

ON ORDER PRIME DIVISOR GRAPHS OF FINITE GROUPS

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Abstract

The order prime divisor graph $\mathcal{PD}(G)$ of a finite group G is a simple graph whose vertex set is G and two vertices $a, b \in G$ are adjacent if and only if either $ab = e$ or $o(ab)$ is some prime number, where e is the identity element of the group G and $o(x)$ denotes the order of an element $x \in G$. In this paper, we establish the necessary and sufficient condition for the completeness of order prime divisor graph $\mathcal{PD}(G)$ of a group G . Concentrating on the graph $\mathcal{PD}(D_n)$, we investigate several properties like degrees, girth, regularity, Eulerianity, Hamiltonicity, planarity etc. We characterize some graph theoretic properties of $\mathcal{PD}(\mathbb{Z}_n)$, $\mathcal{PD}(S_n)$, $\mathcal{PD}(A_n)$.

Keywords: group, dihedral group, complete graph, Eulerian graph, regular graph, planar graph, order prime divisor graph.

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1. INTRODUCTION

Defining graphs over groups help us for studying the interplay between algebraic properties and graph-theoretic properties and structures. For a finite group G , one can associate a certain type of graph, order prime divisor graph $\mathcal{PD}(G)$,

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and investigate the interplay between the group-theoretic properties of G and the graph-theoretic properties of order prime divisor graph $\mathcal{PD}(G)$.

There are a number of constructions of graphs from groups or semigroups in the literature. Here we begin by introducing some well-known graphs associated with semigroups or groups. In 1964, Bosák [1] studied certain graph over semigroups. Then Csákány and Pollák [2] defined intersection graphs of nontrivial proper subgroups of groups. In [9], Zelinka studied intersection graphs of nontrivial subgroups of finite Abelian groups. Later on, the intersection graph of ideals of rings was studied by Chakrabarty, Ghosh, Mukherjee and Sen [3].

In [6], Kelarev and Quinn introduced the notion of the (directed) power graph $P(G)$ of a group G and described the structure of the (directed) power graphs of all finite abelian groups. According to them the (directed) power graph $P(G)$ of a group G is a directed graph with the set G of vertices, and with all edges (u, v) such that $u \neq v$ and v is the power of u . Later on, Chakrabarty, Ghosh and Sen [4] defined the undirected power graph $\mathcal{G}(S)$ of a semigroup S as the undirected graph with vertex set S and distinct vertices a and b are adjacent if $a^m = b$ or $b^m = a$ for some positive integer m .

In 2009, the authors [7] defined order prime graph and studied its properties. According to them the order prime graph $OP(\Gamma)$ of a finite group Γ is a graph with vertex set Γ and two vertices are adjacent in $OP(\Gamma)$ if and only if their orders are relatively prime in Γ .

In this paper, a new type of graph, called order prime divisor graph, is defined and studied its properties. For a finite group G , the order prime divisor graph of G , denoted by $\mathcal{PD}(G)$, is a simple graph with vertex set G and two vertices a, b are adjacent in $\mathcal{PD}(G)$ if and only if either $o(ab) = 1$ or $o(ab) = p$ for some prime p , i.e., either a and b are inverse to each other or ab is an element of prime order. Thus in $\mathcal{PD}(G)$ two vertices a, b are adjacent if and only if $o(ab)$ divides p for some prime number p and that's why we have named this graph as order prime divisor graph. We note that if G is a group, then $o(ab) = o(ba)$ for any two elements $a, b \in G$. Clearly, by definition, order prime divisor graph $\mathcal{PD}(G)$ of a finite group G contains no isolated vertices. Following examples show that cyclic groups may have disconnected order prime divisor graphs where as non cyclic (even non-commutative) groups have connected order prime divisor graphs.



Figure 1. $\mathcal{PD}(\mathbb{Z}_4)$

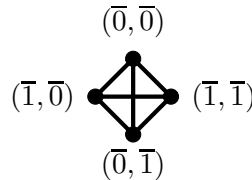


Figure 2. $\mathcal{PD}(\mathbb{Z}_2 \oplus \mathbb{Z}_2)$

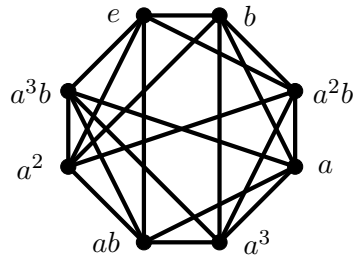


Figure 3. $\mathcal{PD}(D_4)$

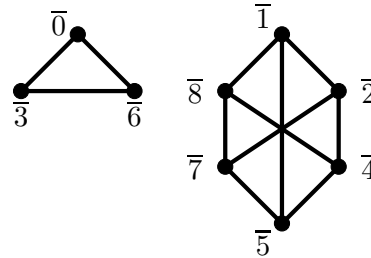


Figure 4. $\mathcal{PD}(\mathbb{Z}_9)$

In this paper, $\mathbb{Z}_n = \{\overline{0}, \overline{1}, \dots, \overline{n-1}\}$ is the additive group of integers modulo n , $U(n) = \{\overline{x} \in \mathbb{Z}_n : \gcd(x, n) = 1\}$ denotes the group of units of the ring $(\mathbb{Z}_n, +, \cdot)$ of order $\varphi(n)$, D_n is the dihedral group of order $2n$, S_n is the permutation group on n symbols, A_n is the alternating group on n symbols, $GL_n(F_q)$ denotes the general linear group over a finite field F_q , $SL_n(F_q)$ denotes the special linear group over a finite field F_q , T denotes a non-commutative group containing 12 elements and is defined by $T = \langle a, b : o(a) = 6, b^2 = a^3, ba = a^{-1}b \rangle$, K_n denotes the complete graph with n vertices, $K_{r,s}$ denotes the complete bipartite graph or biclique where partite sets have sizes r and s , C_n denotes a cycle with n vertices, $\deg(v)$ denotes the degree of a vertex v , $a \leftrightarrow b$ denotes that vertices a, b are adjacent. For usual algebraic terms, we refer to [5], and we refer to [8] for graph-theoretic terms, definitions and notations.

2. SOME PROPERTIES OF $\mathcal{PD}(G)$

In this section, we study some interesting properties of $\mathcal{PD}(G)$. We also establish here the necessary and sufficient condition for the order prime divisor graph $\mathcal{PD}(G)$ of a finite group to be complete.

Theorem 2.1. *For a finite group G , $\mathcal{PD}(G)$ is complete if and only if each non identity element of G is of prime order.*

Proof. Let G be a finite group with order of each non identity element is prime. Let a, b be any two distinct elements of G . If $ab = e$, then $o(ab) = 1$ and thus a and b are adjacent in $\mathcal{PD}(G)$. Suppose $ab \neq e$. Then by the given hypothesis it follows that $o(ab)$ is some prime and hence these two elements a and b are adjacent in $\mathcal{PD}(G)$. Therefore, between any two distinct vertices in $\mathcal{PD}(G)$, there is an edge and hence $\mathcal{PD}(G)$ is complete.

Conversely, let G be finite group for which $\mathcal{PD}(G)$ is complete. Let $a (\neq e)$ be any element of G . Since $\mathcal{PD}(G)$ is complete, we must have an edge between the vertices a and e . Therefore $o(a) = o(ae)$ must be prime. Consequently, order of any non identity element of G is prime. ■

Corollary 2.2. *Let G be a group of prime order. Then $\mathcal{PD}(G)$ is complete.*

Corollary 2.3. *S_3, A_4, A_5 are non-commutative groups whose order prime divisor graphs $\mathcal{PD}(S_3), \mathcal{PD}(A_4), \mathcal{PD}(A_5)$ are complete.*

Corollary 2.4. *Let G be a finite commutative group. Then $\mathcal{PD}(G)$ is complete if and only if $G \cong \underbrace{\mathbb{Z}_p \oplus \mathbb{Z}_p \oplus \cdots \oplus \mathbb{Z}_p}_{n\text{-fold}}$ for some positive integer n .*

Proof. First suppose that $G \cong \underbrace{\mathbb{Z}_p \oplus \mathbb{Z}_p \oplus \cdots \oplus \mathbb{Z}_p}_{n\text{-fold}}$ for some positive integer n .

Then order of any non identity element of G is p and hence by Theorem 2.1, it follows that $\mathcal{PD}(G)$ is complete.

Conversely, let G be a finite commutative group such that $\mathcal{PD}(G)$ is complete. Then by Theorem 2.1, it follows that every non identity element of G is of prime order. Now by the structure theorem of finite commutative group, we have $G \cong \mathbb{Z}_{p_1}^{n_1} \oplus \mathbb{Z}_{p_2}^{n_2} \oplus \cdots \oplus \mathbb{Z}_{p_k}^{n_k}$, where p_1, p_2, \dots, p_k are primes (not necessarily distinct) and n_1, n_2, \dots, n_k are positive integers. First we show that $n_1 = n_2 = \cdots = n_k = 1$. On the contrary, suppose $n_i > 1$, for some $i \in \{1, 2, \dots, k\}$. Then G contains elements of composite order $p_i^{n_i}$, a contradiction. Therefore, $n_1 = n_2 = \cdots = n_k = 1$ and thus $G \cong \mathbb{Z}_{p_1} \oplus \mathbb{Z}_{p_2} \oplus \cdots \oplus \mathbb{Z}_{p_k}$. We now show that $p_1 = p_2 = \cdots = p_k$. Suppose $p_i \neq p_j$, for some $1 \leq i, j \leq k$. Then G contains elements of composite order $p_i p_j$, which is again a contradiction. Therefore, $p_1 = p_2 = \cdots = p_k = p$ (say) and thus $G \cong \underbrace{\mathbb{Z}_p \oplus \mathbb{Z}_p \oplus \cdots \oplus \mathbb{Z}_p}_{k\text{-fold}}$. ■

Theorem 2.5. *If a finite group G has a subgroup of order p (where p is prime), then $\mathcal{PD}(G)$ contains a clique with p vertices.*

Proof. Let H be a subgroup of a finite group G such that $|H| = p$ for some prime number p . Then every non identity element in H is of order p . Therefore, $\mathcal{PD}(H)$ is a complete graph containing p vertices. Since $\mathcal{PD}(H)$ is a subgraph of $\mathcal{PD}(G)$, it follows that $\mathcal{PD}(G)$ has a clique $\mathcal{PD}(H)$ with p vertices. ■

Remark 2.6. (i) The vertices of every clique in $\mathcal{PD}(G)$ may not form a subgroup of G . For example, in the order prime divisor graph $\mathcal{PD}(\mathbb{Z}_4 \oplus \mathbb{Z}_4)$, $\{(\bar{0}, \bar{1}), (\bar{0}, \bar{3}), (\bar{2}, \bar{1}), (\bar{2}, \bar{3})\}, \{(\bar{1}, \bar{0}), (\bar{1}, \bar{2}), (\bar{3}, \bar{0}), (\bar{3}, \bar{2})\}, \{(\bar{1}, \bar{1}), (\bar{1}, \bar{3}), (\bar{3}, \bar{1}), (\bar{3}, \bar{3})\}$ form three different clique but none of them forms a subgroup of $\mathbb{Z}_4 \oplus \mathbb{Z}_4$.

(ii) If the vertices of a clique in $\mathcal{PD}(G)$ form a subgroup H of G then order of H may not be prime. For example, in the order prime divisor graph $\mathcal{PD}(\mathbb{Z}_4 \oplus \mathbb{Z}_4)$, $\{(\bar{0}, \bar{0}), (\bar{0}, \bar{2}), (\bar{2}, \bar{0}), (\bar{2}, \bar{2})\}$ form a subgroup of $\mathbb{Z}_4 \oplus \mathbb{Z}_4$, which is of order 4.

Theorem 2.7. *Let G be a finite group and $p (\geq 5)$ be a prime such that p divides $|G|$. Then $\mathcal{PD}(G)$ is a non planar graph.*

Proof. Let G be a group of order n and $p (\geq 5)$ be a prime such that p divides n . Then by Cauchy's Theorem, G has an element of order p and hence a subgroup H of order p . Now by Theorem 2.5, $\mathcal{PD}(H) = K_p$ is a subgraph of $\mathcal{PD}(G)$. Since $p \geq 5$, it follows that $\mathcal{PD}(G)$ contains K_5 as a subgraph. Hence by Kuratowski's Theorem, it follows that $\mathcal{PD}(G)$ is a non planar graph. ■

Remark 2.8. Converse of Theorem 2.7 is not true in general. From Corollary 2.3, we have $\mathcal{PD}(S_3)$ and $\mathcal{PD}(A_4)$ are complete graphs and hence they are non planar as well as non outerplanar, though there are no prime greater or equal to 5 dividing the order of the groups.

Corollary 2.9. *If a finite group G has a centre of prime order p , then $\mathcal{PD}(G)$ contains a clique with p vertices.*

Corollary 2.10. *If m is a positive integer such that $2^m - 1$ is prime (called Mersenne prime), then $\mathcal{PD}(GL_n(F_{2^m}))$ has a clique with $2^m - 1$ vertices.*

Proof. Now $Z(GL_n(F_{2^m})) = \{A = (a_{ij})_{n \times n} : a_{ij} = 0, 1 \leq i \neq j \leq n; a_{ii} = a \in F_{2^m} \setminus \{0\}\}$ ($n > 1$) implies $|Z(GL_n(F_{2^m}))| = 2^m - 1$. Hence by Corollary 2.9, we have $\mathcal{PD}(GL_n(F_{2^m}))$ has a clique with $2^m - 1$ vertices. ■

Corollary 2.11. *Let F_q be a finite field with q elements and n be a positive integers such that $\gcd(n, q - 1)$ is prime. Then $\mathcal{PD}(SL_n(F_q))$ has a clique with $\gcd(n, q - 1)$ vertices.*

Proof. Let n be a positive integer such that $\gcd(n, q - 1)$ is prime. For $n (> 1)$, we have $Z(SL_n(F_q)) = \{A = (a_{ij})_{n \times n} : a_{ij} = 0, i \neq j; a_{ii} = a \in F_q \setminus \{0\}; a^n = 1\}$ implies $|Z(SL_n(F_q))| = \gcd(n, q - 1)$. Hence by Corollary 2.9, we have $\mathcal{PD}(SL_n(F_q))$ has a clique with $\gcd(n, q - 1)$ vertices. ■

Recall that the girth of a graph with at least one cycle is the length of its shortest cycle. A graph with no cycle has infinite girth. A graph with no cycle is said to be an acyclic graph. A forest is an acyclic graph whereas a tree is a connected acyclic graph.

Theorem 2.12. *Let G be a finite group and p is an odd prime such that p divides $|G|$. Then $\mathcal{PD}(G)$ is neither bipartite nor a tree and $\text{girth}(\mathcal{PD}(G)) = 3$.*

Proof. Let G be a group of order n and p be an odd prime such that p divides n . Then G contains an element x of order p . Since p is an odd prime, we have $x \neq x^{-1}$ and $o(x^{-1}) = p$. This implies $x \leftrightarrow e \leftrightarrow x^{-1} \leftrightarrow x$ forms a cycle in $\mathcal{PD}(G)$ of length 3. Since $\mathcal{PD}(G)$ is a simple graph, we must have $\text{girth}(\mathcal{PD}(G)) = 3$. Also $\mathcal{PD}(G)$ contains an odd cycle implies $\mathcal{PD}(G)$ is neither bipartite nor a tree. ■

Theorem 2.13. *If G_1, G_2 are two finite groups such that $G_1 \cong G_2$, then $\mathcal{PD}(G_1) \cong \mathcal{PD}(G_2)$.*

Proof. Let G_1 and G_2 be two finite groups and $\psi : G_1 \rightarrow G_2$ be an isomorphism. Let $a, b \in G_1$ be adjacent in $\mathcal{PD}(G_1)$. Then either $o(ab) = 1$ or $o(ab) = p$ for some prime p . Since ψ is an isomorphism, we have $o(\psi(a)\psi(b)) = o(\psi(ab)) = o(ab)$. If $o(ab) = 1$, then $o(\psi(a)\psi(b)) = 1$ and hence $\psi(a)$ and $\psi(b)$ are adjacent in $\mathcal{PD}(G_2)$. On the other hand, if $o(ab) = p$, then $o(\psi(a)\psi(b)) = p$ and hence $\psi(a)$ is adjacent to $\psi(b)$ in $\mathcal{PD}(G_2)$. Conversely, if $\psi(a)$ and $\psi(b)$ are adjacent in $\mathcal{PD}(G_2)$, one can easily check that a and b are adjacent in $\mathcal{PD}(G_1)$. Hence $\mathcal{PD}(G_1) \cong \mathcal{PD}(G_2)$. ■

Remark 2.14. The converse of Theorem 2.13 is not true in general. For example we consider two non-isomorphic groups $\mathbb{Z}_{27} \oplus \mathbb{Z}_3$ and $\mathbb{Z}_9 \oplus \mathbb{Z}_9$. Then both the graphs $\mathcal{PD}(\mathbb{Z}_{27} \oplus \mathbb{Z}_3)$ and $\mathcal{PD}(\mathbb{Z}_9 \oplus \mathbb{Z}_9)$ have five components. Out of these five components one component is a 8-regular graph with 9 vertices and each of remaining four components is a 9-regular graph with 18 vertices. Therefore, $\mathcal{PD}(\mathbb{Z}_{27} \oplus \mathbb{Z}_3) \cong \mathcal{PD}(\mathbb{Z}_9 \oplus \mathbb{Z}_9)$ though $\mathbb{Z}_{27} \oplus \mathbb{Z}_3 \not\cong \mathbb{Z}_9 \oplus \mathbb{Z}_9$.

Corollary 2.15. *For a finite group G , $\text{Aut}(G) \subseteq \text{Aut}(\mathcal{PD}(G))$.*

Proof. Follows from Theorem 2.13. ■

Theorem 2.16. *Let G be a finite commutative group. Then $\mathcal{PD}(G)$ has at least two pendant vertices if and only if $G \cong \mathbb{Z}_{2^r}$, for some positive integer r .*

Proof. Let $G \cong \mathbb{Z}_{2^r}$, for some positive integer r . Since $\overline{2^{r-1}} \in \mathbb{Z}_{2^r}$ is the unique element of order 2, we have $\deg(\overline{0}) = 1 = \deg(\overline{2^{r-1}})$ in $\mathcal{PD}(\mathbb{Z}_{2^r})$. Hence $\mathcal{PD}(\mathbb{Z}_{2^r})$ has at least two pendant vertices.

Conversely, let G be a finite commutative group of order n such that $\mathcal{PD}(G)$ contains at least two pendant vertices. First we prove that n has no odd prime divisor. For this, let p be any odd prime divisor of n . Then G contains at least two elements x and y of order p . Now let $a \in G$ be any element. Then $a \leftrightarrow a^{-1}x$ and $a \leftrightarrow a^{-1}y$ in $\mathcal{PD}(G)$ and thus $\deg(a) \geq 2$ in $\mathcal{PD}(G)$. Hence $\mathcal{PD}(G)$ contains no pendant vertices, a contradiction. Therefore, 2 is the only one divisor of n and hence $G \cong \mathbb{Z}_{2^{n_1}} \oplus \mathbb{Z}_{2^{n_2}} \oplus \cdots \oplus \mathbb{Z}_{2^{n_k}}$ for some positive integers n_1, n_2, \dots, n_k . We now show that $k = 1$. On the contrary, let $k > 1$. Then G contains at least three elements of order 2 and hence degree of every vertex in $\mathcal{PD}(G)$ is at least 3. Thus $\mathcal{PD}(G)$ contains no pendant vertices, which is again a contradiction. Therefore, $k = 1$ and consequently $G \cong \mathbb{Z}_{2^r}$, for some positive integer r . ■

Corollary 2.17. *For a finite commutative group G , $\mathcal{PD}(G)$ is a forest if and only if either $G \cong \mathbb{Z}_2$ or $G \cong \mathbb{Z}_4$.*

Proof. First we assume that G is isomorphic to either \mathbb{Z}_2 or \mathbb{Z}_4 . Then clearly $\mathcal{PD}(G)$ is a forest.

Conversely, let G be a finite commutative group such that $\mathcal{PD}(G)$ is a forest. We know that every tree with at least two vertices has at least two pendant vertices and every component of a forest is a tree. Hence by Theorem 2.16, G is of the form \mathbb{Z}_{2^r} , for some positive integer r . We now show that r must be equal to 1 or 2. On the contrary, let $r \geq 3$. Then $\bar{1} \leftrightarrow \overline{2^{r-1} - 1} \leftrightarrow \overline{2^{r-1} + 1} \leftrightarrow \overline{2^r - 1} \leftrightarrow \bar{1}$ forms a cycle in $\mathcal{PD}(\mathbb{Z}_{2^r})$. Hence $\mathcal{PD}(\mathbb{Z}_{2^r})$ is not a forest, a contradiction. This contradiction ensures that $r \leq 2$. Consequently, G is isomorphic to either \mathbb{Z}_2 or \mathbb{Z}_4 . ■

We need a result that follows from [5, Chapter 9, Section 9.5, Corollary 20].

Theorem 2.18. *Let $n \geq 2$ be an integer with factorization $n = p_1^{k_1} p_2^{k_2} \cdots p_r^{k_r}$ in \mathbb{Z} , where p_1, p_2, \dots, p_r are distinct primes. Then*

- (i) $U(n) \cong U(p_1^{k_1}) \times U(p_2^{k_2}) \times \cdots \times U(p_r^{k_r})$,
- (ii) $U(2^\alpha) \cong \mathbb{Z}_2 \times \mathbb{Z}_{2^{\alpha-2}}$, for all $\alpha \geq 2$,
- (iii) $U(p^\alpha) \cong \mathbb{Z}_{p^{\alpha-1}(p-1)}$ for any odd prime p .

Theorem 2.19. *For any integer $n \geq 3$, the order prime divisor graph $\mathcal{PD}(U(2^n))$ has no pendant vertices.*

Proof. For any $n \geq 3$, $U(2^n) \cong \mathbb{Z}_2 \oplus \mathbb{Z}_{2^{n-2}}$ and hence by Theorem 2.16, it follows that $\mathcal{PD}(U(2^n))$ has no pendant vertices. ■

Corollary 2.20. *For any odd prime p and for any positive integer n , the order prime divisor graph $\mathcal{PD}(U(p^n))$ has no pendant vertices.*

Proof. For any odd prime p , $U(p^n) \cong \mathbb{Z}_{p^{n-1}(p-1)}$. Therefore, by Theorem 2.16, it follows that for any odd prime p and for positive integer n , the order prime divisor graph $\mathcal{PD}(U(p^n))$ has no pendant vertices. ■

3. ORDER PRIME DIVISOR GRAPH OF THE GROUP \mathbb{Z}_n

A graph G is said to be a k -regular graph (k is a non negative integer) if the degree of each vertex of G is k . In this section we study k -regular order prime divisor graph of the group $(\mathbb{Z}_n, +)$. From Corollary 2.2, it follows that order prime divisor graph of any group of prime order p is $(p - 1)$ -regular. In this section we study order prime divisor graph of any cyclic group of order $2p$, where p is prime.

Theorem 3.1. *For any cyclic group G of order $2p$, where p is an odd prime, $\mathcal{PD}(G)$ is a p -regular graph.*

Proof. Let G be a cyclic group of order $2p$. Then G contains exactly one element of order 1, $(p-1)$ elements of order p , one element of order 2 and $(p-1)$ elements of order $2p$. Hence G has exactly $(p-1) + 1 = p$ elements of prime order. If x is any element of G , then $o(x) = 1$ or 2 or p or $2p$. We consider the following cases.

Case 1. Suppose $o(x) = 1$, then $x = e$. Now $\deg(e)$ in $\mathcal{PD}(G)$ is exactly equal to the number of prime order elements in G . Therefore, $\deg(e) = p$ in $\mathcal{PD}(G)$.

Case 2. Assume that $o(x) = 2$. Since G is cyclic so G has only one element of order 2. Clearly x is adjacent to e . Also for any other element $y \in G$ with $o(y) = p$, we see that x is adjacent to $x^{-1}y$. Thus the number of such y is $(p-1)$. Therefore the total number of adjacent vertices of x in $\mathcal{PD}(G)$ is $1 + (p-1) = p$.

Case 3. Suppose $o(x) = p$. There are $(p-1)$ elements of order p . In this case e and x^{-1} are both adjacent to x . Moreover, for any other prime order element $z (\neq x, x^2) \in G$, we see that x is adjacent to $x^{-1}z$. The number of such z is $(p-2)$ [($p-3$) elements of order p and one element of order 2]. Therefore the total number of adjacent vertices of x in $\mathcal{PD}(G)$ is $1 + 1 + (p-2) = p$.

Case 4. Suppose that $o(x) = 2p$. Then obviously $o(x^2) = p$. Clearly, x^{-1} is adjacent to x . Moreover, for any other prime order element $u (\neq x^2) \in G$, we see that x is adjacent to $x^{-1}u$. The number of such u is $(p-1)$ [($p-2$) elements of order p and one element of order 2]. Hence the total number of adjacent vertices of x in $\mathcal{PD}(G)$ is $1 + (p-1) = p$.

Therefore, considering all the cases we have $\deg(x) = p$ in $\mathcal{PD}(G)$. Since $x \in G$ is arbitrary, we must have $\mathcal{PD}(G)$ is a p -regular graph. ■

Corollary 3.2. For any odd prime p , $\mathcal{PD}(\mathbb{Z}_{2p})$ is a p -regular graph.

Remark 3.3. Figure 1 shows that $\mathcal{PD}(\mathbb{Z}_4)$ is 1-regular and thus Theorem 3.1 is not true when p is even prime.

Lemma 3.4. $\mathcal{PD}(\mathbb{Z}_{2^n})$ is disconnected for $n \geq 2$ and non regular for $n \geq 3$.

Proof. For $n \geq 2$, the set $\{\bar{0}, \overline{2^{n-1}}\}$ forms a connected component of $\mathcal{PD}(\mathbb{Z}_{2^n})$ and thus $\mathcal{PD}(\mathbb{Z}_{2^n})$ is a disconnected graph.

Now, we consider the graph $\mathcal{PD}(\mathbb{Z}_{2^n})$ for $n \geq 3$. In this graph $\deg(\bar{1}) = 2$ because $\bar{1}$ is adjacent to $\overline{2^n - 1}$ and $\overline{2^{n-1} - 1}$, whereas $\deg(\overline{2^{n-1}}) = 1$, since $o(\overline{2^{n-1}}) = 2$ in the group \mathbb{Z}_{2^n} . Hence $\mathcal{PD}(\mathbb{Z}_{2^n})$ is non regular. ■

Lemma 3.5. For any odd prime p and any integer $n \geq 2$, $\mathcal{PD}(\mathbb{Z}_{p^n})$ is a non regular graph.

Proof. Since \mathbb{Z}_{p^n} is a cyclic group, the number of elements of order p is $\varphi(p) = p-1$. This implies $\deg(\bar{0}) = p-1$ in $\mathcal{PD}(\mathbb{Z}_{p^n})$. Again, $\bar{1}$ is adjacent to

$\overline{p^{n-1}-1}, \overline{2p^{n-1}-1}, \overline{3p^{n-1}-1}, \dots, \overline{(p-1)p^{n-1}-1}$ and $\overline{p^n-1}$ in $\mathcal{PD}(\mathbb{Z}_{p^n})$. Therefore, $\deg(\overline{1}) = p$ in $\mathcal{PD}(\mathbb{Z}_{p^n})$. Hence $\mathcal{PD}(\mathbb{Z}_{p^n})$ is not a regular graph. ■

Lemma 3.6. *If $n \neq p, 2p$ for some prime p and if $n = p_1^{r_1} p_2^{r_2} \dots p_m^{r_m}$, where p_1, p_2, \dots, p_m are distinct primes and r_1, r_2, \dots, r_m are positive integers, then $\mathcal{PD}(\mathbb{Z}_n)$ is not a regular graph.*

Proof. Similar to the proof of Lemma 3.5, we can prove that $\deg(\overline{0}) = \varphi(p_1) + \varphi(p_2) + \dots + \varphi(p_m)$ and $\deg(\overline{1}) = \varphi(p_1) + \varphi(p_2) + \dots + \varphi(p_m) + 1$ in $\mathcal{PD}(\mathbb{Z}_n)$. Hence $\mathcal{PD}(\mathbb{Z}_n)$ is not a regular graph. ■

We are now in a position to characterize all finite cyclic groups \mathbb{Z}_n for which $\mathcal{PD}(\mathbb{Z}_n)$ is regular.

Theorem 3.7. *$\mathcal{PD}(\mathbb{Z}_n)$ is a regular graph if and only if $n = p$ or $2p$ for some prime p .*

Proof. First we assume that $n = p$ for some prime p . Then by Theorem 2.1, it follows that $\mathcal{PD}(\mathbb{Z}_p)$ is a complete graph with p vertices and hence $\mathcal{PD}(\mathbb{Z}_p)$ is a $(p-1)$ -regular graph. On the other hand if $n = 2p$ for some odd prime p , then by Corollary 3.2, we have $\mathcal{PD}(\mathbb{Z}_{2p})$ is a p -regular graph. Moreover, from Figure 1, we see that $\mathcal{PD}(\mathbb{Z}_4)$ is 1-regular.

Converse part follows from Lemma 3.6. ■

Corollary 3.8. *For any positive integer $n (\neq 4)$, if $\mathcal{PD}(\mathbb{Z}_n)$ is regular then it is connected.*

Proof. From Theorem 3.7, we have $\mathcal{PD}(\mathbb{Z}_n)$ is regular if and only if $n = p$ or $2p$ for some prime p . Now for any prime p , $\mathcal{PD}(\mathbb{Z}_p)$ is complete and hence it is connected. If p is an odd prime, then by Theorem 3.7, we have $\mathcal{PD}(\mathbb{Z}_{2p})$ is a p -regular graph with $2p$ vertices and hence it is connected. ■

Remark 3.9. The converse of Corollary 3.8 is not true in general. The following graph shows that $\mathcal{PD}(\mathbb{Z}_{15})$ is connected but not regular.

Definition 3.10 [8]. The line graph of a graph G , written $L(G)$, is the graph whose vertices are the edges of G , with $ef \in E(L(G))$ when $e = uv$ and $f = vw$ in G .

Theorem 3.11. *For any odd prime p ,*

- (i) *the line graph $L(\mathcal{PD}(\mathbb{Z}_p))$ of $\mathcal{PD}(\mathbb{Z}_p)$ is $(2p-4)$ -regular,*
- (ii) *the line graph $L(\mathcal{PD}(\mathbb{Z}_{2p}))$ of $\mathcal{PD}(\mathbb{Z}_{2p})$ is $(2p-2)$ -regular.*

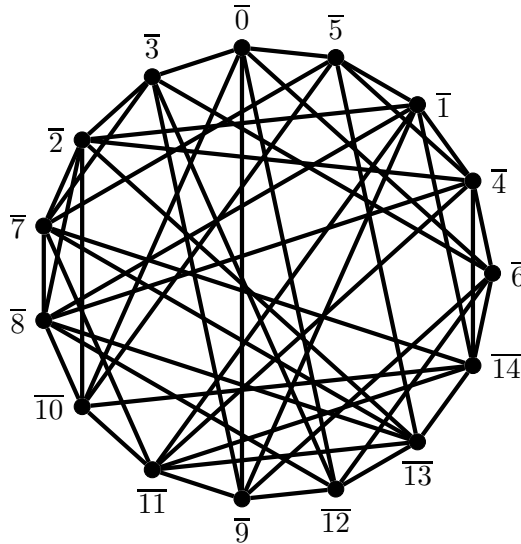


Figure 5. $\mathcal{PD}(\mathbb{Z}_{15})$

Proof. (i) Let p be an odd prime. Then $\mathcal{PD}(\mathbb{Z}_p)$ is $(p-1)$ -regular. Let e be any edge of $\mathcal{PD}(\mathbb{Z}_p)$. Then e represents a vertex e_v in $L(\mathcal{PD}(\mathbb{Z}_p))$. Let a_e and b_e be the end vertices of the edge e in $\mathcal{PD}(\mathbb{Z}_p)$. Again $\deg(a_e) = \deg(b_e) = (p-1)$ in $\mathcal{PD}(\mathbb{Z}_p)$. Since $\mathcal{PD}(\mathbb{Z}_p)$ is simple, the edge e has the vertex a_e in common with $(p-2)$ edges and the vertex b_e in common with $(p-2)$ edges in $\mathcal{PD}(\mathbb{Z}_p)$. Hence $\deg(e_v) = (p-2) + (p-2) = (2p-4)$ in $L(\mathcal{PD}(\mathbb{Z}_p))$. Therefore $L(\mathcal{PD}(\mathbb{Z}_p))$ is $(2p-4)$ -regular graph.

(ii) Since $\mathcal{PD}(\mathbb{Z}_{2p})$, where p is any odd prime, is p -regular, so by the similar argument as in (i) of this theorem, we have the line graph $L(\mathcal{PD}(\mathbb{Z}_{2p}))$ of $\mathcal{PD}(\mathbb{Z}_{2p})$ is $(2p-2)$ -regular. ■

Theorem 3.12 (Dirac [8]). *Let G be a simple graph with $n(> 2)$ vertices. If $\deg(v) \geq \frac{n}{2}$ for every vertex v of G , then G is Hamiltonian.*

Theorem 3.13. *If $n = p$ or $2p$, where p an odd prime, then $\mathcal{PD}(\mathbb{Z}_n)$ is a Hamiltonian graph.*

Proof. Let p be an odd prime. From Theorem 2.1, it follows that $\mathcal{PD}(\mathbb{Z}_p)$ is complete and hence it is Hamiltonian. On the other hand from Theorem 3.7, we have $\mathcal{PD}(\mathbb{Z}_{2p})$ is a p -regular graph and by Theorem 3.12, it follows that $\mathcal{PD}(\mathbb{Z}_{2p})$ is a Hamiltonian graph. ■

Theorem 3.14. *For a finite commutative group G , $\mathcal{PD}(G)$ is a bipartite graph if and only if $G \cong \mathbb{Z}_{2^r}$, for some positive integer r .*

Proof. Let $G \cong \mathbb{Z}_{2^r}$, for some positive integer r . If G is isomorphic to either \mathbb{Z}_2 or \mathbb{Z}_{2^2} then clearly $\mathcal{PD}(G)$ is a bipartite graph. We now consider $r \geq 3$. Then in the order prime divisor graph $\mathcal{PD}(\mathbb{Z}_{2^r})$, $\deg(\overline{0}) = \deg(\overline{2^{r-1}}) = \deg(\overline{2^{r-2}}) = \deg(\overline{3 \cdot 2^{r-2}}) = 1$ and also $\{\overline{0}, \overline{2^{r-1}}\}, \{\overline{2^{r-2}}, \overline{3 \cdot 2^{r-2}}\}$ form two components. Let $\overline{x} \in \mathbb{Z}_{2^r}$ such that $\overline{x} \notin \{\overline{0}, \overline{2^{r-1}}, \overline{2^{r-2}}, \overline{3 \cdot 2^{r-2}}\}$. Then $\{\overline{x}, \overline{2^{r-1} - x}, \overline{2^{r-1} + x}, \overline{2^r - x}\}$ forms a component which is isomorphic to C_4 . Hence every component of $\mathcal{PD}(\mathbb{Z}_{2^r})$ is isomorphic to either K_2 or C_4 . Hence $\mathcal{PD}(\mathbb{Z}_{2^r})$ has no odd cycle and consequently, $\mathcal{PD}(G)$ is a bipartite graph.

Conversely, let G be a finite commutative group of order n such that $\mathcal{PD}(G)$ is a bipartite graph. We now show that n is not divisible by any odd prime p . If any odd prime p divides n , then G contains an element x of order p . Since p is an odd prime, we have $x \neq x^{-1}$ and $o(x^{-1}) = p$. This implies $x \leftrightarrow e \leftrightarrow x^{-1} \leftrightarrow x$ forms a cycle in $\mathcal{PD}(G)$ of length 3. Therefore $\mathcal{PD}(G)$ contains an odd cycle, which contradicts that $\mathcal{PD}(G)$ is a bipartite graph. Hence n is of the form 2^r , for some positive integer r . Therefore $G \cong \mathbb{Z}_{2^{n_1}} \oplus \mathbb{Z}_{2^{n_2}} \oplus \dots \oplus \mathbb{Z}_{2^{n_k}}$ for some positive integers n_1, n_2, \dots, n_k . We now show that $k = 1$. On the contrary, let $k > 1$. Then $\{\overline{(2^{n_1-1}), \overline{0}}, \dots, \overline{0}), (\overline{0}, \overline{2^{n_2-1}}, \dots, \overline{0}), (\overline{2^{n_1-1}}, \overline{2^{n_2-1}}, \dots, \overline{0})\}$ forms a triangle. Thus $\mathcal{PD}(G)$ is not bipartite graph, which is again a contradiction. Therefore, $k = 1$ and thus $G \cong \mathbb{Z}_{2^r}$, for some positive integer r . ■

Theorem 3.15. *Let p be an odd prime and $n \geq 2$ is an integer. Then $\mathcal{PD}(\mathbb{Z}_{p^n})$ have one $(p - 1)$ -regular component and $\frac{p^{n-1}-1}{2}$ components each of them is p -regular.*

Proof. In $\mathcal{PD}(\mathbb{Z}_{p^n})$, $\{\overline{0}, \overline{p^{n-1}}, \overline{2p^{n-1}}, \dots, \overline{(p-1)p^{n-1}}\}$ forms a component with p vertices and this component is of $(p - 1)$ -regular.

Let $A_i = \{\overline{i}, \overline{p^{n-1} - i}, \overline{2p^{n-1} - i}, \dots, \overline{p^n - i}, \overline{p^{n-1} + i}, \overline{2p^{n-1} + i}, \dots, \overline{(p-1)p^{n-1} + i}\} = U_i \cup V_i$, where $U_i = \{\overline{p^{n-1} - i}, \overline{2p^{n-1} - i}, \dots, \overline{p^n - i}\}$ and $V_i = \{\overline{i}, \overline{p^{n-1} + i}, \overline{2p^{n-1} + i}, \dots, \overline{(p-1)p^{n-1} + i}\}$, for all $i = 1, 2, \dots, \frac{p^{n-1}-1}{2}$.

We now show that every A_i , for all $i = 1, 2, \dots, \frac{p^{n-1}-1}{2}$, contains $2p$ elements. Let $\overline{u_1}, \overline{u_2} \in U_i$ be any two elements of U_i . Let $\overline{u_1} = \overline{rp^{n-1} - i}, \overline{u_2} = \overline{sp^{n-1} - i}$ for some $r, s \in \{1, 2, \dots, p\}$. If possible let $\overline{u_1} = \overline{u_2}$, i.e., $rp^{n-1} - i + t_1p^n = sp^{n-1} - i + t_2p^n$, i.e., $(r - s) = (t_2 - t_1)p$ which is possible only when $r = s$ and hence U_i contains p elements. Similarly, we can show that V_i contains p elements. Now we need to show that $U_i \cap V_i = \emptyset$. If possible let $\overline{u} \in U_i \cap V_i$. Then $u = cp^{n-1} - i + t_3p^n = dp^{n-1} + i + t_4p^n$, where $c \in \{1, 2, \dots, p\}$ and $d \in \{0, 1, \dots, (p - 1)\}$, i.e., $(c - d)p^{n-1} + (t_3 - t_4)p^n = 2i$, i.e., $2i$ is divisible by p^{n-1} , a contradiction since $2i \leq p^{n-1} - 1 < p^{n-1}$. Therefore, $U_i \cap V_i = \emptyset$ and hence A_i contains $2p$ elements.

Let $\overline{rp^{n-1} - i} \in U_i$ for some $r \in \{1, 2, \dots, p\}$, and $\overline{sp^{n-1} + i} \in V_i$ for some $s \in \{0, 1, \dots, (p - 1)\}$, be any two elements. In \mathbb{Z}_{p^n} , $o(\overline{rp^{n-1} - i + sp^{n-1} + i}) = p$

and thus every element of U_i is adjacent to each element of V_i . But for any two elements $\overline{rp^{n-1}-i}, \overline{tp^{n-1}-i} \in U_i$ ($r, t \in \{1, 2, \dots, p\}$), we have $o(\overline{r_1p^{n-1}-i} + \overline{r_2p^{n-1}-i}) \neq p$ and thus no two elements of U_i are adjacent. Similarly we can show that no two elements in V_i are adjacent. Hence degree of every vertex in A_i , for all $i = 1, 2, \dots, \frac{p^{n-1}-1}{2}$, is p in $\mathcal{PD}(\mathbb{Z}_{p^n})$.

We now show that every A_i , for all $i = 1, 2, \dots, \frac{p^{n-1}-1}{2}$, forms a component of $\mathcal{PD}(\mathbb{Z}_{p^n})$. Let $x \in A_i$. Then x is adjacent to either \overline{i} or $\overline{p^{n-1}-i}$ in $\mathcal{PD}(\mathbb{Z}_{p^n})$. Therefore every element of A_i is connected to each other by a path of length at most 2. It is easy to verify that there is no edge between a vertex in A_i and a vertex in A_j for $i \neq j$ and $i, j \in \{1, 2, \dots, \frac{p^{n-1}-1}{2}\}$. Therefore, every A_i , for all $i = 1, 2, \dots, \frac{p^{n-1}-1}{2}$, forms a p -regular component with $2p$ vertices. Hence the theorem. ■

4. ORDER PRIME DIVISOR GRAPH OF THE GROUP D_n

For each positive integer $n \geq 3$, the dihedral group of degree n , denoted by D_n , is a non-commutative group containing $2n$ elements and is defined by $D_n = \langle a, b : o(a) = n, o(b) = 2, ba = a^{-1}b \rangle$. The study of dihedral group D_n helps us to characterize non commutative groups. In this section, we establish some graph-theoretic properties of $\mathcal{PD}(D_n)$.

Before going to our results, we first consider the order prime divisor graph $\mathcal{PD}(D_8)$.

Example 4.1.

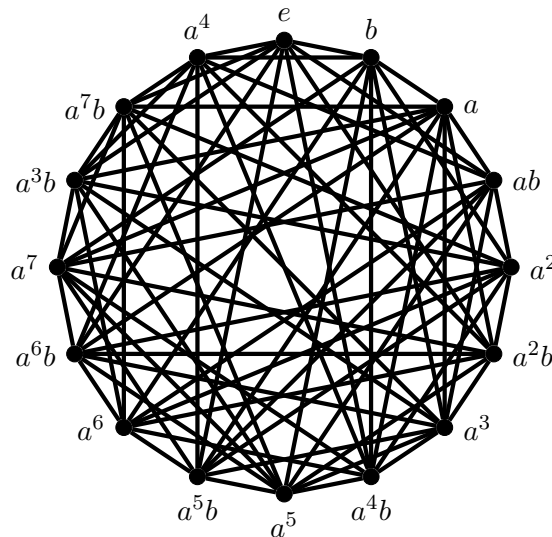


Figure 6. $\mathcal{PD}(D_8)$

From Figure 6, we have $\deg(a) = \deg(a^3) = \deg(a^5) = \deg(a^7) = 10$ and $\deg(e) = \deg(a^2) = \deg(a^4) = \deg(a^6) = \deg(b) = \deg(ab) = \deg(a^2b) = \deg(a^3b) = \deg(a^4b) = \deg(a^5b) = \deg(a^6b) = \deg(a^7b) = 9$ in order prime divisor graph $\mathcal{PD}(D_8)$. Here $8 = 2^3$ and note that degree of any vertex in $\mathcal{PD}(D_8)$ is either $\varphi(2) + 8$ or $\varphi(2) + 8 + 1$.

Theorem 4.2. *Let $n (\geq 3)$ be a number and $n = p_1^{r_1} p_2^{r_2} \cdots p_m^{r_m}$ be the factorization of n as product of distinct primes and their positive powers. Then the degree of a vertex of $\mathcal{PD}(D_n)$ is either $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$ or $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$.*

Proof. Now $D_n = \langle a, b \rangle : o(a) = n, o(b) = 2, ba = a^{-1}b \rangle$. Let $H = \langle a \rangle$ and $K = Hb$. Then $D_n = H \cup K$ and all the n elements of K are of order 2. Also the subgroup H contains $\varphi(p_1)$ elements of order p_1 , $\varphi(p_2)$ elements of order p_2 , and so on, $\varphi(p_m)$ elements of order p_m . Now $\deg(e)$ in $\mathcal{PD}(D_n)$ is exactly equal to the number of prime order elements in D_n . Therefore, $\deg(e) = \varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$ in $\mathcal{PD}(D_n)$. Let $x (\neq e) \in D_n$ be any element.

If $o(x) = 2$, then e is adjacent to x . Also for any other element $y (\neq x) \in G$ with prime order, we see that x is adjacent to $x^{-1}y$. Thus the total number of adjacent vertices of x in $\mathcal{PD}(D_n)$ is $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$.

Suppose $o(x) = p$, where p is an odd prime. Then x^2 is again an element of order p . In this case e and x^{-1} are adjacent to x . Moreover, for any other element $z (\neq x, x^2) \in G$ with prime order, we see that x is adjacent to $x^{-1}z$. Thus the total number of adjacent vertices of x in $\mathcal{PD}(D_n)$ is $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$.

Finally, suppose that $o(x)$ is composite. Then in this case x^{-1} is adjacent to x . If x^2 is an element of prime order, then for any other element $u (\neq x^2) \in G$ with prime order, we see that x is adjacent to $x^{-1}u$. Thus, the total number of adjacent vertices of x in $\mathcal{PD}(D_n)$ is $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$. On the other hand, if $o(x^2)$ is composite, then for any other element $u \in G$ with prime order, we see that x is adjacent to $x^{-1}u$. Hence the total number of adjacent vertices of x in $\mathcal{PD}(D_n)$ is $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$. Thus the proof is completed. ■

Theorem 4.3. *$\mathcal{PD}(D_n)$ ($n \geq 3$) is a regular graph if and only if $n = p$ or $2p$ for some prime p .*

Proof. Let $p (\geq 3)$ be a prime. Now D_p is a non-commutative group of order $2p$ such that every non identity element is of prime order. Hence by Theorem 2.1, it follows that $\mathcal{PD}(D_p)$ is complete and thus it is $(2p - 1)$ -regular.

For $p = 2$, we have from Figure 3 that $\mathcal{PD}(D_{2p}) = \mathcal{PD}(D_4)$ is 5-regular.

We now establish the regularity of the graph $\mathcal{PD}(D_{2p})$, where p is any odd prime. Note that $D_{2p} = \{e, a, a^2, \dots, a^{2p-1}, b, ab, a^2b, \dots, a^{2p-1}b\} = H \cup K$, where $H = \langle a \rangle$ is the cyclic subgroup of D_{2p} generated by a and $K = Hb$ is a right

coset of H , different from H . Here every element of K is of order 2. Moreover, H contains exactly $(p - 1)$ elements of order p and a unique element of order 2. Let $a^r \in H$ and $a^s b \in K$. Then $a^r a^s b = a^{r+s \pmod{2p}} b$, for $r, s = 1, 2, \dots, 2p$. Thus $a^r a^s b \in K$ and hence $o(a^r a^s b) = 2$. Therefore, every element of H is adjacent to every element of K in $\mathcal{PD}(D_{2p})$. Let $a^r, a^s \in H$, then $a^r a^s \in H$, for $r, s = 1, 2, \dots, 2p$. Finally, for any two elements $a^r b, a^s b \in K$, we have $a^r b a^s b \in H$, for $r, s = 1, 2, \dots, 2p$. We now show that every vertex of $\mathcal{PD}(D_{2p})$ is of degree $3p$. For this let x be any vertex of $\mathcal{PD}(D_{2p})$.

Suppose $x \in H$. Then x is adjacent to every element of K . Moreover, similar to the proof of Theorem 3.1, we can conclude that x is adjacent to exactly p elements of H . Hence, if $x \in H$, then $\deg(x) = 3p$. On the other hand, if $x \in K$, then all the $2p$ elements of H are adjacent to x . Since $x \in K$, we must have $x^2 = e$ and $K = Hx$. Also, $Kx = (Hx)x = Hx^2 = H$. Now H contains total p elements of prime order (exactly $p - 1$ elements of order p and 1 element of order 2). Therefore, x is adjacent to exactly p elements of K . Hence total number of adjacent vertices is $3p$ and thus $\deg(x) = 3p$. Therefore, in either cases $\deg(x) = 3p$ in $\mathcal{PD}(D_{2p})$. Consequently, $\mathcal{PD}(D_{2p})$ is a $3p$ -regular graph.

Conversely, we assume that $\mathcal{PD}(D_n)$ is regular. We show that $n = p$ or $2p$ for some prime p . On the contrary we let $n \neq p, 2p$ for any prime p . Let $n = p_1^{r_1} p_2^{r_2} \cdots p_m^{r_m}$, where p_1, p_2, \dots, p_m are distinct primes and r_1, r_2, \dots, r_m are positive integers. Then by Theorem 4.2, it follows that $\deg(e) = \varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$ whereas $\deg(a) = \varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$ in $\mathcal{PD}(D_n)$. This leads to $\mathcal{PD}(D_n)$ is not regular, which is a contradiction. Consequently, $n = p$ or $2p$ for some prime p . ■

From Corollary 3.2, Theorem 4.3, Figure 1 and Figure 2, we have the following result.

Theorem 4.4. *If G is a group of order p or $2p$, where p is prime, then $\mathcal{PD}(G)$ is regular.*

Theorem 4.5. *Let p be an odd prime, then*

- (i) *the line graph $L(\mathcal{PD}(D_p))$ of $\mathcal{PD}(D_p)$ is $(4p - 4)$ -regular.*
- (ii) *the line graph $L(\mathcal{PD}(D_{2p}))$ of $\mathcal{PD}(D_{2p})$ is $(6p - 2)$ -regular.*

Proof. (i) For any prime $p \geq 3$, $\mathcal{PD}(D_p)$ is $(2p - 1)$ -regular graph. Thus by the similar argument of the proof of Theorem 3.11(i), it follows that the line graph $L(\mathcal{PD}(D_p))$ of $\mathcal{PD}(D_p)$ is $(4p - 4)$ -regular.

(ii) For any odd prime p , the graph $\mathcal{PD}(D_{2p})$ is $3p$ -regular. So by the similar argument of the proof of Theorem 3.11(i), we have the line graph $L(\mathcal{PD}(D_{2p}))$ of $\mathcal{PD}(D_{2p})$ is $(6p - 2)$ -regular. ■

Corollary 4.6. *The line graph $L(\mathcal{PD}(D_4))$ of $\mathcal{PD}(D_4)$ is 8-regular graph.*

Proof. Since $\mathcal{PD}(D_4)$ is 5-regular graph, so by the similar argument of the proof of Theorem 3.11(i), it follows that the line graph $L(\mathcal{PD}(D_4))$ of $\mathcal{PD}(D_4)$ is 8-regular. ■

Theorem 4.7. *For any integer $n(\geq 3)$, $\mathcal{PD}(D_n)$ is connected as well as Hamiltonian.*

Proof. Let $n(\geq 3)$ and $n = p_1^{r_1} p_2^{r_2} \cdots p_m^{r_m}$ be the factorization of n as product of distinct primes and their positive powers. Then $\mathcal{PD}(D_n)$ is a graph with $2n$ vertices and by Theorem 4.2, we have degree of each vertex is either $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$ or $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$. Thus $\deg(v) \geq n$ for every vertex in $\mathcal{PD}(D_n)$. Therefore, by Theorem 3.12, it follows that $\mathcal{PD}(D_n)$ is Hamiltonian and hence connected. ■

Theorem 4.8. *The graph $\mathcal{PD}(D_n)$ is not Eulerian for any positive integer $n(\geq 3)$.*

Proof. Let $n(\geq 3)$ and $n = p_1^{r_1} p_2^{r_2} \cdots p_m^{r_m}$ be the factorization of n as product of distinct primes and their positive powers. Then $\mathcal{PD}(D_n)$ is a graph with $2n$ vertices and by Theorem 4.2, we have degree of each vertex is either $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$ or $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$. Now $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$ or $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$ are two consecutive positive integers. So one of them must be even and another must be odd. Therefore, $\mathcal{PD}(D_n)$ contains odd degree vertices. Consequently, $\mathcal{PD}(D_n)$ is not Eulerian. ■

Remark 4.9. For any odd prime p , the graph $\mathcal{PD}(D_p)$ is complete and hence $\text{diam}(\mathcal{PD}(D_p)) = 1$.

Theorem 4.10. *For any composite number $n(\geq 3)$, $\text{diam}(\mathcal{PD}(D_n)) = 2$.*

Proof. Now $D_n = \{\langle a, b \rangle : o(a) = n, o(b) = 2, ba = a^{-1}b\}$. Let $H = \langle a \rangle$, the cyclic subgroup generated by a and $K = Hb$ be the right coset of H different from H . Then $D_n = H \cup K$. Here, every element of K is of order 2. Let $a^r \in H$ and $a^s b \in K$. Then $a^r a^s b = a^{r+s(\text{mod } n)} b$, for $r, s = 1, 2, \dots, n$. Hence $a^r a^s b \in K$ and thus $o(a^r a^s b) = 2$. Therefore, every element of H is adjacent to every element of K in $\mathcal{PD}(D_n)$. Let x, y be any two vertices of $\mathcal{PD}(D_n)$.

Case 1. If H contains exactly one of x or y and K contains the other, then $x \leftrightarrow y$ is a path in $\mathcal{PD}(D_n)$ of length 1.

Case 2. We now consider the other possibility. Without loss of generality, we assume that $x, y \in H$. Then two sub-cases arise.

Subcase (a). Suppose $xy = e$ or $o(xy) = p$ for some prime p . Then $x \leftrightarrow y$ is a path in $\mathcal{PD}(D_n)$ of length 1.

Subcase (b). If x and y are not adjacent in $\mathcal{PD}(D_n)$. Then for any $z \in K$, we get a path $x \leftrightarrow z \leftrightarrow y$ in $\mathcal{PD}(D_n)$ of length 2.

Therefore, there is a path between any two vertices of $\mathcal{PD}(D_n)$. Hence $\mathcal{PD}(D_n)$ is connected and $\text{diam}(\mathcal{PD}(D_n)) = 2$. ■

Theorem 4.11. *For any $n(\geq 3)$, the graph $\mathcal{PD}(D_n)$ is neither bipartite nor a tree. Moreover, $\text{girth}(\mathcal{PD}(D_n)) = 3$.*

Proof. For any $n \geq 3$, $D_n = \{ \langle a, b \rangle : o(a) = n, o(b) = 2, ba = a^{-1}b \}$. Let p be a prime factor of n . Then $n = pq$ for some positive integer q . Now $a^q \in D_n$ such that $o(a^q) = p$. Then $a^q \leftrightarrow b \leftrightarrow e \leftrightarrow a^q$ forms a cycle of length 3. Since $\mathcal{PD}(D_n)$ is a simple graph, it follows that $\text{girth}(\mathcal{PD}(D_n)) = 3$. Since $\mathcal{PD}(D_n)$ contains an odd cycle, it follows that $\mathcal{PD}(D_n)$ is neither bipartite nor a tree. ■

Theorem 4.12. *For any integer $(n \geq 3)$, $\mathcal{PD}(D_n)$ is non planar.*

Proof. We prove that $\mathcal{PD}(D_n)$ is non planar for any integer $n(\geq 3)$. On the contrary, suppose $\mathcal{PD}(D_k)$ is planar for some integer $k(\geq 3)$. First we claim that 2 is only one prime factor of k . If not, let p be an odd prime factor of k and thus $k = p^m q$ for some positive integers m, q with $\text{gcd}(p, q) = 1$. Now $D_k = \{ \langle a, b \rangle : o(a) = k, o(b) = 2, ba = a^{-1}b \}$. Let $x \in D_k$ such that $o(x) = p$. Then the induced subgraph of $\mathcal{PD}(D_k)$ induced by the set of vertices $\{e, x, x^{-1}, b, xb\}$ forms the complete subgraph K_5 . Hence by Kuratowski's Theorem, we conclude that $\mathcal{PD}(D_k)$ is non planar, which contradicts our assumption that $\mathcal{PD}(D_k)$ is planar. This contradiction ensures that 2 is the only one prime factor of k and hence $k = 2^r$ for some positive integer $r \geq 2$.

Now we show that $\mathcal{PD}(D_{2^r})$ is non planar. First we see from Fig. 3 that $\mathcal{PD}(D_4)$ contains complete bipartite graph $K_{3,3}$ with bipartition $\{e, a, a^3\}$ and $\{b, ab, a^3b\}$ as a subgraph. Hence by Kuratowski's Theorem, we have $\mathcal{PD}(D_4)$ is non planar. Moreover, for $r \geq 3$, we have D_{2^r} has a subgroup isomorphic to D_4 . Thus $\mathcal{PD}(D_{2^r})$ has a subgraph isomorphic to $\mathcal{PD}(D_4)$. Since $\mathcal{PD}(D_4)$ is non planar, it follows that $\mathcal{PD}(D_{2^r}) = \mathcal{PD}(D_k)$ is also non planar. Hence the theorem. ■

Theorem 4.13 (Brook's Theorem [8]). *If G is a connected graph other than a complete graph or an odd cycle, then $\chi(G) \leq \Delta(G)$, where $\chi(G)$ and $\Delta(G)$ are the chromatic number and the maximum vertex degree of G respectively.*

Remark 4.14. If n is an odd prime, then $\mathcal{PD}(D_n)$ is a complete graph with $2n$ vertices and hence $\chi(\mathcal{PD}(D_n)) = 2n$.

Theorem 4.15. *Let $n(\geq 3)$ be a composite number and $n = p_1^{r_1} p_2^{r_2} \cdots p_m^{r_m}$ be the factorization of n , where p_1, p_2, \dots, p_m are distinct primes and r_1, r_2, \dots, r_m are positive integers. Then $\chi(\mathcal{PD}(D_n)) \leq \varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$.*

Proof. If $n(\geq 3)$ and $n = p_1^{r_1} p_2^{r_2} \cdots p_m^{r_m}$ be the factorization of n , where p_1, p_2, \dots, p_m are distinct primes and r_1, r_2, \dots, r_m are positive integers. Then by Theorem 4.2, it follows that degree of every vertex in $\mathcal{PD}(D_n)$ is either $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n$ or $\varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$. Therefore, $\Delta(\mathcal{PD}(D_n)) = \varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$. Moreover, $\mathcal{PD}(D_n)$ is connected graph which is neither complete nor an odd cycle. Hence by Theorem 4.13, it follows that $\chi(\mathcal{PD}(D_n)) \leq \varphi(p_1) + \varphi(p_2) + \cdots + \varphi(p_m) + n + 1$. ■

5. ORDER PRIME DIVISOR GRAPHS OF SMALL FINITE GROUPS

Here we discuss all possible order prime divisor graphs $\mathcal{PD}(G)$, where G is a group of order at most 15. For this purpose, we first exhibit the order prime divisor graph $\mathcal{PD}(\mathbb{Z}_{12})$.

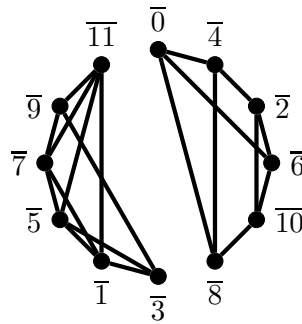


Figure 7. $\mathcal{PD}(\mathbb{Z}_{12})$

Order of Group G	Group G	Order Prime Divisor Graph $\mathcal{PD}(G)$
2	\mathbb{Z}_2	K_2
3	\mathbb{Z}_3	K_3
4	\mathbb{Z}_4 $\mathbb{Z}_2 \oplus \mathbb{Z}_2$	$K_2 \cup K_2$ (Figure 1) K_4 (Figure 2)
5	\mathbb{Z}_5	K_5
6	\mathbb{Z}_6 S_3	3-regular connected graph K_6
7	\mathbb{Z}_7	K_7
8	\mathbb{Z}_8 $\mathbb{Z}_2 \oplus \mathbb{Z}_4$ $\mathbb{Z}_2 \oplus \mathbb{Z}_2 \oplus \mathbb{Z}_2$ D_4 Q_8	$K_2 \cup K_2 \cup C_4$ $K_4 \cup K_4$ K_8 Figure 3 $K_2 \cup K_2 \cup K_2 \cup K_2$

9	\mathbb{Z}_9 $\mathbb{Z}_3 \oplus \mathbb{Z}_3$	Figure 4 K_9
10	\mathbb{Z}_{10} D_5	5-regular connected graph K_{10}
11	\mathbb{Z}_{11}	K_{11}
12	\mathbb{Z}_{12} $\mathbb{Z}_2 \oplus \mathbb{Z}_2 \oplus \mathbb{Z}_3$ A_4 D_6 T	Figure 7 5-regular connected graph K_{12} 9-regular connected graph Union of two 3-regular component
13	\mathbb{Z}_{13}	K_{13}
14	\mathbb{Z}_{14} D_7	7-regular connected graph K_{14}
15	\mathbb{Z}_{15}	Figure 5

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REFERENCES

- [1] J. Bosák, The Graphs of Semigroups, in: Theory of Graphs and Application (Academic Press, New York, 1964) 119–125.
- [2] B. Csákány and G. Pollák, *The graph of subgroups of a finite group*, Czechoslovak Math. J. **19** (1969) 241–247.
<https://doi.org/10.21136/CMJ.1969.100891>
- [3] I. Chakrabarty, S. Ghosh, T.K. Mukherjee and M.K. Sen, *Intersection graphs of ideals of rings*, Discrete Math. **309** (2009) 5381–5392.
<https://doi.org/10.1016/j.disc.2008.11.034>
- [4] I. Chakrabarty, S. Ghosh and M.K. Sen, *Undirected power graphs of semigroups*, Semigroup Forum **78** (2009) 410–426.
<https://doi.org/10.1007/s00233-008-9132-y>
- [5] D.S. Dummit and R.M. Foote, Abstract Algebra, Third Edition (John Wiley and Sons, Inc., New York, 2004).
- [6] A.V. Kelarev and S.J. Quinn, *A combinatorial property and power graphs of groups*, Contributions to General Algebra **12** (2000) 229–235.
- [7] M. Sattanathan and R. Kala, *An introduction to order prime graph*, Int. J. Contemp. Math. Sciences **4** (2009) 467–474.
<https://doi.org/10.1111/j.1439-0507.1967.tb02798.x>

- [8] D.B. West, *Introduction to Graph Theory*, Second Edition (Pearson India Education Services Pvt. Ltd., 2017).
- [9] B. Zelinka, *Intersection graphs of finite Abelian groups*, *Czech. Math. J.* **25** (1975) 171–174.
<https://doi.org/10.21136/CMJ.1975.101307>

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