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Subdivisions of oriented cycles in digraphs with large chromatic number

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Extended Abstract

The chromatic number \( \chi(D) \) of a digraph \( D \) is the chromatic number of its underlying graph. The chromatic number of a class of digraphs \( \mathcal{D} \), denoted by \( \chi(\mathcal{D}) \), is the smallest \( k \) such that \( \chi(D) \leq k \) for all \( D \in \mathcal{D} \), or \( +\infty \) if no such \( k \) exists. If \( \chi(D) \neq +\infty \), we say that \( \mathcal{D} \) has bounded chromatic number.

We are interested in the following question: which are the digraph classes \( \mathcal{D} \) such that every digraph with sufficiently large chromatic number contains an element of \( \mathcal{D} \)? Let us denote by \( \text{Forb}(H) \) (resp. \( \text{Forb}(\mathcal{H}) \)) the class of digraphs that do not contain \( H \) (resp. any element of \( \mathcal{H} \)) as a subdigraph. The above question can be restated as follows:

**Problem 1.** Which are the classes of digraphs \( \mathcal{D} \) such that \( \chi(\text{Forb}(\mathcal{D})) < +\infty \)?

An oriented graph is an orientation of a (simple) graph. An oriented path (resp., an oriented cycle) is said directed if all vertices have in-degree and out-degree at most 1.

Observe that if \( D \) is an orientation of a graph \( G \) and \( \text{Forb}(D) \) has bounded chromatic number, then \( \text{Forb}(G) \) has also bounded chromatic number. A classical result by Erdős implies that \( G \) must be a tree. Burr proved that every \( (k-1)^2 \)-chromatic digraph contains every oriented tree of order \( k \) and conjectured Burr [3] that it could be further improved to \( (2k-2) \)-chromatic digraphs.

For special oriented trees \( T \), better bounds on the chromatic number of \( \text{Forb}(T) \) are known. The most famous one, known as Gallai-Hasse-Roy-Vitaver Theorem [6] states that \( \chi(\text{Forb}(P^+(k))) = k \), where \( P^+(k) \) is the directed path of length \( k \) (a directed path is an oriented path in which all arcs are in the same direction).

The chromatic number of the class of digraphs not containing a prescribed oriented path \( P \) on \( n \) vertices with two blocks (blocks are maximal directed subpaths) has been determined by Addario-Berry et al. [1]:

**Theorem 2** (Addario-Berry et al. [1]). Let \( P \) be an oriented path with two blocks on \( n \geq 4 \) vertices, then \( \chi(\text{Forb}(P)) = n - 1 \).

In this paper, we are interested in the chromatic number of \( \text{Forb}(\mathcal{H}) \) when \( \mathcal{H} \) is an infinite family of oriented cycles. Let us denote by \( S\text{-Forb}(D) \) (resp. \( S\text{-Forb}(\mathcal{D}) \)) the class of digraphs that contain no subdivision of \( D \) (resp. any element of \( \mathcal{D} \)) as a subdigraph. We are particularly interested in the chromatic number of \( S\text{-Forb}(\mathcal{C}) \), where \( \mathcal{C} \) is a family of oriented cycles.

Let us denote by \( C(k) \) the directed cycle of length \( k \). For all \( k \), \( \chi(S\text{-Forb}(C(k))) = +\infty \) because transitive tournaments have no directed cycle. Let us denote by \( C(k, \ell) \) the oriented cycle with two blocks, one of length \( k \) and the other of length \( \ell \). Observe that the oriented cycles with two blocks are the subdivisions of \( C(1,1) \). As pointed by Gyárfás and Thomassen (see [1]), there are acyclic oriented graphs with arbitrarily large chromatic number and no oriented cycles with two blocks. Therefore \( \chi(S\text{-Forb}(C(k, \ell))) = +\infty \). We first generalise this result to every oriented cycle.

**Theorem 3.** For any oriented cycle \( C \), \( \chi(S\text{-Forb}(C)) = +\infty \).

In fact, we show the following stronger theorem.

**Theorem 4.** For any positive integers \( b, c \), there exists an acyclic digraph \( D_c \) with \( \chi(D_c) \geq c \) in which all oriented cycles have more than \( b \) blocks.
We need a construction due to Erdős and Lovász [5] of hypergraphs with high girth and large chromatic number.

**Theorem 5.** [5, Theorem 1'] For $k, g, c \in \mathbb{N}$, there exists a $k$-uniform hypergraph with girth larger than $g$ and weak chromatic number larger than $c$.

We assume $g$ is being fixed, the following construction allow us to find $D_{c+1}$ from $D_c$. Let $p$ be the number of proper $c$-colourings of $D_c$, and let those colourings be denoted by $col^1_c, \ldots, col^p_c$. By Theorem 5 there exists a $c \times p$-uniform hypergraph $\mathcal{H}$ with weak chromatic number $> p$ and girth $> g/2$. Let $X = \{x_1, \ldots, x_n\}$ be the ground set of $\mathcal{H}$.

We construct $D_{c+1}$ from $n$ disjoint copies $D^1_c, \ldots, D^n_c$ of $D_c$ as follows. For each hyperedge $S \in \mathcal{H}$, we do the following:

- We partition $S$ into $p$ sets $S_1, \ldots, S_p$ of cardinality $c$.
- For each set $S_i = \{x_{k_1}, \ldots, x_{k_c}\}$, we choose vertices $v_{k_1} \in D^1_c, \ldots, v_{k_c} \in D^p_c$ such that $col^1_c(v_{k_1}) = 1, \ldots, col^p_c(v_{k_c}) = c$, and add a new vertex $w_{S,i}$ with $v_{k_1}, \ldots, v_{k_c}$ as in-neighbours.

On the other hand, considering strongly connected (strong for short) digraphs may lead to dramatically different result. An example is provided by the following celebrated result due to Bondy [2], which can be rephrased as follows when denoting the class of strong digraphs by $\mathcal{S}$.

**Theorem 6** (Bondy [2]). $\chi(S-\text{Forb}(\mathcal{C}_k) \cap \mathcal{S}) = k - 1$.

Inspired by this theorem, Addario-Berry et al. [1] posed the following problem.

**Problem 7.** Let $k$ and $\ell$ be two positive integers then $\chi(S-\text{Forb}(C(k, \ell) \cap \mathcal{S})) < k + \ell$.

We give evidence for this problem by showing the following weaker statement.

**Theorem 8.** Let $k$ and $\ell$ be two positive integers such that $k \geq \max\{\ell, 3\}$, and let $D$ be a digraph in $S-\text{Forb}(C(k, \ell)) \cap \mathcal{S}$. Then, $\chi(D) \leq (k + \ell - 2)(k + \ell - 3)(2\ell + 2)(k + \ell + 1)$.

We need the following lemma.

The union of two digraphs $D_1$ and $D_2$ is the digraph $D_1 \cup D_2$ with vertex set $V(D_1) \cup V(D_2)$ and arc set $A(D_1) \cup A(D_2)$.

**Lemma 9.** Let $D_1$ and $D_2$ be two digraphs. $\chi(D_1 \cup D_2) \leq \chi(D_1) \times \chi(D_2)$.

A consequence of the previous lemma is that, if we partition the arc set of $D$ into set $A_1 \cdots A_k$, then bounding the chromatic number of all digraphs induced by the $A_i$ implies that $D$ has bounded chromatic number.

**Proof.** Let $D$ be a strong digraph without any copy of $C(k, \ell)$, we exhibit a colouring of $D$ using a bounded number of colours. The proof heavily relies on the technique of levelling. Let $u$ be a vertex of $D$. The level of a vertex $x$, noted $\text{lvl}(x)$ is the length of the shortest dipath from $u$ to $x$. $L(i)$ is the set of vertices at level $i$.

Since $D$ is strongly connected, it has an out-generator $u$. Let $T$ be a BFS-tree with root $u$. We define the following sets of arcs.

\[
A_0 = \{xy \in A(D) \mid \text{lvl}(x) = \text{lvl}(y)\}; \\
A_1 = \{xy \in A(D) \mid 0 < |\text{lvl}(x) - \text{lvl}(y)| < k + \ell - 3; \} \\
A' = \{xy \in A(D) \mid \text{lvl}(x) - \text{lvl}(y) \geq k + \ell - 3\}.
\]

Since $k + \ell - 3 > 0$ and there is no arc $xy$ with $\text{lvl}(y) > \text{lvl}(x) + 1$, $(A_0, A_1, A')$ is a partition of $A(D)$. Observe moreover that $A(T) \subseteq A_1$. We further partition $A'$ into two sets $A_2$ and $A_3$, where $A_2 = \{xy \in A' \mid y$ is an ancestor of $x$ in $T\}$ and $A_3 = A' \setminus A_2$. Then $(A_0, A_1, A_2, A_3)$ is a partition of $A(D)$. Let $D_j = (V(D), A_j)$ for all $j \in \{0, 1, 2, 3\}$. 

Claim 10. $\chi(D_0) \leq k + \ell - 2$.

Proof. Observe that $D_0$ is the disjoint union of the $D[L_i]$ where $L_i = \{v \mid \text{dist}_D(u, v) = i\}$. Therefore it suffices to prove that $\chi(D[L_i]) \leq k + \ell - 2$ for all non-negative integer $i$.

$L_0 = \{u\}$ so the result holds trivially for $i = 0$.

Assume now $i \geq 1$. Suppose for a contradiction $\chi(D[L_i]) \geq k + \ell - 1$. Since $k \geq 3$, by Theorem 2, $D[L_i]$ contains a copy $Q$ of $P^+(k-1, \ell-1)$, the path on two blocks of length $k-1$ and $\ell-1$ with one vertex of indegree 2. Let $v_1$ and $v_2$ be the initial and terminal vertices of $Q$, and let $x$ be the least common ancestor of $v_1$ and $v_2$. By definition, for $j \in \{1, 2\}$, there exists a dipath $P_j$ from $x$ to $v_j$ in $T$. By definition of least common ancestor, $V(P_j) \cap V(P_2) = \{x\}$, $V(P_j) \cap L_i = \{v_j\}$, $j = 1, 2$, and both $P_1$ and $P_2$ have length at least 1. Consequently, $P_1 \cup P_2 \cup Q$ is a subdivision of $C(k, \ell)$, a contradiction. \hfill $\square$

Claim 11. $\chi(D_1) \leq k + \ell - 3$.

Proof. Let $\phi_1$ be the colouring of $D_1$ defined by $\phi_1(x) = \text{lvl}(x) \pmod{k + \ell - 3}$. By definition of $D_1$, this is clearly a proper colouring of $D_1$.

The following two claims are more complicated, we refer the reader to [4] for the complete proofs.

Claim 12. $\chi(D_2) \leq 2\ell + 2$.

Claim 13. $\chi(D_3) \leq k + \ell + 1$.

Claims 10, 11, 12, and 13, together with Lemma 9 yield the result. \hfill $\square$

More generally, one may wonder what happens for other oriented cycles. Our next result generalises Theorem 8 for $\hat{C}_4$ the cycle with 4 blocks.

Theorem 14. Let $D$ be a digraph in $\text{S-Forb}(\hat{C}_4)$. If $D$ admits an out-generator, then $\chi(D) \leq 24$.

Proof. The general idea is the same as in the proof of Theorem 8.

Suppose that $D$ admits an out-generator $u$ and let $T$ be an BFS-tree with root $u$. We partition $A(D)$ into three sets according to the levels of $u$.

$$
A_0 = \{(x, y) \in A(D) \mid \text{lvl}(x) = \text{lvl}(y)\}; \\
A_1 = \{(x, y) \in A(D) \mid |\text{lvl}(x) - \text{lvl}(y)| = 1\}; \\
A_2 = \{(x, y) \in A(D) \mid |\text{lvl}(y) - \text{lvl}(x)| \leq 2\}.
$$

For $i = 0, 1, 2$, let $D_i = (V(D), A_i)$.

Claim 15. $\chi(D_0) \leq 3$.

Proof. Suppose for a contradiction that $\chi(D) \geq 4$. By Theorem 2, it contains a $P^-(1, 1)$ $(y_1, y, y_2)$, that is $(y, y_1)$ and $(y, y_2)$ are in $A(D_0)$. Let $x$ be the least common ancestor of $y_1$ and $y_2$ in $T$. The union of $T[x, y_1]$, $(y, y_1)$, $(y, y_2)$, and $T[x, y_2]$ is a subdivision of $\hat{C}_4$, a contradiction. \hfill $\square$

Claim 16. $\chi(D_1) \leq 2$.

Proof. Since the arc are between consecutive levels, then the colouring $\phi_1$ defined by $\phi_1(x) = \text{lvl}(x) \mod 2$ is a proper 2-colouring of $D_1$. \hfill $\square$
Claim 17. $\chi(D_2) \leq 4$.

Proof. We refer to [4] for the proof of this statement.

Claims 15, 16, 17, and Lemma 9 implies $\chi(D) \leq 24$.

References


