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# On the proper orientation number of bipartite graphs

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## On the proper orientation number of bipartite graphs

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**Abstract:** An *orientation* of a graph  $G$  is a digraph  $D$  obtained from  $G$  by replacing each edge by exactly one of the two possible arcs with the same endvertices. For each  $v \in V(G)$ , the *indegree* of  $v$  in  $D$ , denoted by  $d_D^-(v)$ , is the number of arcs with head  $v$  in  $D$ . An orientation  $D$  of  $G$  is *proper* if  $d_D^-(u) \neq d_D^-(v)$ , for all  $uv \in E(G)$ . The *proper orientation number* of a graph  $G$ , denoted by  $\vec{\chi}(G)$ , is the minimum of the maximum indegree over all its proper orientations. In this paper, we prove that  $\vec{\chi}(G) \leq \lfloor (\Delta(G) + \sqrt{\Delta(G)})/2 \rfloor + 1$  if  $G$  is a bipartite graph, and  $\vec{\chi}(G) \leq 4$  if  $G$  is a tree. It is well-known that  $\vec{\chi}(G) \leq \Delta(G)$ , for every graph  $G$ . However, we prove that deciding whether  $\vec{\chi}(G) \leq \Delta(G) - 1$  is already an  $\mathcal{NP}$ -complete problem. We also show that it is  $\mathcal{NP}$ -complete to decide whether  $\vec{\chi}(G) \leq 2$ , for planar *subcubic* graphs  $G$ . Moreover, we prove that it is  $\mathcal{NP}$ -complete to decide whether  $\vec{\chi}(G) \leq 3$ , for planar bipartite graphs  $G$  with maximum degree 5.

**Key-words:** proper orientation, graph colouring, bipartite graph

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## Sur l'indice d'orientation propre des graphes bipartis

**Résumé :** Une *orientation* d'un graphe  $G$  est un digraphe  $D$  obtenu à partir de  $G$  en remplaçant chaque arête par exactement un des deux arcs possibles avec les mêmes extrémités. Pour tout  $v \in V(G)$ , le *dégré entrant* de  $v$  dans  $D$ , noté  $d_D^-(v)$ , est le nombre d'arcs de  $D$  ayant  $v$  pour tête. Une orientation  $D$  de  $G$  est *propre* si  $d_D^-(u) \neq d_D^-(v)$ , pour tout  $uv \in E(G)$ . L'*indice d'orientation propre* d'un graphe  $G$ , noté  $\vec{\chi}(G)$ , est le plus petit degré maximum d'une orientation propre de  $G$ . Dans ce papier, nous prouvons que  $\vec{\chi}(G) \leq \left\lfloor \left( \Delta(G) + \sqrt{\Delta(G)} \right) / 2 \right\rfloor + 1$  si  $G$  est un graphe biparti, et  $\vec{\chi}(G) \leq 4$  si  $G$  est un arbre. Il est connu que  $\vec{\chi}(G) \leq \Delta(G)$ , pour tout graphe  $G$ . En revanche, nous prouvons que décider si  $\vec{\chi}(G) \leq \Delta(G) - 1$  est déjà un problème  $\mathcal{NP}$ -complet. Nous montrons aussi qu'il est  $\mathcal{NP}$ -complet de décider si  $\vec{\chi}(G) \leq 2$  pour un graphe planaire subcubique  $G$ . Enfin nous montrons qu'il est  $\mathcal{NP}$ -complet de décider si  $\vec{\chi}(G) \leq 3$  pour un graphe planaire biparti  $G$  de degré maximum 5.

**Mots-clés :** orientation propre, coloration de graphe, graphe biparti

## 1 Introduction

In this paper, all graphs are *simple*, that is without loops and multiple edges. We follow standard terminology as used in [3].

An *orientation*  $D$  of a graph  $G$  is a digraph obtained from  $G$  by replacing each edge by just one of the two possible arcs with the same endvertices. For each  $v \in V(G)$ , the *indegree* of  $v$  in  $D$ , denoted by  $d_D^-(v)$ , is the number of arcs with head  $v$  in  $D$ . We use the notation  $d^-(v)$  when the orientation  $D$  is clear from the context. The orientation  $D$  of  $G$  is *proper* if  $d^-(u) \neq d^-(v)$ , for all  $uv \in E(G)$ . An orientation with maximum indegree at most  $k$  is called a *k-orientation*. The *proper orientation number* of a graph  $G$ , denoted by  $\vec{\chi}(G)$ , is the minimum integer  $k$  such that  $G$  admits a proper  $k$ -orientation. This graph parameter was introduced by Ahadi and Dehghan [1]. It is well-defined for any graph  $G$  since one can always obtain a proper  $\Delta(G)$ -orientation (see [1]). In other words,  $\vec{\chi}(G) \leq \Delta(G)$ . Note that every proper orientation of a graph  $G$  induces a proper vertex colouring of  $G$ . Thus,  $\vec{\chi}(G) \geq \chi(G) - 1$ . Hence, we have the following sequence of inequalities:

$$\omega(G) - 1 \leq \chi(G) - 1 \leq \vec{\chi}(G) \leq \Delta(G).$$

These inequalities are best possible in the sense that, for a complete graph  $K$ ,  $\omega(K) - 1 = \chi(K) - 1 = \vec{\chi}(K) = \Delta(K)$ . However, one might expect better upper bounds on some parameter by taking a convex combination of two others. Reed [6] showed that there exists  $\epsilon_0 > 0$  such that  $\chi(G) \leq \epsilon_0 \cdot \omega(G) + (1 - \epsilon_0)\Delta(G)$  for every graph  $G$  and conjectured the following.

**Conjecture 1** (Reed [6]). For every graph  $G$ ,

$$\chi(G) \leq \left\lceil \frac{\Delta(G) + 1 + \omega(G)}{2} \right\rceil.$$

If true, this conjecture would be tight. Johannson [4] settled Conjecture 1 for  $\omega(G) = 2$  and  $\Delta(G)$  sufficiently large.

Likewise, one may wonder if similar upper bounds might be derived for the proper orientation number.

**Problem 1.**

- (a) Does there exist a positive  $\epsilon_1$  such that  $\vec{\chi}(G) \leq \epsilon_1 \cdot \omega(G) + (1 - \epsilon_1)\Delta(G)$ ?
- (b) Does there exist a positive  $\epsilon_2$  such that  $\vec{\chi}(G) \leq \epsilon_2 \cdot \chi(G) + (1 - \epsilon_2)\Delta(G)$ ?

Observe that both questions are intimately related. Indeed if the answer to (a) is positive for  $\epsilon_1$ , then the answer to (b) is also positive for  $\epsilon_1$ . On the other hand, if the answer to (b) is positive for  $\epsilon_2$ , then the answer to (a) is also positive for  $\epsilon_1 = \epsilon_0 \cdot \epsilon_2$  by the above-mentioned result of Reed.

In Section 2, we answer Problem 1 positively in the case of bipartite graphs by showing that

$$\text{if } G \text{ is bipartite, then } \vec{\chi}(G) \leq \left\lceil \frac{\Delta(G) + \sqrt{\Delta(G)}}{2} \right\rceil + 1.$$

We also present bipartite graphs  $G$  such that  $\vec{\chi}(G) = \Delta(G) = k$  for  $k \in \{1, 2, 3\}$ .

In Section 3, we prove that  $\vec{\chi}(T) \leq 4$ , for every tree  $T$ . Moreover, we show that  $\vec{\chi}(T) \leq 3$  if  $\Delta(T) \leq 6$ , and  $\vec{\chi}(T) \leq 2$  if  $\Delta(T) \leq 3$ . We also argue that all these bounds are tight.

In Section 4, we study the computational complexity of computing the proper orientation number of a bipartite graph. In their seminal paper, Ahadi and Dehghan proved that it is  $\mathcal{NP}$ -complete to decide whether  $\vec{\chi}(G) = 2$  for planar graphs  $G$ . We first improve their reduction

and show that it is  $\mathcal{NP}$ -complete to decide whether  $\vec{\chi}(G) \leq 2$ , for planar *subcubic* graphs  $G$ . Moreover, we prove that deciding whether  $\vec{\chi}(G) \leq \Delta(G) - 1$  is an  $\mathcal{NP}$ -complete problem for general graphs  $G$ . Finally, we show that it is also  $\mathcal{NP}$ -complete to decide whether  $\vec{\chi}(G) \leq 3$  for planar bipartite graphs  $G$  with maximum degree 5.

In the final section, we draw some conclusive remarks and discuss some open problems and directions for further research.

## 2 General upper bound

The aim of this section is to prove the following theorem.

**Theorem 1.** *Let  $G$  be a bipartite graph and let  $k$  be a positive integer. If  $\Delta(G) > 2k + \frac{\sqrt{1+8k+1}}{2}$ , then  $\vec{\chi}(G) \leq \Delta(G) - k$ .*

In order to prove this theorem, we describe an algorithm (see Algorithm 1) that produces a proper  $(\Delta(G) - k)$ -orientation.

Let  $G = (X \cup Y, E)$  be a bipartite graph as in the statement of Theorem 1. The algorithm consists of two phases.

The first phase (lines 1 to 8 in Algorithm 1) produces an orientation, not necessarily proper, of the edges of  $G$  in such a way that the indegree of each vertex in  $X$  is at most  $k$  and the indegree of each vertex in  $Y$  is at most  $\Delta(G) - k$ . It proceeds as follows. We first orient all edges  $xy \in E(G)$  from  $x$  to  $y$ , where  $x \in X$  and  $y \in Y$ . Then we define  $k$  matchings as described subsequently.

Let  $G_1 = G$ , and let  $M_1$  be a matching in  $G_1$  that covers all vertices of maximum degree. For each  $i \in \{2, \dots, k\}$ , let  $G_i$  be the graph obtained from  $G_{i-1}$  by removing the edges in  $M_{i-1}$ , that is  $G_i = G_{i-1} - M_{i-1}$ , and let  $M_i$  be a matching in  $G_i$  that covers all vertices of degree  $\Delta(G_i)$ . Such a  $M_i$  exists since it is well known that every bipartite graph  $H$  has a proper  $\Delta(H)$ -edge-colouring. Clearly, we have  $\Delta(G_i) = \Delta(G_{i-1}) - 1$ , for each  $i \in \{2, 3, \dots, k\}$ . Let  $M := \bigcup_{i=1}^k M_i$ . Observe that if a vertex has degree  $\Delta(G) - k + j$  in  $G$ , where  $j \in \{1, 2, \dots, k\}$ , then it is incident to at least  $j$  edges in  $M$ . Hence, for all  $j \in \{1, 2, \dots, k\}$  and for each vertex  $y$  in  $Y$  of degree  $\Delta(G) - k + j$  in  $G$ , we reverse the orientation of exactly  $j$  edges in  $M$  incident to  $y$ . This ends the first phase.

The second phase reverses the orientation of some edges in  $E(G) \setminus M$ , step by step, in order to obtain a  $(\Delta(G) - k)$ -orientation. It remains to prove that this orientation is proper under the assumption of Theorem 1.

Before proving Theorem 1, let us introduce some notation and state a few properties of Algorithm 1. If  $x \in X$  and  $y \in Y$  are adjacent and have the same indegree, then there exists a *conflict* between  $x$  and  $y$ , and that  $x$  (or  $y$ ) *conflicts*. For each  $x \in X$  and  $\ell \in \{0, 1, \dots, \Delta(G) - 1\}$ , let  $N_{\leq \ell}(x) = \{y \in Y : xy \in E(G) \text{ and } d^-(y) \leq \ell\}$  and, similarly, let  $N_{=\ell}(x) = \{y \in Y : xy \in E(G) \text{ and } d^-(y) = \ell\}$ .

Recall that the first phase of this algorithm corresponds to lines 1 to 8 and the second phase to lines 9 to 15. The ‘for’ loop from line 10 to 15 is called the *third loop*.

**Claim 1.1.** *At the end of the first phase of Algorithm 1, the following hold:*

- (a)  $d^-(x) \leq k$  for all  $x \in X$ , and  $d^-(y) \leq \Delta(G) - k$  for all  $y \in Y$ ; and
- (b) if  $x \in X$  is dominated by some  $y \in Y$ , then  $d^-(y) = \Delta(G) - k$ .

*Proof.* Both statements follow directly from the reversal of the orientation of some edges in  $M$  in the first phase.  $\square$

In the second phase of the algorithm, we treat step by step the vertices  $x \in X$  in such a way that, once they satisfy the condition of the ‘while’ loop (line 15), the reversal of the orientation of edges in line 14 ensures that:

- (i)  $x$  does not conflict at the end of the current step; and
- (ii)  $x$  will never conflict after the current step.

The main argument we use to prove the second fact is the following:

**Claim 1.2.** *In the second phase of Algorithm 1, the indegree of every vertex in  $X$  never decreases and the indegree of every vertex in  $Y$  never increases.*

*Proof.* This is straightforward, since all re-orientations are towards  $X$ .  $\square$

Moreover, recall that, when decreasing the indegree of vertices in  $Y$  in the second phase of the algorithm, we only use vertices that have indegree in  $\{\Delta(G) - k - 1, \dots, 2\}$  at the end of the first phase.

**Claim 1.3.** *During a given iteration  $\ell$  of the third loop of Algorithm 1, only vertices belonging to  $Y$  of indegree at most  $\ell$  have their indegree decreased.*

*Proof.* The only edges that are re-oriented are those incident to vertices of  $N_{\leq \ell}(x)$ , which, by definition, have indegree at most  $\ell$ .  $\square$

Using previous claims, we now prove that all vertices in  $X$  that are removed from  $\tilde{X}$  do not conflict at the end of the execution of Algorithm 1.

**Claim 1.4.** *Suppose that  $x$  is removed from  $\tilde{X}$  during a given iteration  $\ell$  of the third loop of Algorithm 1. At the end of the execution of the algorithm, the following hold:*

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**Algorithm 1:** Proper Orientation of Bipartite Graphs

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**Input:** Bipartite graph  $G = (X \cup Y, E)$  and  $k \in \mathbb{N}$  s.t.  $\Delta(G) > 2k + \frac{\sqrt{1+8k+1}}{2}$ .  
**Output:** Proper  $(\Delta(G) - k)$ -orientation for  $G$ .

- 1  $G_1 \leftarrow G$
- 2 Orient all edges in  $G$  from  $X$  to  $Y$
- 3 **for**  $i = 1, \dots, k$  **do**
- 4      $M_i \leftarrow$  matching of  $G_i$  saturating all vertices of degree  $\Delta(G_i)$
- 5      $G_{i+1} \leftarrow G_i - M_i$
- 6  $M \leftarrow \bigcup_{i=1}^k M_i$
- 7 **foreach**  $y \in Y$  **do**
- 8      $\lfloor$  reverse the orientation of  $\max\{0; d_G(y) - \Delta(G) + k\}$  edges of  $M$  incident to  $y$
- 9  $\tilde{X} \leftarrow X$
- 10 **for**  $\ell = \Delta(G) - k - 1, \dots, 2$  **do**
- 11     **while**  $\exists x \in X$  s.t.  $|N_{\leq \ell}(x)| \geq \ell - d^-(x)$  and  $|N_{=\ell}(x)| \leq \ell - d^-(x)$  **do**
- 12          $\tilde{Y} \leftarrow$  set of  $\ell - d^-(x)$  vertices of highest indegree in  $N_{\leq \ell}(x)$
- 13         **foreach**  $y \in \tilde{Y}$  **do**
- 14              $\lfloor$  Reverse the orientation of  $xy$  (i.e. re-orient  $xy$  towards  $x$ )
- 15          $\tilde{X} \leftarrow \tilde{X} \setminus \{x\}$

---



(a)  $d^-(x) = \ell$ ; and

(b)  $x$  has no neighbours of indegree  $\ell$ .

*Proof.* First note that, by Claims 1.1 and 1.3, every vertex in  $\tilde{X}$  is dominated only by vertices of indegree  $\Delta(G) - k$  at the beginning of the second phase. Therefore, at the beginning of iteration  $\ell$  of the third loop, that is before re-orienting the edges incident to  $x$ , the vertex  $x$  dominates all vertices in  $N_{\leq \ell}(x)$ . Thus, after re-orienting  $\ell - d^-(x)$  edges that are incident to  $x$  and to vertices of  $N_{\leq \ell}(x)$ ,  $x$  has indegree exactly  $\ell$ . Note that, after  $x$  is removed from  $\tilde{X}$ , the indegree of  $x$  does not change in the remainder of the second phase. Therefore, Property (a) holds at the end of the execution of Algorithm 1.

Note also that, when  $x$  is removed from  $\tilde{X}$ , it has at most  $\ell - d^-(x)$  neighbours of indegree  $\ell$  (due to the condition of the ‘while’ loop in line 15 of Algorithm 1), and all of these vertices belong to  $\tilde{Y}$ . Thus, they have their indegree decreased by 1 (lines 14 and 14). Therefore, at the end of this iteration of the ‘while’ loop,  $x$  has no neighbour of indegree  $\ell$ . By Claim 1.3 and since  $\ell$  decreases throughout the algorithm, no vertex in  $Y$  of indegree strictly larger than  $\ell$  has its indegree decreased during or after this iteration. Moreover, by Claim 1.2, no vertex in  $Y$  has its indegree increased. Therefore, we conclude that, at the end of the execution of Algorithm 1, Property (b) holds.  $\square$

With those claims in hands, we are now ready to prove Theorem 1.

*Proof of Theorem 1.* Assume that  $G = (X \cup Y, E)$  is a bipartite graph such that  $\Delta(G) > 2k + \frac{\sqrt{1+8k+1}}{2}$ . We shall prove that Algorithm 1 returns a proper  $(\Delta(G) - k)$ -orientation of  $G$ . Note that the above inequality implies that  $k < \frac{\Delta(G)}{2}$ .

By Claim 1.4, at the end of the execution of Algorithm 1, all vertices in  $X \setminus \tilde{X}$  do not conflict. Thus, it suffices to show is that the vertices in  $\tilde{X}$  do not conflict.

Suppose to the contrary that there exists  $x^* \in \tilde{X}$  that conflicts at the end of the execution of Algorithm 1. Let  $y^* \in Y$  be a neighbour of  $x^*$  such that  $d^-(y^*) = d^-(x^*)$  at the end of the execution.

Firstly, note that, at each iteration of the third loop, the condition of the ‘while’ loop in line 15 is not satisfied by  $x^*$ . Thus, during the execution of the second phase, the indegree of  $x^*$  does not change. Moreover, by Claims 1.1 and 1.2, we have  $1 \leq d^-(x^*) = d^-(y^*) \leq k$  at the end of the execution.

We claim that if  $x^*$  is dominated by some vertex  $y \in Y$  at the end of the execution, then there is no conflict between  $x^*$  and  $y$ . Indeed, no edge is re-oriented towards  $x^*$  in the second phase, so  $y$  already dominates  $x$  at the end of the first phase. By Claim 1.1,  $y$  has indegree  $\Delta(G) - k$  at the end of the first phase. Observe that the indegree of  $y$  does not decrease during the second phase because the third loop starts with the value  $\Delta(G) - k - 1$  and, by Claim 1.3, only vertices in  $Y$  with degree at most this value have their indegrees decreased. Since  $k < \frac{\Delta(G)}{2}$ , there is no conflict between  $y$  and  $x^*$ . Thus, during all of the second phase,  $x^*$  is dominated by  $d^-(x)$  vertices of indegree  $\Delta(G) - k$  and dominates its remaining neighbours, among which is  $y^*$ .

We now use the fact that the ‘while’ condition is never satisfied by  $x^*$  to get the contradiction that  $\Delta(G) \leq 2k + \frac{\sqrt{1+8k+1}}{2}$ . By Claim 1.3, vertex  $y^*$  must have its indegree set to  $d^-(x^*)$  no later than iteration  $\ell_1 := d^-(x^*) + 1$  in the third loop. Thus, at the end of iteration  $\ell_1$ ,  $|N_{\leq \ell_1}(x^*)| \geq \ell_1 - d^-(x^*) = 1$  holds since  $y^* \in N_{\leq \ell_1}(x^*)$ . Since the ‘while’ condition is never satisfied by  $x^*$ , we deduce that  $|N_{=\ell_1}(x^*)| > \ell_1 - d^-(x^*) = 1$ . Hence,  $x^*$  has at least two outneighbours, say  $y_1$  and  $y_2$ , of indegree exactly  $\ell_1$ . Note that, by Claim 1.3,  $y_1$  and  $y_2$  have

indegree  $\ell_1$  at the end of the execution of the algorithm. In addition, these vertices are distinct from  $y^*$ .

During iteration  $\ell_1$ , by Claim 1.3, only vertices of indegree at most  $\ell_1$  have their indegrees decreased. Thus, at the end of iteration  $\ell_2 := d^-(x^*) + 2$ ,  $y_1$  and  $y_2$  already have indegree exactly  $\ell_1$ , so we have  $|N_{\leq \ell_2}(x^*)| \geq \ell_2 - d^-(x^*) = 2$ . Since the ‘while’ condition is not satisfied by  $x^*$ , it has at least three outneighbours of indegree exactly  $\ell_2$  at the end of iteration  $\ell_2$ , that is  $|N_{=\ell_2}(x^*)| > 2$ . Moreover, those vertices have indegree  $\ell_2$  at the end of the execution of the algorithm. In the same way, for all  $i \in \{3, 4, \dots, \Delta(G) - k - d^-(x^*) - 1\}$ , setting  $\ell_i = d^-(x^*) + i$ , we show that  $x^*$  has at least  $i + 1$  outneighbours of indegree exactly  $\ell_i$  at the end of iteration  $\ell_i$  of the third loop, and thus at the end of the execution of Algorithm 1.

Hence,  $x^*$  dominates at least  $\xi := \sum_{i=0}^{\Delta(G)-k-d^-(x^*)-1} (i+1)$  vertices. However,  $x^*$  has at most  $\Delta(G)$  neighbours, so

$$\xi = \frac{(\Delta(G) - k - d^-(x^*)) (\Delta(G) - k - d^-(x^*) + 1)}{2} \leq \Delta(G) - d^-(x^*).$$

Solving this inequality, we obtain  $\Delta(G) \leq k + d^-(x^*) + \frac{\sqrt{1+8k+1}}{2}$ . Since  $d^-(x^*) \leq k$ , we conclude that  $\Delta(G) \leq 2k + \frac{\sqrt{1+8k+1}}{2}$ , which contradicts the hypothesis of the theorem. Therefore, no vertex in  $\tilde{X}$  conflicts and thus the orientation produced by Algorithm 1 is a proper  $(\Delta(G) - k)$ -orientation for  $G$ .  $\square$

**Theorem 2.** *If  $G$  is a bipartite graph, then*

$$\vec{\chi}(G) \leq \left\lfloor \frac{\Delta(G) + \sqrt{\Delta(G)}}{2} \right\rfloor + 1.$$

*Proof.* By Theorem 1, for every  $k \in \mathbb{N}$ , if  $\Delta(G) > 2k + \frac{\sqrt{1+8k+1}}{2}$ , then  $\vec{\chi}(G) \leq \Delta(G) - k$ . In order to obtain a good upper bound for  $\vec{\chi}(G)$ , we must find the largest positive integer  $k$  such that the condition of Theorem 1 holds for a given graph  $G$ .

Solving the inequality for  $k$ , we obtain that  $k < \frac{\Delta(G) - \sqrt{\Delta(G)}}{2}$ . Since  $k$  is integer, the condition holds when

$$k \leq \left\lfloor \frac{\Delta(G) - \sqrt{\Delta(G)}}{2} \right\rfloor - 1.$$

Therefore, we conclude that

$$\vec{\chi}(G) \leq \Delta(G) - \left\lfloor \frac{\Delta(G) - \sqrt{\Delta(G)}}{2} \right\rfloor + 1 = \left\lfloor \frac{\Delta(G) + \sqrt{\Delta(G)}}{2} \right\rfloor + 1.$$

$\square$

Note that if  $G$  is bipartite and  $\Delta(G) \in \{2, 3, 4\}$ , then the bound of Theorem 2 is equal to the trivial upper bound  $\vec{\chi}(G) \leq \Delta(G)$ . For  $\Delta(G) = 1$  and  $\Delta(G) = 2$ , this bound is tight due to the paths with 2 and 4 vertices, respectively. In the sequel, we present a tight example for the case  $\Delta(G) = 3$ .

**Proposition 1.** *There exists a bipartite graph  $G$  with  $\Delta(G) = 3$  and  $\vec{\chi}(G) = 3$ .*

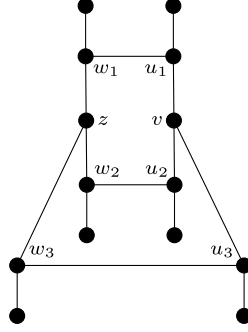


Figure 1: A bipartite graph  $B_3$  for which  $\vec{\chi}(B_3) = \Delta(B_3) = 3$

*Proof.* Consider the bipartite graph  $B_3$  depicted in Figure 1. Suppose to the contrary that there exists a proper 2-orientation  $D$  of  $B_3$ . Observe that, if a vertex  $x$  has a neighbour of degree 1, say  $y$ , then, in any proper orientation,  $x$  has indegree 1 only if  $y$  dominates  $x$ .

If  $d^-(v) = 0$ , then  $v$  dominates  $u_i$ , for all  $i \in \{1, 2, 3\}$ . Note that  $d^-(u_i) \neq 1$  for all  $i \in \{1, 2, 3\}$  due to their neighbours of degree 1. Thus, we obtain  $d^-(u_i) = 2$ , for each  $i \in \{1, 2, 3\}$ . Moreover,  $w_i$  dominates  $z$  and  $u_i$  for all  $i \in \{1, 2, 3\}$ , because  $d^-(w_i) \neq 2$  and  $w_i$  has a neighbour of degree 1. Therefore, we have  $d^-(z) = 3$ , a contradiction.

If  $d^-(v) = 1$ , then w.l.o.g.  $v$  is dominated by  $u_3$ , and dominates  $u_1$  and  $u_2$ . Similarly to the previous case, we have that  $d^-(u_1) = d^-(u_2) = 2$  and  $z$  is dominated by  $w_1$  and  $w_2$ . Thus,  $d^-(z) = 2$  and  $z$  dominates  $w_3$ , a contradiction, since  $w_3$  has a neighbour of degree 1 and  $d^-(w_3) \neq 2$ .

Finally, if  $d^-(v) = 2$ , then  $v$  dominates  $u_i$  for some  $i \in \{1, 2, 3\}$ . We again arrive to a contradiction, since  $u_i$  has a neighbour of degree 1 and  $d^-(u_i) \neq 2$ .

Therefore, there exists no proper 2-orientation of  $B_3$ . Since  $\Delta(B_3) = 3$ , we conclude that  $\vec{\chi}(B_3) = 3$ .  $\square$

Ahadi and Dehghan proved that, for every  $r \in \mathbb{N}$ , if  $G$  is a bipartite  $r$ -regular graph, then  $\vec{\chi}(G) = \lceil \frac{r+1}{2} \rceil$  [1]. In this sense, we next show an upper bound tighter than the one of Theorem 2 for bipartite graphs whose minimum degree is very close to its maximum degree.

**Proposition 2.** *If  $G$  is a bipartite graph, then*

$$\vec{\chi}(G) \leq \Delta(G) - \left\lfloor \frac{\delta(G) - 1}{2} \right\rfloor.$$

*Proof.* Let  $(X, Y)$  be a bipartition of  $G$  and let  $k = \left\lfloor \frac{\delta(G) - 1}{2} \right\rfloor$ . The following steps correspond to exactly the first phase of Algorithm 1.

Consider the orientation of  $G$  defined as follows. We first orient all edges  $xy \in E(G)$  from  $x$  to  $y$ , where  $x \in X$  and  $y \in Y$ . Then, we define  $k$  matchings as described subsequently. Let  $G_1 = G$ , and let  $M_1$  be a matching in  $G_1$  that covers all vertices of maximum degree. For each  $i \in \{2, \dots, k\}$ , let  $G_i = G_{i-1} - M_{i-1}$ , and let  $M_i$  be a matching in  $G_i$  that covers all vertices of degree  $\Delta(G_i)$ . Clearly, we have  $\Delta(G_i) = \Delta(G_{i-1}) - 1$ , for each  $i \in \{2, 3, \dots, k\}$ . Let  $M := \bigcup_{i=1}^k M_i$ . Observe that if a vertex has degree  $\Delta(G) - k + j$  in  $G$ , where  $j \in \{1, 2, \dots, k\}$ , then it is incident to at least  $j$  edges in  $M$ . Hence, for all  $j \in \{1, 2, \dots, k\}$  and for each vertex  $y$  in  $Y$  of degree  $\Delta(G) - k + j$  in  $G$ , we reverse the orientation of exactly  $j$  edges in  $M$  incident to  $y$ .

In this orientation of  $G$ , every vertex of  $X$  has indegree at most  $k$ , and every vertex of  $Y$  has indegree at least  $\delta(G) - k$ , which is larger than  $k$ , and at most  $\Delta(G) - k$ . Therefore, we have a proper  $(\Delta(G) - k)$ -orientation of  $G$ .  $\square$

### 3 Trees

The main goal of this section is to prove the following theorem.

**Theorem 3.** *If  $T$  is a tree, then the following statements hold:*

- (1) *if  $\Delta(T) \leq 3$ , then  $\vec{\chi}(T) \leq 2$ ;*
- (2) *if  $\Delta(T) \leq 6$ , then  $\vec{\chi}(T) \leq 3$ ;*
- (3)  *$\vec{\chi}(T) \leq 4$ .*

Before proving Theorem 3, we show that the three statements of the theorem are tight in the following sense: there is a tree with maximum degree 4 and proper orientation number 3, and a tree with maximum degree 7 and proper orientation number 4.

Let  $R_2$  and  $R_3$  be the trees with root  $x$  depicted in Figures 2(a) and 2(b), respectively.

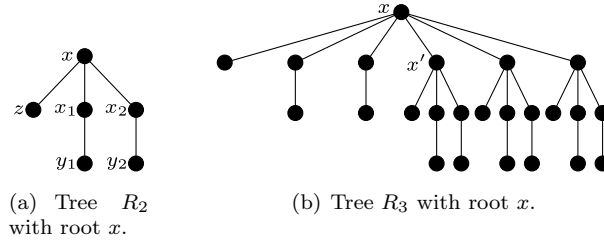


Figure 2: Rooted trees  $R_2$  and  $R_3$ .

Let  $H$  be an induced proper subgraph of  $G$  and let  $x \in V(H)$ . The subgraph  $H$  is  $x$ -pendant if there exist no edges between  $V(H) \setminus \{x\}$  and  $V(G) \setminus V(H)$ .

**Lemma 1.** *Let  $G$  be a graph containing an  $x$ -pendant  $R_2$  and let  $D$  be a proper orientation of  $G$ .*

- (i) *If  $d^-(x) = 1$ , then  $x$  is dominated by  $z$ .*
- (ii) *If  $d^-(x) = 2$ , then  $x$  is dominated by  $x_1$  and  $x_2$ .*

Moreover, if  $d^-(x) \in \{1, 2\}$ , then  $x$  dominates all its neighbours that are not in  $R_2$ .

*Proof.* (i) If  $d^-(x) = 1$ , then  $d^-(z) \neq 1$  because  $D$  is proper. Therefore, we have  $d^-(z) = 0$ , and thus  $z$  dominates  $x$ .

(ii) Suppose that  $d^-(x) = 2$  and  $x$  dominates  $x_i$ , for some  $i \in \{1, 2\}$ . Thus,  $d^-(x_i) \geq 1$  and, since  $D$  is proper, we deduce that  $d^-(x_i) = 1$ . It follows that  $x_i$  dominates  $y_i$ , so  $d^-(y_i) = 1$ , which is a contradiction since  $D$  is proper. Therefore,  $x$  is dominated by  $x_1$  and  $x_2$ .  $\square$

**Corollary 1.** *Let  $T_3$  be the tree obtained from two copies of  $R_2$  with roots  $x$  and  $\hat{x}$  by adding the edge  $x\hat{x}$ . It follows that  $\vec{\chi}(T_3) = 3$ .*

**Lemma 2.** *Let  $G$  be a graph with an  $x$ -pendant  $R_3$ . In any proper 3-orientation of  $G$ ,  $x$  dominates all its neighbours in  $G - R_3$ .*

*Proof.* Suppose to the contrary that there exists a proper 3-orientation  $D$  of  $G$  in which a vertex  $y \in V(G - R_3)$  dominates  $x$ . It follows that  $d^-(x) \geq 1$ . By Lemma 1, we obtain  $d^-(x) = 3$ . Moreover,  $x$  dominates at least one of its neighbours of degree 4 in  $R_3$ , say  $x'$ . Since  $D$  is proper,  $d^-(x') \in \{1, 2\}$ . Therefore, the subtree  $R_2$  rooted at  $x'$  contradicts Lemma 1.  $\square$

**Corollary 2.** *Let  $T_4$  be the tree obtained from two copies of  $R_3$  with roots  $x$  and  $\hat{x}$  by adding the edge  $x\hat{x}$ . It follows that  $\vec{\chi}(T_4) = 4$ .*

In order to prove Theorem 3, we need a few definitions. In a tree  $T$ , a vertex  $x$  is a *twig-vertex* if it is not a leaf and all its neighbours except possibly one are leaves. A *twig* is a subtree induced by a twig-vertex and its adjacent leaves. The *twig rooted at  $x$*  is the twig that contains the twig-vertex  $x$ .

A vertex  $x$  of  $T$  is a *bough-vertex* if it is neither a leaf, nor a twig-vertex, and all its neighbours except possibly one are twig-vertices or leaves. A *bough* is a subtree induced by a bough-vertex  $x$ , the leaves adjacent to  $x$ , and the vertices of the twigs whose roots are adjacent to  $x$ . The *bough rooted at  $x$*  is the bough that contains the bough-vertex  $x$ .

A vertex  $x$  of  $T$  is a *branch-vertex* if it is neither a leaf, nor a twig-vertex, nor a bough-vertex, and all its neighbours except possibly one are bough-vertices, twig-vertices or leaves.

We now proceed to prove Theorem 3.

*Proof of Theorem 3.* We prove the three statements by using similar arguments. For  $i \in \{1, 2, 3\}$ , we consider a minimal counter-example  $M_i$  to statement (i) with respect to the number of vertices, and derive a contradiction that implies that no counter-example exists. Since  $M_i$  is a minimal counter-example, we have  $\vec{\chi}(M_i) > i + 1$ , but  $\vec{\chi}(T) \leq i + 1$ , for any proper subtree  $T$  of  $M_i$ . We use the latter fact to derive a proper  $(i + 1)$ -orientation of  $M_i$ , which contradicts  $\vec{\chi}(M_i) > i + 1$ .

**Claim 3.1.** *For every  $i \in \{1, 2, 3\}$ , every vertex of  $M_i$  is adjacent to at most one leaf.*

*Proof.* Suppose to the contrary that a vertex  $v$  is adjacent to two leaves,  $u$  and  $w$ . Let  $D$  be a proper  $(i + 1)$ -orientation of  $M_i - u$ . In case  $d_D^-(v) \neq 1$ , one can obtain a proper  $(i + 1)$ -orientation of  $M_i$  from  $D$  by orienting  $vu$  from  $v$  to  $u$ . Consequently, we have  $d_D^-(v) = 1$ . Thus,  $vw$  is oriented from  $w$  to  $v$ , because  $D$  is proper. Hence,  $v$  dominates all its neighbours except  $w$  in  $D$ , so  $d_D^-(y) \geq 2$  for all  $y \in N_{M_i}(v) \setminus \{u, w\}$ . In particular,  $u$  and  $w$  are the only leaves adjacent to  $v$ . Therefore, one can obtain a proper  $(i + 1)$ -orientation of  $M_i$  from  $D$  by reversing the orientation of  $vw$  and orienting  $vu$  from  $v$  to  $u$ , a contradiction.  $\square$

**Claim 3.2.** *For every  $i \in \{1, 2, 3\}$ , every twig-vertex of  $M_i$  is adjacent to exactly one leaf.*

*Proof.* It follows directly from the definition of twig-vertex and Claim 3.1.  $\square$

**Claim 3.3.** *For every  $i \in \{1, 2, 3\}$ , every vertex of  $M_i$  is adjacent to at most two twig-vertices.*

*Proof.* Suppose to the contrary that a vertex  $v$  is adjacent to  $p$  twig-vertices  $t_1, \dots, t_p$  with  $p \geq 3$ . By Claim 3.2,  $t_j$  is adjacent to a single leaf  $u_j$ , for every  $j \in \{1, \dots, p\}$ . By minimality of  $M_i$ , the tree  $T = M_i - \bigcup_{j=3}^p \{t_j, u_j\}$  has a proper  $(i + 1)$ -orientation  $D$ . If  $d_D^-(v) \neq 2$ , then  $D$  can be extended to a proper  $(i + 1)$ -orientation of  $M_i$  by orienting the edges  $vt_j$  and  $u_j t_j$  towards  $t_j$ , for all  $j \in \{3, \dots, p\}$ . Hence, we have  $d_D^-(v) = 2$ , and so  $v$  must be dominated by  $t_1$  and  $t_2$  since  $D$  is proper. Thus, every vertex  $y \in N_T(v) \setminus \{t_1, t_2\}$  satisfies  $d_D^-(y) \geq 1$ . Therefore,  $D$  can be extended to a proper  $(i + 1)$ -orientation of  $M_i$  by orienting all edges  $vt_j$  and  $t_j u_j$  towards  $t_j$ , for every  $j \in \{1, \dots, p\}$ , a contradiction.  $\square$

**Claim 3.4.** *For every  $i \in \{1, 2, 3\}$ , every bough-vertex of  $M_i$  is adjacent to exactly one leaf and exactly two twig-vertices. In other words, every bough is isomorphic to  $R_2$ .*

*Proof.* Let  $i \in \{1, 2, 3\}$  and let  $v$  be a bough-vertex of  $M_i$ . By definition of bough-vertex,  $v$  has at most one neighbour that is neither a twig nor a leaf. Let us denote this vertex by  $r$  if it exists. Let  $t_1, \dots, t_p$  be the twig-vertices adjacent to  $v$ . By definition of bough-vertex and Claim 3.3, we have  $p \in \{1, 2\}$ . Furthermore, by Claim 3.2,  $t_j$  is adjacent to a single leaf  $u_j$ , for all  $j \in \{1, \dots, p\}$ .

By Claim 3.1, vertex  $v$  is adjacent to at most one leaf. Suppose to the contrary that  $v$  is adjacent to no leaves. Thus,  $N_{M_i}(v) = \{t_1, \dots, t_p, r\}$ . Let  $T = M_i - \bigcup_{j=1}^p \{t_j, u_j\}$ . By the minimality of  $M_i$ ,  $T$  has a proper  $(i+1)$ -orientation  $D$ . Note that  $d_D^-(v) \leq d_T(v) \leq 1$ . Consequently, one can obtain a proper  $(i+1)$ -orientation of  $M_i$  by orienting the edges  $vt_j$  and  $t_j u_j$  towards  $t_j$ , for every  $j \in \{1, \dots, p\}$ , a contradiction. Hence,  $v$  is adjacent to exactly one leaf  $w$ .

Suppose to the contrary that  $p = 1$ . Let  $D$  be a proper  $(i+1)$ -orientation of  $M_i - \{t_1, u_1\}$ . If  $d_D^-(v) \neq 2$ ,  $D$  can be extended to a proper  $(i+1)$ -orientation of  $M_i$  by orienting  $vt_1$  and  $t_1 u_1$  towards  $t_1$ . It follows that  $d_D^-(v) = 2$ . Thus, the vertex  $r$  exists and  $rv$  and  $vw$  are oriented towards  $v$ . In this case,  $D$  can be extended to a proper  $(i+1)$ -orientation of  $M_i$  by reversing the orientation of  $vw$ , orienting  $vt_1$  towards  $v$ , and  $t_1 u_1$  towards  $u_1$ , a contradiction. Therefore, we conclude that  $p = 2$ .  $\square$

We are now ready to prove (1). By Claim 3.4, the tree  $M_1$  has neither branch-vertices nor two adjacent bough-vertices since  $\Delta(M_1) \leq 3$ . Consequently, by Claims 3.2 and 3.4, the tree  $M_1$  is either the tree  $R_2$  depicted in Figure 2(a), or a path on at most four vertices. It is a simple matter to check that these trees have proper orientation number at most 2. Hence,  $\overrightarrow{\chi}(M_1) \leq 2$ , a contradiction. This proves (1).

An orientation of a tree is *antidirected* if every vertex has indegree 0 or outdegree 0. There are two kinds of antidirected orientations of a rooted tree, one in which the root has indegree 0, called *out-antidirected*, and one in which the root has outdegree 0, called *in-antidirected*. An orientation of a bough in  $M_i$  is *nice* if it is obtained from an in-antidirected orientation by reversing the arc between the root and its adjacent leaf.

**Claim 3.5.** *For every  $i \in \{2, 3\}$ , every vertex  $v$  of  $M_i$  is adjacent to at most three bough-vertices.*

*Proof.* The argument is similar to the one in Claim 3.3. Suppose to the contrary that  $v$  is adjacent to  $p \geq 4$  bough-vertices  $b_j$ ,  $j \in \{1, \dots, p\}$ . For  $j \in \{1, \dots, p\}$ , let  $B_j$  be the bough rooted at  $b_j$ , and let  $T = M_i - \bigcup_{j=4}^p B_j$ . By the minimality of  $M_i$ ,  $T$  has a proper  $(i+1)$ -orientation  $D$ .

If  $d_D^-(v) \neq 3$ , then  $D$  can be extended to a proper  $(i+1)$ -orientation of  $M_i$  by taking the nice orientation of  $B_j$  and orienting  $vb_j$  towards  $b_j$  for all  $j \in \{4, \dots, p\}$ . This orientation is proper because the indegrees of the vertices of  $D$  are unchanged and  $d_D^-(b_j) = 3$  for all  $j \in \{4, \dots, p\}$ . Thus, we have  $d_D^-(v) = 3$ . Since  $D$  is proper, vertex  $v$  is dominated by  $b_1$ ,  $b_2$  and  $b_3$  in  $D$ , and so it dominates all its neighbours that are not bough-vertices. Thus, one can obtain a proper  $(i+1)$ -orientation of  $M_i$  by taking the nice orientation of  $B_j$  and (re-)orienting  $vb_j$  towards  $b_j$  for all  $j \in \{1, \dots, p\}$ . This orientation is proper because the indegrees of the vertices of  $V(T) \setminus (\bigcup_{j=1}^3 V(B_j) \cup \{v\})$  are not changed, the orientation of  $B_j$  for  $j \in \{1, \dots, p\}$  is proper,  $d^-(v) = 0$  and all neighbours of  $v$  are dominated by  $v$ , and so they have indegree at least 1.  $\square$

**Claim 3.6.** *For every  $i \in \{2, 3\}$ , every branch-vertex is adjacent to exactly one leaf, two twig-vertices and three bough-vertices. In other words, every branch is isomorphic to  $R_3$ .*

*Proof.* The arguments are similar to the ones presented in Claim 3.4.

Let  $i \in \{2, 3\}$  and let  $v$  be a branch-vertex of  $M_i$ . By definition of branch-vertex,  $v$  has at most one neighbour that is neither a bough, nor a twig, nor a leaf. Let us denote this vertex by  $r$  if it exists. Let  $b_1, \dots, b_p$  be the bough-vertices that are adjacent to  $v$ , and  $t_1, \dots, t_q$  be the twig-vertices adjacent to  $v$ . By definition of branch-vertex and Claim 3.5 we have  $p \in \{1, 2, 3\}$ , and by Claim 3.3 we have  $q \in \{0, 1, 2\}$ . For  $j \in \{1, \dots, p\}$ , let  $B_j$  be the bough rooted at  $b_j$ . By Claim 3.2, vertex  $t_k$  is adjacent to a single leaf  $u_k$ , for  $k \in \{1, \dots, q\}$ .

Let  $T = M_i - (\bigcup_{j=1}^p B_j \cup \bigcup_{k=1}^q t_k)$ . By minimality of  $M_i$ , the tree  $T$  admits a proper  $(i+1)$ -orientation  $D$ . By Claim 3.1,  $v$  is adjacent to at most one leaf. Suppose to the contrary that  $v$  has no leaves in its neighbourhood. Thus,  $d_D^-(v) \leq d_T(v) \leq 1$ . It follows that  $D$  can be extended to a proper  $(i+1)$ -orientation of  $M_i$  by taking the nice orientation of  $B_j$  and orienting the edge  $vb_j$  towards  $b_j$ , for every  $j \in \{1, \dots, p\}$ , and orienting the edges  $vt_k$  and  $t_k u_k$  towards  $t_k$ , for every  $k \in \{1, \dots, q\}$ . This orientation is indeed proper since  $d^-(b_j) = 3$ , for all  $j \in \{1, \dots, p\}$ , and  $d^-(t_k) = 2$ , for all  $k \in \{1, \dots, q\}$ . Therefore,  $v$  is adjacent to a single leaf  $w$ .

Suppose to the contrary that  $q \leq 1$ . Thus, we have  $d_D^-(v) \leq d_T(v) \leq 2$ . If  $d_D^-(v) \neq 2$ ,  $D$  can be extended to a proper  $(i+1)$ -orientation of  $M_i$  as above, that is by taking the nice orientation of  $B_j$  and orienting the edges  $vb_j$  towards  $b_j$  for  $j \in \{1, \dots, p\}$ , and orienting the edges  $vt_1$  and  $t_1 u_1$  towards  $t_1$  if  $q = 1$ . It follows that  $d_D^-(v) = 2$ , and both  $rv$  and  $wv$  are oriented towards  $v$ . Thus, one can obtain a proper  $(i+1)$ -orientation of  $M_i$  as follows. We use the nice orientation of  $B_j$  and orient the edges  $vb_j$  towards  $b_j$ , for each  $j \in \{1, \dots, p\}$ . In addition, we revert the orientation of  $vw$ , and orient  $vt_1$  and  $t_1 u_1$  away from  $t_1$  if  $q = 1$ . This orientation is indeed proper because the degree of every vertex in  $T - w$  is not changed,  $d_D^-(w) \in \{0, 1\}$ ,  $d_D^-(b_j) = 3$  for all  $j \in \{1, \dots, p\}$ , and  $d_D^-(t_1) = 0$  if  $q = 1$ . Therefore, we obtain  $q = 2$ .

Suppose to the contrary that  $p \leq 2$ . Let  $T' = M_i - \bigcup_{j=1}^p B_j$ . By minimality of  $M_i$ ,  $T'$  admits a proper  $(i+1)$ -orientation  $D'$ . If  $d_{D'}^-(v) \neq 3$ , then by taking the nice orientation of  $B_j$  and orienting the edge  $vb_j$  towards  $b_j$  for  $j \in \{1, \dots, p\}$ , we obtain a proper  $(i+1)$ -orientation of  $M_i$ . If  $d_{D'}^-(v) = 3$ , then at least two vertices  $v_1$  and  $v_2$  in  $\{w, t_1, t_2\}$  dominate  $v$  in  $D'$ . Reverting the orientations of the arcs incident to  $p$  vertices in  $\{v_1, v_2\}$ , orienting all edges  $vb_j$  towards  $v$  and taking the out-antidirected orientation of  $B_j$  for every  $j \in \{1, \dots, p\}$ , we obtain a proper  $(i+1)$ -orientation of  $M_i$ . Therefore, we conclude that  $p = 3$  by Claim 3.5.  $\square$

**Claim 3.7.** For every  $i \in \{2, 3\}$ ,  $M_i$  has a branch-vertex.

*Proof.* Suppose to the contrary that  $M_i$  has no branch-vertex. By Claims 3.4 and 3.2,  $M_i$  is either  $T_3$  (as defined in Corollary 1), or  $R_2$ , or a path on at most 4 vertices. By Corollary 1,  $\vec{\chi}(T_3) = 3$ , and it is easy to check that  $R_2$  and paths on at most four vertices have proper orientation number at most 2, a contradiction.  $\square$

By Claim 3.7,  $M_2$  has a branch-vertex. By Claim 3.6 and since  $\Delta(M_2) \leq 6$ , we deduce that  $M_2$  is isomorphic to  $R_3$ . One can check that  $\vec{\chi}(R_3) = 3$ , a contradiction. This proves (2).

By Claim 3.7,  $M_3$  has a branch-vertex, say  $v$ . By Claim 3.6,  $v$  is adjacent to three bough-vertices  $b_1, b_2, b_3$ . Let  $B_j$  be the bough rooted at  $b_j$  for  $j \in \{1, 2, 3\}$ , and let  $T = M_3 - (B_1 \cup B_2 \cup B_3)$ . By minimality of  $M_3$ ,  $T$  has a proper 4-orientation  $D$ . If  $d_D^-(v) \neq 3$ , then  $D$  can be extended to a proper 4-orientation of  $M_3$  by taking the nice orientation of  $B_j$  and orienting the edge  $vb_j$  towards  $b_j$ , for every  $j \in \{1, 2, 3\}$ . If  $d_D^-(v) = 3$ , then  $D$  can be extended to a proper 4-orientation of  $M_3$  by taking the in-antidirected orientation of  $B_j$  and orienting the edge  $vb_j$  towards  $b_j$ , for every  $j \in \{1, 2, 3\}$ . This proves (3).  $\square$

We now show a class of trees that have proper orientation number 2. A tree is called *even* if the distance between any two leaves is even.

**Proposition 3.** *If  $T$  is an even tree, then  $\vec{\chi}(T) \leq 2$ .*

*Proof.* Let  $r$  be the single neighbour of a leaf of  $T$ . Note that all leaves are at odd distance from  $r$ . We build a proper orientation  $D$  of  $T$  with maximum indegree at most 2 as follows:

- Orient all edges from  $r$  towards the leaves of  $T$ , in other words, orient the edges so that  $d_D^-(r) = 0$  and  $d_D^-(v) = 1$ , for every  $v \in V(T) \setminus \{r\}$ .
- For each vertex at even distance from  $r$  ( $r$  excluded), reverse one of its outgoing edges. This is possible since none of these vertices are leaves.

Observe that the vertices with indegree 2 are exactly those at even distance from  $r$  ( $r$  excluded). Since  $r$  has indegree 0 and its neighbours have indegree 1, the obtained orientation is proper.  $\square$

## 4 $\mathcal{NP}$ -completeness

In this section, we study the computational complexity of determining the proper orientation number of a graph.

Ahadi and Dehgan [1] showed that it is  $\mathcal{NP}$ -complete to decide whether  $\vec{\chi}(G) \leq 2$  for planar graphs  $G$  by using a reduction from the PLANAR 3-SAT problem. We first improve this result by showing that it is  $\mathcal{NP}$ -complete to decide whether the proper orientation number of planar subcubic graphs is at most 2. A graph  $G$  is *subcubic* if  $\Delta(G) \leq 3$ . We also prove the following more general result, losing, however, the planarity property: for every integer  $k \geq 3$ , it is  $\mathcal{NP}$ -complete to determine whether  $\vec{\chi}(G) < k$ , for graphs  $G$  with maximum degree  $k$ . In the sequel, we show that it is  $\mathcal{NP}$ -complete to decide whether  $\vec{\chi}(G) \leq 3$ , for planar bipartite graphs  $G$  with maximum degree 5.

In the proofs of these results, we present reductions from variants of the PLANAR 3-SAT problem. A 3-CNF formula is a boolean formula  $\phi = (X, \mathcal{C})$  in conjunctive normal form in which  $X$  is a set of  $n$  variables, and  $\mathcal{C}$  is a set of  $m$  clauses such that every clause has exactly 3 literals and does not contain more than one literal of the same variable. The *formula graph* of a 3-CNF formula  $\phi = (X, \mathcal{C})$ , denoted by  $G(\phi)$ , is a bipartite graph with vertex set  $X \cup \mathcal{C}$  in which a variable-vertex  $x$  is connected by an edge to a clause-vertex  $C$  if, and only if, the clause  $C$  contains either the literal  $x$  or  $\neg x$ . We say  $\phi$  is *planar* if, and only if, the formula graph  $G(\phi)$  is planar. The PLANAR 3-SAT problem is equivalent to the 3-SAT problem restricted to planar formulas. It is known that the PLANAR 3-SAT problem is  $\mathcal{NP}$ -complete [5].

For ease of notation, we denoted by  $[t]$  the set of integers  $\{1, 2, \dots, t\}$ , for every  $t \in \mathbb{N}$ . Recall that an induced subgraph  $H$  of a graph  $G$  is *x-pendant* if  $x \in V(H)$ , and all edges between  $V(H)$  and  $V(G) \setminus V(H)$  are incident to  $x$ . In addition, if there exists a single edge  $xy$  between  $x$  and  $V(G) \setminus V(H)$ , we say that  $H$  is *x-pendant at y*. If  $H$  is vertex-transitive, we simply say that  $H$  is *pendant at y*.

### 4.1 Planar subcubic graphs

Recall that  $\vec{\chi}(G) \leq \Delta(G)$ , for any graph  $G$ . On the other hand, the following theorem shows that, for any integer  $k \geq 3$ , it is already  $\mathcal{NP}$ -complete to determine whether  $\vec{\chi}(G) < k$ , for graphs  $G$  with maximum degree  $k$ .

**Theorem 4.** *Let  $k$  be an integer such that  $k \geq 3$ . The following problem is  $\mathcal{NP}$ -complete:*

INPUT : A graph  $G$  with  $\Delta(G) = k$  and  $\delta(G) = k - 1$ .

QUESTION :  $\vec{\chi}(G) \leq k - 1$ ?



We first prove the case where  $k = 3$  and then show how to generalize the proof for larger values of  $k$ . Furthermore, the case  $k = 3$  has the additional characteristic, which is not true in the general case, that we may assume the graph  $G$  to be planar.

In order to prove that it is  $\mathcal{NP}$ -complete to decide whether the proper orientation number of a planar subcubic graph is at most 2, we modify the reduction proposed by Ahadi and Dehgan by using a different gadget for the variables of a 3-CNF formula. Let us first prove a lemma that allows us to force the orientation of some edges in any proper  $k$ -orientation of a graph.

**Lemma 3.** *Let  $k$  be a positive integer, and let  $G$  be a graph containing a clique  $K$  of size  $k+1$ . In any proper  $k$ -orientation of  $G$ , all edges between  $V(K)$  and  $V(G) \setminus V(K)$  are oriented from  $V(K)$  to  $V(G) \setminus V(K)$ .*

*Proof.* Consider a proper  $k$ -orientation  $D$  of  $G$ . Clearly, all vertices of  $K$  must have distinct indegrees. Thus, for every  $i \in \{0, \dots, k\}$ , there exists exactly one vertex in  $K$  with indegree  $i$ . It follows that  $D[V(K)]$  is a transitive tournament, and every vertex in  $K$  has all its in-neighbours belonging to  $K$ . Therefore, all edges in  $G$  between  $V(K)$  and  $V(G) \setminus V(K)$  are oriented from  $V(K)$  to  $V(G) \setminus V(K)$ .  $\square$

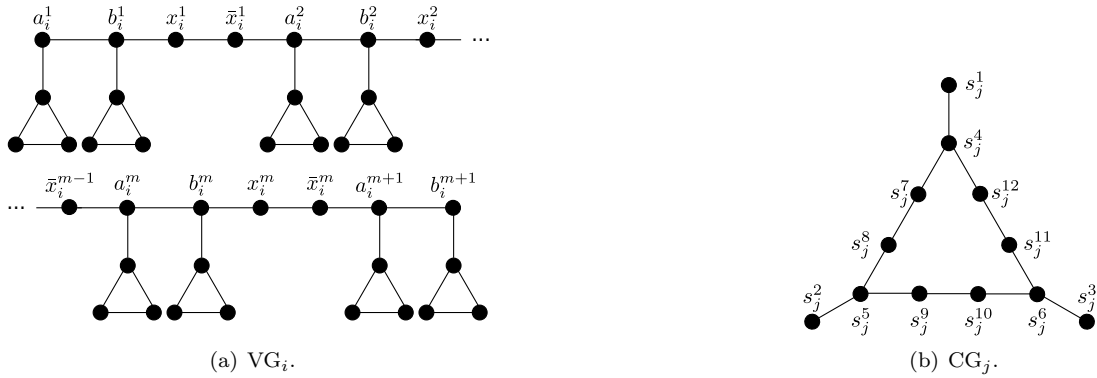


Figure 3: The variable gadget  $VG_i$  and the clause gadget  $CG_j$ .

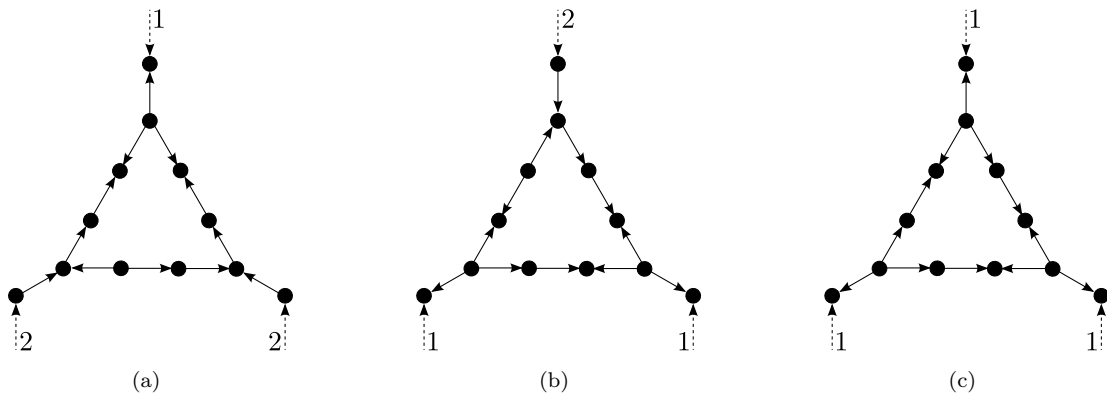


Figure 4: Suitable clause orientations.

**Theorem 5.** *The following problem is NP-complete:*

INPUT : A planar graph  $G$  with  $\Delta(G) = 3$  and  $\delta(G) = 2$ .

QUESTION :  $\vec{\chi}(G) \leq 2$ ?

*Proof.* This problem is trivially in NP because every proper 2-orientation is a certificate.

Let  $\phi = (X, \mathcal{C})$  be an instance of the PLANAR 3-SAT problem where  $X = \{x_1, \dots, x_n\}$  and  $\mathcal{C} = \{C_1, \dots, C_m\}$ , and let  $G(\phi)$  be a formula graph of  $\phi$ . In what follows, we show how to construct a planar graph  $G'(\phi)$  such that  $\vec{\chi}(G'(\phi)) \leq 2$  if, and only if,  $\phi$  is satisfiable.

Firstly, for every variable  $x_i$  of  $X$ , we create a variable gadget  $\text{VG}_i$  (see Figure 3(a)). This gadget has  $4m + 2$  vertices:  $a_i^j, b_i^j$ , for every  $j \in [m + 1]$ , and  $x_i^j, \bar{x}_i^j$  for every  $j \in [m]$ . These vertices form a path  $P_i$ , where  $a_i^j$  is linked to  $b_i^j$ , for every  $j \in [m + 1]$ ;  $x_i^j$  is linked to  $\bar{x}_i^j$  and to  $b_i^j$ , and  $\bar{x}_i^j$  is linked to  $a_i^{j+1}$ , for every  $j \in [m]$ . In addition, for all  $j \in [m + 1]$ , there is a pendant  $K_3$  at  $a_i^j$  and a pendant  $K_3$  at  $b_i^j$ .

Next, for every clause  $C_j$  in  $\mathcal{C}$ , we create the clause gadget  $\text{CG}_j$  depicted in Figure 3(b).

To finish the construction of  $G'(\phi)$ , we need to link the variable gadgets to the clause gadgets in such a way that the obtained graph is planar. Observe that we just need not to cross the edges linking the gadgets, because each gadget is itself planar and the formula graph  $G(\phi)$  is planar. Consider a planar embedding  $\tilde{G}(\phi)$  of  $G(\phi)$ . For each  $x \in X$ , let  $\mathcal{C}_x = \{C \in \mathcal{C} : x \in C \text{ or } \neg x \in C\}$  and let  $\pi_x : [|\mathcal{C}_x|] \rightarrow \mathcal{C}_x$  be a permutation of the elements in  $\mathcal{C}_x$  in the clockwise order around  $x$  in the planar embedding  $\tilde{G}(\phi)$ . In the graph  $G'(\phi)$ , for  $t \in [|\mathcal{C}_x|]$  and  $C_j = \pi_x(t)$ , we link the vertex  $x^t$  (resp.  $\bar{x}^t$ ) in the gadget associated to the variable  $x$  to one of the vertices  $s_j^1, s_j^2$  or  $s_j^3$ . We link the vertices of the variable gadgets to the vertices of the clause gadgets in such a way that, for every  $j \in [m]$ , the vertices  $s_j^1, s_j^2$  and  $s_j^3$  have degree 2 in  $G'(\phi)$ . Therefore, we have that  $G'(\phi)$  is planar,  $\delta(G'(\phi)) = 2$  and  $\Delta(G'(\phi)) = 3$ .

Let us now prove that  $\phi$  is satisfiable if, and only if,  $\vec{\chi}(G'(\phi)) \leq 2$ .

Let  $D$  be a proper 2-orientation of  $G'(\phi)$ . Due to Lemma 3 and to the pendant  $K_3$  at vertices of the path  $P_i$ , the indegree of each vertex in  $P_i$  must be either 1 or 2, for every  $i \in [n]$ . Consequently, for every fixed  $i \in [n]$ , we either have  $d_D^-(x_i^j) = 1$  and  $d_D^-(\bar{x}_i^j) = 2$ , or  $d_D^-(x_i^j) = 2$  and  $d_D^-(\bar{x}_i^j) = 1$ , for each  $j \in [m]$ . Moreover, these indegrees are just due to the orientations of the edges in the corresponding variable gadget. It means that every edge  $xs \in E(G'(\phi))$  such that  $x$  belongs to a variable gadget and  $s$  belongs to a clause gadget is oriented from  $x$  to  $s$ . Thus, for every  $j \in [m]$  and  $t \in \{1, 2, 3\}$ , the vertex  $s_j^t$  has indegree at least 1 in  $D$  and it must be different from the indegree of its neighbour in a variable gadget.

**Claim 5.1.** *In the clause gadget  $\text{CG}_j$ , at least one of the vertices  $s_j^1, s_j^2$  and  $s_j^3$  has indegree equal to 2.*

*Proof.* Suppose to the contrary that  $d_D^-(s_j^1) = d_D^-(s_j^2) = d_D^-(s_j^3) = 1$ . Thus,  $s_j^t$  dominates  $s_j^{t+3}$  and  $d_D^-(s_j^{t+3}) = 2$ , for all  $t \in \{1, 2, 3\}$ . Suppose first that  $s_j^{12}$  dominates  $s_j^4$ . It follows that  $s_j^4$  dominates  $s_j^7$ . Consequently,  $s_j^7$  has indegree 1 and dominates  $s_j^8$ , and so the edge  $s_j^5 s_j^8$  cannot be properly oriented (recall that  $d_D^-(s_j^5) = 2$ ). Similarly, one get a contradiction if  $s_j^4$  dominates  $s_j^{12}$ . Therefore, we obtain that  $s_j^4$  has indegree 1, a contradiction.  $\square$

By the construction of  $G'(\phi)$ , the orientation  $D$  induces an assignment  $\Gamma : X \rightarrow \{\text{TRUE}, \text{FALSE}\}$  in which, for every  $j \in [m]$ ,  $\Gamma(x) = \text{TRUE}$  if, and only if,  $d_D^-(x^j) = 1$ . By Claim 5.1, for each  $j \in [m]$ , there exists  $t \in \{1, 2, 3\}$  such that  $d_D^-(s_j^t) = 2$ . Thus,  $\Gamma$  is a truth assignment that satisfies  $\phi$ .

Reciprocally, suppose that  $\phi$  is satisfiable. Let  $\Gamma : X \rightarrow \{\text{TRUE}, \text{FALSE}\}$  be a truth assignment that satisfies  $\phi$ . Consider a variable  $x \in X$ . If  $\Gamma(x) = \text{TRUE}$ , then, orient  $a^j b^j$  towards  $b^j$

for every  $j \in [m + 1]$ , and orient  $b^j x^j$  towards  $x^j$ ,  $x^j \bar{x}^j$  towards  $\bar{x}^j$  and  $a^{j+1} \bar{x}^j$  towards  $\bar{x}^j$  for every  $j \in [m]$ . If  $\Gamma(x) = \text{FALSE}$ , orient  $b^j a^j$  towards  $a^j$  for every  $j \in [m + 1]$ , and orient  $b^j x^j$  towards  $x^j$ ,  $\bar{x}^j x^j$  towards  $x^j$  and  $a^{j+1} \bar{x}^j$  towards  $\bar{x}^j$  for every  $j \in [m]$ . Thus, for every  $j \in [m]$ , if  $\Gamma(x) = \text{TRUE}$ , then  $d^-(x^j) = 1$  and  $d^-(\bar{x}^j) = 2$ , otherwise,  $d^-(x^j) = 2$  and  $d^-(\bar{x}^j) = 1$ . Since  $\Gamma$  satisfies  $\phi$ , no clause has three false literals. Consequently, no clause gadget has all three vertices  $s^1$ ,  $s^2$  and  $s^3$  forced to have indegree 1 due to neighbours of indegree 2 in the corresponding variable gadgets. In this case, we can extend this proper 2-orientation of the variables gadgets to a proper 2-orientation of  $G'(\phi)$  using one of the suitable clause orientations depicted in Figure 4. Therefore, we have  $\vec{\chi}(G'(\phi)) \leq 2$ .  $\square$

The reduction presented in the proof of Theorem 5 can be easily adapted to prove Theorem 4.

*Proof of Theorem 4.* Let  $\phi$  be a 3-CNF formula and let  $G'(\phi)$  be the graph described in the proof of Theorem 5. Let  $k \geq 3$  be an integer and let  $G''(\phi)$  be the graph obtained from  $G'(\phi)$  by adding  $k - 3$  pendant  $K_k$  at each vertex of  $G'(\phi)$ , and replacing each pendant  $K_3$  at a vertex by a pendant  $K_k$  at the same vertex. By the construction, one can easily check that  $\delta(G''(\phi)) = k - 1$  and  $\Delta(G''(\phi)) = k$ .

Note that, in every proper  $(k - 1)$ -orientation, all the vertices of  $G''(\phi)$  except those belonging to the pendant  $K_k$ 's have indegree equal to  $k - 1$  or  $k - 2$ . Therefore, using similar arguments to those presented in the proof of Theorem 5, we conclude that  $\phi$  is satisfiable if, and only if,  $\vec{\chi}(G''(\phi)) \leq k - 1$ .  $\square$

**Theorem 6.** *The following problem is NP-complete:*

INPUT : A planar graph  $G$  with  $\Delta(G) = 4$  and  $\delta(G) = 3$ .

QUESTION :  $\vec{\chi}(G) \leq 3$ ?

*Proof.* Considering a planar 3-CNF formula and observing that the complete graph on four vertices  $K_4$  is planar, the result follows directly from the proof of Theorem 4.  $\square$

## 4.2 Planar bipartite graphs

In this subsection, we prove that computing the proper orientation number of a graph is still NP-hard for planar bipartite graphs of bounded degree. The idea of our reduction is roughly the same as in Theorems 4 and 5, although we use another class of 3-SAT formulas in order to obtain bipartite instances and the gadgets of the reduction are more complicated.

The gadget we use to replace the pendant cliques of the proofs of Theorems 4 and 5 is the graph  $B_5$ , depicted in Figure 5. The following lemma, analogously to Lemma 3, allows us to force the orientation of some edges in any proper 3-orientation of a graph.

**Lemma 4.** *Let  $G$  be a graph with a  $v$ -pendant  $B_5$  at  $y$ . In any proper 3-orientation of  $G$ ,  $y$  is dominated by  $v$ .*

*Proof.* Suppose to the contrary that there exists a proper 3-orientation  $D$  of  $G$  such that  $y$  dominates  $v$ .

If  $d^-(v) = 1$ , then  $v$  dominates  $u_i$  for all  $i \in \{1, 2, 3, 4\}$ . Moreover, by Lemma 1,  $d^-(u_i) = 3$  for  $i \in \{1, 2, 3\}$ . Thus, for  $i \in \{1, 2, 3\}$ ,  $d^-(w_i) \leq 2$ . Hence, again by Lemma 1,  $w_i$  dominates  $u_i$  and  $z$ . It follows that  $d^-(z) = 3$  and  $z$  dominates  $w_4$ . This contradicts Lemma 1.

If  $d^-(v) = 2$ , then  $v$  is dominated by  $u_4$ , otherwise  $u_4$  has the same indegree as one of its two neighbours. Thus,  $v$  dominates  $u_i$  for  $i \in \{1, 2, 3\}$ . Similarly to the previous case, we obtain a contradiction.

If  $d^-(v) = 3$ , then  $v$  dominates  $u_i$ , for some  $i \in \{1, 2, 3\}$ . Therefore,  $d^-(u_i) \in \{1, 2\}$ , which contradicts Lemma 1.  $\square$

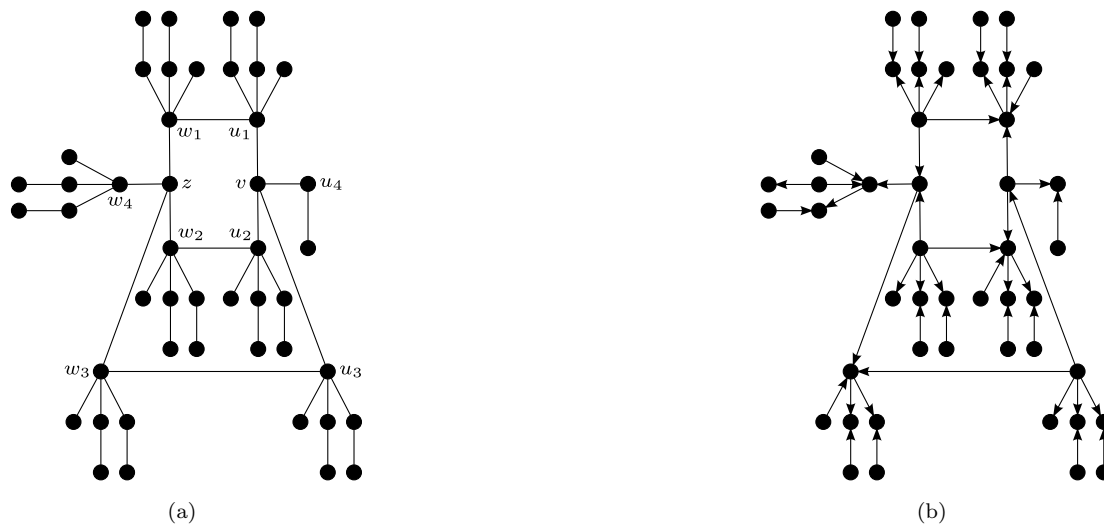


Figure 5: The bipartite graph  $B_5$  (a) and one of its proper 3-orientations (b).

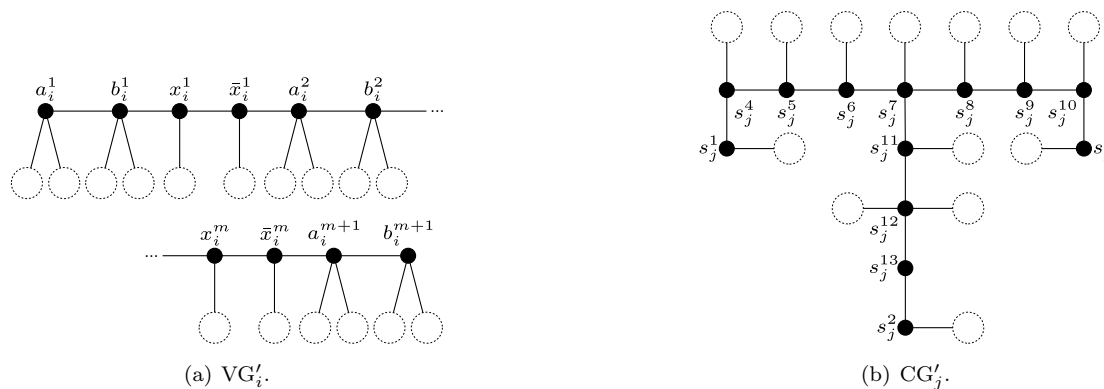


Figure 6: The variable gadget  $VG'_i$  and the clause gadget  $CG'_j$ .

By Theorem 1, all planar bipartite graphs with maximum degree 5 have proper orientation at most 4. On the other hand, we next show that it is  $\mathcal{NP}$ -complete to decide whether  $\vec{\chi}(G) \leq 3$  for such graphs.

**Theorem 7.** *The following problem is  $\mathcal{NP}$ -complete:*

INPUT : A planar bipartite graph  $G$  with  $\Delta(G) = 5$ .

QUESTION :  $\vec{\chi}(G) \leq 3$ ?

*Proof.* Again, this problem is in  $\mathcal{NP}$  because any proper 3-orientation of  $G$  is a certificate.

A 3-SAT formula  $\phi$  is said to be *monotone* if each clause has only positive literals (a positive clause) or only negative literals (a negative clause). Recall that a 3-CNF formula  $\phi$  is planar if the formula graph  $G(\phi)$  is planar. The problem of deciding whether a planar monotone 3-SAT formula is satisfiable was recently shown to be  $\mathcal{NP}$ -complete [2]. Let  $\phi$  be a planar monotone 3-CNF formula with clauses  $\mathcal{C} = \{C_1, \dots, C_m\}$  and variables  $X = \{x_1, \dots, x_n\}$  and let  $G(\phi)$  be the formula graph corresponding to  $\phi$ . In what follows, we show how to construct a planar bipartite graph  $G'(\phi)$  with  $\Delta(G') = 5$  such that  $\vec{\chi}(G'(\phi)) \leq 3$  if, and only if,  $\phi$  is satisfiable.

Firstly, for each variable  $x_i$ , we create a variable gadget  $\text{VG}'_i$  depicted in Figure 6(a). This gadget has  $4m + 2$  vertices:  $a_i^j, b_i^j$  for every  $j \in [m + 1]$ , and  $x_i^j, \bar{x}_i^j$  for every  $j \in [m]$ . These vertices form a path  $P_i$ , where  $a_i^j$  is linked to  $b_i^j$ , for every  $j \in [m + 1]$ ;  $x_i^j$  is linked to  $\bar{x}_i^j$  and to  $b_i^j$ , and  $\bar{x}_i^j$  is linked to  $a_i^{j+1}$ , for every  $j \in [m]$ . The gadget  $\text{VG}'_i$  also contains  $6m + 4$   $v$ -pendant  $B_5$ : two at  $a_i^j$ , two at  $b_i^j$ , for every  $j \in [m + 1]$ , one at  $x_i^j$  and another at  $\bar{x}_i^j$  for every  $j \in [m]$  (these  $B_5$  graphs are represented by the dashed white circles in Figure 6(a)).

For every clause  $C_j$  of  $\mathcal{C}$ , we create a clause gadget  $\text{CG}'_j$  as depicted in Figure 6(b). It is obtained from two paths  $s_j^1 s_j^4 \dots s_j^{10} s_j^3$  and  $s_j^{11} s_j^{12} s_j^{13} s_j^2$  linked by the edge  $s_j^7 s_j^{11}$ . Moreover, there exists a  $v$ -pendant  $B_5$  at all these vertices, except at  $s_j^{13}$ , and we have an additional  $v$ -pendant  $B_5$  at  $s_j^{12}$  (these  $B_5$  graphs are represented by the dashed white circles in Figure 6(b)).

To finish the construction of  $G'(\phi)$ , we need to link the variable gadgets to the clause gadgets in such a way that the obtained graph is planar. Observe that we just need not to cross the edges linking the gadgets since each gadget is itself planar and the formula graph  $G(\phi)$  is planar. We can accomplish this in the same way as described in the proof of Theorem 5. Since each clause has exactly three literals, we add these edges so that, for every  $j \in [m]$ , the vertices  $s_j^1, s_j^2$  and  $s_j^3$  have degree 3 in  $G'(\phi)$ . Thus,  $G'(\phi)$  is planar, and  $\Delta(G'(\phi)) = 5$  due to the graph  $B_5$ .

Let us now prove that  $G'(\phi)$  is bipartite. Clearly, we can properly colour the vertices of each variable gadget with colours  $A$  and  $B$ . Suppose that we assign the colour  $A$  to the vertex  $x_i^j$ , for each  $i \in [n]$  and  $j \in [m]$ . For each  $j \in [m]$ , we can assign the same colour ( $A$  or  $B$ ) to the vertices  $s_j^1, s_j^2$  and  $s_j^3$  since  $\phi$  is monotone. Note that we can easily extend this partial colouring to the other vertices in each clause and variable gadget in  $G'(\phi)$ . Thus,  $G'(\phi)$  is bipartite.

Let us now prove that  $\vec{\chi}(G'(\phi)) \leq 3$  if, and only if,  $\phi$  is satisfiable.

Suppose first that  $\vec{\chi}(G'(\phi)) \leq 3$ . Let  $D$  be a proper 3-orientation of  $G'(\phi)$ . By Lemma 4 and due to the  $v$ -pendant  $B_5$  graphs that are attached to the vertices in each path  $P_i$ , the indegrees of the vertices in this path are either 2 or 3, for every  $i \in [n]$ . Consequently, for a given  $i \in [n]$ , we either have  $d_D^-(x_i^j) = 2$  and  $d_D^-(\bar{x}_i^j) = 3$ , or  $d_D^-(x_i^j) = 3$  and  $d_D^-(\bar{x}_i^j) = 2$ , for all  $j \in [m]$ . Moreover, these indegrees are just due to the orientations of the edges belonging to the corresponding variable gadget. Thus, every edge  $xs \in E(G'(\phi))$  such that  $x$  belongs to a variable gadget and  $s$  belongs to a clause gadget is oriented from  $x$  to  $s$ . Consequently, for each  $j \in [m]$  and  $t \in \{1, 2, 3\}$ , the vertex  $s_j^t$  has indegree at least 2 in  $D$  since it has a  $v$ -pendant  $B_5$  attached to it.

**Claim 7.1.** *In every proper 3-orientation of  $G'(\phi)$ , for every  $j \in [m]$ , one of the vertices  $s_j^1, s_j^2$  and  $s_j^3$  has indegree 3.*

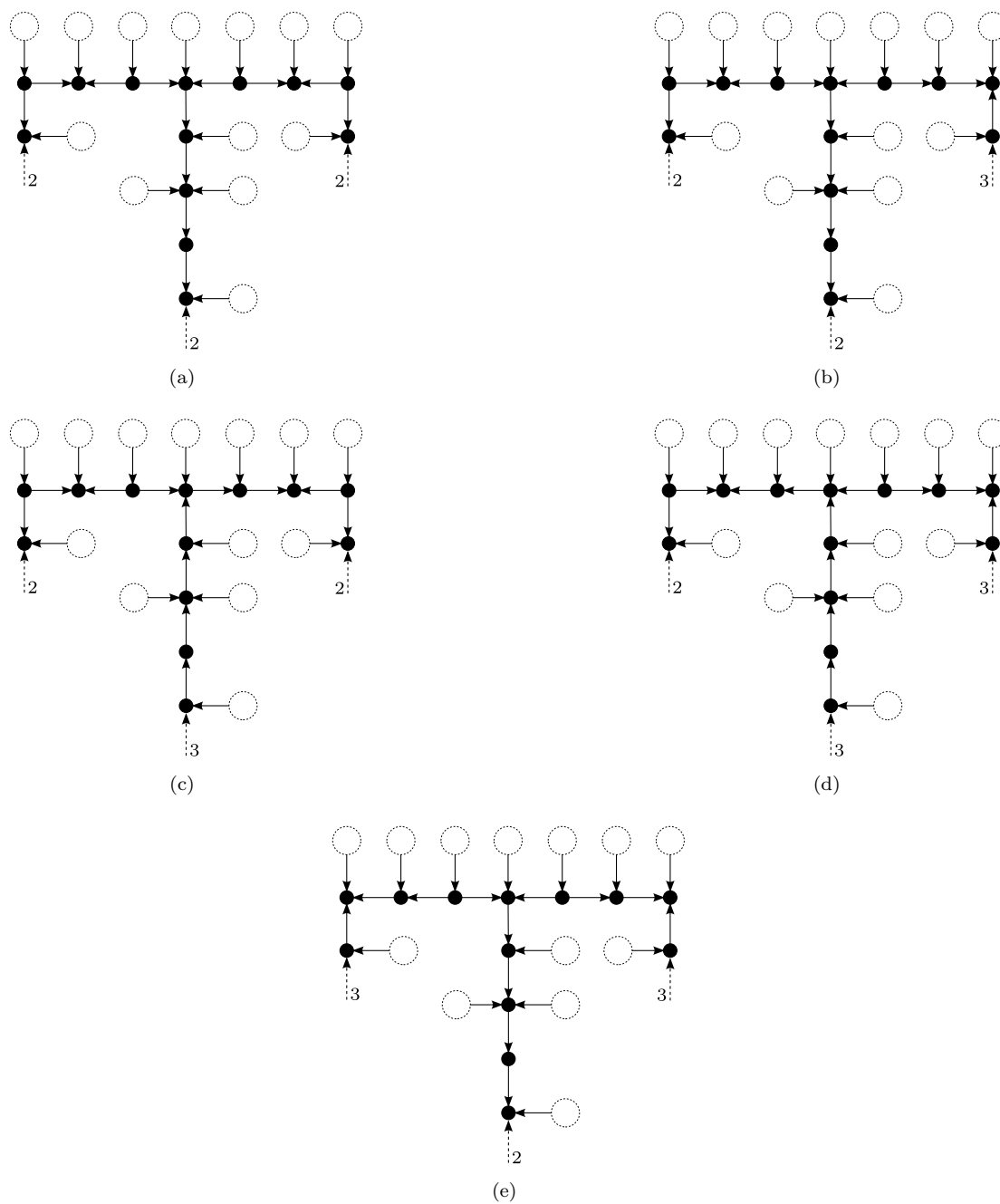


Figure 7: Suitable 3-orientations of the clauses.

*Proof.* Suppose to the contrary that there exists a proper 3-orientation  $D$  of  $G'(\phi)$  such that  $d_D^-(s_j^1) = d_D^-(s_j^2) = d_D^-(s_j^3) = 2$ , for some  $j \in [m]$ . Thus, the edges  $s_j^2 s_j^{13}$ ,  $s_j^{13} s_j^{12}$ ,  $s_j^{12} s_j^{11}$  and  $s_j^{11} s_j^7$  are oriented from  $s_j^2$  to  $s_j^{13}$ ,  $s_j^{13}$  to  $s_j^{12}$ ,  $s_j^{12}$  to  $s_j^{11}$ , and from  $s_j^{11}$  to  $s_j^7$  in  $D$ . Since  $s_j^7$  is adjacent to a vertex with indegree 2 and it has indegree at least 2 in this orientation, it is dominated by either  $s_j^6$  or  $s_j^8$ . If  $s_j^6$  dominates  $s_j^7$ , then the edges  $s_j^7 s_j^8$ ,  $s_j^8 s_j^9$ , and  $s_j^9 s_j^{10}$  are oriented from  $s_j^7$  to  $s_j^8$ ,  $s_j^8$  to  $s_j^9$ , and from  $s_j^{10}$  to  $s_j^9$ . Therefore, we have  $d_{D'}^-(s_j^3) = d_{D'}^-(s_j^{10}) = 2$ , a contradiction. By symmetry, we obtain a similar contradiction if  $s_j^8$  dominates  $s_j^7$ .  $\square$

Let  $\Gamma: X \rightarrow \{\text{TRUE}, \text{FALSE}\}$  be the truth assignment defined as  $\Gamma(x) = \text{TRUE}$  if, and only if,  $d_D^-(x^j) = 2$  for some  $j \in [m]$ . By Claim 7.1,  $\Gamma$  satisfies  $\phi$ .

Reciprocally, suppose that  $\phi$  is satisfiable. Let  $\Gamma: X \rightarrow \{\text{TRUE}, \text{FALSE}\}$  be a truth assignment that satisfies  $\phi$ .

First, orient each  $v$ -pendant  $B_5$  according to Figure 5(b). Moreover, for each  $v$ -pendant  $B_5$ , orient the edge between  $v$  and  $y$ , the only neighbour of  $v$  in  $V(G'(\phi)) \setminus V(B_5)$ , towards  $y$ . Note that the indegree of  $v$  is equal to 1 in every  $v$ -pendant  $B_5$ . Consider a variable  $x \in X$ . We define an orientation of  $G'(\phi)$  as follows:

- If  $\Gamma(x) = \text{TRUE}$ , orient  $a^j b^j$  towards  $b^j$  for every  $j \in [m+1]$ , and orient  $b^j x^j$  towards  $x^j$ ,  $x^j \bar{x}^j$  towards  $\bar{x}^j$  and  $a^{j+1} \bar{x}^j$  towards  $\bar{x}^j$  for every  $j \in [m]$  (see Figure 8(a)).
- If  $\Gamma(x) = \text{FALSE}$ , orient  $b^j a^j$  towards  $a^j$  for every  $j \in [m+1]$ , and orient  $b^j x^j$  towards  $x^j$ ,  $\bar{x}^j x^j$  towards  $x^j$  and  $a^{j+1} \bar{x}^j$  towards  $\bar{x}^j$  for every  $j \in [m]$  (see Figure 8(b)).

Thus, if  $\Gamma(x) = \text{TRUE}$ , then  $d_D^-(x^j) = 2$  and  $d_D^-(\bar{x}^j) = 3$ , otherwise  $d_D^-(x^j) = 3$  and  $d_D^-(\bar{x}^j) = 2$ , for every  $j \in [m]$ . Since  $\Gamma$  satisfies  $\phi$ , no clause has three false literals. Consequently, in every clause gadget, at least one the vertices  $s^1$ ,  $s^2$  and  $s^3$  has indegree different from 2 due to its neighbours in the corresponding variable gadgets. Thus, we can extend this proper 3-orientation of the variables gadgets to a proper 3-orientation of  $G'(\phi)$  using one of the suitable clause orientations depicted in Figure 7. Note that the orientation of  $G'(\phi)$  described above is proper and each vertex has indegree at most 3. Therefore,  $\vec{\chi}(G'(\phi)) \leq 3$ .  $\square$



Figure 8: Suitable orientations of the gadget  $x_i$ .

## 5 Conclusive remarks and further research

### 5.1 Around Problem 1

The upper bound given by Theorem 2 is likely not tight. Hence, it is natural to ask for the maximum proper orientation number  $f(k)$  over all bipartite graphs with maximum degree  $k$ .

Since a  $k$ -regular graph on  $n$  vertices has  $nk/2$  edges, all its orientations must have maximum indegree at least  $\lceil \frac{k+1}{2} \rceil$ . Together with Theorem 2, this implies

$$\left\lceil \frac{k+1}{2} \right\rceil \leq f(k) \leq \left\lfloor \frac{k+\sqrt{k}}{2} \right\rfloor + 1.$$

We have shown that  $f(1) = 1$ ,  $f(2) = 2$  and  $f(3) = 3$ . The next question is to determine whether  $f(4)$  equals 3 or 4. More generally, one may ask the following.

**Problem 2.** Does there exist a constant  $C$  such that  $\vec{\chi}(G) \leq \frac{\Delta(G)}{2} + C$  for all bipartite graph  $G$ ? In other words, does  $f(k) \leq \frac{k}{2} + C$  hold for all  $k \in \mathbb{N}$ ?

This is true for bipartite graphs whose minimum degree is very close from its maximum degree as shown by Proposition 2.

Problem 1(a) may be seen as determining the largest  $\epsilon_0$  such that  $\vec{\chi}(G) \leq \epsilon_0 \cdot \omega(G) + (1 - \epsilon_0)\Delta(G)$  for all graph  $G$ . Regular graphs show that  $\epsilon_0 \leq 1/2$ . Such graphs might be extremal graphs with respect to Problem 1(a).

**Problem 3.** Is the following relaxation of Conjecture 1 true?

$$\text{For every graph } G, \vec{\chi}(G) \leq \left\lceil \frac{\Delta(G) + 1 + \omega(G)}{2} \right\rceil.$$

A natural approach towards this problem and Problem 1(a) would be to study triangle-free graphs, that are the graphs with clique number 2. A first step would be to improve the upper bound on the proper orientation number for  $\Delta(G)$  large.

## 5.2 Graphs with bounded treewidth or bounded maximum average degree

Let us denote by  $\text{tw}(G)$  the treewidth of  $G$ . It is well-known that  $\chi(G) \leq \text{tw}(G) + 1$ . Theorem 3 states that the proper orientation number of graphs with treewidth 1 is bounded. It is then natural to ask if the same holds for larger values of the treewidth.

**Problem 4.** Can  $\vec{\chi}(G)$  be bounded by a function of  $\text{tw}(G)$ ?

One can observe that, for fixed integers  $t$  and  $k$ , determining whether  $\vec{\chi}(G) \leq k$  in a graph  $G$  of treewidth at most  $t$  can be done in polynomial time using a standard dynamic programming approach.

It is well known that graphs with bounded treewidth have bounded maximum average degree. Recall that the *maximum average degree*  $\text{Mad}(G)$  of a graph  $G$  is defined as

$$\text{Mad}(G) = \max \left\{ \frac{2|E(H)|}{|V(H)|} : H \text{ is a subgraph of } G \right\}.$$

It is well-known [7] that every graph  $G$  admits an orientation with maximum outdegree at most  $\lceil \text{Mad}(G)/2 \rceil$ . Moreover,  $\chi(G) \leq \text{Mad}(G) + 1$  because every graph  $G$  is  $\lfloor \text{Mad}(G) \rfloor$ -degenerate. It is thus very natural to generalize Problem 4 and to look for an upper-bound on  $\vec{\chi}(G)$  depending only on  $\text{Mad}(G)$ .

**Problem 5.** Can  $\vec{\chi}(G)$  be bounded by a function of  $\text{Mad}(G)$ ?



Theorem 3 settles Problem 5 for graphs  $G$  with  $\text{Mad}(G) < 2$ , i.e. forests. A next step towards Problem 5 would be to prove that the proper orientation number is bounded for some classes of graphs in which the maximum average degree is bounded. All minor-closed families (except the one of all graphs) are such classes. The most famous of these families and perhaps a natural direction for future research is the class of planar graphs.

**Problem 6.** Does there exist a constant  $k$  such that  $\vec{\chi}(G) \leq k$  for all planar graphs  $G$ ?

### 5.3 Split graphs

A *split graph* is a graph whose vertex set may be partitioned into a clique  $K$  and a stable set  $S$ . We assume, without loss of generality, that  $K$  is maximal, that is no vertex in  $S$  is adjacent to all vertices in  $K$ . The pair  $(K, S)$  is then called a *canonical partition* of  $G$ . For such a partition, we have  $\omega(G) = |K|$ . It is well-known that split graphs can be recognized in polynomial time, and that finding a canonical partition of a split graph can also be found in polynomial time.

**Proposition 4.** *If  $G$  is a split graph, then one can decide in polynomial-time whether  $\vec{\chi}(G) = \omega(G) - 1$ .*

*Proof.* Let  $(K, S)$  be a canonical partition of  $G$ . Let  $H$  be the following bipartite graph obtained from  $G$ : the vertex set of  $H$  is  $K \cup \{w_0, \dots, w_{|K|-1}\}$  and, for every  $v \in K$  and  $i \in \{0, \dots, |K|-1\}$ , there exists an edge between  $v$  and  $w_i$  if, and only if,  $v$  has no neighbour (in  $S$ ) with degree  $i$  in  $G$ .

Let us now prove that  $\vec{\chi}(G) = \omega(G) - 1$  if, and only if,  $H$  has a perfect matching.

Suppose that there exists a proper orientation  $D$  of  $G$  with maximum indegree  $|K| - 1$ . By Lemma 3, all edges between  $K$  and  $S$  must be oriented from  $K$  to  $S$ , so  $d_D^-(u) = d_G(u)$  for all  $u \in S$ . It follows that, for each  $v \in K$ ,  $d_D^-(v) \notin \{d_G(u) : u \in S \cap N(v)\}$ . Moreover, there exists exactly one vertex in  $K$  of indegree  $i$ , for each  $i \in \{0, \dots, |K| - 1\}$ . Therefore, the edge set  $\{vw_i : v \in K \text{ and } i = d_D^-(v)\}$  is a perfect matching in  $H$ .

Suppose that  $H$  has a perfect matching  $M$ . Consider the orientation of  $G$  defined as follows. We orient the edges in the clique  $K$  so that  $v \in K$  has indegree  $i$  if, and only if,  $vw_i \in M$ , where  $i \in \{0, \dots, |K| - 1\}$ . In addition, we orient all edges between  $K$  and  $S$  towards  $S$  in the graph  $G$ . Note that  $d_G(u) < |K| - 1$  for all  $u \in S$  since  $(K, S)$  is a canonical partition. By the construction of  $H$ , the orientation described above is a proper  $(\omega(G) - 1)$ -orientation of  $G$ .  $\square$

However, one further step does not seem trivial.

**Problem 7.** Can one decide in polynomial time whether  $\vec{\chi}(G) \leq \omega(G)$  for every split graph  $G$ ?

**Problem 8.** Can one decide in polynomial time whether  $\vec{\chi}(G) = \omega(G) - 1$  for every complement of bipartite graph  $G$ ?

**Problem 9.**

- (a) Does there exist a function  $h$  such that  $\vec{\chi}(G) \leq h(\omega(G))$  for every split graph  $G$ ?
- (b) Does there exist a function  $h$  such that  $\vec{\chi}(G) \leq h(\omega(G))$  for every complement of bipartite graph  $G$ ?

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