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# An oriented version of the 1-2-3 Conjecture

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## Abstract

The well-known 1-2-3 Conjecture addressed by Karoński, Łuczak and Thomason asks whether the edges of every undirected graph  $G$  with no isolated edge can be assigned weights from  $\{1, 2, 3\}$  so that the sum of incident weights at each vertex yields a proper vertex-colouring of  $G$ . In this work, we consider a similar problem for oriented graphs. We show that the arcs of every oriented graph  $\vec{G}$  can be assigned weights from  $\{1, 2, 3\}$  so that every two adjacent vertices of  $\vec{G}$  receive distinct sums of outgoing weights. This result is tight in the sense that some oriented graphs do not admit such an assignment using the weights from  $\{1, 2\}$  only. We finally prove that deciding whether two weights are sufficient for a given oriented graph is an NP-complete problem. These results also hold for product or list versions of this problem.

**Keywords:** oriented graph, neighbour-sum-distinguishing arc-weighting, complexity, 1-2-3 Conjecture

## 1 Introduction

Let  $G$  be an undirected graph with vertex and edge sets  $V(G)$  and  $E(G)$ , respectively. For every vertex  $v$  of  $G$ , we denote by  $N(v)$  the set of vertices neighbouring  $v$ . A  $k$ -edge-weighting  $w$  of  $G$  is an assignment  $w : E(G) \rightarrow \{1, 2, \dots, k\}$ . From  $w$ , one naturally deduces a vertex-colouring  $\phi_w$  of  $G$ , where  $\phi_w(v) = \sum_{u \in N(v)} w(vu)$  for every vertex  $v$ . In other words, any vertex  $v$  receives the sum of its incident weights by  $w$  as its “colour”. If  $\phi_w$  is proper, i.e. we have  $\phi_w(u) \neq \phi_w(v)$  for every two adjacent vertices  $u$  and  $v$  of  $G$ , then we say that  $w$  is *neighbour-sum-distinguishing* (*nsd* for short).

The study of neighbour-sum-distinguishing edge-weighting of graphs was initiated in 2004, with Karoński, Łuczak and Thomason posing the following conjecture.

**1-2-3 Conjecture [8].** *Every graph with no isolated edge admits a nsd 3-edge-weighting.*

Despite many efforts to tackle it, the 1-2-3 Conjecture is still an open question. The best result towards the 1-2-3 Conjecture at the moment is due to Kalkowski, Karoński and Pfender, who proved that every graph with no isolated edge admits a nsd 5-edge-weighting [7].

Many edge-weighting problems inspired by the 1-2-3 Conjecture have been introduced in the literature. As examples, let us mention the notions of *detectable colouring* [1] or *locally irregular edge-colouring* [3] of graphs. We refer the interested reader to [11], where numerous more variants of the original problem are surveyed. Most of these works are devoted to undirected graphs, but one could wonder about an oriented version of the 1-2-3 Conjecture.

We first introduce some terminology related to oriented graphs. Let  $\vec{G}$  be an oriented graph, i.e. a loopless directed graph whose every two vertices are joined by at most one arc in either direction, with vertex and arc sets  $V(\vec{G})$  and  $A(\vec{G})$ , respectively. Given a vertex  $v$  of  $\vec{G}$ , we denote by  $N^-(v)$  (resp.  $N^+(v)$ ) the set  $\{u \in V(\vec{G}) : \vec{uv} \in A(\vec{G})\}$  (resp.  $\{u \in V(\vec{G}) : \vec{vu} \in A(\vec{G})\}$ ). The *indegree* (resp. *outdegree*) of  $v$ , denoted  $d^-(v)$  (resp.  $d^+(v)$ ), is  $|N^-(v)|$  (resp.  $|N^+(v)|$ ).

To our knowledge, the only link between the 1-2-3 Conjecture and oriented graphs is the following problem. Let  $w$  be a  $k$ -arc-weighting of  $\vec{G}$ , and let  $q_w^-(v)$  and  $q_w^+(v)$  be  $\sum_{u \in N^-(v)} w(\vec{uv})$  and  $\sum_{u \in N^+(v)} w(\vec{vu})$ , respectively, for every vertex  $v$ . The functions  $q_w^-$  and  $q_w^+$  naturally yield a vertex-colouring  $q_w$  of  $\vec{G}$ , where  $q_w(v) = q_w^+(v) - q_w^-(v)$  for every vertex  $v$  of  $\vec{G}$ . It was proved in [4] that every oriented graph admits a 2-arc-weighting  $w$  which yields a *proper* vertex-colouring  $q_w$ . A list version of the same result was also proved independently in [2] and [9] using different methods.

We here investigate another problem. As for the undirected case, a  $k$ -arc-weighting  $w$  of  $\vec{G}$  yields a vertex-colouring  $\phi_w$  of  $\vec{G}$  where  $\phi_w(v) = \sum_{u \in N(v)^+} w(\vec{vu})$  for every  $v \in V(\vec{G})$ . This time, the “colour” of  $v$  by  $\phi_w$ , sometimes called its *weighted outdegree* (with respect to  $w$ ), is the sum of its outgoing weights (one could similarly consider the sum of its ingoing weights). Again, if  $\phi_w$  has the property to be proper, then we say that  $w$  is *neighbour-sum-distinguishing* (nsd for short).

A quick investigation on small oriented graphs suggests that all oriented graphs should admit a nsd 3-arc-weighting. Besides, there exist oriented graphs, such as the circuit on 3 vertices, which do not admit a nsd 2-arc-weighting. We hence investigate the following question.

**Question 1.** *Does every oriented graph admit a nsd 3-arc-weighting?*

Although Question 1 and the 1-2-3 Conjecture are quite similar in essence, the two underlying problems do not seem to share any systematic relationship. The fact that weighting some arc  $\vec{uv}$  only affects the weighted outdegree of  $u$  makes Question 1 easier to handle. We hence answer this question in the affirmative in Section 2. We then turn our concern on conditions for some specific classes of oriented graphs to admit a nsd 2-arc-weighting in Section 3. We next prove, in Section 4, that an “easy” characterization of oriented graphs which admit a nsd 2-arc-weighting cannot exist unless  $P=NP$ . For this purpose, we show that the problem of deciding whether an oriented graph admits a nsd 2-arc-weighting is NP-complete. Concluding remarks can be found in Section 5. In particular, we point out that our results directly apply to product or list versions of the problem.

## 2 All oriented graphs admit a nsd 3-arc-weighting

Our first result states that every oriented graph admits a nsd 3-arc-weighting. This relies on the fact that every oriented graph has a “convenient” vertex, i.e. a vertex which admits a large number of potential weighted outdegrees compared to its number of neighbours. The existence of such a vertex allows the use of an inductive proof scheme. Our proof also yields a polynomial-time algorithm for finding a nsd 3-arc-weighting of every oriented graph.

**Theorem 1.** *Every oriented graph  $\vec{G}$  admits a nsd 3-arc-weighting.*

*Proof.* The claim is proved by induction on the size of  $\vec{G}$ , i.e. its number of arcs. As a base case, the claim is clearly true when  $\vec{G}$  has size 0 or 1. Suppose now that the claim is true for every oriented graph with at most  $m - 1$  arcs, and assume  $\vec{G}$  has size  $m \geq 2$ .

Note that  $\vec{G}$  necessarily has a vertex  $v$  such that  $d^+(v) > 0$  and  $d^+(v) \geq d^-(v)$  since otherwise we would have  $\sum_{v \in V(\vec{G})} d^-(v) \neq \sum_{v \in V(\vec{G})} d^+(v)$ . A nsd 3-arc-weighting of  $\vec{G}$  is then obtained as follows. Start by removing the arcs outgoing from  $v$ . According to the induction hypothesis, the remaining oriented graph admits a nsd 3-arc-weighting  $w$ . Now put back the arcs outgoing from  $v$  to  $\vec{G}$ , and extend  $w$  to these arcs in such a way that the weighted outdegree of  $v$  is different from the weighted outdegrees of the  $d^-(v) + d^+(v)$  vertices neighbouring  $v$ . This is possible since there are  $2d^+(v) + 1$  potential weighted outdegrees for  $v$ , namely those from  $\{d^+(v), d^+(v) + 1, \dots, 3d^+(v)\}$ , while the number of forbidden weighted outdegrees is at most  $d^-(v) + d^+(v) < 2d^+(v) + 1$  by our assumption on  $d^-(v)$  and  $d^+(v)$ . Because assigning a weight to the arcs outgoing from  $v$  does

not affect the weighted outdegree by  $w$  of any vertex neighbouring  $v$ , the extension of  $w$  to  $\vec{G}$  remains neighbour-sum-distinguishing.  $\square$

### 3 Conditions for some families of oriented graphs to admit a nsd 2-arc-weighting

By Theorem 1, we know that every oriented graph admits a nsd 3-arc-weighting. Throughout this section, we focus on some common families of oriented graphs and exhibit conditions for their members to admit a nsd 2-arc-weighting.

#### 3.1 Acyclic oriented graphs

An oriented graph is *acyclic* if it does not admit a circuit as an induced subgraph. We show that every such oriented graph admits a nsd 2-arc-weighting.

**Theorem 2.** *Every acyclic oriented graph admits a nsd 2-arc-weighting.*

*Proof.* We prove the claim by induction on the order, i.e. the number of vertices, of acyclic oriented graphs. As a starting point, note that an oriented graph with only one vertex admits a nsd 2-arc-weighting. Suppose now that the claim is true for every acyclic oriented graph with order at most  $n - 1$  for some  $n \geq 2$ , and let  $\vec{G}$  be an acyclic oriented graph on  $n$  vertices.

Since  $\vec{G}$  is acyclic, there are vertices of  $\vec{G}$  with indegree 0. Let  $v$  be such a vertex, and consider the graph  $\vec{G}'$  obtained by removing  $v$  from  $\vec{G}$ . Clearly  $\vec{G}'$  is acyclic and admits a nsd 2-arc-weighting  $w$  according to the induction hypothesis. We now extend  $w$  to  $\vec{G}$ , i.e. we weight the arcs outgoing from  $v$  in such a way that  $w$  remains neighbour-sum-distinguishing. There are  $d^+(v) + 1$  possible weighted outdegrees for  $v$ , namely those from  $\{d^+(v), d^+(v)+1, \dots, 2d^+(v)\}$ , while there are at most  $d^+(v)$  forbidden weighted outdegrees for  $v$ , namely the weighted outdegrees by  $w$  of the vertices in  $N^+(v)$ . Since weighting the arcs outgoing from  $v$  does not alter the weighted outdegree of any vertex neighbouring  $v$ , we can choose an available weighted outdegree for  $v$  and weight the arcs outgoing from  $v$  consequently. This completes the proof.  $\square$

#### 3.2 Oriented graphs whose underlying graphs are $k$ -colourable

Given an undirected graph  $G$ , a *proper  $k$ -vertex-colouring* of  $G$  is a partition of  $V(G)$  into  $k$  parts  $V_1, \dots, V_k$  such that  $V_i$  is an independent set for every

$i \in \{1, 2, \dots, k\}$ . The least number of parts of a proper vertex-colouring of  $G$  is referred to as the *chromatic number* of  $G$ , denoted  $\chi(G)$ . Assuming  $\vec{G}$  is any orientation of  $G$ , i.e.  $\vec{G}$  is obtained by orienting every edge of  $G$  in either direction, we denote by  $\text{und}(\vec{G})$  the *underlying* undirected graph of  $\vec{G}$ , that is  $G$ .

As pointed out in some references of the literature (see e.g. [1] or [8]), first partitioning a graph into several independent sets before weighting its edges can be a good method for finding a specific edge-weighting. This is also the case regarding neighbour-sum-distinguishing arc-weighting, as shown in the following result.

**Theorem 3.** *Every oriented graph  $\vec{G}$  admits a nsd  $\chi(\text{und}(\vec{G}))$ -arc-weighting.*

*Proof.* Let  $k = \chi(\text{und}(\vec{G}))$ , and  $V_0, \dots, V_{k-1}$  be a proper  $k$ -vertex-colouring of  $\text{und}(\vec{G})$ . Process the vertices of  $\vec{G}$  in arbitrary order. If the vertex  $v$  belongs to the part  $V_i$ , then weight the arcs outgoing from  $v$  with weights from  $\{1, 2, \dots, k\}$  in such a way that the weighted outdegree of  $v$  is congruent to  $i$  modulo  $k$ , e.g. by assigning  $i$  to one arc outgoing to  $v$  (or  $k$  if  $i = 0$ ), and  $k$  to all of its other outgoing arcs. This is possible unless  $d^+(v) = 0$  since, in such a situation, the only possible weighted outdegree for  $v$  is 0. Once the process is achieved, two adjacent vertices  $u$  and  $v$  cannot have the same weighted outdegrees since otherwise either  $u$  and  $v$  would both belong to some part  $V_i$ , which is impossible since  $V_i$  is an independent set, or we would have  $d^+(u) = d^+(v) = 0$ , which is impossible since  $u$  and  $v$  are adjacent.  $\square$

As a corollary of Theorem 3, we get in particular the following result.

**Corollary 4.** *Every oriented graph  $\vec{G}$  whose underlying graph is bipartite admits a nsd 2-arc-weighting.*

### 3.3 Tournaments

Our strategy for weighting the arcs of any tournament  $\vec{T}$  is based on the following lemma, which could be also deduced from result of Landau regarding so-called *score sequences* (see [10], Theorem 29).

**Lemma 5.** *For every  $k \in \{1, 2, \dots, |V(\vec{T})|\}$ , let  $n_k \geq 0$  denote the number of vertices with outdegree at most  $k$  of any tournament  $\vec{T}$ . Then  $n_k \leq 2k + 1$ .*

*Proof.* Let  $k$  be fixed, with  $1 \leq k \leq |V(\vec{T})|$ . Denote by  $X \subseteq V(\vec{T})$  the set of the  $n_k$  vertices of  $\vec{T}$  whose outdegree is at most  $k$ , and by  $s$  the sum of outdegrees of the vertices in  $X$ . Naturally, we have  $s \leq n_k k$ . We also

have  $s \geq \frac{n_k(n_k-1)}{2}$  since  $X$  induces a tournament, and there may be arcs of  $\vec{T}$  whose tails lie in  $X$ , and whose heads do not lie in  $X$ . We hence get  $\frac{n_k(n_k-1)}{2} \leq n_k k$ , which implies that  $n_k \leq 2k + 1$ .  $\square$

We now give a characterization of tournaments which admit a nsd 2-arc-weighting.

**Theorem 6.** *For every  $k \in \{1, 2, \dots, |V(\vec{T})|\}$ , let  $n_k \geq 0$  denote the number of vertices with outdegree at most  $k$  of any tournament  $\vec{T}$ . Then  $\vec{T}$  admits a nsd 2-arc-weighting if and only if  $n_k \leq k + 1$  for every  $k \in \{1, 2, \dots, |V(\vec{T})|\}$ .*

*Proof.* The proof is based on the following simple weighting scheme for  $\vec{T}$ . Process the vertices of  $\vec{T}$  in increasing order of their outdegrees. For each vertex  $v$ , weight the arcs outgoing from  $v$  in such a way that the weighted outdegree of  $v$  gets the smallest possible value which does not appear among the weighted outdegrees of the vertices considered in earlier steps of the process. Assume  $k = d^+(v)$ . Since the weighted outdegree of  $v$  can take any value from  $\{k, k + 1, \dots, 2k\}$  and at most  $n_k - 1 < k + 1$  vertices have been considered in earlier steps of the process, there is necessarily one non-conflicting value which can be chosen as the weighted outdegree of  $v$ . We then just have to weight the arcs outgoing from  $v$  consequently.

The ‘‘only if’’ condition of the statement follows from the fact that if we have  $n_k \in \{k + 2, k + 3, \dots, 2k + 1\}$  for some value of  $k$  (the upper bound on  $n_k$  follows from Lemma 5), then we need to increase the range of possible values as the weighted outdegree of  $v$ , i.e. to allow the use of a third weight.  $\square$

### 3.4 Cartesian products of oriented graphs

Let  $\vec{G}$  and  $\vec{H}$  be two oriented graphs. The *Cartesian product* of  $\vec{G}$  and  $\vec{H}$ , denoted  $\vec{G} \square \vec{H}$ , is the oriented graph with vertex set  $V(\vec{G}) \times V(\vec{H})$ , and whose two vertices  $(u_1, v_1)$  and  $(u_2, v_2)$  are joined by an arc from  $(u_1, v_1)$  towards  $(u_2, v_2)$  if and only if  $u_1 = u_2$  and  $\overrightarrow{v_1 v_2} \in E(\vec{H})$ , or  $\overrightarrow{u_1 u_2} \in E(\vec{G})$  and  $v_1 = v_2$ .

The Cartesian product of graphs is a classical graph operation which has been studied a lot since its introduction [6]. The reason for focusing on the Cartesian product of oriented graphs is that if  $\vec{G}$  and  $\vec{H}$  both admit a nsd  $k$ -arc-weighting for some value of  $k$ , one could expect  $\vec{G} \square \vec{H}$  to need  $k'$  weights to obtain a nsd arc-weighting, where  $k'$  depends on  $k$ . In the next result, we show that the existence of nsd  $k$ -arc-weightings of  $\vec{G}$  and  $\vec{H}$  implies the existence of a nsd  $k$ -arc-weighting of  $\vec{G} \square \vec{H}$ .

**Theorem 7.** *Assume  $\vec{G}$  and  $\vec{H}$  admit a nsd  $k$ - and  $\ell$ -arc-weighting, respectively. Then  $\vec{G} \square \vec{H}$  admits a nsd  $\max\{k, \ell\}$ -arc-weighting.*

*Proof.* Let  $w_{\vec{G}}$  and  $w_{\vec{H}}$  be nsd  $k$ - and  $l$ -arc-weighting of  $\vec{G}$  and  $\vec{H}$ , respectively. Let  $w$  be a  $\max\{k, l\}$ -arc-weighting of  $\vec{G} \square \vec{H}$  defined as follows:

$$w(\overrightarrow{(u_1, v_1)(u_2, v_2)}) = \begin{cases} w_{\vec{H}}(\overrightarrow{v_1 v_2}) & \text{if } u_1 = u_2, \\ w_{\vec{G}}(\overrightarrow{u_1 u_2}) & \text{otherwise.} \end{cases}$$

Assume  $\overrightarrow{(u_1, v_1)(u_2, v_2)}$  is an arc of  $\vec{G} \square \vec{H}$ . Then we have  $\phi_w((u_1, v_1)) = \phi_{w_{\vec{G}}}(u_1) + \phi_{w_{\vec{H}}}(v_1)$  and  $\phi_w((u_2, v_2)) = \phi_{w_{\vec{G}}}(u_2) + \phi_{w_{\vec{H}}}(v_2)$ . Since  $(u_1, v_1)$  and  $(u_2, v_2)$  are adjacent, we have either  $u_1 = u_2$  or  $v_1 = v_2$  by construction. Assume  $u_1 = u_2$  without loss of generality. Then  $\phi_{w_{\vec{G}}}(u_1) = \phi_{w_{\vec{G}}}(u_2)$ . Now, because  $w_{\vec{H}}$  is neighbour-sum-distinguishing, we have  $\phi_{w_{\vec{H}}}(v_1) \neq \phi_{w_{\vec{H}}}(v_2)$ . It then follows that  $\phi_w((u_1, v_1)) \neq \phi_w((u_2, v_2))$ .  $\square$

An immediate corollary of Theorem 7 is the following result.

**Corollary 8.** *Assume  $\vec{G}$  and  $\vec{H}$  both admit a nsd 2-arc-weighting. Then  $\vec{G} \square \vec{H}$  admits a nsd 2-arc-weighting.*

## 4 Algorithmic complexity

In this section, we focus on the complexity of the following decision problem.

NEIGHBOUR-SUM-DISTINGUISHING  $k$ -ARC-WEIGHTING -  $k$ -NSDAW

Instance: An oriented graph  $\vec{G}$ .

Question: Does  $\vec{G}$  admit a nsd  $k$ -arc-weighting?

An oriented graph  $\vec{G}$  admits a nsd 1-arc-weighting if and only if every two adjacent vertices of  $\vec{G}$  have distinct outdegrees. Since this property can be checked in polynomial time, the problem 1-NSDAW is in P. Besides, every problem  $k$ -NSDAW with  $k \geq 3$  is also in P since the answer to every of its instances is *yes*, according to Theorem 1.

We deal with the complexity of the remaining problem, i.e. 2-NSDAW. We show this problem to be NP-complete in Theorem 11 below, by reduction from 3-SAT. For this purpose, we first introduce several gadgets to “force” the propagation of a nsd 2-arc-weighting along an oriented graph.

We first introduce two kinds of *forbidding* gadgets. A forbidding gadget  $\vec{F}$  is composed of one *root vertex* with outdegree 0 adjacent to *forcing vertices*. The weighting property of  $\vec{F}$  is that each of its forcing vertices has always the same weighted outdegree by every nsd 2-arc-weighting of  $\vec{F}$ . Assume  $x_1, x_2, \dots, x_k$  denote the respective outdegrees of the forcing vertices. Then, after having identified the root of  $\vec{F}$  with a vertex  $v$  of some graph



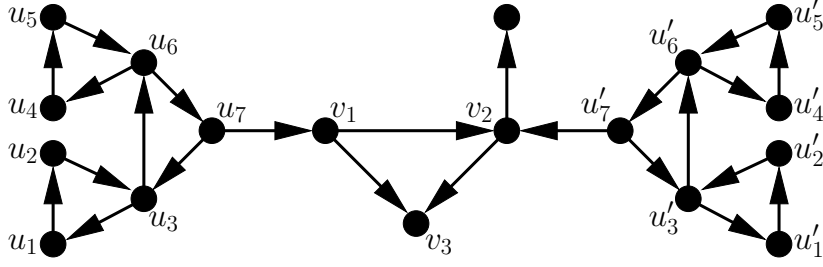


Figure 1: The forbidding gadget  $\overrightarrow{F_{3,4}}$ .

$\overrightarrow{G}$ , the vertex  $v$  cannot have weighted outdegree  $x_1, x_2, \dots, x_k$  by any nsd 2-arc-weighting of  $\overrightarrow{G}$  because of the forcing vertices of  $\overrightarrow{F}$  neighbouring  $v$ .

First, we define a  $(2k - 1, 2k)$ -forbidding gadget, denoted  $\overrightarrow{F_{2k-1, 2k}}$ , for every integer  $k \geq 2$ . These gadgets are defined inductively. The gadget  $\overrightarrow{F_{3,4}}$  is the one depicted in Figure 1. The root of  $\overrightarrow{F_{3,4}}$  is  $v_3$ , while its forcing vertices are  $v_1$  and  $v_2$ . Now, for any value of  $k \geq 3$  such that the oriented graphs  $\overrightarrow{F_{2k'-1, 2k'}}$  have been defined for every  $k' < k$ , the oriented graph  $\overrightarrow{F_{2k-1, 2k}}$  is constructed as follows. Let  $v_1^k, v_2^k$  and  $v_3^k$  be three distinct vertices joined by  $\overrightarrow{v_1^k v_2^k}, \overrightarrow{v_1^k v_3^k}$  and  $\overrightarrow{v_2^k v_3^k}$ . Now, for every  $k' \in \{2, 3, \dots, k - 1\}$ , identify  $v_1^k$  and the root of a copy of  $\overrightarrow{F_{2k'-1, 2k'}}$ . Repeat the same procedure but with  $v_2^k$  instead of  $v_1^k$  and new copies of the forbidding gadgets. Finally add an arc from  $v_1^k$  towards  $k - 2$  new vertices with outdegree 0, and similarly from  $v_2^k$  towards  $k - 1$  new vertices with outdegree 0. The root of  $\overrightarrow{F_{2k-1, 2k}}$  is  $v_3^k$ , while its forcing vertices are  $v_1^k$  and  $v_2^k$ .

**Lemma 9.** *Let  $k \geq 2$  be fixed. In every nsd 2-arc-weighting of  $\overrightarrow{F_{2k-1, 2k}}$ , one of the forcing vertices has weighted outdegree  $2k - 1$ , while the other forcing vertex has weighted outdegree  $2k$ .*

*Proof.* We prove the claim by induction on  $k$ . At each step, let  $w$  be a nsd 2-arc-weighting of the considered forbidding gadget. Start with  $\overrightarrow{F_{3,4}}$ . Since  $u_1$  and  $u_2$  are adjacent and both have outdegree 1, we have  $\{\phi_w(u_1), \phi_w(u_2)\} = \{1, 2\}$ . By the same argument, we have  $\{\phi_w(u_4), \phi_w(u_5)\} = \{1, 2\}$ . Since  $u_3$  and  $u_6$  are adjacent, both adjacent to vertices with weighted outdegree 2, and have outdegree 2, we necessarily have  $\{\phi_w(u_3), \phi_w(u_6)\} = \{3, 4\}$ . Because  $u_7$  is adjacent to  $u_3$  and  $u_6$  and has outdegree 2, we necessarily get  $\phi_w(u_7) = 2$ . Repeating the same arguments to the oriented subgraph of  $\overrightarrow{F_{3,4}}$  induced by the  $u'_i$ 's, we also obtain  $\phi_w(u'_7) = 2$ . Finally, since  $v_1$  and  $v_2$  are adjacent, both adjacent to a vertex with weighted outdegree 2, and have outdegree 2, we have  $\{\phi_w(v_1), \phi_w(v_2)\} = \{3, 4\}$  as claimed.

Assume the claim is true for every  $k$  up to  $i - 1$ , and consider  $\overrightarrow{F_{2k-1, 2k}}$ .

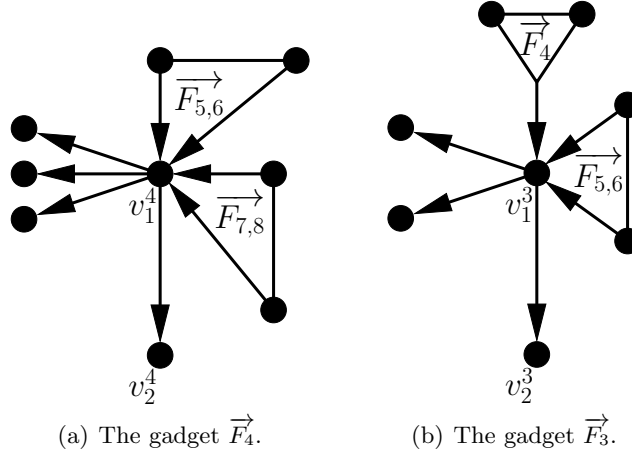


Figure 2: Two examples of forbidding gadgets. A triangle represents a forbidding gadget.

Because  $v_1^k$  and  $v_2^k$  have outdegree  $k$  by construction, their weighted outdegree by  $w$  can only take value from  $\{k, k + 1, \dots, 2k\}$ . However, since these two vertices are both identified with the roots of forbidding gadgets  $\overrightarrow{F_{3,4}}, \overrightarrow{F_{5,6}}, \dots, \overrightarrow{F_{2k-3,2k-2}}$ , their weighted outdegree cannot take value from  $\{3, 4, \dots, 2k - 3, 2k - 2\}$  according to the induction hypothesis. Therefore, we have  $\{\phi_w(v_1^k), \phi_w(v_2^k)\} = \{2k - 1, 2k\}$  since  $v_1^k$  and  $v_2^k$  are adjacent.  $\square$

We now define a  $k$ -forbidding gadget, denoted  $\overrightarrow{F_k}$ , for every integer  $k \geq 3$ . The oriented graph  $\overrightarrow{F_k}$  originally consists in an arc  $\overrightarrow{v_1^k v_2^k}$ . We call  $v_2^k$  and  $v_1^k$  the root and the forcing vertex of  $\overrightarrow{F_k}$ , respectively. Next add an arc from  $v_1^k$  towards  $k - 1$  new vertices with outdegree 0. The end of the construction depends on the parity of  $k$ . If  $k$  is even, then identify  $v_1^k$  and the root of each of the forbidding gadgets  $\overrightarrow{F_{k+1,k+2}}, \overrightarrow{F_{k+3,k+4}}, \dots, \overrightarrow{F_{2k-1,2k}}$ . Otherwise, i.e. if  $k$  is odd, then identify  $v_1^k$  and the roots of  $\overrightarrow{F_{k+1}}, \overrightarrow{F_{k+2,k+3}}, \overrightarrow{F_{k+4,k+5}}, \dots, \overrightarrow{F_{2k-1,2k}}$ . The gadgets  $\overrightarrow{F_3}$  and  $\overrightarrow{F_4}$  are depicted in Figure 2.

**Lemma 10.** *Let  $k \geq 3$  be fixed. In every nsd 2-arc-weighting of  $\overrightarrow{F_k}$ , the forcing vertex has weighted outdegree  $k$ .*

*Proof.* Let  $w$  be a nsd 2-arc-weighting of  $\overrightarrow{F_k}$ . Assume  $k$  is even. Since  $v_1^k$  has outdegree  $k$ , its weighted outdegree by  $w$  can only take value from  $\{k, k + 1, \dots, 2k\}$ . But, because  $v_1^k$  is the root of forbidding gadgets  $\overrightarrow{F_{k+1,k+2}}, \overrightarrow{F_{k+3,k+4}}, \dots, \overrightarrow{F_{2k-1,2k}}$ , it is adjacent to vertices with weighted outdegrees  $k + 1, k + 2, \dots, 2k$  according to Lemma 9. Hence, the only remaining weighted

outdegree for  $v_1^k$  by  $w$  is  $k$ . The claim follows similarly when  $k$  is odd, the value  $k + 1$  being forbidden as the weighted outdegree of  $v_1^k$  because it was identified with the root of a forbidding gadget  $\overrightarrow{F_{k+1}}$  with  $k+1$  being even.  $\square$

Thanks to the two kinds of forbidding gadgets introduced above, we can now “force” a vertex of some oriented graph to have a specific weighted outdegree by any nsd 2-arc-weighting. Let  $v$  be a vertex of some oriented graph  $\overrightarrow{G}$ , and  $k \geq d^+(v)$  be some integer. Assume we are given a set  $D \subseteq \{k, k + 1, \dots, 2k\}$  of “allowed” weighted outdegrees for  $v$  by any nsd 2-arc-weighting of  $\overrightarrow{G}$ . Then, by “turning  $v$  into a  $D$ -vertex”, we refer to the following operations:

- first add arcs from  $v$  towards  $k - d^+(v)$  new vertices with outdegree 0 so that  $v$  has outdegree  $k$ ,
- then identify  $v$  and the respective root of each of the forbidding gadgets  $\overrightarrow{F_i}$  with  $i \in \{k, k + 1, \dots, 2k\} - D$ .

Clearly, because of the forcing vertices neighbouring  $v$ , the weighted outdegree of  $v$  by any nsd 2-arc-colouring of  $\overrightarrow{G}$  necessarily takes value among  $D$ .

We are now ready to introduce our hardness reduction.

**Theorem 11.** *The problem 2-NSDAW is NP-complete.*

*Proof.* Given a 2-arc-weighting  $w$  of  $\overrightarrow{G}$ , one can first compute the vertex-colouring  $\phi_w$  of  $\overrightarrow{G}$  from  $w$ , and then check whether it is proper. Since this procedure can be achieved in polynomial time, 2-NSDAW is in NP.

We now prove that 2-NSDAW is NP-hard by reduction from the following classical NP-complete problem [5].

3-SAT

Instance: A 3CNF formula  $F$  over clauses  $C_1, \dots, C_m$  and variables  $x_1, \dots, x_n$ .

Question: Does  $F$  admit a satisfying truth assignment?

Note that we can assume that every possible literal appears in  $F$ . Indeed, if  $\ell_i$  does not appear in any clause of  $F$ , then the 3CNF formula  $F \wedge (\ell_i \vee \ell_i \vee \overline{\ell_i})$  is satisfiable if and only if  $F$  is satisfiable. By repeating this procedure for all literals which do not appear in  $F$ , we obtain a formula equivalent to  $F$  but involving all possible literals over its variables. This procedure is achieved in polynomial time.

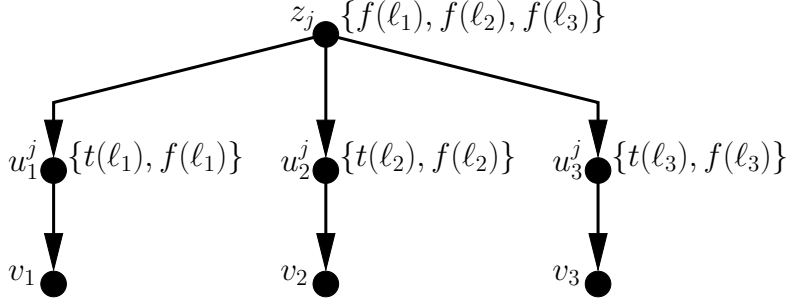


Figure 3: Partial resulting clause gadget for a clause  $C_j = (\ell_1 \vee \ell_2 \vee \ell_3)$ . The integer sets represent the allowed weighted outdegrees at each vertex by a nsd 2-arc-weighting of  $\overrightarrow{G}_F$ .

We introduce some more terminology regarding an instance of 3-SAT. The  $2n$  literals of  $F$  over its  $n$  variables are denoted by  $\ell_1, \ell_2, \dots, \ell_{2n}$ , the ordering being arbitrary. By  $n_i \geq 1$ , we refer to the number of distinct clauses of  $F$  that contain the literal  $\ell_i$  for every  $i \in \{1, 2, \dots, 2n\}$ . By  $c_j \in \{1, 2, 3\}$ , we denote the number of distinct literals which appear in the clause  $C_j$  for every  $j \in \{1, 2, \dots, m\}$ . In the case where  $c_j = 1$ , i.e.  $C_j$  is of the form  $(\ell_i \vee \ell_i \vee \ell_i)$ , note that  $\ell_i$  is set to true by every satisfying truth assignment of  $F$ . In such a situation, we say that  $\ell_i$  is *forced* to true by  $C_j$ .

Our hardness reduction is described below. From a 3CNF formula  $F$ , we construct an oriented graph  $\overrightarrow{G}_F$  such that  $F$  is satisfiable if and only if  $\overrightarrow{G}_F$  admits a nsd 2-arc-weighting  $w_F$ .

Let  $t$  and  $f$  be two injective mappings from  $\{x_1, x_2, \dots, x_n\}$  to  $\{2n, 2n + 1, \dots, 3n - 1\}$  and  $\{3n, 3n + 1, \dots, 4n\}$ , respectively. Assuming  $\ell_j = x_i$  and  $\ell_{j'} = \bar{x}_i$ , i.e.  $\ell_j$  and  $\ell_{j'}$  are the literals associated with the variable  $x_i$ , we set  $t(\ell_j) = f(\ell_{j'}) = t(x_i)$  and  $f(\ell_j) = t(\ell_{j'}) = f(x_i)$ .

First, for every literal  $\ell_i$  of  $F$ , add a vertex  $v_i$  in  $\overrightarrow{G}_F$ . Now consider every clause  $C_j$  of  $F$ . We associate a *clause gadget* in  $\overrightarrow{G}_F$  with  $C_j$ , its structure depending on the value of  $c_j$ . Denote by  $\ell_{j_1}, \dots, \ell_{j_{c_j}}$  the distinct literals of  $C_j$ . Let  $\overrightarrow{u_{j_1}^j v_{j_1}}, \dots, \overrightarrow{u_{j_{c_j}}^j v_{j_{c_j}}}$  be  $c_j$  arcs of  $\overrightarrow{G}_F$ , where  $u_{j_1}^j, \dots, u_{j_{c_j}}^j$  are new vertices. If  $c_j = 1$ , i.e.  $\ell_{j_1}$  is forced to true by  $C_j$ , then turn  $u_{j_1}^j$  into a  $\{t(\ell_{j_1})\}$ -vertex. Otherwise, i.e.  $c_j \in \{2, 3\}$ , turn each vertex  $u_{j_i}^j$  into a  $\{t(\ell_{j_i}), f(\ell_{j_i})\}$ -vertex, add a vertex  $z_j$  to  $\overrightarrow{G}_F$ , add arcs from  $z_j$  towards  $u_{j_1}^j, \dots, u_{j_{c_j}}^j$ , and turn  $z_j$  into a  $\{f(\ell_{j_1}), \dots, f(\ell_{j_{c_j}})\}$ -vertex. This construction is depicted in Figure 3.

**Claim 1.** *Let  $C_j = (\ell_{j_1} \vee \ell_{j_2} \vee \ell_{j_3})$  be a clause of  $F$ . Then at least one of  $t(\ell_{j_1})$ ,  $t(\ell_{j_2})$  and  $t(\ell_{j_3})$  belongs to  $\{\phi_{w_F}(u_{j_1}^j), \phi_{w_F}(u_{j_2}^j), \phi_{w_F}(u_{j_3}^j)\}$ .*

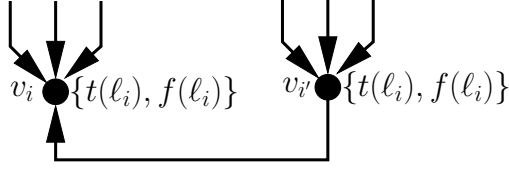


Figure 4: Partial subgraph of  $\overrightarrow{G}_F$  for two literals  $\ell_i$  and  $\ell_{i'}$  such that  $\ell_{i'} = \overline{\ell_i}$ . The integer sets represent the allowed weighted outdegrees at each vertex by a nsd 2-arc-weighting of  $\overrightarrow{G}_F$ .

*Proof.* The claim is true when  $c_j = 1$  since  $u_{j_1}^j$  is a  $\{t(\ell_{j_1})\}$ -vertex. When  $c_j \in \{2, 3\}$ , note that we cannot have  $\phi_{w_F}(u_{j_1}^j) = f(\ell_{j_1}), \dots, \phi_{w_F}(u_{j_{c_j}}^j) = f(\ell_{j_{c_j}})$  since  $z_j$  is a  $\{f(\ell_{j_1}), \dots, f(\ell_{j_{c_j}})\}$ -vertex. On the contrary, note that if there is an  $i \in \{1, 2, \dots, c_j\}$  such that  $\phi_{w_F}(u_{j_i}^j) = t(\ell_{j_i})$ , then we can weight the arcs outgoing from  $z_j$  in such a way that the weighted outdegree of  $z_j$  by  $w_F$  is  $f(\ell_{j_i})$ .  $\square$

Let  $i \in \{1, 2, \dots, 2n\}$ . Note that, so far, the vertex  $v_i$  has indegree  $n_i$ . Consider  $i' \in \{1, 2, \dots, 2n\}$  such that  $\ell_{i'} = \overline{\ell_i}$ . To finish the construction of  $\overrightarrow{G}_F$ , add the arc  $\overrightarrow{v_{i'}v_i}$ , and turn  $v_i$  and  $v_{i'}$  into  $\{t(\ell_i), f(\ell_i)\}$ -vertices. This step of the construction is illustrated in Figure 4.

**Claim 2.** Let  $i \in \{1, 2, \dots, 2n\}$ , and  $i_1, i_2, \dots, i_{n_i}$  be the indexes of the distinct clauses of  $F$  that contain  $\ell_i$ . Then  $\phi_{w_F}(u_i^{i_1}) = \phi_{w_F}(u_i^{i_2}) = \dots = \phi_{w_F}(u_i^{i_{n_i}})$ .

*Proof.* Recall that the  $u_i^{i_j}$ 's can only have weighted outdegree  $t(\ell_i)$  or  $f(\ell_i)$  by  $w_F$ . Now note that if one of the  $u_i^{i_j}$ 's has weighted outdegree  $t(\ell_i)$  by  $w_F$  while another such vertex has weighted outdegree  $f(\ell_i)$ , then  $w_F$  cannot be extended to the arcs outgoing from  $v_i$  since  $v_i$  is a  $\{t(\ell_i), f(\ell_i)\}$ -vertex. On the contrary, if all the  $u_i^{i_j}$ 's neighbouring  $v_i$  have the same weighted outdegree, say  $t(\ell_i)$ , then the arcs outgoing from  $v_i$  can be weighted in such a way that  $\phi_{w_F}(v_i) = f(\ell_i)$ .  $\square$

**Claim 3.** Let  $i, i' \in \{1, 2, \dots, 2n\}$  be two integers such that  $\ell_{i'} = \overline{\ell_i}$ . Then  $\phi_{w_F}(v_i) \neq \phi_{w_F}(v_{i'})$ .

*Proof.* The claim follows from the fact that  $v_i$  and  $v_{i'}$  are adjacent.  $\square$

We now claim that  $F$  has a satisfying truth assignment if and only if  $\overrightarrow{G}_F$  admits its nsd 2-arc-weighting  $w_F$ . Assume  $C_j = (\ell_{j_1} \vee \ell_{j_2} \vee \ell_{j_3})$  is a clause of  $F$ , and that having  $\phi_{w_F}(u_{j_i}^j) = t(\ell_{j_i})$  (resp.  $f(\ell_{j_i})$ ) simulates the assignment of  $\ell_{j_i}$  to true (resp. false) in  $C_j$  by a truth assignment

of  $F$ . Then, by Claim 1, every clause gadget of  $\overrightarrow{G}_F$  must have a vertex  $w_{j_i}^j$  whose weighted outdegree by  $w_F$  is  $t(\ell_{j_i})$ . This simulates the fact that every clause of  $F$  must have one true literal by a satisfying truth assignment of  $F$ . Claim 2 depicts the fact that, by a truth assignment of  $F$ , every literal of  $F$  provides the similar truth value to every clause it appears in. Finally, Claim 3 represents the fact that two opposite literals cannot be assigned the same truth value by a truth assignment of  $F$ . With these arguments, we can deduce a satisfying truth assignment of  $F$  from  $w_F$ , and vice-versa.  $\square$

## 5 Discussion

Recall that the proof of Theorem 1 mainly relies on the fact that the number of possible weighted outdegrees by an arc-weighting for a vertex with outdegree  $d$  is sufficiently large, i.e. at least  $2d + 1$ , when the weights from  $\{1, 2, 3\}$  are allowed for each arc. By showing this property to hold for any triple  $\{a, b, c\}$  of weights, we can strengthen Theorem 1.

**Lemma 12.** *Let  $v$  be a vertex with outdegree  $d$  of some oriented graph  $\overrightarrow{G}$ , and  $\{a, b, c\}$  be a set of three real numbers. Then there are at least  $2d + 1$  possible weighted outdegrees for  $v$  by any arc-weighting of  $\overrightarrow{G}$  assigning value among  $\{a, b, c\}$  to the arcs outgoing from  $v$ .*

*Proof.* We prove this claim by induction on  $d$ . If  $d = 1$ , then the arc outgoing from  $v$  can be weighted either  $a$ ,  $b$ , or  $c$  by an arc-weighting of  $\overrightarrow{G}$ . Since  $a$ ,  $b$  and  $c$  are distinct, there are exactly three weighted outdegrees for  $v$ , namely  $a$ ,  $b$  and  $c$ , respectively.

Assume the claim is true for every value of  $d$  up to  $i - 1$ , and assume  $d = i$ . Let  $\overrightarrow{G}'$  be the oriented graph obtained by removing exactly one arc  $\overrightarrow{vu}$  outgoing from  $v$ . Then there are at least  $2(d - 1) + 1$  possible weighted outdegrees for  $v$  by any arc-weighting of  $\overrightarrow{G}'$  taking value among  $\{a, b, c\}$  according to the induction hypothesis. Let  $D'$  be the set of these possible weighted outdegrees, and denote  $inf$  and  $sup$  the minimum and maximum elements of  $D'$ , respectively, and  $w'_{inf}$  and  $w'_{sup}$  two arc-weighting of  $\overrightarrow{G}'$  such that  $\phi_{w'_{inf}}(v) = inf$  and  $\phi_{w'_{sup}}(v) = sup$ , respectively.

Assume  $a < b < c$ . Note that if the result holds for  $\{a, b, c\}$ , then it also holds for  $\{-a, -b, -c\}$ . Hence, we only have two cases to consider, namely

1.  $0 \leq a < b < c$ , and
2.  $a < 0 \leq b < c$ .

In the first case, by extending every arc-weighting of  $\vec{G}'$  to  $\vec{G}$  by weighting the arc  $\vec{v}u$  with weight  $a$ , we directly obtain that the set  $D = \{x+a : x \in D'\}$  is a set of at least  $2(d-1) + 1$  possible weighted outdegrees for  $v$ . The two remaining weighted outdegrees for  $v$  are obtained by extending  $w'_{sup}$  by weighting  $b$  or  $c$  the arc  $\vec{v}u$ . We then obtain that  $sup + b$  and  $sup + c$  are two other possible weighted outdegrees for  $v$  since none of these two values can appear in  $D$  because  $a < b < c$ . There are thus at least  $2d + 1$  possible weighted outdegrees for  $v$ .

In the second case, by extending every arc-weighting of  $\vec{G}'$  to  $\vec{G}$  by weighting  $b$  the arc  $\vec{v}u$ , we get that  $D = \{x + b : x \in D'\}$  is a set of at least  $2(d-1) + 1$  weighted outdegrees for  $v$ . The two remaining weighted outdegrees for  $v$  are obtained by extending  $w'_{inf}$  and  $w'_{sup}$  to  $\vec{G}$  by weighting  $a$  and  $c$ , respectively, the arc  $\vec{v}u$ . From these two extensions, we get that  $v$  can also have weighted outdegree  $inf + a$  and  $sup + c$ , which do not appear in  $D$  by our assumptions on  $a$ ,  $b$  and  $c$ . This completes the proof.  $\square$

As a corollary of Lemma 12, we directly get that the proof of Theorem 1 is applicable no matter what are the three weights allowed to weight the arcs outgoing from any vertex. This implies the following list version of our main result.

**Corollary 13.** *For every vertex  $v$  of some oriented graph  $\vec{G}$ , let  $L(v)$  be an arbitrary list of three distinct real weights allowed at  $v$ . Then  $\vec{G}$  admits a nsd arc-weighting such that the arcs outgoing from any vertex  $v$  are weighted with values among  $L(v)$ .*

As for the undirected case, one can also consider a variant of the problem investigated in this work where the weighted outdegree of a vertex is the *product* of its outgoing weights rather than their sum (see e.g. [12]). Formally, from a  $k$ -arc-weighting  $w$  of some oriented graph  $\vec{G}$  one obtains a vertex-colouring  $\rho_w$  defined as  $\rho_w(v) = \prod_{u \in N^+(v)} w(\vec{v}u)$  for every  $v \in V(\vec{G})$ . If  $\rho_w$  is proper, then we say that  $w$  is *neighbour-product-distinguishing* (*npd* for short).

Regarding npd-arc-weightings, note that the range of possible weighted outdegrees for a vertex is as wider as in the product version than in the sum version when the weights from  $\{1, 2, 3\}$  are allowed (this can be proved in a similar manner as Lemma 12). Hence, our proof of Theorem 1 is also a proof that every oriented graph admits a npd-3-arc-weighting.

**Theorem 14.** *Every oriented graph  $\vec{G}$  admits a npd-3-arc-weighting.*

Note that there are  $k + 1$  possible weighted outdegrees for a vertex with outdegree  $k$  by a npd-2-arc-weighting of some oriented graph, namely those

from  $\{1, 2, 4, \dots, 2^k\}$ . Since there are as many possible weighted outdegrees for a vertex by a nsd 2-arc-weighting and a npd-2-arc-weighting, our results from Section 3 also hold regarding npd-2-arc-weightings.

Finally, we can adapt the reduction scheme from Section 4 to prove that it is NP-complete to decide whether a given oriented graph admits a npd-2-arc-weighting. The forbidding gadgets can be obtained, for instance, as follows. Start from the circuit  $\overrightarrow{u_1 u_2 u_3 u_1}$  on 3 vertices, and add an arc  $\overrightarrow{u_1 u_4}$  where  $u_4$  is a new vertex. This resulting oriented graph  $\overrightarrow{F_4}$  is a 4-forbidding gadget since  $u_1$  necessarily gets weighted outdegree 4 by any npd-2-arc-weighting. The root of  $\overrightarrow{F_4}$  is  $u_4$ . Now consider another oriented graph  $\overrightarrow{F_{1,2}}$  with vertices  $v_1, v_2, v_3$  and  $v_4$  such that  $\overrightarrow{v_1 v_2}, \overrightarrow{v_1 v_3}, \overrightarrow{v_2 v_3}$  and  $\overrightarrow{v_2 v_4}$  are arcs, and  $v_1$  and  $v_2$  are each identified with the root of one copy of  $\overrightarrow{F_4}$ . Clearly, since  $v_1$  and  $v_2$  are adjacent vertices with outdegree 2, and they are both identified with the root of a gadget  $\overrightarrow{F_4}$ , their weighted outdegree can only be 1 and 2 without loss of generality, and  $\overrightarrow{F_{1,2}}$  is thus a  $(1, 2)$ -forbidding gadget with root  $v_3$ . Now to obtain a  $2^k$ -forbidding gadget  $\overrightarrow{F_{2^k}}$  assuming that a  $2^{k'}$ -forbidding gadget has been defined for every  $k' < k$  (with the exception that there is a  $(1, 2)$ -forbidding gadget rather than a 1-forbidding gadget and a 2-forbidding gadget), start from the arc  $\overrightarrow{w_1 w_2}$ , then add arcs from  $w_1$  towards  $k - 1$  new vertices so that  $w_1$  has outdegree  $k$ , and finally identify  $w_1$  and the roots of all the forbidding gadgets constructed in previous steps. Clearly,  $w_1$  can only have weighted outdegree  $2^k$  by every npd-2-arc-weighting of  $\overrightarrow{F_{2^k}}$ . Thus,  $\overrightarrow{F_{2^k}}$  is a  $2^k$ -forbidding gadget with root  $w_2$ . With these forbidding gadgets, our reduction scheme can then be directly adapted for the product version of the problem.

Another direction for extending our problem could be to consider undirected graphs.

**Question 2.** *What is the least  $k \in \{1, 2, 3\}$  such that every undirected graph admits an orientation which admits a nsd  $k$ -arc-weighting?*

Recall that an oriented graph admits a nsd 1-arc-weighting if and only if every two of its adjacent vertices have distinct outdegrees. According to a result from [4], the answer to Question 2 is 1. We give a reformulated proof of this statement using our terminology.

**Lemma 15.** *Every undirected graph  $G$  admits an orientation in which every two adjacent vertices have distinct outdegrees.*

*Proof.* We prove this result by induction on the order  $n$  of  $G$ . Since the result is true for  $n = 1$ , we assume the claim is true for every  $n$  up to  $i - 1$ , and now consider  $n = i$ . Let  $v$  be a vertex whose degree is maximum in



$G$ . According to the induction hypothesis, the graph  $G' = G - v$  admits an orientation  $\vec{G}'$  in which every two adjacent vertices have distinct outdegrees. Note that in  $\vec{G}'$ , the outdegree of every vertex in  $N(v)$  is at most  $d(v) - 1$  since  $v$  has maximum degree in  $G$ . Now start from  $\vec{G}'$ , and let  $\vec{G}$  be the orientation of  $G$  obtained by orienting all edges incident with  $v$  from  $v$  towards its neighbours. Since the outdegree of  $v$  in  $\vec{G}$  is then  $d(v)$ , and the outdegrees of all vertices neighbouring  $v$  are not altered, the orientation still satisfies the claim.  $\square$

**Corollary 16.** *Every undirected graph admits an orientation which admits a nsd 1-arc-weighting.*

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