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A Note on Nonabelian (64, 28, 12) Difference Sets

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Abstract. The existence of difference sets in abelian 2-groups is a recently settled problem [5]; this note extends the abelian constructs of difference sets to nonabelian groups of order 64.

1. Introduction.

A difference set D in a finite group G (of order v) is a subset of size k so that every nonidentity element of G can be represented λ times as differences from elements in D . For groups of order a power of 2, the existence of difference sets in the abelian groups is a recently settled problem [5]. The nonabelian case is more difficult; this paper discusses a technique for using the structure of the abelian difference sets to obtain difference sets in nonabelian groups of order 64.

It is helpful to consider the ring $Z[G]$. If $A \subset G$, we will abuse notation by writing $A = \sum_{a' \in A} a'$ as an element of $Z[G]$. Also, $A^{(-1)} = \sum_{a' \in A} (a')^{-1}$. By the definition of a difference set, $D \subset G$ is a difference set iff $DD^{(-1)} = (k - \lambda)1 + \lambda G$. In the $v = 64$ case, this is $DD^{(-1)} = 16(1) + 12G$.

All groups in this paper will be written multiplicatively, including abelian groups. Subgroups will be denoted $\langle \cdot, \cdot \rangle$, where the generators are included in the brackets.

2. The abelian case.

The abelian case $Z_{16} \times Z_4$ is discussed in [1], [2], [4].

Theorem 2.1. $Z_{16} \times Z_4$ has a difference set.

We will provide the difference set and leave it to the reader to verify the theorem (either by a straight check or by character theory). All elements of the group can be written as powers of a and b , where $a^{16} = b^4 = 1$. If we take the subgroup $H = \langle a^4, b^2 \rangle$, we can write $G = \cup g_i H$.

Take the following subsets of H :

$$\begin{array}{ccccccc} D_2 & D_3 & D_4 & D_5 & D'_5 & D_6 & D'_6 \\ \langle a^4 \rangle & \langle a^8, b^2 \rangle & \langle a^4 b^2 \rangle & \left(\begin{array}{c} \langle a^8 b^2 \rangle \\ \cup_{a^4 \langle a^8 b^2 \rangle} \end{array} \right) & \left(\begin{array}{c} \langle a^{12} \langle a^8 b^2 \rangle \rangle \\ \cup_{a^8 \langle a^8 b^2 \rangle} \end{array} \right) & \left(\begin{array}{c} \langle b^2 \rangle \\ \cup_{a^4 \langle b^2 \rangle} \end{array} \right) & \left(\begin{array}{c} \langle a^{12} \langle b^2 \rangle \rangle \\ \cup_{a^8 \langle b^2 \rangle} \end{array} \right) \end{array}$$

The claim is that $aD_2 \cup abD_3 \cup a^3D_4 \cup D_5 \cup bD'_5 \cup a^2D_6 \cup a^6bD'_6$ is a difference set in $Z_{16} \times Z_4$.

The following lemma is proved in [3].

Lemma 2.2. *If $i \neq j$, then $D_i D_j^{(-1)} = 2H$.*

This lemma excludes two important cases, which are covered in the next lemma.

Lemma 2.3.

- (a) $D_5 D_5^{(-1)} = D'_5 D_5^{-1} = 4(a^8 + b^2) + 2(a^4 + a^4 b^2 + a^{12} + a^{12} b^2)$
 (b) $D_6 D_6^{(-1)} = D'_6 D_6^{-1} = 4(a^8 + a^8 b^2) + 2(a^4 + a^4 b^2 + a^{12} + a^{12} b^2)$
 (c) $D_5 D_5^{(-1)} + b^2 D_5 D_5^{(-1)} = 4H$
 (d) $D_6 D_6^{(-1)} + a^8 b^2 D_6 D_6^{(-1)} = 4H$.

Notice that these lemmas can be considered in the group ring $Z[H]$ since all the D_i are subsets of H .

3. The nonabelian case.

Let \bar{G} be any group of order 64 with a normal subgroup $\bar{H} \cong Z_4 \times Z_2$. We can choose an isomorphism $f: H \rightarrow \bar{H}$, where H is the $Z_4 \times Z_2$ from the abelian case. Define $\bar{D}_i = \{f(d_i) \mid d_i \in D_i\}$.

Theorem 3.1. *A group \bar{G} with a normal subgroup \bar{H} isomorphic to $Z_4 \times Z_2$ has a difference set if:*

- (a) *there are 4 distinct coset representatives $\bar{g}_5, \bar{g}'_5, \bar{g}_6, \bar{g}'_6$ in \bar{G}/\bar{H} so that $\bar{g}_5 (\bar{g}'_5)^{-1} = \bar{g}'_5 \bar{g}_5^{-1} (f(b^2))$ and $\bar{g}_6 (\bar{g}'_6)^{-1} = \bar{g}'_6 \bar{g}_6^{-1} (f(a^8 b^2))$,*
 (b) $\bar{g} \bar{D}_i \bar{D}_i^{(-1)} \bar{g}^{-1} = \bar{D}_i \bar{D}_i^{(-1)}$ *for every $\bar{g} \in \bar{G}$,*
 (c) $\bar{g}_5 \bar{D}_5 \bar{D}_5^{(-1)} \bar{g}_5^{-1} = \bar{g}_5 \bar{g}'_5^{-1} \bar{D}_5 \bar{D}_5^{(-1)}$, $\bar{g}'_5 \bar{D}_5 \bar{D}_5^{(-1)} \bar{g}'_5^{-1} = \bar{g}'_5 \bar{g}_5^{-1} \bar{D}_5 \bar{D}_5^{(-1)}$, *and the same if we replace 5 by 6.*

Proof: Pick three distinct coset representatives $\bar{g}_2, \bar{g}_3, \bar{g}_4$ in \bar{G}/\bar{H} that are also distinct from $\bar{g}_5, \bar{g}'_5, \bar{g}_6, \bar{g}'_6$. We claim that $\bar{D} = \bar{g}_2 \bar{D}_2 \cup \bar{g}_3 \bar{D}_3 \cup \bar{g}_4 \bar{D}_4 \cup \bar{g}_5 \bar{D}_5 \cup \bar{g}'_5 \bar{D}_5 \cup \bar{g}_6 \bar{D}_6 \cup \bar{g}'_6 \bar{D}_6$ is a difference set in \bar{G} . Consider the group ring equation

$$\bar{D} \bar{D}^{(-1)} = \sum_{i,j} \bar{g}_i \bar{D}_i \bar{D}_j^{(-1)} \bar{g}_j^{-1}. \quad (1)$$

We can apply Lemmas 2.2 and 2.3 to this situation since f is a group ring isomorphism from $Z[H]$ to $Z[\bar{H}]$. If $i \neq j$, Lemma 2.2 implies

$$\bar{g}_i \bar{D}_i \bar{D}_j^{(-1)} \bar{g}_j^{-1} = \bar{g}_i (2\bar{H}) \bar{g}_j^{-1} = \bar{g}_i \bar{g}_j^{-1} (2\bar{H}). \quad (2)$$

Combining Lemma 2.3, (a), and (c),

$$\begin{aligned} & \bar{g}_5 \bar{D}_5 \bar{D}_5^{(-1)} \bar{g}_5^{-1} + \bar{g}'_5 \bar{D}_5 \bar{D}_5^{(-1)} \bar{g}'_5^{-1} \\ &= \bar{g}_5 \bar{g}'_5^{-1} \bar{D}_5 \bar{D}_5^{(-1)} + \bar{g}'_5 \bar{g}_5^{-1} \bar{D}_5 \bar{D}_5^{(-1)} \\ &= \bar{g}_5 \bar{g}'_5^{-1} \bar{D}_5 \bar{D}_5^{(-1)} + \bar{g}_5 \bar{g}'_5^{-1} f(b^2) \bar{D}_5 \bar{D}_5^{(-1)} \\ &= \bar{g}_5 \bar{g}'_5^{-1} (f[D_5 D_5^{(-1)} + b^2 D_5 D_5^{(-1)}]) \\ &= \bar{g}_5 \bar{g}'_5^{-1} (f(4H)) = \bar{g}_5 \bar{g}'_5^{-1} (4\bar{H}) \end{aligned} \quad (3)$$

$$\bar{g}_6 \bar{D}_6 \bar{D}_6^{(-1)} \bar{g}_6'^{-1} + \bar{g}_6' \bar{D}_6' \bar{D}_6'^{(-1)} \bar{g}_6'^{-1} = \bar{g}_6 \bar{g}_6'^{-1} (4 \bar{H}). \quad (4)$$

Putting (1), (2), (3), (4) and (b) together,

$$\begin{aligned} & \bar{D} \bar{D}^{(-1)} \\ &= \left(\sum_{i \neq j} \bar{g}_i \bar{g}_j^{-1} \right) 2 \bar{H} + \sum_i \bar{g}_i \bar{D}_i \bar{D}_i^{(-1)} \bar{g}_i^{-1} + \bar{g}_5 \bar{g}_5'^{-1} (4 \bar{H}) + \bar{g}_6 \bar{g}_6'^{-1} (4 \bar{H}) \\ &= \left(\sum_{i \neq j} \bar{g}_i \bar{g}_j^{-1} \right) 2 \bar{H} + \sum_i \bar{D}_i \bar{D}_i^{(-1)} + \bar{g}_5 \bar{g}_5'^{-1} (4 \bar{H}) + \bar{g}_6 \bar{g}_6'^{-1} (4 \bar{H}). \end{aligned} \quad (5)$$

\bar{D} is a union of 7 subsets of cosets of \bar{H} out of 8 possible cosets. Thus, in \bar{G}/\bar{H} , the coset representatives used by \bar{D} form an (8, 7, 6) difference set. Other than \bar{H} , each of the 7 cosets appear 6 times, and each time they are multiplied by $2 \bar{H}$; therefore, each coset is covered $6(2) = 12$ times. \bar{H} is covered by $\sum_i \bar{D}_i \bar{D}_i^{(-1)}$, which is the same as the abelian case. This implies

$$\bar{D} \bar{D}^{(-1)} = 16 \bar{1} + 12 \bar{G}, \quad (6)$$

so \bar{D} is a difference set in \bar{G} . ■

Corollary 3.2. *The following groups have difference sets as defined in the proof of Theorem 3.1; the groups are defined by their generators, followed by the isomorphism f and $\bar{g}_5, \bar{g}_5', \bar{g}_6, \bar{g}_6'$.*

- | | | | | |
|----|---------------------------------|---|--|--|
| 1. | $\bar{a}^{16} = \bar{b}^4 = 1,$ | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^3;$ | $f: \bar{a}^4 \rightarrow \bar{a}^4, \bar{b}^2 \rightarrow \bar{b}^2;$ | $(1, \bar{b}, \bar{a}^2, \bar{a}^4 \bar{b})$ |
| 2. | " | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^5;$ | " | $(1, \bar{b}, \bar{a}^2, \bar{a}^6 \bar{b})$ |
| 3. | " | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^7;$ | " | $(1, \bar{b}, \bar{a}^2, \bar{a}^3 \bar{b})$ |
| 4. | " | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^9;$ | " | $(1, \bar{b}, \bar{a}^2, \bar{a}^6 \bar{b})$ |
| 5. | " | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^{11};$ | " | $(1, \bar{b}, \bar{a}^2, \bar{a}^4 \bar{b})$ |
| 6. | " | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^{13};$ | " | $(1, \bar{b}, \bar{a}^2, \bar{a}^6 \bar{b})$ |
| 7. | $\bar{a}^{16} = \bar{b}^8 = 1,$ | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^7, \bar{a}^8 = \bar{b}^4;$ | $f: \bar{a}^4 \rightarrow \bar{a}^4, \bar{b}^2 \rightarrow \bar{a}^4 \bar{b}^2;$ | $(\bar{a}^6 \bar{b}, \bar{a}^2, 1, \bar{b})$ |
| 8. | " | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^9, \bar{a}^8 = \bar{b}^4;$ | " | $(\bar{a}^2, \bar{a}^6 \bar{b}, 1, \bar{b})$ |
| 9. | " | $\bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^{-1}, \bar{a}^8 = \bar{b}^4;$ | " | $(\bar{a}^6 \bar{b}, \bar{a}^2, 1, \bar{b})$ |

Remarks.

- (1) Not all groups which contain $Z_4 \times Z_2$ will have difference sets; $Z_{32} \times Z_2$ does not have a difference set, nor does the group defined by $\bar{a}^{16} = \bar{b}^4 = 1, \bar{b}\bar{a}\bar{b}^{-1} = \bar{a}^{-1}$. Condition 3.1(a) fails in these cases, and that condition appears to be the most difficult of the three to satisfy.
- (2) Theorem 3.1 can probably be generalized, but analogies would be needed for Lemma 2.3 and Condition 3.1(a).
- (3) Groups 3.2.2, 3.2.4, and 3.2.6 are contained in [3]; they are included here for completeness.

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