a) is true.

(b) If $G = UV$ with $[U, V] = 1$ and $UZ(G) \neq Z(G) \neq VZ(G)$,
 then $G/G' = p^4$.

By (a) we have $U' \cap V' = 1$, and the hypothesis yields $U' \neq 1 \neq V'$. So both commutator subgroups U', V' have order p and $UZ(G)/Z(G)$ and $VZ(G)/Z(G)$ are elementary abelian of even rank. Using (a) again we see that both these quotient groups must be of order p^2 and (b) follows.

From now on we consider $G/Z(G)$ as a F_p -vector space V with two alternating forms, as outlined just before this Proposition. By (b) we have

(c) If $\dim V > 4$, there is no proper decomposition of V into an orthogonal sum.

We assume $\dim V = m > 5$. If there is a linear combination $rf_1 + sf_2$ ($(r, s) \neq (0, 0)$) which is degenerate on V , then V is a string with respect to $rf_1 + sf_2 = g$ and one of f_1, f_2 , say f . So there are generators $x_1Z(G), \dots, x_mZ(G)$ of $G/Z(G)$ and a, b of G' such

$$[x_{2t-1}, x_{2t}] = a, \quad [x_{2t}, x_{2t+1}] = b, \quad [x_h, x_k] = 1 \quad \text{for } |h - k| > 1.$$

Using pre-images as before we have

$$[[\tilde{x}_1, \tilde{x}_2], \tilde{x}_k] = [[\tilde{x}_2, \tilde{x}_k], \tilde{x}_1]^{-1} [[\tilde{x}_k, \tilde{x}_1], \tilde{x}_2]^{-1} = 1 \quad \text{for } k > 3,$$

and, using the same argument,

$$[[\tilde{x}_1, \tilde{x}_2], \tilde{x}_k] = [[\tilde{x}_5, \tilde{x}_6], \tilde{x}_k] = 1 \quad \text{for } k \leq 3,$$

$$[[\tilde{x}_2, \tilde{x}_3], \tilde{x}_k] = 1 \quad \text{for } k > 4,$$

$$[[\tilde{x}_2, \tilde{x}_3], \tilde{x}_k] = [[\tilde{x}_4, \tilde{x}_5], \tilde{x}_k] = 1 \quad \text{for } k \leq 2,$$

$$[[\tilde{x}_2, \tilde{x}_3], \tilde{x}_3] = [[\tilde{x}_4, \tilde{x}_5], \tilde{x}_3] = [[\tilde{x}_5, \tilde{x}_3], \tilde{x}_4]^{-1} [[\tilde{x}_3, \tilde{x}_4], \tilde{x}_5]^{-1} = 1,$$

$$[[\tilde{x}_2, \tilde{x}_3], \tilde{x}_4] = [[\tilde{x}_3, \tilde{x}_4], \tilde{x}_2]^{-1} [[\tilde{x}_4, \tilde{x}_2], \tilde{x}_3]^{-1} = 1,$$

and neither \tilde{a} nor \tilde{b} are outside $Z(H)$, a contradiction. This shows

(d) If V is a string, $\dim V \leq 5$.

Assume now that V is not a string but all bilinear forms are non-degenerate on V and $\dim V \geq 6$. Consider a subspace W of codimension 1 of V ; by Proposition 2 we know that W is the orthogonal sum of a completely nondegenerate part and a string. If $\dim V \geq 8$ either the orthogonal sum is nontrivial and \tilde{a}, \tilde{b} commute with all elements of the pre-image of W , or W is a string of dimension 7 at least, with the same consequence. Since this holds for all W , this also holds for V , a contradiction. We have found

(e) $\dim V \geq 7$.

If $\dim V = 6$, each W must be a string by Proposition 2 (i). We choose a basis $x_1Z(G), \dots, x_6Z(G)$ of $G/Z(G)$ and determine the maximal subgroups U_i of G such that $[U_i, x_i] = \langle b \rangle$.

We have corresponding subspaces W_i of codimension 1 of V . These subspaces are strings and allow a basis as a string such that x_i appears as the first basis element y_1 . Now

$$[[\tilde{y}_1, \tilde{y}_2], \tilde{y}_i] = [[\tilde{y}_3, \tilde{y}_4], \tilde{y}_i] = 1,$$

$$[[\tilde{y}_2, \tilde{y}_3], \tilde{y}_i] = [[\tilde{y}_4, \tilde{y}_5], \tilde{y}_i] = 1,$$

and \tilde{a}, \tilde{b} commute with every of the \tilde{x}_i , the final contradiction

(f) $\dim V < 6,$

and this proves the Proposition.

2. Construction of some groups H .

To show that Proposition 3 is in a sense bestpossible we construct groups H for the case

$$G' = Z(G) = C_p \times C_p, \quad G^p = 1.$$

This excludes $p = 2$, where more scrutinous observations are necessary. In each case a basis of $H_3 \cap Z(H)$ will be given such that the order of this characteristic subgroup is maximal. It is not too difficult to determine all $T \subset H_3 \cap Z(H)$ such that $(H/T)/Z(H/T)$ is still isomorphic to G ; for brevity we do not concern ourselves with this task.

Case A: $|G/G'| = p^3.$

Here we have

$$G = \left\langle x_1, x_2, x_3 \left| \begin{array}{l} [x_1, x_2] = a, [x_2, x_3] = b \\ x_i^p = [[x_i, x_j], x_k] = [x_1, x_3] = 1 \end{array} \right. \right\rangle.$$

In the notation as before we find

$$H_3 \cap Z(H) = \langle [[\tilde{x}_1, \tilde{x}_2], \tilde{x}_1], [[\tilde{x}_2, \tilde{x}_3], \tilde{x}_3], [[\tilde{x}_1, \tilde{x}_2], \tilde{x}_2], \\ [[\tilde{x}_2, \tilde{x}_3], \tilde{x}_2], [[\tilde{x}_1, \tilde{x}_2], \tilde{x}_3] = [[\tilde{x}_2, \tilde{x}_3], \tilde{x}_1]^{-1} \rangle.$$

Case B: $|G/G'| = p^4$, the string case.

Then

$$G = \left\langle x_1, x_2, x_3, x_4 \left| \begin{array}{l} [x_1, x_2] = [x_3, x_4] = a \\ [x_2, x_3] = b \\ x_i^p = [[x_i, x_j], x_k] = 1 \\ [x_i, x_j] = 1 \text{ for } |i - j| > 1 \end{array} \right. \right\rangle.$$

and

$$H_3 \cap Z(H) = \left\langle \begin{array}{l} [[\tilde{x}_1, \tilde{x}_2], \tilde{x}_3] = [[\tilde{x}_2, \tilde{x}_3], \tilde{x}_1]^{-1} \\ [[\tilde{x}_2, \tilde{x}_3], \tilde{x}_4] = [[\tilde{x}_1, \tilde{x}_2], \tilde{x}_2]^{-1} \\ [[\tilde{x}_2, \tilde{x}_3], \tilde{x}_2], [[\tilde{x}_2, \tilde{x}_3], \tilde{x}_3] \end{array} \right\rangle.$$

Case C: $|G/G'| = p^4$ and G is a direct product $\langle x_1, x_2 \rangle \times \langle x_3, x_4 \rangle$.

Then

$$H_3 \cap Z(H) = \langle [[\tilde{x}_1, \tilde{x}_2], \tilde{x}_1], [[\tilde{x}_1, \tilde{x}_2], \tilde{x}_2], [[\tilde{x}_3, \tilde{x}_4], \tilde{x}_3], [[\tilde{x}_3, \tilde{x}_4], \tilde{x}_4] \rangle.$$

Case D: $|G/G'| = p^4$, completely nondegenerate case.

Here G can be described as a group with the galois field of order p^2 as operator domain, and $H_3 \cap Z(H) \leq p^4$.

The actual description would depend on the prime p .

Case E: $G/G' = p^5$.

Here

$$G = \left\langle x_1, x_2, x_3, x_4, x_5 \left| \begin{array}{l} [x_1, x_2] = [x_3, x_4] = a \\ [x_2, x_3] = [x_4, x_5] = b \\ x_i^p = 1 = [[x_i, x_j], x_k] \\ [x_i, x_j] = 1 \text{ for } |i-j| > 1 \end{array} \right. \right\rangle.$$

and

$$H_3 \cap Z(H) = \langle [[\tilde{x}_2, \tilde{x}_3], \tilde{x}_4] = [[\tilde{x}_3, \tilde{x}_4], \tilde{x}_2]^{-1} \rangle.$$

(In particular H does not exist if $x_2^p = [x_3, x_4]$.)

REMARKS. (1) The quotient groups $H_2 \cap Z(H)/H_3 \cap Z(H)$ have orders bounded by p in Case *A*, p^4 in Cases *B*, *C*, *D* and p^8 in Case *E*.

(2) If $G = H/Z(H)$ and G is a p -group, if further $|\langle x \rangle| = p$, then also $G \times \langle x \rangle$ is a central quotient: Choose a maximal subgroup M of G and an element y such that $G = \langle M, y \rangle$, and form the extension K of $\langle x, z \rangle$ by H such that $z^p = 1 = [x, z]$, $[x, \tilde{y}] = z$, $[x, \tilde{t}] = [z, \tilde{t}] = 1$ for all \tilde{t} in the pre-image \tilde{M} of M in H . Now $K/Z(K)$ is isomorphic to $G \times \langle x \rangle$.

This shows that groups H do exist as constructed in this section as long as $G^p = 1$, even if $G' \not\subseteq Z(G)$.

3. An example for higher rank.

Consider

$$G = \left\langle \begin{array}{l} s_i, t_i, \quad i \leq n \\ m_{ij} = m_{ji}, \quad i \neq j, \quad i, j \leq n \end{array} \middle| \begin{array}{l} s_i^2 = t_i^2 = m_{ij}^2 = 1 \\ [s_i, t_i] = [s_j, s_j, m_{ij}] = c_i \\ [s_i, t_j] = [s_i, s_j] = [t_i, t_j] = 1 \quad \text{for } i \neq j \\ [m_{ij}, t_k] = 1 \quad \text{for all } i, j, k \\ [m_{ij}, s_k] = 1 \quad \text{for } i \neq k \neq j \\ [m_{jk}, m_{55}] = 1 \quad \text{for all } i, j, u, v \\ [[g_1, g_2], g_3] = 1 \quad \text{for all } g_1 \text{ in } G \end{array} \right\rangle$$

This group is isomorphic to a central quotient $H/Z(H)$ where

$$\begin{aligned} H_3 \cap Z(H) &= \langle [[\tilde{s}_i, \tilde{t}_i], \tilde{s}_i] = [[\tilde{s}_j, \tilde{m}_{ij}], \tilde{s}_i] = \\ &= [[\tilde{s}_i, \tilde{m}_{ij}], \tilde{s}_j] = [[\tilde{s}_j, \tilde{t}_j], \tilde{s}_j] \quad \text{for all } i, j \rangle. \end{aligned}$$

This follows from the fact that the vector space corresponding to the subgroup $\langle t_i, s_i, m_{ij}, s_j t_j, Z(G) \rangle$ is a string.

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