

ON GENERALISED MINIMAL DOMINATION PARAMETERS  
FOR PATHS

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Abstract

A subset  $X$  of vertices of a graph is a  $k$ -minimal  $P$ -set if  $X$  has property  $P$ , but the removal of any  $\ell$  vertices from  $X$ , where  $\ell \leq k$ , followed by the addition of any  $(\ell-1)$  vertices destroys the property  $P$ . We note that 1-minimality is the usual minimality concept. In this paper we determine  $\Gamma_k(P_n)$ , the largest cardinality of a  $k$ -minimal dominating set of the  $n$ -vertex path  $P_n$ . We also prove for any  $n$ -vertex graph  $G$ ,  $\Gamma_2(G)\gamma(\bar{G}) \leq n$  and finally a "Gallai-type" theorem for  $k$ -minimal parameters is established.

## 1. Introduction

The concept of minimality may be generalised as follows. Let  $S$  be a set and  $P$  a property enjoyed by some of the subsets of  $S$ . A subset of  $S$  with (without) property  $P$  is called a  $P$ -set ( $\bar{P}$ -set). A subset  $X$  of  $S$  is called a  $k$ -minimal  $P$ -set if  $X$  has the property  $P$ , but for all  $\ell$  satisfying  $1 \leq \ell \leq k$ , all  $\ell$ -subsets  $U$  of  $X$  and all  $(\ell-1)$ -subsets  $R$  of  $S$ ,  $(X-U) \cup R$  is a  $\bar{P}$ -set. We note that 1-minimality is the usual concept of minimality. In this paper the set  $S$  will be the vertex set  $V$  of a graph and a subset  $X \subseteq V$  has property  $P$  if and only if  $X$  is dominating. This specialization of the above defines a  $k$ -minimal dominating set of a graph. We define  $\Gamma_k(G)$  to be the largest cardinality of a  $k$ -minimal dominating set of  $G$ . Let  $\gamma(G) \left[ \Gamma(G) \right]$  be the smallest (largest) cardinality of a minimal dominating set of  $G$ . The following inequalities are obvious for any graph  $G$ .

$$\gamma(G) \leq \dots \leq \Gamma_k(G) \leq \dots \leq \Gamma_2(G) \leq \Gamma_1(G) = \Gamma(G).$$

In this work, we first strengthen the theorem of Jaegar and Payan [4] which asserts that the product of domination numbers of a graph and its complement is at most the number of vertices in the graph. The examination of their proof, in fact, motivated the new extended definitions of minimality given here. The principal result of the paper is the exact determination of  $\Gamma_k(P_n)$ . This calculation is surprisingly complex although the evaluations of  $\gamma(P_n)$  and  $\Gamma(P_n)$  are trivial.

It is clear that many other parameters of graphs and more general structures, which are defined in terms of minimality may also be similarly generalized and that the maximality concept may also be extended. In [1],

Cockayne, MacGillivray and Mynhardt compute  $\beta_k(P_n)$  and  $\beta_k(C_n)$  where  $\beta_k(G)$  is the smallest cardinality of a  $k$ -maximal independent set of vertices of  $G$ . The final result of this paper is a generalization of a theorem of Gallai [3] concerning certain  $k$ -maximal and  $k$ -minimal parameters.

For an excellent bibliography of the study of domination in graphs, the reader is referred to [5]. Extensions of Gallai's theorem are given in [2].

## 2. The Results

### 2.1. The Jaegar-Payan generalisation.

In [4] Jaegar and Payan proved the following Nordhaus-Gaddum type result for the domination number.

Theorem 1 (Jaegar and Payan). For any  $n$  vertex graph  $G$ ,  $\gamma(G)\gamma(\bar{G}) \leq n$ .

We show here that their proof may be adapted to prove the stronger result:-

Theorem 2. For any  $n$ -vertex graph  $G$ ,  $\Gamma_2(G)\gamma(\bar{G}) \leq n$ .

Proof. The result is trivial for  $\Gamma_2(G) = 1$ , hence we assume  $\Gamma_2(G) = t \geq 2$ . Let  $X = \{x_1, \dots, x_t\}$  be a largest 2-minimal dominating set. Since  $X$  is dominating, there exists a partition of  $V(G)$  into classes  $V_1, \dots, V_t$ , such that for each  $i = 1, \dots, t$ ,  $x_i \in V_i$  and  $x_i$  is adjacent to all other vertices in  $V_i$ . Let  $\mathcal{P}$  be such a partition such that the number of vertices which are adjacent to all other vertices in their class, is maximum. We show that each class of  $\mathcal{P}$  is a dominating set of  $\bar{G}$ .

For suppose  $V_1$  (say) does not dominate  $\bar{G}$ . Then there exists a vertex  $x$  which is in  $V_2$  (say) and is adjacent in  $G$  to all vertices of  $V_1$ . Vertex  $x$  is not adjacent to all vertices of  $V_2$ , for otherwise  $[X - \{x_1, x_2\}] \cup \{x\}$  dominates  $G$ , contrary to 2-minimality. Therefore  $x \neq x_2$  and we now consider the partition  $\mathcal{P}' = V_1^i, \dots, V_t^i$  where  $V_1^i = V_1 \cup \{x\}$ ,  $V_2^i = V_2 - \{x\}$ ,  $V_j^i = V_j$  for  $2 < j \leq t$ . We have  $x_i \in V_1^i$  for  $i = 1, \dots, t$  and  $\mathcal{P}'$  has at least one extra vertex (the vertex  $x$ ) which is adjacent to all other members of its class. This contradicts the maximum property of  $\mathcal{P}$ . Thus each  $V_i$  dominates  $\bar{G}$  and

$$n = \sum_{i=1}^t |V_i| \geq \sum_{i=1}^t \gamma(\bar{G}) = \Gamma_2(G) \gamma(\bar{G}). \quad \blacksquare$$

The domatic number  $d(G)$  of  $G$  is the largest order of a partition of  $V(G)$  into dominating sets of  $G$ . The following deduction from the proof of Theorem 2 is obvious.

Corollary 1. For any graph  $G$ ,  $\Gamma_2(G) \leq d(\bar{G})$ .

## 2.2. The calculation of $\Gamma_k(P_n)$ .

Define an  $\ell$ -subset  $Q$  of a dominating set  $X$  of a graph  $G$  to be stable (unstable) if and only if there does not exist (there exists) an  $(\ell-1)$ -subset  $R$  of  $V - X$  such that  $(X-Q) \cup R$  is dominating. Notice that a dominating set  $X$  is  $k$ -minimal if for each  $1 \leq \ell \leq k$ , all  $\ell$ -subsets of  $X$  are stable. Let  $P_n$  have the (left to right) vertex sequence  $v_1, \dots, v_n$ . The simple proof of the following proposition is omitted.

Proposition 1. If  $X$  is a  $(k-1)$ -minimal but not  $k$ -minimal dominating set of  $P_n$ , then any unstable  $k$ -set in  $X$  consists of consecutive vertices of  $X$  i.e. if  $X = \{v_{m_1}, v_{m_2}, \dots, v_{m_t}\}$  where  $m_1 \leq m_2 \leq \dots \leq m_t$ , then any unstable  $k$ -set in  $X$  may be written as  $\{v_{m_{i+1}}, v_{m_{i+2}}, \dots, v_{m_{i+k}}\}$  for some  $i$ .

In what follows  $P_n \langle i, m \rangle$  where  $1 \leq i \leq m \leq n$ , will denote the subgraph of  $P_n$  induced by the vertex subset  $\{v_i, v_{i+1}, \dots, v_m\}$ . Our first lemmas 1(a) and (b) give necessary conditions for consecutive vertices of  $P_n$  to appear in a  $k$ -minimal dominating set.

Lemma 1(a). For any  $k, n \geq 1$ , if  $X$  is a  $k$ -minimal dominating set of  $P_n$  such that  $\{v_{i-1}, v_i\} \subseteq X$  for some  $i$ , then exactly one of the following holds:

(i)  $n < i + 3k$ , in which case  $n = i + 3r + 1$ , where  $0 \leq r \leq k-1$  and

$$V[P_n \langle i, n \rangle] \cap X = \{v_{i+3j} \mid j = 0, 1, \dots, r\};$$

(ii)  $n \geq i + 3k$  and  $V[P_n \langle i, i+3k \rangle] \cap X = \{v_{i+3j} \mid j = 0, \dots, k\}$ .

Proof. By induction on  $k$ . Let  $k = 1$  and let  $X$  be a 1-minimal (i.e. minimal) dominating set of  $P_n$  with  $\{v_{i-1}, v_i\} \subseteq X$  for some  $i$ . Suppose  $n < i + 3$ . If  $n = i$ , then  $X$  is not minimal, hence  $n \geq i + 1$ . If  $n = i + 2$  then  $v_{i+2} = v_n$  is dominated, therefore  $v_{i+1}$  or  $v_{i+2}$  is in  $X$ . In either case  $X$  is not minimal so the case  $n = i + 2$  cannot occur. Therefore  $n = i + 1$  and (i) holds. If  $n \geq i + 3$ , it is easily seen that  $v_{i+1}$  or  $v_{i+2}$  in  $X$  contradicts minimality and hence  $v_{i+3}$  must be in  $X$  so that  $v_{i+2}$  is dominated. Hence the assertion (ii) holds.

Now suppose that the result is true for  $k - 1$  where  $k \geq 2$  and let  $X$  be a  $k$ -minimal dominating set of  $P_n$  with  $\{v_{i-1}, v_i\} \subseteq X$ .

Case 1. Let  $n < i + 3(k-1)$ . Since  $X$  is  $(k-1)$ -minimal, by the induction hypothesis, condition (i) holds.

Case 2. Let  $i + 3(k-1) \leq n$ . By the induction hypothesis,

$$V[P_n \langle i, i+3(k-1) \rangle] \cap X = \{v_{i+3j} \mid j = 0, \dots, k-1\}. \quad (1)$$

If  $n = i + 3(k-1)$ , then

$$X' = \left[ X - \{v_{i+3j} \mid j = 0, \dots, k-1\} \right] \cup \{v_{i+3j+2} \mid j = 0, \dots, k-2\}$$

dominates  $P_n$ , which contradicts the  $k$ -minimality of  $X$ . If

$n = i + 3(k-1) + 2$ , then since  $v_n$  is dominated,  $v_n$  or  $v_{n-1}$  is in  $X$ .

Again  $X'$  dominates and we conclude that either  $n = i + 3(k-1) + 1$  in which case (i) is satisfied, or  $n \geq i + 3k$ . In this case, it follows from (1) and

the  $1$ -minimality of  $X$ , that neither  $v_{i+3(k-1)+1}$  nor  $v_{i+3(k-1)+2}$  is in  $X$ .

Therefore  $v_{i+3k} \in X$  to dominate its predecessor and (ii) holds. This

completes the proof of Lemma 1(a). ■

Lemma 1(a) has a "dual" form concerning the vertices to the left of a consecutive pair  $v_{i-1}, v_i$  in a  $k$ -minimal dominating set. The proof is similar to that of Lemma 1(a) and is omitted.

Lemma 1(b). For any  $k, n \geq 1$ , if  $X$  is a  $k$ -minimal dominating set of  $P_n$  such that  $\{v_{i-1}, v_i\} \subseteq X$  for some  $i$ , then exactly one of the following holds: -

(i)  $i - 1 - 3k < 1$  (i.e.  $i < 2 + 3k$ ), in which case  $1 = i - 1 - 3r - 1$

(i.e.  $i = 3r$ ) for some  $r$ ,  $1 \leq r \leq k$ , and

$$V[P_n \langle 1, i-1 \rangle] \cap X = \{v_{i-1-3j} \mid 0 \leq j \leq r-1\};$$

(ii)  $i - 1 - 3k \geq 1$  (i.e.  $i \geq 3k + 2$ ) and

$$V[P_n \langle i-1-3k, i-1 \rangle] \cap X = \{v_{i-1-3j} \mid 0 \leq j \leq k\}.$$

By a  $\Gamma_k$ -set we mean a  $k$ -minimal dominating set of largest cardinality.

Theorem 3. For any  $k, n \geq 1$ ,  $P_n$  has a  $\Gamma_k$ -set which is independent.

Proof. Let  $n$  and  $k$  be such that the statement is false. Since the result follows easily if  $k = 1$ , it is clear that  $k \geq 2$ . Let  $X$  be a  $\Gamma_k$ -set in  $P_n$  such that  $P_n \langle X \rangle$  has as few edges as possible and let  $i$  be the largest integer such that  $v_{i-1}, v_i \in X$ . By the choice of  $X$  and Lemma 1, respectively, neither  $v_{i+1}$  nor  $v_{i+2}$  is an end vertex of  $P_n$  and  $\{v_{i+1}, v_{i+2}\} \cap X = \emptyset$ ; hence  $n \geq i + 3$  and  $v_{i+3} \in X$ . Consider the set  $X' = [X - \{v_i\}] \cup \{v_{i+1}\}$  which clearly dominates  $P_n$ . By the choice of  $X$ ,  $X'$  is not  $k$ -minimal. Hence there is a smallest integer  $\ell \leq k$  for which there exists an  $\ell$ -set  $Q \subseteq X'$  such that  $(X' - Q) \cup R$  dominates  $P_n$  for some  $(\ell-1)$ -set  $R \subseteq V(P_n)$ .



Suppose  $v_{i+1} \in Q$ . By the choice of  $\ell$ ,  $v_{i+1} \notin R$ . But then  $\left[ X - \left[ \left[ Q - \{v_{i+1}\} \right] \cup \{v_i\} \right] \right] \cup R = (X' - Q) \cup R$  which dominates  $P_n$ , contradicting the  $k$ -minimality of  $X$ . Hence  $v_{i+1} \notin Q$ . By the choice of  $\ell$  and by Proposition 1, either  $Q \subseteq \{v_1, v_2, \dots, v_{i-1}\}$  or  $Q \subseteq \{v_{i+3}, v_{i+4}, \dots, v_n\}$ . If  $Q \subseteq \{v_1, v_2, \dots, v_{i-1}\}$ , then since  $(X' - Q) \cup R$  dominates  $P_n$ , it is clear that  $(X - Q) \cup R$  dominates  $P_n$ .

Hence  $Q \subseteq \{v_{i+3}, v_{i+4}, \dots, v_n\}$ . If  $v_{i+3} \notin Q$  then  $v_{i+3} \in (X' - Q) \cup R$  in which case  $(X - Q) \cup R$  dominates  $P_n$ .

Hence, again by Proposition 1 and Lemma 1,  $Q = \{v_{i+3j} \mid j = 1, 2, \dots, \ell\}$ . By the choice of  $i$ ,  $v_{i+3\ell+1} \notin X'$ . Hence at least  $3\ell - 3 + 1$  vertices of  $P$  are not dominated by  $X' - Q$  and since  $\gamma(P_{3\ell-3+1}) = \left\lceil \frac{3(\ell-1)+1}{3} \right\rceil$ , no  $(\ell-1)$ -set  $R \subseteq V(P_n)$  exists such that  $(X' - Q) \cup R$  dominates  $P_n$ . This contradiction completes the proof. ■

We now state and prove the principal result of the paper.

Theorem 4. For all  $k \geq 1$  and  $n \geq 2$ ,

$$\Gamma_k(P_n) = \begin{cases} \left\lceil \frac{(k+1)n}{3k+1} \right\rceil & \text{if } n \equiv 3\ell + 1 \pmod{3k+1} \text{ for some } \ell \in \{0, 1, \dots, k-1\} \\ \left\lceil \frac{(k+1)(n+1)}{3k+1} \right\rceil & \text{otherwise.} \end{cases}$$

Proof of lower bound. Write  $n$  as  $n = h + r$ , where  $h = m(3k+1)$  for some integer  $m$ , and  $0 \leq r \leq 3k$ . Let

$$X = \{v_i \in V(P_n) \mid i \equiv 1 \pmod{3k+1} \text{ or } i \equiv 3\ell \pmod{3k+1}, 1 \leq \ell \leq k\}.$$

Clearly,  $X$  dominates  $P_n$  unless  $r = 3\ell + 2$  for some  $\ell$ ,  $1 \leq \ell \leq k-1$ .

Define

$$Y = \begin{cases} \left[ X - \{v_{h+3j} \mid 1 \leq j \leq \ell\} \right] \cup \{v_{h+3j+1} \mid 1 \leq j \leq \ell\} & \text{if } r = 3\ell + 2 \\ & \text{for some } \ell, 1 \leq \ell \leq k-1 \\ X & \text{otherwise.} \end{cases}$$

Then  $Y$  dominates  $P_n$  for all  $n$ . Moreover, we show that  $Y$  is  $k$ -minimal unless  $r = 3\ell$  for some  $\ell$ ,  $1 \leq \ell \leq k-1$ .

In order to see this, suppose firstly that  $r = 3\ell$  for some  $\ell$ ,  $1 \leq \ell \leq k-1$ . Let  $Q = \{v_{h+1}\} \cup \{v_{h+3j} \mid 1 \leq j \leq \ell\}$ . Then  $|Q| = \ell + 1 \leq k$  and exactly  $3\ell$  vertices of  $P_n$ , the vertices of  $P_n \langle h+1, n \rangle$ , are not dominated by  $Y - Q$ . But  $\gamma(P_{3\ell}) = \left\lceil \frac{3\ell}{3} \right\rceil = \ell$  and hence there exists an  $\ell$ -set  $R$  such that  $(Y-Q) \cup R$  dominates  $P_n$ . In particular,  $R = \{v_{h+3j-1} \mid 1 \leq j \leq \ell\}$ .

Now suppose  $r \neq 3\ell$  for any  $\ell$ ,  $1 \leq \ell \leq k-1$ . Let  $S$  be any subset of  $Y$  consisting of  $k$  consecutive vertices of  $Y$ . Note that at least  $3(k-1) + 1$  consecutive vertices of  $P_n$  are not dominated by  $Y - S$  and since  $\gamma\left[P_{3(k-1)+1}\right] = \left\lceil \frac{3(k-1)+1}{3} \right\rceil = k$ , no set  $T$  with fewer than  $k$  vertices exists such that  $(Y-S) \cup T$  dominates  $P_n$ . Hence  $S$  is stable and therefore any subset of  $Y$  consisting of fewer than  $k$  consecutive vertices of  $P_n$  is also stable. Now let  $s$  be the smallest integer such that  $Y$  is not  $s$ -stable. By Proposition 1, any unstable  $s$ -subset of  $Y$  consists of  $s$  consecutive vertices of  $Y$ . Since any set of  $k$  or fewer consecutive vertices of  $Y$  is stable,  $s > k$  and  $Y$  is  $k$ -minimal as asserted.

In view of the above, define

$$Z = \begin{cases} (Y-Q) \cup R & \text{if } r = 3\ell \text{ for some } \ell, 1 \leq \ell \leq k-1 \\ Y & \text{otherwise,} \end{cases}$$

where  $Q$  and  $R$  are as above.  $Z$  is a  $k$ -minimal dominating set of  $P_n$  for all  $n$ ; hence  $\Gamma_k(P_n) \geq |Z|$ . Moreover,

$$|Z| = (k+1)m + |Z \cap V(P_n \langle h+1, n \rangle)| \quad (2)$$

(where  $n = h + r$  with  $h = m(3k+1)$  and  $0 \leq r \leq 3k$ ),

and

$$|Z \cap V(P_n \langle h+1, n \rangle)| = \begin{cases} \ell & \text{if } r = 3\ell \text{ for some } \ell, 1 \leq \ell \leq k-1 \\ k+1 & \text{if } r = 3k \\ \ell+1 & \text{if } r = 3\ell+2 \text{ for some } \ell, 0 \leq \ell \leq k-1 \\ \ell+1 & \text{if } r = 3\ell+1 \text{ for some } \ell, 0 \leq \ell \leq k-1. \end{cases} \quad (3)$$

It is easily verified from (2) and (3), that in the first three cases of (3),  $|Z| = \left\lfloor \frac{(k+1)(n+1)}{3k+1} \right\rfloor$  and in the fourth case  $|Z| = \left\lceil \frac{(k+1)n}{3k+1} \right\rceil$ . This completes the proof of the lower bound.

Proof of upper bound. We first prove the following lemma:

Lemma 2. If  $X$  is an independent  $\Gamma_k$ -set of  $P_n$ , then among any  $3k+1$  consecutive vertices of  $P_n$ , at most  $k+1$  are in  $X$ .

Proof of Lemma. Suppose there are  $3k+1$  consecutive vertices  $S = \{v_i, v_{i+1}, \dots, v_{i+3k}\}$  of  $P_n$  such that  $|S \cap X| \geq k+2$ . Let  $j$  ( $\ell$  respectively) be the smallest (largest) integer such that  $v_j \in S \cap X$  ( $v_\ell \in S \cap X$ ) and let  $S' = \{v_{j+2}, v_{j+3}, \dots, v_{\ell-2}\}$ . Then  $|S' \cap X| = |S \cap X| - 2 \geq k$  while  $|S'| \leq 3k-3$ . But  $\gamma(P_{3k-3}) = \left\lceil \frac{3k-3}{3} \right\rceil = k-1$  and therefore there exists a set  $R$  with  $|R| \leq k-1$  which dominates  $S'$ .

Clearly  $\left[ X - (S' \cap X) \right] \cup R$  dominates  $P_n$ , contradicting the  $k$ -minimality of  $X$ . Hence the lemma is proved.

To continue with the proof of the upper bound, we again put  $n = h + r$  with  $h = m(3k+1)$  for some integer  $m$ , and  $0 \leq r \leq 3k$ . Suppose, contrary to the result,

$$\Gamma_k(P_n) > \begin{cases} \left\lfloor \frac{(k+1)n}{3k+1} \right\rfloor & \text{if } r = 3\ell + 1 \text{ for some } \ell, 0 \leq \ell \leq k-1 \\ \left\lfloor \frac{(k+1)(n+1)}{3k+1} \right\rfloor & \text{otherwise,} \end{cases}$$

$$\text{i.e., } \Gamma_k(P_n) \geq \begin{cases} (k+1)m + \ell + 1 & \text{if } r = 3\ell \text{ for some } \ell, 1 \leq \ell \leq k-1 \\ (k+1)m + \ell + 2 & \text{if } r = 3\ell + 1 \text{ for some } \ell, 0 \leq \ell \leq k-1 \\ (k+1)m + \ell + 2 & \text{if } r = 3\ell + 2 \text{ for some } \ell, 0 \leq \ell \leq k-1 \\ (k+1)m + k + 2 & \text{if } r = 3k. \end{cases}$$

By Theorem 3,  $P_n$  has an independent  $\Gamma_k$ -set  $X$ . Let  $X' = X \cap V(P_n \langle 1, h \rangle)$ . By Lemma 2,  $|X'| \leq (k+1)m$ , which implies

$$|X - X'| \geq \begin{cases} \ell + 1 & \text{if } r = 3\ell \text{ for some } \ell, 1 \leq \ell \leq k-1 \\ \ell + 2 & \text{if } r = 3\ell + 1 \text{ for some } \ell, 0 \leq \ell \leq k-1 \\ \ell + 2 & \text{if } r = 3\ell + 2 \text{ for some } \ell, 0 \leq \ell \leq k-1 \\ k + 2 & \text{if } r = 3k. \end{cases}$$

The last case, i.e.  $|X - X'| \geq k + 2$  for  $r = 3k$ , contradicts Lemma 2 applied to  $P_n \langle h, n \rangle$ . Hence three cases remain.

Case 1. Let  $r = 3\ell + 1$  for some  $\ell$ ,  $0 \leq \ell \leq k-1$  and consider the  $3(k-\ell)$  vertices of the subgraph  $P_n \langle h-3(k-\ell)+1, h \rangle$  of  $P_n$ . At least  $3(k-\ell)-2$  of these are not dominated by  $X - V(P_n \langle h-3(k-\ell)+1, h \rangle)$  and therefore

$$|X' \cap V(P_n \langle h-3(k-\ell)+1, h \rangle)| \geq \left\lceil \frac{3(k-\ell)-2}{3} \right\rceil = k - \ell.$$

But then

$$|X \cap V(P_n \langle h-3(k-\ell)+1, n \rangle)| \geq k - \ell + \ell + 2 = k + 2$$

while  $|V(P_n \langle h-3(k-\ell)+1, n \rangle)| = 3k + 1$ , contradicting Lemma 2.

Case 2. Let  $r = 3\ell$  where  $1 \leq \ell \leq k-1$ . If  $v_h \in X'$  or  $v_{h-1} \in X'$ , then  $X - X'$  is unstable since  $\gamma(P_{3\ell}) = \left\lceil \frac{3\ell}{3} \right\rceil = \ell < \ell + 1$ . Hence  $\{v_{h-1}, v_h\} \cap X' = \emptyset$  and therefore  $v_{h-2} \in X'$ ,  $v_{h+1} \in X - X'$ . Consider the  $3(k-\ell)+1$  vertices of  $P_n \langle h-3(k-\ell), h \rangle$ . At least  $3(k-\ell)-1$  of these are not dominated by  $X - V(P_n \langle h-3(k-\ell), h \rangle)$  and therefore

$$|X' \cap V(P_n \langle h-3(k-\ell), h \rangle)| \geq \left\lceil \frac{3(k-\ell)-1}{3} \right\rceil = k - \ell.$$

If  $|X'| < (k+1)m$ , then  $|X - X'| \geq \ell + 2$  so that

$$|X \cap V(P_n \langle h-3(k-\ell), n \rangle)| \geq k - \ell + \ell + 2 = k + 2$$

while  $|V(P_n \langle h-3(k-\ell), n \rangle)| = 3k+1$ , contradicting Lemma 2. Hence

$|X'| = (k+1)m$ . Since  $\{v_{h-1}, v_h\} \cap X' = \emptyset$ ,

$$|X' \cap V(P_n \langle 1, h-2 \rangle)| = (k+1)m.$$

Consider the subgraphs  $P_n \langle 1, 3k-1 \rangle$  and  $P_n \langle 3k, h-2 \rangle$  of  $P_n$ . Clearly,  $P_n \langle 3k, h-2 \rangle$  has order  $(3k+1)(m-1)$  so that

$$|X' \cap V(P_n \langle 3k, h-2 \rangle)| \leq (k+1)(m-1) \text{ by Lemma 2.}$$

Therefore  $|X' \cap V(P_n \langle 1, 3k-1 \rangle)| \geq k + 1$ .

Let  $j$  be the largest integer such that  $v_j \in X' \cap V(P_n \langle 1, 3k-1 \rangle) = X''$  and consider  $P_n \langle 1, j-2 \rangle$ . Clearly  $X'' \cap V(P_n \langle 1, j-2 \rangle) = Q$  satisfies  $|Q| \geq k$ , while  $P_n \langle 1, j-2 \rangle$  has order at most  $3k-3$ . Since  $\gamma(P_{3k-3}) = k-1$ , there exists a set  $R$  containing  $k-1$  vertices which dominates  $P_n \langle 1, j-2 \rangle$ . But then  $(X-Q') \cup R$  dominates  $P_n$ , where  $Q'$  is any  $k$ -subset of  $Q$ , contradicting the  $k$ -minimality of  $X$ .

Case 3. Let  $r = 3\ell + 2$  where  $0 \leq \ell \leq k-1$ . If  $\{v_{h-2}, v_{h-1}, v_h\} \cap X \neq \emptyset$ , then at most  $3\ell + 3$  vertices remain to be dominated by  $Q = X - X'$  which has at least  $\ell + 2$  vertices. But  $\gamma(P_{3\ell+3}) = \ell + 1$ ; hence there exists an  $(\ell+1)$ -element subset  $R$  of  $V(P_n)$  such that  $(X-Q) \cup R$  dominates  $P_n$ , contradicting the  $k$ -minimality of  $X$  if  $\ell \leq k-2$ . Hence in this case,  $\{v_{h-2}, v_{h-1}, v_h\} \cap X' = \emptyset$  implying that  $v_{h-1}$  is not dominated, which is impossible. If  $\ell = k-1$ , then by Lemma 2,  $\{v_{h-1}, v_h\} \cap X' = \emptyset$  and  $|X-X'| = \ell + 2 = k + 1$ , so that  $v_{h-2} \in X'$  and  $|X'| = (k+1)m$ . As in case 2, a contradiction of the  $k$ -minimality of  $X$  can now be obtained. ■

### 2.3 A generalization of Gallai's Theorem.

The point covering number  $\alpha(G)$  of a graph  $G$  (i.e. smallest number of vertices which cover all the edges) and the independence number  $\beta(G)$  (i.e. largest cardinality of an independent set of vertices) are related by the well-known result of Gallai [3].

Theorem 5 (Gallai). For any  $n$  vertex graph,  $\alpha(G) + \beta(G) = n$ .

In order to generalize this result we need three definitions. Let  $P$  be a property associated with the subsets of a set  $S$ . The subset  $X$  of  $S$  is a  $k$ -maximal  $P$ -set if  $X$  is a  $P$ -set but the addition of any  $\ell$  elements to  $X$  where  $\ell \leq k$ , followed by the removal of any  $\ell-1$  elements, yields a  $\bar{P}$ -set.

Let  $Y \subseteq S$  be a  $Q$ -set if and only if it intersects every  $\bar{P}$ -set (i.e. it is a transversal of the family of  $\bar{P}$ -sets).

Finally property  $P$  is hereditary if each subset of a  $P$ -set is also a  $P$ -set.

Theorem 6. Let  $P$  be a hereditary property. Then  $X$  is a  $k$ -maximal  $P$ -set if and only if  $S - X$  is a  $k$ -minimal  $Q$ -set.

Proof. Let  $X$  be a  $k$ -maximal  $P$ -set and  $Y = S - X$ .  $Y$  is a transversal of the  $\bar{P}$ -sets for otherwise there is a  $\bar{P}$ -set entirely contained in  $X$  contrary to the hereditary property. Suppose  $Y$  is not a  $k$ -minimal  $Q$ -set. Then for some  $\ell$ -subset  $T$  of  $Y$  where  $\ell \leq k$  and an  $(\ell-1)$ -subset  $U$  of  $S - Y$ ,  $(Y-T) \cup U$  is a  $Q$ -set.

Consider the set  $(X \cup T) - U$ . It is not a  $\bar{P}$ -set since it does not intersect the  $Q$ -set  $(Y - T) \cup U$ . Hence  $(X \cup T) - U$  is a  $P$ -set which contradicts the  $k$ -maximality of  $X$ . Therefore  $Y$  is a  $k$ -minimal  $Q$ -set. The proof of the converse is similar and omitted. ■

If  $\alpha_k(S, P)$  and  $\beta_k(S, P)$  denote the smallest cardinality of a  $k$ -minimal  $Q$ -set and the largest cardinality of a  $k$ -maximal  $P$ -set, we have immediately:-

Corollary 2. If  $P$  is a hereditary property on the subsets of  $S$

$$\alpha_k(S, P) + \beta_k(S, P) = |S|.$$

In the special case where  $k = 1$ ,  $S = V(G)$  and  $P$ -sets are independent sets of vertices, corollary 2 reduces to Gallai's Theorem.

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