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# On disjoint directed cycles with prescribed minimum lengths

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## On disjoint directed cycles with prescribed minimum lengths

Frédéric Havet<sup>\*†</sup>, A. Karolinna Maia<sup>\*‡§</sup>

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**Abstract:** In this paper, we show that the  $k$ -Linkage problem is polynomial-time solvable for digraphs with circumference at most 2. We also show that the directed cycles of length at least 3 have the Erdős-Pósa Property : for every  $n$ , there exists an integer  $t_n$  such that for every digraph  $D$ , either  $D$  contains  $n$  disjoint directed cycles of length at least 3, or there is a set  $T$  of  $t_n$  vertices that meets every directed cycle of length at least 3. From these two results, we deduce that if  $F$  is the disjoint union of directed cycles of length at most 3, then one can decide in polynomial time if a digraph contains a subdivision of  $F$ .

**Key-words:**  $k$ -linkage, circumference, disjoint directed cycles, subdivision.

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## **Cycles dirigés disjoints avec des longueurs minimales prescrites.**

**Résumé :** Dans ce rapport, nous montrons que le problème du  $k$ -linkage est résoluble en temps polynomial pour les digraphes de circonférence au plus 2. Nous montrons également que les cycles dirigés de longueur au moins 3 possède la Propriété d'Erdős-Pósa : pour tout  $n$ , il existe un entier  $t_n$  tel que pour tout digraphe  $D$ , soit  $D$  a  $n$  cycles dirigés disjoints de longueur au moins 3, soit il y a un ensemble  $T$  d'au plus  $t_n$  sommets qui intersecte tous les cycles dirigés de longueur au moins 3. De ces deux résultats, nous déduisons que si  $F$  est l'union disjointe de cycles dirigés de longueur au plus 3, alors on peut décider en temps polynomial si un digraphe contient une subdivision de  $F$ .

**Mots-clés :**  $k$ -linkage, circonférence, cycles dirigés disjoints, subdivision

## 1 Introduction

All digraphs considered in this paper are strict, that is they have no loops nor multiple arcs. We rely on [2] for classical notation and concepts.

Let  $D_1$  and  $D_2$  be two digraphs, the disjoint union of  $D_1$  and  $D_2$  is denoted by  $D_1 + D_2$ . For any digraph  $D$ , we set  $2D = D + D$  and for any integer  $n$  greater than 2,  $nD = (n - 1)D + D$ . In other words,  $nD$  is the disjoint union of  $n$  copies of  $D$ .

A digraph is *connected* if its underlying graph is connected. The *components* of a digraph are the (connected) components of its underlying graph. Hence, a digraph is the disjoint union of its components.

A *linkage*  $L$  in a digraph  $D$  is a subdigraph which is the disjoint union of directed paths. If  $L = P_1 + \dots + P_k$  and  $P_i$  is a directed  $(x_i, y_i)$ -path,  $1 \leq i \leq k$ , then we say that  $L$  is a *k-linkage from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$* . If  $X, Y \subseteq V(D)$  and  $\{x_1, \dots, x_k\} \subseteq X$  and  $\{y_1, \dots, y_k\} \subseteq Y$ , then we say that  $L$  is a *k-linkage from  $X$  to  $Y$* .

If  $P$  is a directed path, then its initial vertex is denoted by  $s(P)$  and its terminal vertex by  $t(P)$ .

### 1.1 Finding a subdivision of a digraph

A *subdivision of a digraph  $F$* , also called an *F-subdivision*, is a digraph obtained from  $F$  by replacing each arc  $ab$  of  $F$  by a directed  $(a, b)$ -path.

It is natural to consider the following decision problem.

**F-SUBDIVISION**

Input: A digraph  $D$ .

Question: Does  $D$  contain a subdivision of  $F$ ?

The analogue problem for undirected graphs can be solved in polynomial time for any undirected graph  $F$ . It follows from the Robertson and Seymour algorithm [11] that solves in polynomial time the undirected linkage problem, which is the following.

**UNDIRECTED  $k$ -LINKAGE**

Input: A graph  $G$  and  $2k$  distinct vertices  $x_1, \dots, x_k, y_1, \dots, y_k$ .

Question: Is there a  $k$ -linkage from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$  in  $G$ ?

However, for digraphs, Fortune, Hopcroft and Wyllie [4] showed that the following  $k$ -LINKAGE problem is NP-complete for all  $k \geq 2$ .

**$k$ -LINKAGE**

Input: A digraph  $D$  and  $2k$  distinct vertices  $x_1, \dots, x_k, y_1, \dots, y_k$ .

Question: Is there a  $k$ -linkage from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$  in  $D$ ?

Using reductions to this problem, Bang-Jensen et al. [1] found many digraphs  $F$  for which  $F$ -SUBDIVISION is NP-complete. It is in particular the case of every digraph in which every vertex  $v$  is *big* (that is such that either  $d^+(v) \geq 3$ , or  $d^-(v) \geq 3$ , or  $d^+(v) = d^-(v) = 2$ ). On the other hand, they gave polynomial-time algorithms to solve the problem for many others digraphs. This leads them to conjecturing that there is a sharp dichotomy between NP-complete and polynomial-time solvable instances. According to this conjecture, there are only two kinds of digraphs  $F$ : the *hard* ones, for which  $F$ -Subdivision is NP-complete, and the *tractable* ones, for which it is polynomial-time solvable. However there is no very clear picture of which graphs should be tractable and which ones should be hard, although some conjectures give some outline. Motivated by directed treewidth and a conjecture of Johnson et al. [7], Seymour (see [1]) posed the following conjecture.

**Conjecture 1** (Seymour). If  $F$  is a planar digraph with no big vertices, then  $F$ -SUBDIVISION is polynomial-time solvable.

Bang-Jensen et al. [1] proposed the following sort of counterpart conjecture.

**Conjecture 2** (Bang-Jensen et al. [1]).  $F$ -Subdivision is NP-complete for every non-planar digraph  $F$ .

As an evidence to Conjecture 1, Havet et al. [6] proved it when  $F$  has order at most 4. Bang-Jensen et al. [1] also proved that every directed cycle is tractable. In this paper, we are interested in the case when  $F$  is the disjoint union of directed cycles. Conjecture 1 restricted to this particular case is the following.

**Conjecture 3.** If  $F$  is a disjoint union of directed cycles, then  $F$ -SUBDIVISION is polynomial-time solvable.

Observe that if  $F$  is the disjoint union of  $n$  directed cycles of lengths  $\ell_1, \dots, \ell_n$ , then a subdivision of  $F$  is the disjoint union of  $n$  directed cycles  $C_1, \dots, C_n$ , each  $C_i$  being of length at least  $\ell_i$ . We denote the directed cycle of length  $\ell$ , or *directed  $\ell$ -cycle*, by  $\vec{C}_\ell$ . A directed cycle of length at least  $\ell$  is called *directed  $\ell^+$ -cycle*.

A particular case of Conjecture 3 is when all the directed cycles of  $F$  have the same length.

**Conjecture 4.** For any two positive integers  $n$  and  $\ell$  with  $\ell \geq 2$ ,  $n\vec{C}_\ell$ -SUBDIVISION is polynomial-time solvable.

In fact, we show in Subsection 2.1 that Conjectures 3 and 4 are equivalent.

An  $n\vec{C}_2$ -subdivision is the disjoint union of  $n$  directed cycles. Therefore Conjecture 4 for  $\ell = 2$  can be deduced (See Theorem 13) from the following two theorems.

**Theorem 5** (Fortune, Hopcroft and Wyllie [4]). *For each fixed  $k$ , the  $k$ -LINKAGE problem is polynomial-time solvable for acyclic digraphs.*

**Theorem 6** (Reed et al. [10]). *For every integer  $n \geq 0$ , there exists an integer  $t_n$  such that for every digraph  $D$ , either  $D$  has a  $n$  pairwise-disjoint directed cycles, or there exists a set  $T$  of at most  $t_n$  vertices such that  $D - T$  is acyclic.*

Theorem 6 is a directed analogue of the following theorem due to Erdős and Pósa.

**Theorem 7** (Erdős and Pósa [3]). *Let  $n$  be a positive integer. There exists  $t_n^*$  such that for every graph  $G$ , either  $G$  has  $n$  pairwise-disjoint cycles, or there exists a set  $T$  of at most  $t_n^*$  vertices such that  $G - T$  is acyclic.*

More precisely Erdős and Pósa [3] proved that there exist two absolute constants  $c_1$  and  $c_2$  such that  $c_1 \cdot n \log n \leq t_n^* \leq c_2 \cdot n \log n$ .

We believe that a similar approach may be used to prove Conjecture 4 for all  $\ell$ . We show in Section 2.2 that Conjecture 4 for some  $\ell$  is implied by the two following conjectures for the same  $\ell$ .

The *circumference* of a non-acyclic digraph  $D$ , denoted  $\text{circ}(D)$ , is the length of a longest directed cycle in  $D$ . If  $D$  is acyclic, then its *circumference* is defined by  $\text{circ}(D) = 1$ .

**Conjecture 8.** Let  $\ell \geq 2$  be an integer. For any positive integer  $k$ ,  $k$ -LINKAGE is polynomial-time solvable for digraphs with circumference at most  $\ell - 1$ ?

This conjecture already appears as a problem in [1].

**Conjecture 9.** Let  $\ell \geq 2$  be an integer. For every integer  $n \geq 0$ , there exists an integer  $t_n = t_n(\ell)$  such that for every digraph  $D$ , either  $D$  has a  $n$  pairwise-disjoint directed  $\ell^+$ -cycles, or there exists a set  $T$  of at most  $t_n$  vertices such that  $D - T$  is no directed  $\ell^+$ -cycles.

The main results of this paper (Theorems 14 and 16) prove both Conjecture 8 and Conjecture 9 for  $\ell = 3$ . By virtue of Theorem 13 they imply the following.

**Theorem 10.** *For any positive integer  $n$ ,  $n\vec{C}_3$ -SUBDIVISION is polynomial-time solvable.*

Combined with Lemma 12, this result in turn implies the following.

**Corollary 11.** *If  $F$  is the disjoint union of cycles of length at most 3, then  $F$ -SUBDIVISION is polynomial-time solvable.*

## 2 Reducing to Conjectures 8 and 9

For a digraph  $D$  and an integer  $\ell \geq 2$ , we denote by  $\nu_\ell(D)$  the maximum  $n$  such that  $D$  has  $n$  disjoint directed cycles of length at least  $\ell$ , and by  $\tau_\ell(D)$  the minimum  $t$  such that there exists  $T \subseteq V(D)$  with  $|T| = t$  meeting all directed cycles of length at least  $\ell$ . Evidently  $\nu_\ell(D) \leq \tau_\ell(D)$  and Conjecture 9 states that for every fixed  $\ell$  there exists a function  $f$  such that  $\tau_\ell(D) \leq f(\nu_\ell(D))$ .

### 2.1 Equivalence of Conjectures 3 and 4

Conjecture 4 is a particular case of Conjecture 3. We now show how Conjecture 3 can be deduced from Conjecture 4.

**Lemma 12.** *Let  $F$  be a disjoint union of  $n$  directed cycles, all of length at most  $\ell$ . If  $m\vec{C}_\ell$ -SUBDIVISION is polynomial-time solvable for all  $1 \leq m \leq n$ , then  $F$ -SUBDIVISION is also polynomial-time solvable.*

*Proof.* Let  $n$  be a positive integer. Assume that  $m\vec{C}_\ell$ -SUBDIVISION is polynomial-time solvable for any  $m \leq n$ .

Let  $F = \vec{C}_{\ell_1} + \dots + \vec{C}_{\ell_n}$  with  $\ell_1 \leq \dots \leq \ell_n \leq \ell$ . Any  $F$ -subdivision is a disjoint union of  $n$  directed cycles  $\vec{C}_{p_1} + \dots + \vec{C}_{p_n}$  with  $p_1 \leq \dots \leq p_n$  such that  $\ell_i \leq p_i$  for all  $1 \leq i \leq n$ . The *threshold* of such a subdivision is the largest integer  $t$  such that  $p_t < \ell$ .

For  $t = 0$  to  $n$ , we check whether there is an  $F$ -subdivision with threshold  $t$  with the following ‘brute force’ procedure. We enumerate all possible disjoint unions of directed cycles  $U = \vec{C}_{p_1} + \dots + \vec{C}_{p_t}$  with  $p_1 \leq \dots \leq p_t \leq \ell - 1$  and  $\ell_i \leq p_i$  for all  $1 \leq i \leq t$ . There are at most  $O(|V(D)|^{(t-1)(\ell-1)})$  such  $U$ . For each such  $U$ , we check if  $D - U$  contains an  $(n - t)\vec{C}_\ell$ -subdivision (whose union with  $U$  would be an  $F$ -subdivision with threshold  $t$ ). This can be done in polynomial time by the hypothesis.

The algorithm is a succession of (at most)  $n + 1$  polynomial-time procedures, so it runs in polynomial time.  $\square$

### 2.2 Conjectures 8 and 9 imply Conjecture 4

**Theorem 13.** *Let  $\ell \geq 1$  be an integer. If Conjectures 8 and 9 hold for  $\ell$ , then for every positive integer  $n$ ,  $n\vec{C}_\ell$ -SUBDIVISION is polynomial-time solvable.*

*Proof.* Let  $D$  be a digraph. Let  $t = t_n(\ell)$  with  $t_n(\ell)$  as in Conjecture 9. We first check if  $\tau_\ell(D) \leq t$ . This can be done by brute force, testing for each subset  $T$  of  $V(D)$  of size  $t$  whether it meets all directed  $\ell^+$ -cycles. Such a test can be done by checking whether  $D - T$  has circumference  $\ell - 1$ , that is, has no  $\vec{C}_\ell$ -subdivision. Since there are  $O(|V(D)|^t)$  sets of size  $t$ , and  $\vec{C}_\ell$ -SUBDIVISION is polynomial-time solvable, this can be done in polynomial time.

If no  $t$ -subset  $T$  meets all directed  $\ell^+$ -cycles, then  $\tau_\ell(D) > t$ . Therefore, because Conjecture 9 holds for  $\ell$ ,  $D$  contains an  $n\vec{C}_\ell$ -subdivision. So we return ‘yes’.

If we find a set  $T$  of size  $t$  that meets all directed  $\ell^+$ -cycles, then  $\text{circ}(D - T) \leq \ell - 1$ . We use another brute force algorithm which is based on traces.



A *trace* is either a directed  $\ell^+$ -cycle or a linkage. Observe that for any directed  $\ell^+$ -cycle  $C$  and any subset  $Z$  of  $V(D)$ , the intersection  $C \cap D[Z]$  is a trace. A trace contained in  $D[Z]$  is called a  $Z$ -*trace*.

Now every  $\ell^+$ -cycle intersects  $T$  in a non-empty trace because  $\text{circ}(D - T) \leq \ell - 1$ . We describe a polynomial-time procedure that, given a set of  $n$  pairwise disjoint traces  $T_1, \dots, T_n$ , checks whether there is an  $n\vec{C}_\ell$ -subdivision  $C_1 + \dots + C_n$  such that  $T_i = C_i \cap D[T]$  for all  $1 \leq i \leq n$ . Now since  $T$  has size  $t$ , there is a bounded number of possible sets of  $n$  pairwise disjoint traces  $T$ -traces (at most  $\binom{t}{n+1}(B_t + 1)$ , where  $B_t$  is the number of partitions of a set of size  $t$ ). Hence running the above procedure for all possible such set of  $T$ -traces, we obtain a polynomial-time algorithm that decides whether  $D$  contains an  $n\vec{C}_\ell$ -subdivision.

Let  $\mathcal{T} = \{T_1, \dots, T_n\}$  be a set of  $n$  pairwise disjoint  $T$ -traces. Set  $\bar{T} = V(D) \setminus T$ . A *trace* is *suitable* if it has at least  $\ell$  vertices, at most  $t$  components, and the initial and terminal vertices of all components are in  $\bar{T}$ .

For each  $T_i$ , we shall describe a set  $\mathcal{T}_i$  of suitable traces such that a directed  $\ell^+$ -cycle  $C$  such that  $C \cap T = T_i$  contains at least one trace in  $\mathcal{T}_i$ . The set  $\mathcal{T}_i$  is constructed as follows. Let  $\mathcal{U}_i$  be the set of traces that can be obtained from  $T_i$  by extending each components  $P$  of  $T_i$  at both ends by an inneighbour of  $s(P)$  and an outneighbour of  $t(P)$  in  $\bar{T}$ . Clearly,  $\mathcal{U}_i$  has size at most  $|V(D)|^2 k$ , where  $k$  is the number of components of  $T_i$ . By construction, each trace of  $\mathcal{U}_i$  has its initial and terminal vertices in  $\bar{T}$  and has no more components than  $T_i$ . Moreover, a directed  $\ell^+$ -cycle  $C$  such that  $C \cap T = T_i$  contains one trace in  $\mathcal{U}_i$ . However, the set  $\mathcal{U}_i$  might not be our set  $\mathcal{T}_i$  because certain traces in it might be too small.

For any trace  $U$ , let  $g(U)$  be set set of all possible traces obtained from  $U$  by adding one vertex of  $\bar{T}$  has outneighbour of a terminal vertex of one component of  $U$ . Clearly,  $g(U)$  has size at most  $k|V(D)|$ , where  $k$  is the number of components of  $U$ , and a directed  $\ell^+$ -cycle  $C$  containing  $U$  must contains a trace in  $g(U)$ . Moreover, every trace of  $g(U)$  has size  $|V(U)| + 1$ , and no more components than  $U$ . Set  $g^i(U) = \{U\}$  if  $i$  is a non-positive integer and for all positive integer  $i$ , define  $g^i(U) = \bigcup_{U' \in g^{i-1}(U)} g(U')$ . Now the set  $\bigcup_{U \in \mathcal{U}_i} g^{\ell - |V(U)|}(U)$  is our desired  $\mathcal{T}_i$ . Moreover,  $\mathcal{T}_i$  is of size at most  $t^t \cdot |V(D)|^t$ .

To have a polynomial-time procedure to decide whether there is an  $n\vec{C}_\ell$ -subdivision  $C_1 + \dots + C_n$  such that  $T_i = C_i \cap T$  for all  $1 \leq i \leq n$ , it suffices to have a procedure that, given an  $n$ -tuple  $(T'_1, \dots, T'_n)$  of disjoint traces such that  $T'_i \in \mathcal{T}_i$ , decides whether there is an  $n\vec{C}_\ell$ -subdivision  $C_1 + \dots + C_n$  such that  $T'_i$  is a subdigraph of  $C_i$  for all  $1 \leq i \leq n$ , and to run it on each possible such  $n$ -tuple. Such a procedure can be done as follows. Let  $P_1^i, \dots, P_{k_i}^i$  be the components of  $T'_i$ . For each  $n$ -tuple of circular permutations  $(\sigma_1, \dots, \sigma_n)$  of  $\mathfrak{S}_{k_1} \times \dots \times \mathfrak{S}_{k_n}$ , one checks whether in the digraph  $D'$  induced by the vertices of  $\bar{T}$  which are not internal vertices of any of the components of the union of the  $T'_i$ , if there is a linkage from

$$(s(P_1^1), \dots, s(P_{k_1}^1), s(P_1^2), \dots, s(P_{k_2}^2), \dots, s(P_1^n), \dots, s(P_{k_n}^n))$$

to

$$(t(P_{\sigma_1(1)}^1), \dots, t(P_{\sigma_1(k_1)}^1), t(P_{\sigma_2(1)}^2), \dots, t(P_{\sigma_2(k_2)}^2), \dots, t(P_{\sigma_n(1)}^n), \dots, t(P_{\sigma_n(k_n)}^n)).$$

Now the digraph  $D'$  is a subdigraph of  $D - T$  and so has circumference at most  $\ell - 1$ , and the linkage we are looking for has at most  $t$  components. Thus each of these instances of  $(k_1 + \dots + k_n)$ -LINKAGE can be solved in time  $O(|V(D)|^m)$  for some absolute constant  $m$  because Conjecture 8 holds for  $\ell$ .  $\square$

### 3 Linkage in digraphs with circumference at most 2

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

**Theorem 14.** *For each fixed  $k$ , the  $k$ -LINKAGE problem is polynomial-time solvable for digraphs with circumference at most 2.*

We first prove the following lemma.

**Lemma 15.** *Let  $\mathcal{D}$  be a class of digraphs and  $\mathcal{S}$  be the class of strong digraphs. If  $k'$ -LINKAGE is polynomial-time solvable on  $\mathcal{D} \cap \mathcal{S}$  for any  $k' \leq k$ , then  $k$ -LINKAGE is polynomial-time solvable on  $\mathcal{D}$ .*

*Proof.* Let  $D$  be a digraph in  $\mathcal{D}$ . Let  $\sim$  be the relation defined on  $V(D)$  by  $u \sim v$  if and only if  $u$  and  $v$  are in the same strong component. It is clearly an equivalence relation on  $V(D)$  with equivalence classes the strong components of  $D$ . Let  $D/\sim$  be the quotient of  $D$  by  $\sim$ , that is the digraph whose vertices are the strong components of  $D$ , and in which there is an arc from a strong component  $S$  to another  $S'$  if and only if there is an arc of  $D$  with tail in  $S$  and head in  $S'$ . One can also see  $D/\sim$  as the digraph obtained by contracting each strong component into a vertex. It is well-known that  $D/\sim$  is an acyclic digraph, therefore there is an ordering  $S_1, \dots, S_p$  of the strong components such that there is no arc  $S_j S_{j'}$  in  $D/\sim$  with  $j > j'$ . This implies that for every  $j > j'$ , there is no directed  $(x, y)$ -path in  $D$  with  $x \in S_j$  and  $y \in S_{j'}$ . Let  $\tilde{D}$  be the digraph  $D \setminus \bigcup_{j=1}^p A(S_j)$ , the digraph whose arcs are those between non-equivalent vertices with respect to  $\sim$ .

Form a new digraph  $\mathbf{D}$  whose vertices are the  $k$ -tuples  $\mathbf{v} = (v_1, \dots, v_k)$  of distinct vertices of  $D$ . For any such  $k$ -tuple  $\mathbf{v}$ , there is a minimum index  $m$  such that  $S_m$  intersects  $\{v_1, \dots, v_k\}$ . Let  $I = \{i \mid v_i \in S_m\}$ . Set  $I = \{i_1, \dots, i_{k'}\}$  with  $i_1 < i_2 < \dots < i_{k'}$ .

For each  $k'$ -tuple  $(w_1, w_2, \dots, w_{k'})$  of distinct vertices of  $V(D) \setminus \{v_1, v_2, \dots, v_k\}$  such that there exists a  $k'$ -tuple  $(u_1, u_2, \dots, u_{k'})$  of vertices in  $V(S_m)$  such that there is a linkage from  $(v_{i_1}, v_{i_2}, \dots, v_{i_{k'}})$  to  $(u_1, u_2, \dots, u_{k'})$  in  $S_m$  and  $u_j w_j$  is an arc in  $\tilde{D}$  for all  $1 \leq j \leq k'$ , we put an arc from  $\mathbf{v}$  to the  $k$ -tuple obtained from it by replacing  $v_i$  by  $w_i$  for all  $i \in I$ . We say that such an arc in  $\mathbf{D}$  is labelled by  $S_m$ .

Observe that there are  $O(n^{k'})$   $k'$ -tuples  $(u_1, u_2, \dots, u_{k'})$  of  $V(S_m)$ , and for each of them one can decide in polynomial time whether there is a linkage from  $(v_{i_1}, v_{i_2}, \dots, v_{i_{k'}})$  to  $(u_1, u_2, \dots, u_{k'})$  because  $k'$ -LINKAGE is polynomial-time solvable on  $\mathcal{D}$  by hypothesis. Hence in polynomial time, we can construct the digraph  $\mathbf{D}$  which has polynomial size.

We now prove that for any two sets of  $k$  distinct vertices  $\{x_1, \dots, x_k\}$  and  $\{y_1, \dots, y_k\}$ , there is a  $k$ -linkage from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$  if and only if there is a directed path from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$  in  $\mathbf{D}$ .

Suppose first that there is a  $k$ -linkage  $(P_1, \dots, P_k)$  from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$ . Since, when  $j > j'$ , there are no directed  $(x, y)$ -paths in  $D$  with  $x \in S_j$  and  $y \in S_{j'}$ , each  $P_i$  goes through the strong components  $S_1, \dots, S_p$  in that order, possibly avoiding some. For each  $1 \leq m \leq p$  and each  $1 \leq i \leq k$ , let  $v_i(m)$  the first vertex in  $\bigcup_{j=m}^p S_j$  along  $P_i$  if  $\bigcup_{j=m}^p S_j$  and  $P_i$  intersect, and  $v_i(m) = y_i$  otherwise.

Let  $M = \{m_1, \dots, m_r\}$  with  $m_1 \leq m_2 \leq \dots \leq m_r$ , be the set of indices  $m$  such that  $S_m \cap \bigcup_{i=1}^k P_i \neq \emptyset$ . By definition of  $\mathbf{D}$ ,  $\mathbf{v}(m_q)\mathbf{v}(m_{q+1})$  is an arc in  $\mathbf{D}$ . Thus  $\mathbf{v}(m_1)\mathbf{v}(m_2)\dots\mathbf{v}(m_r)$  is a directed path from  $(x_1, x_2, \dots, x_k)$  to  $(y_1, y_2, \dots, y_k)$  in  $\mathbf{D}$ .

Suppose now that  $\mathbf{D}$  has a directed path  $\mathbf{Q}$  from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$  in  $\mathbf{D}$ . We construct directed walks  $P_i$ ,  $1 \leq i \leq k$ , by the following procedure. At the beginning  $P_i = (x_i)$  for all  $1 \leq i \leq k$ . For each arc  $\mathbf{a} = \mathbf{vw}$  of  $\mathbf{Q}$  one after another from the initial vertex to the terminal vertex of  $\mathbf{Q}$ , we do the following.

Let  $I = \{i_1, \dots, i_{k'}\}$  be set of indices  $i$  such that  $v_i \neq w_i$ . By definition of  $\mathbf{D}$ , there is a strong component  $S$  of  $D$ , a  $k'$ -tuple  $(u_1, \dots, u_{k'})$  of disjoint vertices of  $S$ , and such that there is a linkage  $(R_1, \dots, R_{k'})$  from  $(v_{i_1}, v_{i_2}, \dots, v_{i_{k'}})$  to  $(u_1, u_2, \dots, u_{k'})$  in  $S$  and  $u_j w_j \in A(\tilde{D})$  for all  $1 \leq j \leq k'$ . In that case, we extend each  $P_{i_j}$ ,  $1 \leq j \leq r$ , by appending  $R_j u_j w_j$  at the end of it. Observe that  $R_j$  might be a path reduced to the single vertex  $v_{i_j} = u_j$ .

Observe that in  $\mathbf{D}$  an arc labelled by a strong component  $S_m$  enters a  $k$ -tuple of vertices that all belong to components  $S_j$  with  $j > m$ . In particular,  $\mathbf{Q}$  contains at most one arc labelled with any strong component  $S_m$ . This implies that each  $P_i$  is a directed  $(x_i, y_i)$ -path. Combined with the fact that each  $(R_1, \dots, R_{k'})$  as defined above is a linkage, it implies that the  $P_i$  are disjoint.  $\square$

We can easily derive Theorem 14 from Lemma 15.

*Proof of Theorem 14.* Let  $\mathcal{C}_2$  be the class of digraphs with circumference at most 2. A strong digraph  $D$  in  $\mathcal{C}_2$  is obtained from a tree  $T$  by replacing every edge by a directed 2-cycle. Hence there is a  $k$ -linkage from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$  in  $D$  if and only if there is a  $k$ -linkage from  $(x_1, \dots, x_k)$  to  $(y_1, \dots, y_k)$  in  $T$ . Since UNDIRECTED  $k$ -LINKAGE is polynomial-time solvable, it follows that  $k$ -LINKAGE is polynomial-time solvable on  $\mathcal{C}_2 \cap \mathcal{S}$ . Thus, by Lemma 15, it is polynomial-time solvable on  $\mathcal{C}_2$ .  $\square$

## 4 Packing directed $3^+$ -cycles

The aim of this section is to prove by induction on  $n$  the following theorem.

**Theorem 16.** *For every integer  $n \geq 0$ , there exists an integer  $t_n$  such that for every digraph  $D$ , either  $\nu_3(D) \geq n$  or  $\tau_3(D) \leq t_n$ .*

Our proof follows the same approach as the one used by Reed et al. [10] to prove Theorem 6. A key ingredient in their proof is that if  $P$  is a directed  $(a, b)$ -path and  $Q$  is a directed  $(b, a)$ -path, then  $P \cup Q$  contains a directed cycle. However, in such a case,  $P \cup Q$  does not necessarily contain a  $3^+$ -cycle. However,  $P \cup Q$  does not contain a  $3^+$ -cycle if and only if  $Q$  is the converse of  $P$ . The *converse* of a directed path  $P = (x_1, \dots, x_m)$  is the directed path  $(x_m, \dots, x_1)$ .

**Lemma 17.** *Let  $a$  and  $b$  two distinct vertices, and let  $P$  be a directed  $(a, b)$ -path and  $Q$  be a directed  $(b, a)$ -path. Then  $P \cup Q$  contains a directed  $3^+$ -cycle if and only if  $Q$  is not the converse of  $P$ .*

*Proof.* Clearly, if  $Q$  is the converse of  $P$ , then  $P \cup Q$  contains no directed  $3^+$ -cycle.

Conversely, we prove by induction on the length  $m$  of  $P$  that if  $Q$  is not the converse of  $P$ , then  $P \cup Q$  contains a directed  $3^+$ -cycle. It holds trivially if  $m = 1$ . So we may assume that  $m \geq 1$ . Let  $P = (x_0, x_1, \dots, x_m)$ . Let  $y$  be the penultimate vertex of  $Q$ . If  $y = x_1$ , then  $Q - x_0$  is not the converse of  $P - x_0$ . Hence, by the induction hypothesis, there is a directed  $3^+$ -cycle in  $(P - x_0) \cup (Q - x_0)$ , and so in  $P \cup Q$ . Assume now that  $y \neq x_1$ , then let  $z$  be the penultimate vertex in  $V(P \cap Q)$  along  $Q$ . If  $z = x_1$ , then  $Q[x_1, x_0]$  has length at least 2, and so  $(x_0, x_1) \cup Q[x_1, x_0]$  is a directed  $3^+$ -cycle on  $P \cup Q$ . If  $z \neq x_1$ , then  $P[x_0, z] \cup Q[z, x_0]$  is a directed  $3^+$ -cycle on  $P \cup Q$ .  $\square$

In the proof we will have to make sure that some directed paths are not converse of some others. We follow the lines of the proof of Reed et al. [10] in order to emphasize the extra work required to deal with directed  $3^+$ -cycle.

### 4.1 Main proof

First replacing ‘directed cycle’ by ‘directed  $3^+$ -cycle’ in the proof of Theorem (2.2) of [10], we obtain the following analogue of (2.2) of [10].

**Lemma 18.** *Let  $n \geq 1$  be an integer such that  $t_{n-1}$  exists, and let  $k$  be an integer. Then there exists an integer  $t'(k)$  such that the following holds. Let  $D$  be a digraph with  $\nu_3(D) < n$ , and  $\tau_3(D) \geq 2t'(k)$ , and let  $T$  be a set of size  $\tau_3(D)$  such that  $D - T$  has no directed  $3^+$ -cycles. For any disjoint subsets  $A, B \subseteq T$  with  $|A| = |B| = k$ , there are distinct vertices  $a_1, \dots, a_k$  in  $A$  and distinct vertices  $b_1, \dots, b_k$  in  $B$ , and two  $k$ -linkages  $L_1, L_2$  of  $D$ , so that*

- (i)  $L_1$  links  $(a_1, \dots, a_k)$  to  $(b_1, \dots, b_k)$ ,
- (ii)  $L_2$  links  $(b_1, \dots, b_k)$  to one of  $(a_1, \dots, a_k)$ ,  $(a_k, \dots, a_1)$ ,

(iii) every directed  $3^+$ -cycle of  $L_1 \cup L_2$  meets  $\{a_1, \dots, a_k, b_1, \dots, b_k\}$ .

However, for our purpose we need an extra condition on the two linkages  $L_1$  and  $L_2$ . This is in fact why we needed a stronger statement than Lemma 18.

**Lemma 19.** *Let  $n \geq 1$  be an integer such that  $t_{n-1}$  exists, and let  $k$  be an even integer. Then there exists an integer  $t(k)$  such that the following holds. Let  $D$  be a digraph with  $v_3(D) < n$ , and  $\tau_3(D) \geq t(k)$ , and let  $T$  be a set of size  $\tau_3(D)$  such that  $D - T$  has no directed  $3^+$ -cycles. Then there are distinct vertices  $a_1, \dots, a_k, b_1, \dots, b_k$  in  $T$ , and two  $k$ -linkages  $L_1, L_2$  of  $D$  so that*

- (i)  $L_1$  links  $(a_1, \dots, a_k)$  to  $(b_1, \dots, b_k)$ ,
- (ii)  $L_2$  links  $(b_1, \dots, b_k)$  to one of  $(a_1, \dots, a_k), (a_k, \dots, a_1)$ ,
- (iii) every directed  $3^+$ -cycle of  $L_1 \cup L_2$  meets  $\{a_1, \dots, a_k, b_1, \dots, b_k\}$ ,
- (iv) no component of  $L_1$  is the converse of a component of  $L_2$ .

To prove this lemma, we will need Erdős-Pósa Theorem (Theorem 7) and the following lemma.

**Lemma 20.** *Let  $r$  be a positive integer. Let  $T$  be a tree and  $S$  a set of at least  $3r - 2$  vertices of  $T$ . Then there exists a vertex  $x$  of  $T$  and two subsets  $A$  and  $B$  of  $S$ , both of size  $r$  such that every  $(A, B)$ -path in  $T$  goes through  $x$ .*

*Proof.* Let  $E_r$  be the set of edges  $e$  such that both components of  $T \setminus e$  have at least  $r$  vertices of  $S$ . We divide the proof in two cases depending on whether or not  $E_r$  is empty.

Assume first that  $E_r \neq \emptyset$ . Let  $e = xy$  be an edge of  $E_r$ , and let  $T_x$  be the component of  $T \setminus e$  containing  $x$  and  $T_y$  containing  $y$ . Both  $T_x$  and  $T_y$  contain at least  $r$  vertices of  $S$ . Let  $A$  (resp.  $B$ ) be a set of  $r$  vertices of  $S \cap V(T_x)$  (resp.  $S \cap V(T_y)$ ). Then every  $(A, B)$ -path in  $T$  goes through  $e$  and so through  $x$ .

Assume now that  $E_r = \emptyset$ .

**Claim 20.1.** *There exists a vertex  $x$  such that all components of  $T - x$  have less than  $r$  vertices of  $S$ .*

*Subproof.* Let us orient the edges of  $T$  as follows. Let  $e = uv$  be an edge of  $T$ . Since  $e \notin E_r$  is empty, exactly one component of  $T \setminus e$  contains less than  $r$  vertices of  $S$ . Without loss of generality, this component is the one containing  $v$ . Orient the edge  $e$  from  $u$  to  $v$ . Now every orientation of a tree contains a vertex  $x$  with outdegree 0. Consider a component  $C$  of  $T - x$ . It contains exactly one neighbour  $y$  of  $x$ , and it is precisely the component of  $T \setminus xy$  containing  $y$ . Thus  $|C \cap S| < r$  because the edge is oriented from  $x$  to  $y$ . Hence all components of  $T - x$  have less than  $r$  vertices.  $\diamond$

Take a vertex  $x$  as in the above claim. Let  $C_1, \dots, C_m$  be the components of  $T - x$ . Then  $|C_j| \leq r - 1$  for all  $1 \leq j \leq m$ . Let  $i$  be the smallest integer such that  $T_i = \bigcup_{j=1}^i C_j$  contains at least  $r$  vertices of  $S$ . Clearly,  $T_i$  contains at most  $2r - 2$  vertices in  $S$ , and thus there are at least  $r$  vertices in  $T - T_i$ . Let  $A$  (resp.  $B$ ) be a set of  $r$  vertices in  $T_i$  (resp.  $T - T_i$ ). Then  $x$  is in every  $(A, B)$ -path.  $\square$

**Remark 21.** The bound  $3r - 2$  in the above lemma is tight. Indeed consider a tree  $T$  with a set  $S$  of  $3r - 3$  leaves and four other vertices  $x, y_1, y_2$  and  $y_3$  such that for every  $i \in \{1, 2, 3\}$ ,  $y_i$  is adjacent to  $x$  and  $r - 1$  leaves. One can check that for every vertex  $x$  and two sets  $A$  and  $B$  of  $r$  leaves there is an  $(A, B)$ -path avoiding  $x$ .

*Proof of Lemma 19.* Let  $t_n^*$  be as in Erdős-Pósa Theorem (Theorem 7); let  $r = k + 2t_n^* + 2$ ; let  $t(k) = \max\{3r - 2 + t_n^*, 2t'(r)\}$ , let where  $t'$  is as in Lemma 18. We claim that  $t(k)$  satisfies the lemma.

Let  $G_2$  be the undirected graph with vertex set  $V(D)$  in which two vertices  $x$  and  $y$  are adjacent if and only if  $D[\{x, y\}]$  is a directed 2-cycle. To each cycle in  $G_2$  correspond two directed cycles in  $D$ , one in each direction. Thus  $G_2$  has less than  $n$  disjoint cycles. Hence by Erdős-Pósa Theorem, there is a set  $U \subset V(D)$  of size  $t_n^*$  such that  $G_2 - U$  is acyclic.

Choose  $T \subseteq V(D)$  with  $|T| = \tau_3(D)$ , meeting all directed  $3^+$ -cycles of  $D$ . Since  $t(k) \geq 3r - 2 + t_n^*$ , there is a set  $S$  of size  $3r - 2$  in  $T \setminus U$ . Since  $G_2 - U$  is acyclic, we can extend it into a tree  $T_2$ . Hence, by Lemma 20, there exists a vertex  $x$  in  $V(T_2)$  and two sets  $A$  and  $B$  in  $S$  of size  $r$  such that every  $(A, B)$ -path in  $T_2$  goes through  $x$ . Since  $G_2 - U$  is a subgraph of  $T_2$ , every  $(A, B)$ -path in  $G_2 - U$  goes through  $x$ .

Since  $|T| \geq 2t'(r)$ , by Lemma 18, there are distinct vertices  $a_1, \dots, a_{k'}$  in  $A$  and distinct vertices  $b_1, \dots, b_{k'}$  in  $B$ , and two  $k'$ -linkages  $L'_1, L'_2$  of  $D$  so that

- (i)  $L'_1$  links  $(a'_1, \dots, a'_{k'})$  to  $(b'_1, \dots, b'_{k'})$ ,
- (ii)  $L'_2$  links  $(b'_1, \dots, b'_{k'})$  to one of  $(a'_1, \dots, a'_{k'})$ ,  $(a'_{k'}, \dots, a'_1)$ ,
- (iii) every directed  $3^+$ -cycle of  $L'_1 \cup L'_2$  meets  $\{a'_1, \dots, a'_{k'}, b'_1, \dots, b'_{k'}\}$ .

For  $1 \leq i \leq k'$ , let  $P_i$  be the component of  $L_1$  with initial vertex  $a'_i$  and  $Q_i$  the component of  $L_2$  with initial vertex  $b'_i$ .

Clearly, if  $L'_2$  links  $(b'_1, \dots, b'_{k'})$  to  $(a'_{k'}, \dots, a'_1)$ , then condition (iv) is also verified by  $L'_1$  and  $L'_2$ , because  $k'$  is even as  $k$  is even. For  $1 \leq i \leq k$ , set  $a_i = a'_{i+(k'-k)/2}$  and  $b_i = b'_{i+(k'-k)/2}$ , and let  $L_1 = \{P_j \mid 1 + k'/2 - k/2 \leq j \leq k'/2 + k/2\}$  and  $L_2 = \{Q_j \mid 1 + k'/2 - k/2 \leq j \leq k'/2 + k/2\}$ . Then  $a_1, \dots, a_k, b_1, \dots, b_k$ ,  $L_1$  and  $L_2$  satisfy the lemma.

Assume now that  $L'_2$  links  $(b'_1, \dots, b'_{k'})$  to one of  $(a'_1, \dots, a'_{k'})$ . At most  $t_n^*$  of the  $P_i$  intersect  $U$  and at most  $t_n^*$  of the  $Q_i$  intersect  $U$ . Thus, since  $k' \geq k + 2t_n^* + 1$ , there are at least  $k + 1$  indices  $i$  such that both  $P_i$  and  $Q_i$  do not intersect  $U$ . Without loss of generality, we may assume that these indices are  $\{1, \dots, k + 1\}$ . Now for  $1 \leq i \leq k + 1$ , if  $P_i$  is the converse of  $Q_i$ , then  $P_i$  is also a path in  $G_2 - U$  and thus it must go through  $x$ . Hence there is at most one index  $i$ , say  $k + 1$ , such that  $P_i$  is the converse of  $Q_i$ . Hence  $a_1, \dots, a_k, b_1, \dots, b_k$ ,  $L_1$  and  $L_2$  satisfy the lemma.  $\square$

We say a digraph is *divalent* if every vertex has indegree 2 and outdegree 2, or indegree 1 and outdegree 1. In Subsection 4.2 we shall prove the following lemma which is the analogue of Lemma (2.3) of [10].

A pair  $\{L_1, L_2\}$  of linkages is *fully intersecting* if each component of  $L_1$  meets each component of  $L_2$ , and it is *acyclic* if  $L_1 \cup L_2$  has no directed cycles,

**Lemma 22.** *For every positive integer  $n$ , there exists a positive integer  $k_1$  such that for every divalent digraph  $D$ , if there is a fully intersecting and acyclic pair of  $k_1$ -linkages in  $D$  then  $\nu_3(D) \geq n$ .*

Lemma 22 is proved in Subsection 4.2. We assume it for the moment. We will show how to combine it with Lemma 19 to prove Theorem 16. First we prove the following lemma, which is the analogue of Lemma (2.4) of [10].

**Lemma 23.** *For every non-negative integer  $n$ , there exists a positive integer  $k$  so that the following holds. Let  $D$  be a digraph, and let  $a_1, \dots, a_k, b_1, \dots, b_k$  be distinct vertices of  $D$ . Let  $L_1, L_2$  be linkages in  $D$  linking  $(a_1, \dots, a_k)$  to  $(b_1, \dots, b_k)$ , and  $(b_1, \dots, b_k)$  to one of  $(a_1, \dots, a_k)$ ,  $(a_k, \dots, a_1)$ , respectively, such that no component of  $L_2$  is the converse of  $L_1$ . Let every directed  $3^+$ -cycle of  $L_1 \cup L_2$  meet  $\{a_1, \dots, a_k, b_1, \dots, b_k\}$ . Then  $\nu_3(D) \geq n$ .*

The proof of this lemma is similar to the one of Lemma (2.4) of [10]. However, some extra technical details are required. When reducing to a divalent digraph, we also have to get rid of directed 2-cycles, and Claim 24.1 is now required.

As in [10], we shall also need Ramsey's theorem [9], which can be stated as follows.

**Theorem 24** (Ramsey [9]). *For all positive integers  $q, l, r$ , there exists a (minimum) integer  $R_l(r; q)$  so that the following holds. Let  $Z$  be a set with  $|Z| \geq R_l(r; q)$ , let  $Q$  be a set with  $|Q| = q$ , and for each  $X \subset Z$  with  $|X| = l$  let  $f(X) \in Q$ . Then there exists  $S \subseteq Z$  with  $|S| = r$  and there exists  $x \in Q$  so that  $f(X) = x$  for all  $X \subseteq S$  with  $|X| = l$ .*

*Proof of Lemma 23, assuming Lemma 22.* Let  $n \geq 1$ . Let  $k' = \max\{k_1, \lceil n/4 \rceil\}$  with  $k_1$  as in Lemma 22. Let  $k = 2R_2(4k'; 9)$  defined as in Theorem 24. We claim that  $n$  and  $k$  satisfy Lemma 23.

For let  $a_1, \dots, a_k, b_1, \dots, b_k, L_1, L_2$  be as in the statement of Lemma 23.

Let  $G_i = P_i \cup P_{k+1-i} \cup Q_i \cup Q_{k+1-i}$ .

We show by induction on  $|E(D)| + |V(D)|$  that  $v_3(D) \geq n$ . If  $L_1 \cup L_2 \neq D$ , then the result follows immediately by induction, so we may assume that  $L_1 \cup L_2 = D$ .

Assume that either the arc  $e = uv$  belongs to  $P_i \cap Q_j$ , or the arc  $uv$  is in  $P_i$  and the arc  $vu$  is in  $Q_j$ , then consider the graph  $D'$  and the two linkages  $L'_1$  and  $L'_2$  obtained by contracting  $uv$ . These two linkages clearly satisfy the hypothesis of Lemma 23 since directed cycles can only be shorten while contracting.

We therefore may assume that every arc of  $D$  belongs to exactly one of  $L_1, L_2$ , and that  $D$  has no directed 2-cycles. In particular,  $D$  is divalent and every directed cycle of  $D$  meets  $\{a_1, \dots, a_k, b_1, \dots, b_k\}$ .

For  $1 \leq i \leq k$ , let  $P_i$  be the component of  $L_1$  with initial vertex  $a_i$ , and let  $Q_i$  be the component of  $L_2$  with initial vertex  $b_i$ .

For  $1 \leq h < i \leq k/2$ , define  $f(\{h, i\})$  as follows. If  $G_i$  and  $G_h$  are disjoint, let  $f(\{h, i\}) = 0$ . Otherwise, at least one of the eight digraphs  $P_i \cap Q_h, P_{k+1-i} \cap Q_h, P_i \cap Q_{k+1-h}, P_{k+1-i} \cap Q_{k+1-h}, Q_i \cap P_h, Q_{k+1-i} \cap P_h, Q_i \cap P_{k+1-h}, Q_{k+1-i} \cap P_{k+1-h}$  is non-null. Number them  $1, \dots, 8$  in order; we define  $f(\{h, i\}) \in \{0, 1, \dots, 8\}$ .

Since  $k = 2R_2(4k'; 9)$ , by Theorem 24, there exists  $S \subseteq \{1, \dots, \frac{1}{2}k\}$  with  $|S| = 4k'$  and  $x$  with  $0 \leq x \leq 8$  such that  $f(\{h, i\}) = x$  for all  $h, i \in S$  with  $h < i$ .

If  $x = 0$ , then the subdigraphs  $G_i$  are pairwise disjoint for all  $i \in S$ . But as we shall prove in Claim 24.1, each  $G_i$  contains a directed  $3^+$ -cycle, and so  $v_3(D) \geq |S| = 4k' \geq n$ .

**Claim 24.1.** *Each  $G_i$  contains a directed  $3^+$ -cycle.*

*Subproof.* If  $Q_i$  is a directed  $(b_i, a_i)$ -path, then by assumption  $Q_i$  is not the converse of  $P_i$ . Thus by Lemma 17  $P_i \cup Q_i$  contains a directed  $3^+$ -cycle, and so  $G_i$  also does.

Assume now that  $Q_i$  is a directed  $(b_i, a_{k+1-i})$ -path, and so  $Q_{k+1-i}$  is a directed  $(b_{k+1-i}, a_i)$ -path.  $Q_i$  contains a directed path  $R_1$  with initial vertex  $u_1$  in  $P_i$  and terminal vertex  $v_1$  in  $P_{k+1-i}$  whose internal vertices are not in  $P_i \cup P_{k+1-i}$ . Now  $Q_{k+1-i}$  contains a directed path  $R_2$  with initial vertex  $u_2$  in  $P_{k+1-i}[v_1, b_{k+1-i}]$  and terminal vertex  $v_2$  in  $P_i[a_1, u_1]$  whose internal vertices are not in  $P_i \cup P_{k+1-i}$ . Observe that  $u_1, u_2, v_1$  and  $v_2$  are all distinct because  $P_i$  and  $P_{k+1-i}$  are disjoint and  $Q_i$  and  $Q_{k+1-i}$  are disjoint. Hence the  $R_1 \cup P_{k+1-i}[v_1, u_2] \cup R_2 \cup P_i[v_2, u_1]$  is a directed  $4^+$ -cycle in  $G_i$ .  $\diamond$

Assume now that  $x = 1$ . Let  $S = I \cup J$ , where  $|I| = k'$ ,  $|J| = 3k'$  and  $i < j$  for all  $i \in I$  and  $j \in J$ . Then for all  $i \in I$  and all  $j \in J$ ,  $P_i$  meets  $Q_j$ . There are  $2k'$  vertices that are endvertices of paths  $P_i, i \in I$ , an each of them is an endvertex of at most one  $Q_j, j \in J$ . Since  $|J| \geq 3k'$ , there exists  $J' \subset J$  with  $|J'| = k'$  so that  $P_i$  and  $Q_j$  have no common endvertex for  $i \in I$  and  $j \in J'$ . Let  $L'_1$  be the union of the components  $P_i, i \in I$  and  $L'_2$  be the union of the components  $Q_j, j \in J'$ . Now every directed cycle in  $L'_1 \cup L'_2$  meets  $\{a_1, \dots, a_k, b_1, \dots, b_k\}$ , and each of  $a_1, \dots, a_k, b_1, \dots, b_k$  is incident with at most one arc of  $L'_1 \cup L'_2$  since  $P_i$  and  $Q_j$  have no common endvertex for  $i \in I$  and  $j \in J'$ . Hence  $L'_1 \cup L'_2$  has no directed cycles. We thus have the result by Lemma 22.

The cases  $2 \leq x \leq 8$  are similar to the case  $x = 1$ .  $\square$

*Proof of Theorem 16, assuming Lemma 22.* We prove Theorem 16 by induction on  $n$ ; we therefore assume that  $n \geq 1$  and  $t_{n-1}$  exists, and we show that  $t_n$  exists. Let  $k$  be as in Lemma 23, and let  $t$  be as in Lemma 19. We claim that there is no digraph  $D$  with  $v_3(D) < n$  and  $\tau_3(D) \geq t$ . For suppose that  $D$  is such a digraph. By Lemma 19, there exists  $a_1, \dots, a_k, b_1, \dots, b_k$  and  $L_1, L_2$  as in Lemma 18, and so  $v_3(D) \geq n$  by Lemma 23, a contradiction. Thus there is no such  $D$ , and consequently  $t_n$  exists and  $t_n < t$ .  $\square$

## 4.2 Proving Lemma 22

In this section, following Section 3 of [10], we show that if a digraph  $D$  contains a kind of grid, with some additional paths, then  $v_3(D)$  is large. We then use this lemma to prove Lemma 22.

Let  $p, q$  be positive integers. A  $(p, q)$ -web in a digraph  $D$  is a fully intersecting and acyclic pair  $(L_1, L_2)$  of linkages such that  $L_1$  has  $p$  components and  $L_2$  has  $q$  components.

Let  $p, q$  be positive integers. A  $(p, q)$ -fence in a digraph  $D$  is a sequence  $(P_1, \dots, P_{2p}, Q_1, \dots, Q_q)$  with the following properties:

- (i)  $P_1, \dots, P_{2p}$  are pairwise disjoint directed paths of  $D$ , and so are  $Q_1, \dots, Q_q$ ;
- (ii) for  $1 \leq i \leq 2p$  and  $1 \leq j \leq q$ ,  $P_i \cap Q_j$  is a directed path (and therefore non-null);
- (iii) for  $1 \leq j \leq q$ , the directed paths  $P_1 \cap Q_j, \dots, P_{2p} \cap Q_j$  are in order in  $Q_j$ , and the initial vertex of  $Q_j$  is in  $V(P_1)$  and its terminal vertex is in  $V(P_{2p})$ ;
- (iv) for  $1 \leq i \leq 2p$ , if  $i$  is odd then  $P_i \cap Q_1, \dots, P_i \cap Q_q$  are in order in  $P_i$ , and if  $i$  is even then  $P_i \cap Q_q, \dots, P_i \cap Q_1$  are in order in  $P_i$ .

Let  $Q_j$  be a directed  $(a_j, b_j)$ -path ( $1 \leq l \leq q$ ); we call  $\{a_1, \dots, a_q\}$  the *top* of the fence, and  $\{b_1, \dots, b_q\}$  its *bottom*.

The following lemma is the analogue to Lemma (3.1) of [10]. It only differs in the conclusion  $v_3(D) \geq n$ , instead of  $v(D) \geq n$ .

**Lemma 25.** *For every positive integer  $n$ , there are positive integers  $p, r$  with the following property. For any  $q \geq 2$ , let  $(P_1, \dots, P_{2p}, Q_1, \dots, Q_q)$  be a  $(p, q)$ -fence in a digraph  $D$ , and let there be  $r$  disjoint paths in  $D$  from the bottom of the fence to the top. Then  $v_3(D) \geq n$ .*

Combining Lemmas (4.4), (4.5) and (4.7) of [10] we directly obtain the following lemma.

**Lemma 26.** *For all positive integers  $p, q$ , there are positive integers  $p'$  and  $q'$  so that for every digraph  $G$ , if  $D$  contains a  $(p', q')$ -web then it contains a  $(p, q)$ -fence.*

In exactly the same way that Reed et al. deduced Lemma (2.3) from Lemmas (3.1), (4.4), (4.5) and (4.7) in [10], one can deduce Lemma 22 from Lemmas 25 and 26.

Hence it only remains to prove Lemma 25.

## 4.3 Proof Lemma 25

Consider the following lemma (Lemma (3.2)) from [10].

**Lemma 27** (Reed et al. [10]). *Let  $(P_1, \dots, P_{2p}, Q_1, \dots, Q_q)$  be a  $(p, q)$ -fence in a digraph  $D$ , with top  $A$  and bottom  $B$ . Let  $A' \subseteq A$  and  $B' \subseteq B$  with  $|A'| = |B'| = r$ , for  $r \leq p$ . Then there are directed paths  $Q'_1, \dots, Q'_r$  in  $P_1, \dots, P_{2p}, Q_1, \dots, Q_q$  so that  $(P_1, \dots, P_{2p}, Q'_1, \dots, Q'_r)$  is a  $(p, r)$ -fence with top  $A'$  and bottom  $B'$ .*

**Remark 28.** In the proof of this lemma, the proven  $(p, r)$ -fence is a subgraph of the  $(p, q)$ -fence, with  $A' \subseteq A$  and  $B' \subseteq B$ . Moreover, if  $p \geq 2$ , then  $Q_j$  has order at least 4 for  $1 \leq j \leq q$ , because  $Q_j$  intersects every  $P_i$   $1 \leq i \leq 2p$ . So, if  $p \geq 2$ ,  $Q'_l$  has size at least 4, for  $1 \leq l \leq r$ .

We need also an analogue of Lemma (3.3) of [10]:

**Lemma 29.** *Let  $n \geq 1$  be an integer, and let  $p \geq 2n$  and  $N \geq 2n^2 - 3n + 2$  be integers. For some integer  $q \geq 1$  let  $(P_1, \dots, P_{2p}, Q_1, \dots, Q_q)$  be a  $(p, q)$ -fence in a digraph  $D$ . Let  $R_1, \dots, R_N$  be disjoint directed paths of  $D$  from the bottom of the fence to the top, so that each  $R_k$  has no vertex or arc in  $P_1 \cup \dots \cup P_{2p} \cup Q_1 \cup \dots \cup Q_q$  except its endvertices. Then  $v_3(D) \geq n$ .*

The proof of this lemma is exactly the same as the one of Lemma (3.3) of [10]. The disjoint directed cycles showed in the proof are of the form  $Q'_j R_m$ , for  $Q'_j$  in a  $(p, r)$ -fence  $(P_1, \dots, P_{2p}, Q'_1, \dots, Q'_q)$ , subgraph of the  $(p, q)$ -fence  $(P_1, \dots, P_{2p}, Q_1, \dots, Q_q)$ . Since  $p \geq 2n \geq 2$ , by Remark 28 each  $Q'_j$  has length at least 2, and so  $Q'_j R_m$  has length at least 3. Hence  $v_3(D) \geq n$ .

We prove Lemma 25 by induction on  $n$ . The proof is almost identical to the one of Lemma (3.1) in [10]. The only differences are the easy case  $n = 1$ , for which we need here to take  $p = 2$  (instead of  $p = 1$ ) to be sure that the directed cycle is of length at least 3, and the use in place of Lemma (3.3) of its analogue, namely Lemma 29.

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