

# Paths with two blocks in $n$ -chromatic digraphs

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## Abstract

We show that every oriented path of order  $n \geq 4$  with two blocks is contained in every  $n$ -chromatic digraph.

Gallai-Roy's celebrated theorem [11, 12] states that every  $n$ -chromatic digraph contains a directed path of length  $n - 1$ . More generally, one can ask which digraphs are contained in every  $n$ -chromatic digraph. Such digraphs are called  $n$ -universal. Since there exist  $n$ -chromatic graphs with arbitrarily large girth [7],  $n$ -universal digraphs must be oriented trees. Burr [3] proved that every oriented tree of order  $n$  is  $(n - 1)^2$ -universal and he conjectured that every oriented tree of order  $n$  is  $(2n - 2)$ -universal. This is a generalization of Sumner's conjecture which states that every oriented tree of order  $n$  is contained in every tournament (orientation of a complete graph) of order  $2n - 2$ . The first linear bound for tournaments was given by Häggkvist and Thomason [8]. The best bound so far,  $3n - 3$ , was obtained by El Sahili [5], refining an idea of [10].

Regarding oriented paths in general, there is no better upper bound than the one given by Burr for oriented trees. However in tournaments, Havet and Thomassé [9] proved that except for three particular cases, every tournament of order  $n$  contains every oriented path of order  $n$ .

A *path with two blocks* is an oriented path of order  $k + l + 1$  starting with  $k$  forward arcs and followed by  $l$  backward arcs for some  $k \geq 1$  and  $l \geq 1$ . We denote such a path by  $P(k, l)$ . El-Sahili conjectured [4] that every path of order  $n \geq 4$  with two blocks is  $n$ -universal, and Bondy and El-Sahili [4] proved it if one of the two blocks has length one. The condition  $n \geq 4$  is necessary because of odd circuits. Recently, El-Sahili and Kouider [6] showed that every path of order  $n$  with two blocks is  $(n + 1)$ -universal.

In this paper, we show that every path of order  $n \geq 4$  with two blocks is  $n$ -universal, proving El-Sahili's conjecture.

A natural question is to ask for cycles with two blocks instead of paths. In this context, Benhocine and Wojda [1] proved that every tournament on  $n \geq 4$  vertices contains every cycle of order  $n$  with two blocks. As pointed out by Gyárfás and Thomassen, this does not extend to  $n$ -chromatic digraphs. Consider for this the following inductive construction: Let  $D_1$  be the singleton digraph. Then,  $D_{i+1}$  is constructed starting with  $i$  disjoint copies  $C_1, \dots, C_i$  of  $D_i$  and adding, for every set  $X$  of  $i$  vertices, one in each  $C_i$ , a vertex dominated exactly by  $X$ . By construction, the chromatic number of  $D_i$  is exactly  $i$  and there are no cycle with two blocks.

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# 1 Final spanning out-forests.

An *out-arborescence*  $T$  is an oriented tree having exactly one vertex  $r$  with in-degree zero. The vertex  $r$  is the *root* of  $T$ . An *out-forest* is a disjoint union of out-arborescences. Let  $F$  be an out-forest and  $x$  a vertex of  $F$ . The *level* of  $x$  is the number of vertices of a longest directed path of  $F$  ending at  $x$ . For instance, the level 1 vertices are the roots of the out-arborescences of  $F$ . We denote by  $F_i$  the set of vertices with level  $i$  in  $F$ . A vertex  $y$  is a *descendant* of  $x$  in  $F$  if there is a directed path from  $x$  to  $y$  in  $F$ .

Let  $F$  be a spanning out-forest of  $D$ . If there is an arc  $xy$  in  $D$  from  $F_i$  to  $F_j$ , with  $i \geq j$ , and  $x$  is not a descendant of  $y$ , then the out-forest  $F'$  obtained by adding  $xy$  and removing the arc of  $F$  with head  $y$  (if such exists that is if  $j > 1$ ) is called an *elementary improvement* of  $F$ . An out-forest  $F'$  is an *improvement* of  $F$  if it can be obtained from an out-forest  $F$  by a sequence of elementary improvements. The key-observation is that if  $F'$  is an improvement of  $F$  then the level of every vertex in  $F'$  is at least its level in  $F$ . Moreover, at least one vertex of  $F$  has its level in  $F'$  strictly greater than its level in  $F$ . Thus, one cannot perform infinitely many improvements. A spanning out-forest  $F$  is *final* if there is no elementary improvement of  $F$ .

We say that  $x$  *dominates*  $y$  if  $xy$  is an arc of  $D$ . The following proposition follows immediately from the definition of final spanning out-forest:

**Proposition 1** *Let  $D$  be a digraph and  $F$  a final spanning out-forest of  $D$ . If a vertex  $x \in F_i$  dominates in  $D$  a vertex  $y \in F_j$  for  $j \leq i$  then  $x$  is a descendant of  $y$  in  $F$ . In particular, every level of  $F$  is a stable set in  $D$ .*

The notion of final forests are useful in the context of universal digraphs. For instance it gives an easy proof of Gallai-Roy's theorem. Indeed consider a final spanning out-forest of an  $n$ -chromatic digraph  $D$ . Since every level is a stable set by Proposition 1, there are at least  $n$  levels. Hence  $D$  contains a directed path of length at least  $n$ . Final forests are also useful for finding paths with two blocks, as illustrated by the following proof due to El-Sahili and Kouider [6].

**Lemma 1** *Let  $F$  be a final spanning out-forest of a digraph  $D$ . We assume that there is an arc  $vw$  from  $F_i$  to  $F_j$ . Then*

- (i) *If  $k \leq i < j - l$ , then  $D$  contains a  $P(k, l)$ .*
- (ii) *If  $k < j \leq i - l$ , then  $D$  contains a  $P(k, l)$ .*

**Proof.** (i) Let  $P_l$  be the directed path of  $F$  which starts at  $F_{j-l}$  and ends at  $w$  and  $P_{k-1}$  be the directed path in  $F$  starting at  $F_{i-(k-1)}$  and ending at  $v$ . Then  $P_{k-1} \cup vw \cup P_l$  is a  $P(k, l)$ .

(ii) Let  $P_{l-1}$  be the directed path in  $F$  which starts at  $F_{i-l+1}$  and ends at  $v$ . Let  $P_k$  be the directed path in  $F$  starting at  $F_{j-k}$  and ending at  $w$ . Then  $P_k \cup P_{l-1} \cup vw$  is a  $P(k, l)$ . ■

**Corollary 1** (El-Sahili and Kouider [6]) *Every digraph with chromatic number at least  $k + l + 2$  contains a  $P(k, l)$ .*

**Proof.** Let  $F$  be a final spanning out-forest of  $D$ . Color the levels  $F_1, \dots, F_k$  of  $F$  with colors  $1, \dots, k$ . Then color the level  $F_i$ , where  $i > k$ , with color  $j \in \{k + 1, \dots, k + l + 1\}$  such that  $j \equiv i \pmod{l + 1}$ . Since this is not a proper coloring, there exists an arc which satisfies the hypothesis of Lemma 1. ■

Our goal is now to extend this proof to the case of  $(k + l + 1)$ -chromatic digraphs.

## 2 Good circuits; the strongly connected case.

Let us recall the following extension of Gallai-Roy's theorem to strongly connected digraphs:

**Theorem 1** (Bondy [2]) *Every strongly connected digraph  $D$  has a circuit of length at least  $\chi(D)$ .*

Let  $S \subset V(D)$  be a set of vertices. We denote by  $D[S]$  the subdigraph induced by the vertices of  $S$ . Let  $k$  be a positive integer and  $D$  be a digraph. A directed circuit  $C$  of  $D$  is  $k$ -good if  $|C| \geq k$  and  $\chi(D[V(C)]) \leq k$ . Note that Theorem 1 states that every strongly connected digraph  $D$  has a  $\chi(D)$ -good circuit.

**Lemma 2** *Let  $D$  be a strongly connected digraph and  $k$  be in  $\{3, \dots, \chi(D)\}$ . Then  $D$  has a  $k$ -good circuit.*

**Proof.** By Bondy's theorem, there exists a circuit with length at least  $\chi(D)$ , implying the claim for the value  $k = \chi(D)$ . Suppose  $k < \chi(D)$ , in particular  $\chi(D) > 3$ . Let us now consider a shortest circuit  $C$  with length at least  $k$ . We claim that  $C$  is  $k$ -good. Suppose for contradiction that  $\chi(D[V(C)]) \geq k + 1$ . We may assume by induction on the number of vertices that  $D = D[V(C)]$ . Furthermore, if  $D$  contains a circuit of length 2, we can remove one of its arcs, in such a way that  $\chi(D)$  and the circuit  $C$  are unchanged. Thus, we can assume that  $D$  has no circuit of length two, has a hamiltonian circuit  $C$  of length at least  $k$ , has chromatic number greater than  $k$ , and that every circuit of length at least  $k$  is hamiltonian. Our goal is to reach a contradiction.

We claim that every vertex  $u$  has in-degree at most  $k - 2$  in  $D$ . Indeed, if  $v_1, \dots, v_{k-1}$  were in-neighbors of  $u$ , listed in such a way that  $v_1, \dots, v_{k-1}, u$  appear in this order along  $C$ , the circuit obtained by shortcutting  $C$  through the arc  $v_{k-2}u$  would have length at least  $k$  since the out-neighbor of  $u$  in  $C$  is not an in-neighbor of  $u$ . This contradicts the minimality of  $C$ . The same argument gives that every vertex has out-degree at most  $k - 2$  in  $D$ .

A *handle decomposition* of  $D$  is a sequence  $H_1, \dots, H_r$  such that:

- i)  $H_1$  is a circuit of  $D$ .
- ii) For every  $i = 2, \dots, r$ ,  $H_i$  is a handle, that is, a directed path of  $D$  (with possibly the same endvertices) starting and ending in  $V(H_1 \cup \dots \cup H_{i-1})$  but with no inner vertex in this set.
- iii)  $D = H_1 \cup \dots \cup H_r$ .

An  $H_i$  which is an arc is a *trivial handle*. It is well-known that  $r$  is invariant for all handle decompositions of  $D$  (indeed,  $r$  is the number of arcs minus the number of vertices plus one). However the number of nontrivial handles is not invariant. Let us then consider  $H_1, \dots, H_r$ , a handle decomposition of  $D$  with minimum number of trivial handles. Free to enumerate first the nontrivial handles, we can assume that  $H_1, \dots, H_p$  are not trivial and  $H_{p+1}, \dots, H_r$  are arcs. Let  $D' := H_1 \cup \dots \cup H_p$ . Clearly  $D'$  is a strongly connected spanning subgraph of  $D$ . Observe that since  $\chi(D) > 3$ ,  $D$  is not an induced circuit, in particular  $p > 1$ .

We denote by  $x_1, \dots, x_q$  the handle  $H_p$  minus its endvertices.

If  $q = 1$ , the digraph  $D' \setminus x_1$  is strongly connected, and therefore  $D \setminus x_1$  is also strongly connected. Moreover its chromatic number is at least  $k$ . Thus by Bondy's theorem, there exists a circuit of length at least  $k$  in  $D \setminus x_1$ , a contradiction.

If  $q = 2$ , note that  $x_2$  is the unique out-neighbor of  $x_1$  in  $D$ , otherwise we would make two non trivial handles out of  $H_p$ , contradicting the maximality of the number of non trivial handles. Similarly,  $x_1$  is the unique in-neighbor of  $x_2$ . Since the outdegree and the indegree of every vertex is at most  $k - 2$ , both  $x_1$  and  $x_2$  have degree at most  $k - 1$  in the underlying graph of  $D$ . Since  $\chi(D) > k$ , it follows that  $\chi(D \setminus \{x_1, x_2\}) > k$ . Since  $D \setminus \{x_1, x_2\}$  is strongly connected, it contains, by Bondy's theorem, a circuit with length at least  $k$ , contradicting the minimality of  $C$ .

Hence, we may assume  $q > 2$ . For every  $i = 1, \dots, q - 1$ , by the maximality of  $p$ , the unique arc in  $D$  leaving  $\{x_1, \dots, x_i\}$  is  $x_i x_{i+1}$  (otherwise we would make two nontrivial handles out of  $H_p$ ). Similarly,

for every  $j = 2, \dots, q$ , the unique arc in  $D$  entering  $\{x_j, \dots, x_q\}$  is  $x_{j-1}x_j$ . In particular, as for  $q = 2$ ,  $x_1$  has out-degree 1 in  $D$  and  $x_q$  has in-degree 1 in  $D$ .

Another consequence is that the underlying graph of  $D \setminus \{x_1, x_q\}$  has two connected components  $D_1 := D \setminus \{x_1, x_2, \dots, x_q\}$  and  $D_2 := \{x_2, \dots, x_{q-1}\}$ . Since the degrees of  $x_1$  and  $x_q$  in the underlying graph of  $D$  are at most  $k-1$  and  $D$  is at least  $(k+1)$ -chromatic, it follows that  $\chi(D_1)$  or  $\chi(D_2)$  is at least  $(k+1)$ -chromatic. Since  $D_1$  is strongly connected, we cannot have  $\chi(D_1) \geq k+1$ , otherwise, again by Bondy's theorem,  $D_1$  would contain a circuit of length at least  $k$  but shorter than  $C$ , which is impossible. Thus  $\chi(D_2) \geq k+1$ . Furthermore, since  $H_p$  cannot be decomposed into two nontrivial handles in  $D$ , the arcs  $x_i x_j$  in  $D_2$  with  $i < j$  are exactly the arcs  $x_i x_{i+1}$ . In particular, the strongly connected components of  $D_2$  are of the form  $\{x_i, \dots, x_{i+j}\}$ , and thus have at most one arc entering them, and one arc leaving them. Thus, one strongly connected component of  $D_2$  has chromatic number at least  $k+1$ , and we reach a contradiction by Bondy's theorem. ■

The existence of good circuits directly gives our main theorem in the case of strongly connected digraphs. However, we will not need this result for the proof of the general case.

**Lemma 3** *Let  $k+l = n-1$  and  $D$  be a strongly connected  $n$ -chromatic digraph. If  $D$  contains an  $(l+1)$ -good circuit then  $D$  contains a  $P(k, l)$ .*

**Proof.** Suppose  $C$  is an  $(l+1)$ -good circuit. Since  $\chi(D[V(C)]) \leq l+1$ , the chromatic number of the (strongly connected) contracted digraph  $D/C$  is at least  $k+1$ . Thus by Bondy's theorem,  $D/C$  has a circuit of length at least  $k+1$ , and in particular the vertex  $C$  is the end of a path  $P$  of length  $k$  in  $D/C$ . Finally  $P \cup C$  contains a  $P(k, l)$ . ■

**Corollary 2** *Let  $k+l = n-1 \geq 3$  and  $D$  be an  $n$ -chromatic strongly connected digraph. Then  $D$  contains a  $P(k, l)$ .*

**Proof.** Since  $P(k, l)$  and  $P(l, k)$  are isomorphic, we may assume that  $l \geq 2$ . By Lemma 2,  $D$  has an  $(l+1)$ -good circuit, and thus contains a  $P(k, l)$  according to Lemma 3. ■

### 3 The general case.

We now turn to the proof of the main result.

**Theorem 2** *Let  $k+l = n-1 \geq 3$  and  $D$  be an  $n$ -chromatic digraph. Then  $D$  contains a  $P(k, l)$ .*

**Proof.** We again assume that  $l \geq k$ , and therefore  $l \geq 2$ . Suppose for contradiction that  $D$  does not contain  $P(k, l)$ . Let  $F$  be a final spanning out-forest of  $D$ .

We first prove that  $D$  contains an  $(l+1)$ -good circuit  $C$  which is disjoint from  $F_1 \cup \dots \cup F_{k-1}$ . For this, we consider the following coloring of  $D$  (called *canonical*): for  $1 \leq i \leq k-1$ , the vertices of  $F_i$  are colored  $i$ , and for  $i \geq k$ , the vertices of  $F_i$  are colored  $j$ , where  $j \in \{k, \dots, k+l\}$  and  $j \equiv i \pmod{l+1}$ . Since we colored  $D$  with less than  $n$  colors, this coloring is improper. In particular, there exists an arc  $vw$  from  $F_i$  to  $F_j$  where  $i, j \geq k$  and  $j \equiv i \pmod{l+1}$ . By Lemma 1 (i), we reach a contradiction if  $i < j$ . Thus  $j < i$ , and by Lemma 1 (ii), we necessarily have  $j = k$  and  $i \geq k+l+1$ . By Proposition 1,  $v$  is a descendant of  $w$  in  $F$ . In particular  $F \cup vw$  has a circuit  $C$  of length at least  $l+1$ . If the induced digraph on  $C$  has chromatic number at most  $l+1$ ,  $C_0 := C$  is  $(l+1)$ -good. If not, by Lemma 2, it contains an  $(l+1)$ -good circuit  $C_0$ .

We inductively define couples  $(D^i, F^i)$  as follows: Set  $D^0 := D$ ,  $F^0 := F$ . Then, if there exists an  $(l+1)$ -good circuit  $C^i$  of  $D^i \setminus (F_1^i \cup \dots \cup F_{k-1}^i)$ , define  $D^{i+1} := D^i \setminus V(C^i)$  and let  $F^{i+1}$  be any final improvement of  $F^i \setminus V(C^i)$ .

With the previous definitions, we have  $D_1 = D \setminus V(C)$ . This inductive definition certainly stops on some  $(D^p, F^p)$  where  $D^p$  admits a canonical coloring as a proper coloring.

Let us be a little more precise: at each inductive step, the circuit  $C^i$  must contain a vertex  $v^i$  of  $F_k^i$ , otherwise the union of  $C^i$  and a path of  $F^i$  starting at  $F_1^i$  and ending at  $C^i$  would certainly contain a  $P(k, l)$ , since  $C^i$  has length at least  $l + 1$ . We denote by  $u^i$  the unique in-neighbor of  $v^i$  in  $F_{k-1}^i$ . Observe that the level of  $u^i$  in  $F^j$ , where  $j > i$ , always increases since we apply improvements. Observe also that  $u^i$  cannot reach a level greater than  $k - 1$ , otherwise  $u^i$  would be the end of a path  $P$  of length  $k - 1$  in  $D \setminus C^i$  and thus  $C^i \cup P \cup u^i v^i$  would contain a  $P(k, l)$ . Thus every circuit  $C^i$ ,  $i = 0, \dots, p - 1$ , has an in-neighbor  $u^i$  in  $F_{k-1}^p$ .

Let us now reach a contradiction, by properly coloring  $D$  with  $n - 1$  colors. We first color the levels  $F_1^p, \dots, F_{k-1}^p$  with colors  $1, \dots, k - 1$ . We will now color the remaining induced graph  $D' := D \setminus (F_1^p \cup \dots \cup F_{k-1}^p)$  with colors  $k, \dots, k + l$ . Therefore, we first establish some claims. The proof of some of them follows easily from the fact that  $D$  has no  $P(k, l)$  and  $l \geq k$  and is left to the reader.

**Claim 1** *There is no arc between two distinct  $C^i$ 's.*

**Claim 2** *No vertex of  $C^i$  has a neighbor, in- or out-, in any level  $F_j^p$  for any  $j > k$ . Moreover, no vertex of  $C^i$  has an in-neighbor in  $F_k^p$ .*

Let us call *dangerous vertices* the out-neighbors of the  $C^i$ 's in  $F_k^p$  and *safe vertices* the non-dangerous vertices in  $F_k^p$ . Let  $b$  be a dangerous vertex.

**Claim 3**  *$b$  has in-neighbors in a unique  $C^i$ .*

**Claim 4**  *$b$  has at most  $l$  in-neighbors in  $C^i$ .*

**Proof.** Suppose for contradiction that  $w_1, \dots, w_{l+1}$  are in-neighbors of  $b$  in  $C^i$ , enumerated with respect to the cyclic order of  $C^i$  and so that  $w_1$  is the first vertex  $w_j$  along  $C^i$  which follows  $v^i$  (in other words  $C^i[v^i, w_1] \cap \{w_1, \dots, w_{l+1}\} = \{w_1\}$ ). Let  $P$  be the path of  $F^p$  starting at  $F_1^p$  and ending at  $u^i$ . Now  $P \cup u^i v^i \cup C[v^i, w_1] \cup w_1 b \cup C[w_2, w_{l+1}] \cup w_{l+1} b$  contains a  $P(k, l)$ , a contradiction. ■

Let  $S_b$  be the set of descendants of  $b$  in  $F^p$ .

**Claim 5** *Every arc  $xy$  entering  $S_b$  in  $D'$  is such that  $y = b$  and  $x \in C^i$ .*

**Proof.** Let  $xy$  be an arc of  $D'$  with  $y \in S_b$  and  $x \notin S_b$ . If  $y \neq b$ ,  $y$  would be a strict descendant of  $b$  in  $F^p$ . By Claim 2,  $x$  is not in some  $C^j$ . Thus  $x \in F^p$ , and is not a descendant of  $b$  by hypothesis. In particular  $F^p \cup xy$  contains two  $(F_k^p, y)$ -directed paths  $P_1, P_2$  such that  $P_1 \cap P_2 = y$  and one of them, say  $P_1$ , starts at  $b$ . Extending  $P_1$  via  $C^i$  and  $P_2$  via  $F_1^p \cup \dots \cup F_{k-1}^p$  would give a  $P(k, l)$ .

So  $y = b$ . By Proposition 1 and the fact that  $x \notin S_b$ ,  $x$  is not a vertex of  $F^p$ . So  $x$  belongs to some  $C^j$ , and by Claim 3,  $x$  belongs to  $C^i$ . ■

**Claim 6** *There is no arc leaving  $S_b$  in  $D'$ .*

**Proof.** Assume for contradiction that  $xy$  is an arc of  $D'$  such that  $x \in S_b$  and  $y \notin S_b$ . If  $y \in F^p$ , there exists two paths ending at  $y$ , one starting from  $b$  and the other starting from another vertex of  $F_k^p$ , which is impossible. Thus  $y$  belongs to some  $C^j$ , but this is again impossible because of Claim 2. ■

Let us now color the vertices of  $D'$ .

Every  $C^i$  is  $(l + 1)$ -good and thus  $(l + 1)$ -colorable. Moreover, by Claim 1, we can properly color the union of the  $C_i$ 's with the colors  $k, \dots, k + l$ .

By Claim 2 and the definition of safe vertices, there is no arc between the  $C^i$ 's and the descendants of safe vertices in  $F^p$ . Hence we can properly extend our coloring to the safe vertices and their descendance in a canonical way. Now we have to properly extend the coloring to  $S_b$  for every dangerous vertex  $b$ . Observe that between  $S_b$  and  $D' \setminus S_b$ , by Claim 5 and 6, there are only arcs starting at some given  $C^i$  and ending at  $b$ . By Claim 4, there are at most  $l$  of these arcs. Thus, there is one color  $c$  amongst  $k, \dots, k+l$  which is not used by one in-neighbor of  $b$  in  $C^i$ . Color  $b$  with color  $c$ . Then extend to a proper coloring to  $S_b$  in a periodical way: a vertex in  $F_i \cap S_b$  is assigned  $j \in \{k, \dots, k+l\}$  if  $j \equiv i + c_b \pmod{l+1}$ . Doing this for every dangerous vertex provide a proper  $(n-1)$ -coloring of  $D$  and thus a contradiction. ■

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