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## DIFFERENCE BASES IN DIHEDRAL GROUPS

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**ABSTRACT.** A subset  $B$  of a group  $G$  is called a *difference basis* of  $G$  if each element  $g \in G$  can be written as the difference  $g = ab^{-1}$  of some elements  $a, b \in B$ . The smallest cardinality  $|B|$  of a difference basis  $B \subset G$  is called the *difference size* of  $G$  and is denoted by  $\Delta[G]$ . The fraction  $\delta[G] := \Delta[G]/\sqrt{|G|}$  is called the *difference characteristic* of  $G$ . We prove that for every  $n \in \mathbb{N}$  the dihedral group  $D_{2n}$  of order  $2n$  has the difference characteristic  $\sqrt{2} \leq \delta[D_{2n}] \leq \frac{48}{\sqrt{586}} \approx 1.983$ . Moreover, if  $n \geq 2 \cdot 10^{15}$ , then  $\delta[D_{2n}] < \frac{4}{\sqrt{6}} \approx 1.633$ . Also we calculate the difference sizes and characteristics of all dihedral groups of cardinality  $\leq 80$ .

### 1. Introduction

A subset  $B$  of a group  $G$  is called a *difference basis* for a subset  $A \subset G$  if each element  $a \in A$  can be written as  $a = xy^{-1}$  for some  $x, y \in B$ . The smallest cardinality of a difference basis for  $A$  is called the *difference size* of  $A$  and is denoted by  $\Delta[A]$ . For example, the set  $\{0, 1, 4, 6\}$  is a difference basis for the interval  $A = [-6, 6] \cap \mathbb{Z}$  witnessing that  $\Delta[A] \leq 4$ .

The definition of a difference basis  $B$  for a set  $A$  in a group  $G$  implies that  $|A| \leq |B|^2$  and gives a lower bound  $\sqrt{|A|} \leq \Delta[A]$ . The fraction

$$\delta[A] := \frac{\Delta[A]}{\sqrt{|A|}} \geq 1$$

is called the *difference characteristic* of  $A$ .

For a real number  $x$  we put

$$\lceil x \rceil = \min\{n \in \mathbb{Z} : n \geq x\} \text{ and } \lfloor x \rfloor = \max\{n \in \mathbb{Z} : n \leq x\}.$$

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The following proposition is proved in [3, 1.1].

**Proposition 1.** *Let  $G$  be a finite group. Then*

- (1)  $\frac{1+\sqrt{4|G|-3}}{2} \leq \Delta[G] \leq \lceil \frac{|G|+1}{2} \rceil$ ,
- (2)  $\Delta[G] \leq \Delta[H] \cdot \Delta[G/H]$  and  $\delta[G] \leq \delta[H] \cdot \delta[G/H]$  for any normal subgroup  $H \subset G$ ;
- (3)  $\Delta[G] \leq |H| + |G/H| - 1$  for any subgroup  $H \subset G$ .

In [10] Kozma and Lev proved (using the classification of finite simple groups) that each finite group  $G$  has difference characteristic  $\delta[G] \leq \frac{4}{\sqrt{3}} \approx 2.3094$ .

In this paper we shall evaluate the difference characteristics of dihedral groups and prove that each dihedral group  $D_{2n}$  has  $\delta[D_{2n}] \leq \frac{48}{\sqrt{586}} \approx 1.983$ . Moreover, if  $n \geq 2 \cdot 10^{15}$ , then  $\delta[D_{2n}] < \frac{4}{\sqrt{6}} \approx 1.633$ . We recall that the *dihedral group*  $D_{2n}$  is the isometry group of a regular  $n$ -gon. The dihedral group  $D_{2n}$  contains a normal cyclic subgroup of index 2. A standard model of a cyclic group of order  $n$  is the multiplicative group

$$C_n = \{z \in \mathbb{C} : z^n = 1\}$$

of  $n$ -th roots of 1. The group  $C_n$  is isomorphic to the additive group of the ring  $\mathbb{Z}_n = \mathbb{Z}/n\mathbb{Z}$ .

Difference bases have applications in the study of structure of superextensions of groups, see [1, 3].

A subset  $B$  of a group  $G$  is called a *basis* of  $G$  if each element  $g \in G$  can be written as  $g = ab$  for some  $a, b \in B$ . Bases in dihedral groups were studied in [7].

**Theorem 2.** *For any numbers  $n, m \in \mathbb{N}$  the dihedral group  $D_{2nm}$  has the difference size*

$$2\sqrt{nm} \leq \Delta[D_{2nm}] \leq \Delta[D_{2n}] \cdot \Delta[C_m]$$

and the difference characteristic  $\sqrt{2} \leq \delta[D_{2nm}] \leq \delta[D_{2n}] \cdot \delta[C_m]$ .

*Proof.* It is well-known that the dihedral group  $D_{2nm}$  contains a normal cyclic subgroup of order  $nm$ , which can be identified with the cyclic group  $C_{nm}$ . The subgroup  $C_m \subset C_{nm}$  is normal in  $D_{2nm}$  and the quotient group  $D_{2nm}/C_m$  is isomorphic to  $D_{2n}$ . Applying Proposition 1(2), we obtain the upper bounds  $\Delta[D_{2n}] \leq \Delta[D_{2nm}/C_m] \cdot \Delta[C_m] = \Delta[D_{2n}] \cdot \Delta[C_m]$  and  $\delta[D_{2nm}] \leq \delta[D_{2n}] \cdot \delta[C_m]$ .

Next, we prove the lower bound  $2\sqrt{nm} \leq \Delta[D_{2nm}]$ . Fix any element  $s \in D_{2nm} \setminus C_{nm}$  and observe that  $s = s^{-1}$  and  $sxs^{-1} = x^{-1}$  for all  $x \in C_{nm}$ . Fix a difference basis  $D \subset D_{2nm}$  of cardinality  $|D| = \Delta[D_{2nm}]$  and write  $D$  as the union  $D = A \cup sB$  for some sets  $A, B \subset C_{nm} \subset D_{2nm}$ . We claim that  $AB^{-1} = C_{nm}$ . Indeed, for any  $x \in C_{nm}$  we get  $xs \in sC_{nm} \cap (A \cup sB)(A \cup sB)^{-1} = AB^{-1}s^{-1} \cup sBA^{-1}$  and hence

$$x \in AB^{-1}s^{-1}s^{-1} \cup sBA^{-1}s^{-1} = AB^{-1} \cup B^{-1}A = AB^{-1}.$$

So,  $C_{nm} = AB^{-1}$  and hence  $nm \leq |A| \cdot |B|$ . Then  $\Delta[D_{2nm}] = |A| + |B| \geq \min\{l + k : l, k \in \mathbb{N}, lk \geq nm\} \geq 2\sqrt{nm}$  and  $\delta[D_{2nm}] = \frac{\Delta[D_{2nm}]}{\sqrt{2nm}} \geq \frac{2\sqrt{nm}}{\sqrt{2nm}} = \sqrt{2}$ . □

**Corollary 3.** *For any number  $n \in \mathbb{N}$  the dihedral group  $D_{2n}$  has the difference size*

$$2\sqrt{n} \leq \Delta[D_{2n}] \leq 2 \cdot \Delta[C_n]$$

and the difference characteristic  $\sqrt{2} \leq \delta[D_{2n}] \leq \sqrt{2} \cdot \delta[C_n]$ .

The difference sizes of finite cyclic groups were evaluated in [2] with the help of the difference sizes of the order-intervals  $[1, n] \cap \mathbb{Z}$  in the additive group  $\mathbb{Z}$  of integer numbers. For a natural number  $n \in \mathbb{N}$  by  $\Delta[n]$  we shall denote the difference size of the order-interval  $[1, n] \cap \mathbb{Z}$  and by  $\delta[n] := \frac{\Delta[n]}{\sqrt{n}}$  its difference characteristic. The asymptotics of the sequence  $(\delta[n])_{n=1}^\infty$  was studied by Rédei and Rényi [11], Leech [9] and Golay [8] who eventually proved that

$$\sqrt{2 + \frac{4}{3\pi}} < \sqrt{2 + \max_{0 < \varphi < 2\pi} \frac{2 \sin(\varphi)}{\varphi + \pi}} \leq \lim_{n \rightarrow \infty} \delta[n] = \inf_{n \in \mathbb{N}} \delta[n] \leq \delta[6166] = \frac{128}{\sqrt{6166}} < \delta[6] = \sqrt{\frac{8}{3}}.$$

In [2] the difference sizes of the order-intervals  $[1, n] \cap \mathbb{Z}$  were applied to give upper bounds for the difference sizes of finite cyclic groups.

**Proposition 4.** *For every  $n \in \mathbb{N}$  the cyclic group  $C_n$  has difference size  $\Delta[C_n] \leq \Delta[\lceil \frac{n-1}{2} \rceil]$ , which implies that*

$$\limsup_{n \rightarrow \infty} \delta[C_n] \leq \frac{1}{\sqrt{2}} \inf_{n \in \mathbb{N}} \delta[n] \leq \frac{64}{\sqrt{3083}} < \frac{2}{\sqrt{3}}.$$

The following upper bound for the difference sizes of cyclic groups were proved in [2].

**Theorem 5.** *For any  $n \in \mathbb{N}$  the cyclic group  $C_n$  has the difference characteristic:*

- (1)  $\delta[C_n] \leq \delta[C_4] = \frac{3}{2}$ ;
- (2)  $\delta[C_n] \leq \delta[C_2] = \delta[C_8] = \sqrt{2}$  if  $n \neq 4$ ;
- (3)  $\delta[C_n] \leq \frac{12}{\sqrt{73}} < \sqrt{2}$  if  $n \geq 9$ ;
- (4)  $\delta[C_n] \leq \frac{24}{\sqrt{293}} < \frac{12}{\sqrt{73}}$  if  $n \geq 9$  and  $n \neq 292$ ;
- (5)  $\delta[C_n] < \frac{2}{\sqrt{3}}$  if  $n \geq 2 \cdot 10^{15}$ .

For some special numbers  $n$  we have more precise upper bounds for  $\Delta[C_n]$ . A number  $q$  is called a *prime power* if  $q = p^k$  for some prime number  $p$  and some  $k \in \mathbb{N}$ .

The following theorem was derived in [2] from the classical results of Singer [13], Bose, Chowla [4], [5] and Rusza [12].

**Theorem 6.** *Let  $p$  be a prime number and  $q$  be a prime power. Then*

- (1)  $\Delta[C_{q^2+q+1}] = q + 1$ ;
- (2)  $\Delta[C_{q^2-1}] \leq q - 1 + \Delta[C_{q-1}] \leq q - 1 + \frac{3}{2}\sqrt{q-1}$ ;
- (3)  $\Delta[C_{p^2-p}] \leq p - 3 + \Delta[C_p] + \Delta[C_{p-1}] \leq p - 3 + \frac{3}{2}(\sqrt{p} + \sqrt{p-1})$ .

The following Table 1 of difference sizes and characteristics of cyclic groups  $C_n$  for  $n \leq 100$  is taken from [2].

TABLE 1. Difference sizes and characteristics of cyclic groups  $C_n$  for  $n \leq 100$ .

$n$	$\Delta[C_n]$	$\delta[C_n]$	$n$	$\Delta[C_n]$	$\delta[C_n]$	$n$	$\Delta[C_n]$	$\delta[C_n]$	$n$	$\Delta[C_n]$	$\delta[C_n]$
1	1	1	26	6	1.1766...	51	8	1.1202...	76	10	1.1470...
2	2	1.4142...	27	6	1.1547...	52	9	1.2480...	77	10	1.1396...
3	2	1.1547...	28	6	1.1338...	53	9	1.2362...	78	10	1.1322...
4	3	1.5	29	7	1.2998...	54	9	1.2247...	79	10	1.1250...
5	3	1.3416...	30	7	1.2780...	55	9	1.2135...	80	11	1.2298...
6	3	1.2247...	31	6	1.0776...	56	9	1.2026...	81	11	1.2222...
7	3	1.1338...	32	7	1.2374...	57	8	1.0596...	82	11	1.2147...
8	4	1.4142...	33	7	1.2185...	58	9	1.1817...	83	11	1.2074...
9	4	1.3333...	34	7	1.2004...	59	9	1.1717...	84	11	1.2001...
10	4	1.2649...	35	7	1.1832...	60	9	1.1618...	85	11	1.1931...
11	4	1.2060...	36	7	1.1666...	61	9	1.1523...	86	11	1.1861...
12	4	1.1547...	37	7	1.1507...	62	9	1.1430...	87	11	1.1793...
13	4	1.1094...	38	8	1.2977...	63	9	1.1338...	88	11	1.1726...
14	5	1.3363...	39	7	1.1208...	64	9	1.125	89	11	1.1659...
15	5	1.2909...	40	8	1.2649...	65	9	1.1163...	90	11	1.1595...
16	5	1.25	41	8	1.2493...	66	10	1.2309...	91	10	1.0482...
17	5	1.2126...	42	8	1.2344...	67	10	1.2216...	92	11	1.1468...
18	5	1.1785...	43	8	1.2199...	68	10	1.2126...	93	12	1.2443...
19	5	1.1470...	44	8	1.2060...	69	10	1.2038...	94	12	1.2377...
20	6	1.3416...	45	8	1.1925...	70	10	1.1952...	95	12	1.2311...
21	5	1.0910...	46	8	1.1795...	71	10	1.1867...	96	12	1.2247...
22	6	1.2792...	47	8	1.1669...	72	10	1.1785...	97	12	1.2184...
23	6	1.2510...	48	8	1.1547...	73	9	1.0533...	98	12	1.2121...
24	6	1.2247...	49	8	1.1428...	74	10	1.1624...	99	12	1.2060...
25	6	1.2	50	8	1.1313...	75	10	1.1547...	100	12	1.2

Using Theorem 6(1), we shall prove that for infinitely many numbers  $n$  the lower and upper bounds given in Theorem 2 uniquely determine the difference size  $\Delta[D_{2n}]$  of  $D_{2n}$ .

**Theorem 7.** *If  $n = 1 + q + q^2$  for some prime power  $q$ , then*

$$\Delta[D_{2n}] = 2 \cdot \Delta[C_n] = \lceil 2\sqrt{n} \rceil = \lceil \sqrt{2|D_{2n}|} \rceil = 2 + 2q.$$

*Proof.* By Theorem 6(1),  $\Delta[C_n] = 1 + q$ . Since

$$2\sqrt{q^2 + q + 1} = 2\sqrt{n} \leq \Delta[D_{2n}] \leq \Delta[D_2] \cdot \Delta[C_n] = 2 \cdot \Delta[C_n] = 2 + 2q,$$

it suffices to check that  $(2 + 2q) - 2\sqrt{q^2 + q + 1} < 1$ , which is equivalent to  $\sqrt{q^2 + q + 1} > q + \frac{1}{2}$  and to  $q^2 + q + 1 > q^2 + q + \frac{1}{4}$ .  $\square$

A bit weaker result holds also for the dihedral groups  $D_{8(q^2+q+1)}$ .

**Proposition 8.** *If  $n = 1 + q + q^2$  for some prime power  $q$ , then*

$$4q + 3 \leq \Delta[D_{8n}] \leq 4q + 4.$$

*Proof.* By Theorem 6(1),  $\Delta[C_n] = 1 + q$ . Since  $\Delta[D_8] = 4$  (see Table 2), by Theorem 2,

$$4\sqrt{q^2 + q + 1} = 2\sqrt{4n} \leq \Delta[D_{8n}] \leq \Delta[D_8] \cdot \Delta[C_n] = 4(1 + q).$$

To see that  $4q + 3 \leq \Delta[D_{8n}] \leq 4q + 4$ , it suffices to check that  $(4 + 4q) - 4\sqrt{q^2 + q + 1} < 2$ , which is equivalent to  $\sqrt{q^2 + q + 1} > q + \frac{1}{2}$  and to  $q^2 + q + 1 > q^2 + q + \frac{1}{4}$ .  $\square$

In Table 2 we present the results of computer calculation of the difference sizes and characteristics of dihedral groups of order  $\leq 80$ . In this table  $lb[D_{2n}] := \lceil \sqrt{4n} \rceil$  is the lower bound given in Theorem 2. With the boldface font we denote the numbers  $2n \in \{14, 26, 42, 62\}$ , equal to  $2(q^2 + q + 1)$  for a prime power  $q$ . For these numbers we know that  $\Delta[D_{2n}] = lb[D_{2n}] = 2q + 2$ . For  $q = 2$  and  $n = q^2 + q + 1 = 7$  the table shows that  $\Delta[D_{56}] = \Delta[D_{8n}] = 11 = 4q + 3$ , which means that the lower bound  $4q + 3$  in Proposition 8 is attained.

**Theorem 9.** *For any number  $n \in \mathbb{N}$  the dihedral group  $D_{2n}$  has the difference characteristic*

$$\sqrt{2} \leq \delta[D_{2n}] \leq \frac{48}{\sqrt{586}} \approx 1.983.$$

Moreover, if  $n \geq 2 \cdot 10^{15}$ , then  $\delta[D_{2n}] < \frac{4}{\sqrt{6}} \approx 1.633$ .

*Proof.* By Corollary 3,  $\sqrt{2} \leq \delta[D_{2n}] \leq \sqrt{2} \cdot \delta[C_n]$ . If  $n \geq 9$  and  $n \neq 292$ , then  $\delta[C_n] \leq \frac{24}{\sqrt{293}}$  by Theorem 5(4), and hence  $\delta[D_{2n}] \leq \sqrt{2} \cdot \delta[C_n] \leq \sqrt{2} \cdot \frac{24}{\sqrt{293}} = \frac{48}{\sqrt{586}}$ . If  $n = 292$ , then known values  $\delta[C_{73}] = \frac{9}{\sqrt{73}}$  (given in Table 1),  $\delta[D_8] = \frac{4}{\sqrt{8}} = \sqrt{2}$  (given in Table 2) and Theorem 2 yield the upper bound

$$\delta[D_{2 \cdot 292}] = \delta[D_{8 \cdot 73}] \leq \delta[D_8] \cdot \delta[C_{73}] = \sqrt{2} \cdot \frac{9}{\sqrt{73}} < \frac{48}{\sqrt{586}}.$$

Analyzing the data from Table 2, one can check that  $\delta[D_{2n}] \leq \frac{48}{\sqrt{586}} \approx 1.983$  for all  $n \leq 8$ .

If  $n \geq 2 \cdot 10^{15}$ , then  $\delta[C_n] < \frac{2}{\sqrt{3}}$  by Theorem 5(5), and hence

$$\delta[D_{2n}] \leq \sqrt{2} \cdot \delta[C_n] < \frac{4}{\sqrt{6}}.$$

$\square$

**Question 10.** *Is  $\sup_{n \in \mathbb{N}} \delta[D_{2n}] = \delta[D_{22}] = \frac{8}{\sqrt{22}} \approx 1.7056$ ?*

To answer Question 10 affirmatively, it suffices to check that  $\delta[D_{2n}] \leq \frac{8}{\sqrt{22}}$  for all  $n < 1\,212\,464$ .

TABLE 2. Difference sizes and characteristics of dihedral groups  $D_{2n}$  for  $2n \leq 80$ .

$2n$	$lb[D_{2n}]$	$\Delta[D_{2n}]$	$2\Delta[C_n]$	$\delta[D_{2n}]$	$2n$	$lb[D_{2n}]$	$\Delta[D_{2n}]$	$2\Delta[C_n]$	$\delta[D_{2n}]$
2	2	2	2	1.4142...	<b>42</b>	10	10	10	1.5430...
4	3	3	4	1.5	44	10	10	12	1.5075...
6	4	4	4	1.6329...	46	10	11	12	1.6218...
8	4	4	6	1.4142...	48	10	10	12	1.4433...
10	5	5	6	1.5811...	50	10	11	12	1.5556...
12	5	5	6	1.4433...	52	11	11	12	1.5254...
<b>14</b>	6	6	6	1.6035...	54	11	12	12	1.6329...
16	6	6	8	1.5	56	11	11	12	1.4699...
18	6	7	8	1.6499...	58	11	12	14	1.5756...
20	7	7	8	1.5652...	60	11	12	14	1.5491...
22	7	8	8	1.7056...	<b>62</b>	12	12	12	1.5240...
24	7	7	8	1.4288...	64	12	12	14	1.5
<b>26</b>	8	8	8	1.5689...	66	12	13	14	1.6001...
28	8	8	10	1.5118...	68	12	13	14	1.5764...
30	8	8	10	1.4605...	70	12	12	14	1.4342...
32	8	9	10	1.5909...	72	12	13	14	1.5320...
34	9	9	10	1.5434...	74	13	14	14	1.6274...
36	9	9	10	1.5	76	13	14	16	1.6059...
38	9	10	10	1.6222...	78	13	14	14	1.5851...
40	9	9	12	1.4230...	80	13	14	16	1.5652...

**Proposition 11.** *The inequality  $\delta[D_{2n}] \leq \sqrt{2} \cdot \delta[C_n] \leq \frac{8}{\sqrt{22}}$  holds for all  $n \geq 1\,212\,464$ .*

*Proof.* It suffices to prove that  $\delta[C_n] \leq \frac{4}{\sqrt{11}}$  for all  $n \geq 1\,212\,464$ . To derive a contradiction, assume that  $\delta[C_n] > \frac{4}{\sqrt{11}}$  for some  $n \geq 1\,212\,464$ . Let  $(q_k)_{k=1}^\infty$  be an increasing enumeration of prime powers. Let  $k \in \mathbb{N}$  be the unique number such that  $12q_k^2 + 14q_k + 15 < n \leq 12q_{k+1}^2 + 14q_{k+1} + 15$ . By Corollary 4.9 of [2],  $\Delta[C_n] \leq 4(q_{k+1} + 1)$ . The inequality  $\delta[C_n] > \frac{4}{\sqrt{11}}$  implies

$$4(q_{k+1} + 1) \geq \Delta[C_n] > \frac{4}{\sqrt{11}}\sqrt{n} \geq \frac{4}{\sqrt{11}}\sqrt{12q_k^2 + 14q_k + 16}.$$

By Theorem 1.9 of [6], if  $q_k \geq 3275$ , then  $q_{k+1} \leq q_k + \frac{q_k}{2\ln^2(q_k)}$ . On the other hand, using WolframAlpha computational knowledge engine it can be shown that the inequality  $1 + x + \frac{x}{2\ln^2(x)} \leq \frac{1}{\sqrt{11}}\sqrt{12x^2 + 14x + 16}$  holds for all  $x \geq 43$ . This implies that  $q_k < 3275$ .

Analyzing the table<sup>1</sup> of (maximal gaps between) primes, it can be shown that  $11(q_{k+1} + 1)^2 \leq 12q_k^2 + 14q_k + 16$  if  $q_k \geq 331$ . So,  $q_k \leq 317$ ,  $q_{k+1} \leq 331$  and  $11 \cdot (q_{k+1} + 1)^2 = 11 \cdot 332^2 = 1\,212\,464 \leq n$ , which contradicts  $4(q_{k+1} + 1) > \frac{4}{\sqrt{11}}\sqrt{n}$ .  $\square$

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<sup>1</sup>See <https://primes.utm.edu/notes/GapsTable.html> and <https://primes.utm.edu/lists/small/1000.txt>