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The (≤ 5)-hypomorphy of digraphs up to complementation

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Abstract. Two digraphs $G = (V, E)$ and $G' = (V, E')$ are isomorphic up to complementation if G' is isomorphic to G or to the complement $\bar{G} := (V, \{(x, y) \in V^2 : x \neq y, (x, y) \notin E\})$ of G . The boolean sum $G \dot{+} G'$ is the symmetric digraph $U = (V, E(U))$ defined by $\{x, y\} \in E(U)$ if and only if $(x, y) \in E$ and $(x, y) \notin E'$, or $(x, y) \notin E$ and $(x, y) \in E'$. Let k be a nonnegative integer. The digraphs G and G' are ($\leq k$)-hypomorphic up to complementation if for every t -element subset X of V , with $t \leq k$, the induced subdigraphs $G_{\downarrow X}$ and $G'_{\downarrow X}$ are isomorphic up to complementation. The digraphs G and G' are hereditarily isomorphic (resp. hereditarily isomorphic up to complementation) if for each subset X of V , the induced subdigraphs $G_{\downarrow X}$ and $G'_{\downarrow X}$ are isomorphic (resp. isomorphic up to complementation). Here, we give the form of the pair $\{G, G'\}$ whenever G and G' are two digraphs, (≤ 5)-hypomorphic up to complementation and such that the boolean sum $U := G \dot{+} G'$ and the complement \bar{U} are both connected, and thus we deduce that G and G' are hereditarily isomorphic up to complementation; we prove also that the value 5 is optimal. The case U or \bar{U} is not connected is studied in a forth come paper.

Keywords: Digraph, isomorphism, k -hypomorphy up to complementation, hereditary isomorphy up to complementation, boolean sum, symmetric digraph, tournament, indecomposability

2010 Mathematics Subject Classification: 05C50; 05C60

1 Introduction

In this paper, we study the reconstruction of digraphs up to complementation (definitions and notations are given in section 2). Ulam's reconstruction conjecture on digraphs [22], still unsolved for graphs, is well-known (see [2, 3]). Fraïssé made a related conjecture about relational structures. The case of binary relations was solved by Lopez [14, 15, 16], he showed that all binary relations are (≤ 6)-reconstructible. The case of ternary relations

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was solved negatively by Pouzet [17]. On the other hand, Stockmeyer [20] showed that the tournaments are not, in general, (-1) -reconstructible, invalidating so the conjecture of Ulam for digraphs. In 1993, Hagendorf raised the $(\leq k)$ -half-reconstruction problem for digraphs and solved it with Lopez [12, 13], they showed that *the finite digraphs are (≤ 12) -half-reconstructible*. In 1995, Boudabbous and Lopez [6] showed that *the finite tournaments are (≤ 7) -half-reconstructible*. This motivated, in 2013, M.Alzohairi, M.Bouaziz and Y.Boudabbous to introduce the concept of $(\leq k)$ -hereditary reconstructibility of posets [1]. In 2015, Y.Boudabbous proposed the problem of $(\leq k)$ -hereditarily reconstruction of digraphs. He solved this problem for tournaments with A.Boussairi, A. Chaïchaâ and N. El Amri [5].

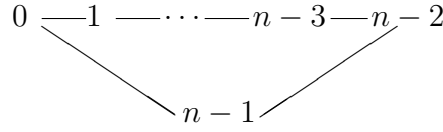
We say that a symmetric digraph G is *connected* if for any distinct vertices a and b of G , there are vertices $a = x_0, x_1, \dots, x_m = b$ of G , such that $x_i \xrightarrow{G} x_{i+1}$ for each $i \in \{0, \dots, m-1\}$. Otherwise G is said *disconnected*. A *component* of G is a maximal connected subdigraph of G . Let $G = (V, E)$ and $G' = (V, E')$ be two digraphs, 2-hypomorphic up to complementation. *The boolean sum $G \dot{+} G'$* of G and G' is the symmetric digraph $U = (V, E(U))$ defined by $\{x, y\} \in E(U)$ if and only if $(x, y) \in E$ and $(x, y) \notin E'$, or $(x, y) \notin E$ and $(x, y) \in E'$. Clearly $\bar{U} = \bar{G} \dot{+} G'$. Denote $\mathfrak{D}_{G, G'}$ the binary relation on V such that: for $x \in V$, $x \mathfrak{D}_{G, G'} x$; and for $x \neq y \in V$, $x \mathfrak{D}_{G, G'} y$ if there exists a sequence $x = x_0, x_1, \dots, x_m = y$ of elements of V satisfying $(x_i, x_{i+1}) \in E$ if and only if $(x_i, x_{i+1}) \notin E'$, for each i , $0 \leq i \leq m-1$. The relation $\mathfrak{D}_{G, G'}$ is an equivalence relation called *the difference relation*, its classes are called *difference classes*, this relation was introduced by Lopez [14]. Then clearly C is a connected component of $U := G \dot{+} G'$ if and only if C is an equivalence class of $\mathfrak{D}_{G, G'}$, and thus $\mathfrak{D}_{G, G'}$ and $\mathfrak{D}_{\bar{G}, G'}$ have only one class if and only if U and \bar{U} are connected. In 2003, Dammak [8] proved the following result.

Proposition 1.1 ([8]) *Let T and T' be two finite tournaments, (≤ 5) -hypomorphic up to complementation, and $U := T \dot{+} T'$. If U and \bar{U} are connected, then T and T' are total orders.*

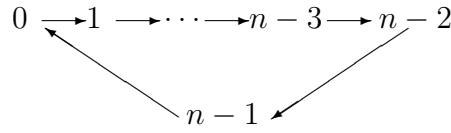
In 1999, Ille raised the problem of the $(\leq k)$ -reconstruction up to complementation of digraphs. The case of symmetric digraphs was solved by Dammak, Lopez, Pouzet and Si Kaddour [9, 10], they proved that, *the symmetric digraphs on v vertices are t -reconstructible up to complementation* for every $4 \leq t \leq v-3$. In fact, the case $t = v-3$ was solved in [10] using the following result established by Pouzet, Si Kaddour and Trotignon [18].

Theorem 1.2 [18] *If G and G' are two symmetric digraphs, 3-hypomorphic up to complementation and $|V(G)| \geq 10$, then the connected components of $U := G \dot{+} G'$, or of its complement \bar{U} , are cycles of even length or paths.*

We define the symmetric digraph P_n in the following manner, $V(P_n) = \{0, 1, \dots, n-1\}$, and for $i \neq j \in \{0, 1, \dots, n-1\}$, $\{i, j\}$ is an edge of P_n when $|i-j| = 1$. Thus $P_n := 0 \text{---} 1 \text{---} \dots \text{---} n-2 \text{---} n-1$. A *path* is a symmetric digraph isomorphic to P_n . A *cycle* is a symmetric digraph isomorphic to $C_n := (V(P_n), E(P_n) \cup \{\{0, n-1\}\})$ for some integer $n \geq 3$.

Figure 1: C_n

We define the digraph \vec{P}_n by, for $i \neq j \in \{0, 1, \dots, n-1\}$, $i \xrightarrow{\vec{P}_n} j$ when $j = i+1$. Thus $\vec{P}_n := 0 \rightarrow 1 \rightarrow \dots \rightarrow n-2 \rightarrow n-1$. We call *directed path* or *oriented path* a digraph isomorphic to \vec{P}_n , and *directed cycle* or *oriented cycle* a digraph isomorphic to $\vec{C}_n := (V(\vec{P}_n), E(\vec{P}_n) \cup \{(n-1, 0)\})$ for some integer $n \geq 3$.

Figure 2: \vec{C}_n

We define \vec{P}_n^f (resp. \vec{C}_n^f) obtained from \vec{P}_n (resp. \vec{C}_n) by switching the void pairs by the full pairs. Thus $\vec{P}_n^f = (\vec{P}_n)^*$ and $\vec{C}_n^f = (\vec{C}_n)^*$.

A *total order* is a tournament T such that for $x, y, z \in V(T)$, if $x \xrightarrow{T} y$ and $y \xrightarrow{T} z$ then $x \xrightarrow{T} z$. Given a total order $O = (V, E)$, for $x, y \in V$, $x < y$ means $x \xrightarrow{O} y$. Thus, a total order on n vertices can be denoted by $v_0 < v_1 < \dots < v_{n-1}$.

Our main result is the following.

Theorem 1.3 *Let G and G' be two digraphs on the same set V of $n \geq 4$ vertices such that G and G' are (≤ 5) -hypomorphic up to complementation. Let $U := G \dot{+} G'$. If U and \bar{U} are connected, then G' and G are hereditarily isomorphic up to complementation; more precisely one of the following holds:*

- 1) G and G' are two total orders.
- 2) $G \simeq \vec{P}_n$ or $G \simeq \vec{C}_n$, and $G' = G^*$.
- 3) $G \simeq \vec{P}_n$ or $G \simeq \vec{C}_n$, and $G' = \overline{G^*}$.
- 4) $G \simeq \vec{P}_n^f$ or $G \simeq \vec{C}_n^f$, and $G' = G^*$.
- 5) $G \simeq \vec{P}_n^f$ or $G \simeq \vec{C}_n^f$, and $G' = \overline{G^*}$.

In Proposition 3.5, we prove that the value 5 is optimal by giving two digraphs G, G' , on the same vertex set V with $|V| \geq 5$, which are (≤ 4) -hypomorphic up to complementation and not (≤ 5) -hypomorphic up to complementation, $U := G \dot{+} G'$ and \bar{U} are connected but G and G' are not isomorphic up to complementation, and thus not hereditarily isomorphic up to complementation.

From Theorem 1.3, we deduce trivially the following result for digraphs which is similar to Theorem 1.2.

Corollary 1.4 *Let G and G' be two digraphs on the same set V of $n \geq 4$ vertices such that G and G' are (≤ 5) -hypomorphic up to complementation and $U := G \dot{+} G'$. If U and \bar{U} are connected and G is not a total order, then U or \bar{U} is a cycle or a path.*

2 Definitions and notations

A *directed graph* or simply *digraph* G consists of a finite and nonempty set V of vertices together with a prescribed collection E of ordered pairs of distinct vertices, called the set of the *edges* of G . Such a digraph is denoted by $(V(G), E(G))$ or simply (V, E) . Given a digraph $G = (V, E)$, to each nonempty subset X of V associate the *subdigraph* $(X, E \cap (X \times X))$ of G induced by X denoted by $G_{\upharpoonright X}$. Given a proper subset X of V , $G_{\upharpoonright V \setminus X}$ is also denoted by $G - X$, and by $G - v$ whenever $X = \{v\}$. With each digraph $G = (V, E)$ associate its *dual* $G^* = (V, E^*)$ and its *complement* $\bar{G} = (V, \bar{E})$ defined as follows. Given $x \neq y \in V$, $(x, y) \in E^*$ if $(y, x) \in E$, and $(x, y) \in \bar{E}$ if $(x, y) \notin E$.

Let $G = (V, E)$ be a digraph, for $x \neq y \in V$, $x \xrightarrow{G} y$ or $y \xleftarrow{G} x$ (or simply $x \rightarrow y$ if there is no confusion) means $(x, y) \in E$ and $(y, x) \notin E$; $x \xrightarrow{G} y$ (or simply $x \xrightarrow{G} y$) means $(x, y) \in E$ and $(y, x) \in E$; $x \dots_G y$ (or $x \dots y$ or $x \not\xrightarrow{G} y$) means $(x, y) \notin E$ and $(y, x) \notin E$. For $X, Y \subseteq V$, $X \xrightarrow{G} Y$ and $X \dots_G Y$ (or $X \not\xrightarrow{G} Y$) are defined in the same way. If $X = \{x\}$ or $Y = \{y\}$, we can replace X by x and Y by y .

Given a digraph $G = (V, E)$, two distinct vertices x and y of G form a *directed pair* or *oriented pair* if either $x \xrightarrow{G} y$ or $x \xleftarrow{G} y$. Otherwise, $\{x, y\}$ is a *neutral pair*; it is *full* if $x \xrightarrow{G} y$, and *void* if $x \dots_G y$. Two interesting types of digraphs are symmetric digraphs and tournaments. A digraph $G = (V, E)$ is a *symmetric digraph* or *graph* (resp. *tournament*) whenever for $x \neq y \in V$, $x \xrightarrow{G} y$ or $x \dots_G y$ (resp. $x \xrightarrow{G} y$ or $y \xrightarrow{G} x$). If $G = (V, E)$ is a graph, each edge (x, y) of G is identified with the pair $\{x, y\}$ and is called an *edge* of G . For instance, given a set V , (V, \emptyset) is the *empty graph* on V whereas $(V, [V]^2)$ is the *complete graph* on V , where $[V]^2$ is the set of pairs $\{x, y\}$ of distinct elements of V .

Given two digraphs $G = (V, E)$ and $G' = (V', E')$, a bijection f from V onto V' is an *isomorphism* from G onto G' provided that for any $x, y \in V$, $(x, y) \in E$ if and only if $(f(x), f(y)) \in E'$. The digraphs G and G' are *isomorphic*, which is denoted by $G \simeq G'$, if there exists an isomorphism from one onto the other, otherwise $G \not\simeq G'$. A digraph H *embeds* into G , or H is *embeddable* in G , if H is isomorphic to an induced subdigraph of G .

Given two digraphs G and G' on the same vertex set V . They are *equal up to complementation* if $G' = G$ or $G' = \bar{G}$. Let k be an integer with $0 < k < |V|$, the digraphs G and G' are *k -hypomorphic* (resp. *$(-k)$ -hypomorphic*) if for every k -element (resp. $(|V| - k)$ -element) subset X of V , the induced subdigraphs $G_{\upharpoonright X}$ and $G'_{\upharpoonright X}$ are isomorphic. The digraphs G and G' are *$(\leq k)$ -hypomorphic* if they are t -hypomorphic for each integer $t \leq k$. A digraph G is *k -reconstructible* (resp. *$(-k)$ -reconstructible*) if any digraph k -hypomorphic (resp. $(-k)$ -hypomorphic) to G is isomorphic to G . A digraph G is *$(\leq k)$ -reconstructible* if any digraph $(\leq k)$ -hypomorphic to G is isomorphic to G . The digraphs G and G' are *isomorphic up to complementation* (resp. *hemimorphic*) if G' is isomorphic to G or \bar{G} (resp. to G or G^*). The digraphs G' and G are *hereditarily isomorphic* [19] if for each nonempty subset X of V , the digraphs $G_{\upharpoonright X}$ and $G'_{\upharpoonright X}$ are isomorphic. They are *hered-*

itarily isomorphic up to complementation [4] if they are hereditarily isomorphic, or G' and \overline{G} are hereditarily isomorphic. Let k be a positive integer, the digraphs G and G' are k -hypomorphic up to complementation (resp. k -hemimorphic) if for every k -element subset X of V , the induced subdigraphs $G'_{\upharpoonright X}$ and $G_{\upharpoonright X}$ are isomorphic up to complementation (resp. hemimorphic). The digraphs G and G' are $(\leq k)$ -hypomorphic up to complementation (resp. $(\leq k)$ -hemimorphic) if they are t -hypomorphic up to complementation (resp. t -hemimorphic) for each integer $t \leq k$. A digraph G is k -reconstructible up to complementation (resp. k -half-reconstructible) if any digraph k -hypomorphic up to complementation (resp. k -hemimorphic) to G is isomorphic up to complementation (resp. hemimorphic) to G . A digraph G is $(\leq k)$ -reconstructible up to complementation (resp. $(\leq k)$ -half-reconstructible) if any digraph $(\leq k)$ -hypomorphic up to complementation (resp. $(\leq k)$ -hemimorphic) to G is isomorphic up to complementation (resp. hemimorphic) to G .

A 3 -cycle is a tournament isomorphic to $\overrightarrow{C_3} := (\{0, 1, 2\}, \{(0, 1), (1, 2), (2, 0)\})$. A *flag* is a digraph hemimorphic to $(\{0, 1, 2\}, \{(0, 1), (1, 2), (2, 1)\})$. A *peak* is a digraph hemimorphic to $(\{0, 1, 2\}, \{(0, 1), (0, 2), (1, 2), (2, 1)\})$ or to $(\{0, 1, 2\}, \{(0, 1), (0, 2)\})$. Let G be a digraph, the *positive degree* (resp. *negative degree*) of a vertex x of G , denoted $d_G^+(x)$ (resp. $d_G^-(x)$), is the number of $y \in V(G)$ such that $x \rightarrow_G y$ (resp. $y \rightarrow_G x$). Notice that, here, $d_G^+(x)$ (resp. $d_G^-(x)$) is not the *outdegree* (resp. *indegree*) of the vertex x . The *type* of G is (e, e') where e and e' are respectively the number of full pairs of G and \overline{G} . Let $G = (V, E)$ and $G' = (V, E')$ be two digraphs and $a, b \in V$. We say that $\{a, b\}$ have the same character in G and G' if and only if $G_{\upharpoonright \{a, b\}} \simeq G'_{\upharpoonright \{a, b\}}$.

Let $G = (V, E)$ be a graph, the *degree* of a vertex x of G , denoted $d_G(x)$, is the number of $y \in V(G)$ such that $x \text{---}_G y$.

3 The Gallai decomposition Theorem

Given a digraph $G = (V, E)$, a subset I of V is an *interval* of G if for every $x \in V \setminus I$ either $x \rightarrow_G I$ or $x \leftarrow_G I$ or $x \text{---}_G I$ or $x \dots_G I$. For instance, \emptyset , V and $\{x\}$ (where $x \in V$) are intervals of G , called *trivial intervals*. A digraph is *indecomposable* if all its intervals are trivial, otherwise it is *decomposable*.

The graph Q_n (see Figure 3) is defined in the following manner. For $i \neq j \in \{0, 1, \dots, n-1\}$, $\{i, j\}$ is an edge of Q_n whenever either $i, j \in \{0, 1, \dots, n-3\}$ and $|i-j|=1$ or $\{i, j\} = \{n-2, \ell\}$, where $\ell \in \{0, 1, \dots, n-4\} \cup \{n-1\}$.

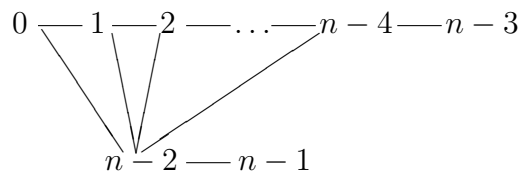


Figure 3: Q_n .

Theorem 3.1 [7] *Let $S = (V, E)$ be an indecomposable graph with $|V| \geq 4$. Let W denotes the set of $x \in V$ such that there is a subset X of V satisfying $S_{\upharpoonright X}$ is isomorphic*

to P_4 and $x \in X$. We have: $|V \setminus W| \leq 1$. Furthermore, if $V \setminus W = \{x\}$, then there are a subset X of V containing x and an isomorphism f from $S_{\downarrow X}$ onto Q_5 such that $f(x) = v_0$.

Theorem 3.2 [7] *Let $S = (V, E)$ be an indecomposable graph with $|V| \geq 5$. For $a \neq b \in V$, there is a subset X of V satisfying: $a, b \in X$ and there is an isomorphism f from $S_{\downarrow X}$ or $\overline{S}_{\downarrow X}$ onto P_k or Q_k , where $k \geq 5$, such that $f(\{a, b\}) = \{0, k - 1\}$.*

We begin with a well-known property of the intervals. Given a digraph $G = (V, E)$, if X and Y are disjoint intervals of G , then $X \xrightarrow{G} Y$, or $X \xleftarrow{G} Y$, or $X \xrightarrow{G} Y$, or $X \dots_G Y$. This property leads to consider interval partitions of G , that is, partitions of V , all the elements of which are intervals of G . The elements of such a partition P become the vertices of the quotient $G/P = (P, E/P)$ of G by P defined as follows: given $X \neq Y \in P$, $(X, Y) \in E/P$ if $(x, y) \in E$ for $x \in X$ and $y \in Y$. Given a digraph $G = (V, E)$, a subset X of V is a *strong interval* [11] of G provided that X is an interval of G and for each interval Y of G , we have: if $X \cap Y \neq \emptyset$, then $X \subseteq Y$ or $Y \subseteq X$. For $|V| \geq 2$, the family of the maximal strong intervals under inclusion which are distinct from V is denoted by $P(G)$. The family $P(G)$ constitutes an interval partition of V . Now we state the Gallai decomposition theorem.

Theorem 3.3 [11] *Given a digraph $G = (V, E)$, with $|V| \geq 2$. The corresponding quotient $G/P(G)$ is a complete digraph or an empty digraph or a total order or an indecomposable digraph with at least 3 vertices.*

The inverse operation of the quotient is the *lexicographic sum* defined as follows: let m be an integer, $m \geq 1$, $S = (\{0, 1, \dots, m - 1\}, E)$ be a digraph and for $i < m$, $G_i = (V_i, E_i)$ be a digraph such that the V_i 's are nonempty and pairwise disjoint. The *lexicographic sum over S of the G_i 's* or simply the *S-sum* of the G_i 's, is the digraph denoted by $S(G_0, G_1, \dots, G_{m-1})$ and defined on the union of the V_i 's as follows: given $x \in V_i$ and $y \in V_j$, where $i, j \in \{0, 1, \dots, m - 1\}$, (x, y) is an edge of $S(G_0, G_1, \dots, G_{m-1})$ if either $i = j$ and $(x, y) \in E_i$ or $i \neq j$ and $(i, j) \in E$: this digraph replaces each vertex i of S by G_i . We say that the vertex i of S is *dilated by G_i* .

From Theorem 3.3, we have immediately this result.

Corollary 3.4 *Given a graph $G = (V, E)$. If G and \overline{G} are connected, if and only if $G = S(G_0, G_1, \dots, G_{m-1})$, where S is an indecomposable graph with at least 4 vertices and G_i is a graph for each $i \in \{0, 1, \dots, m - 1\}$.*

The following result shows the optimality of the value 5 in Theorem 1.3.

Proposition 3.5 *Let $A_3 := \{\{a_0, b_0, c_0\}, \{(a_0, b_0), (b_0, c_0), (c_0, a_0)\}\}$. Let G (resp. G') be the digraph obtained from \overrightarrow{P}_n (resp. $(\overrightarrow{P}_n)^*$) by dilating the vertex 0 by A_3 . Let $U := G \dot{+} G'$. Then G and G' are (≤ 4) -hypomorphic up to complementation, not (≤ 5) -hypomorphic up to complementation, U and \overline{U} are connected, but G and G' are not isomorphic up to complementation, and thus not hereditarily isomorphic up to complementation.*

Proof. Note that A_3 is an oriented cycle isomorphic to C_3 . The graph U is obtained from P_n by dilating the vertex 0 by the empty graph with vertex set $\{a_0, b_0, c_0\}$. By Corollary 3.4, U and \bar{U} are connected. Clearly G and G' are (≤ 4) -hypomorphic up to complementation. The subdigraphs $G_{\upharpoonright\{a_0, b_0, c_0, 1, 2\}}$ and $G'_{\upharpoonright\{a_0, b_0, c_0, 1, 2\}}$ are not isomorphic because $d_{G'}^+(1) = 3$ but $d_{G'}^+(x) \leq 2$ for all vertex x . The subdigraphs $\bar{G}_{\upharpoonright\{a_0, b_0, c_0, 1, 2\}}$ and $G'_{\upharpoonright\{a_0, b_0, c_0, 1, 2\}}$ are not isomorphic because there are full edges in $\bar{G}_{\upharpoonright\{a_0, b_0, c_0, 1, 2\}}$ whereas there are none in $G'_{\upharpoonright\{a_0, b_0, c_0, 1, 2\}}$. Thus G and G' are not (≤ 5) -hypomorphic up to complementation. As $d_G^+(1) = 3$ and there is no vertex x in G of degree 3, and there are full edges in \bar{G} whereas there are none in G' , then G and G' are not isomorphic up to complementation. Thus G and G' are not hereditarily isomorphic up to complementation. \square

4 Preliminary results

Theorem 4.1 [21] *Let G be a graph. If G and \bar{G} are connected then G embeds a P_4 .*

Remark 4.2 *Let G and G' be two digraphs on the same set V such that G and G' are (≤ 3) -hypomorphic up to complementation. Let $U := G \dot{+} G'$ and $a, b, c \in V$. If $G_{\upharpoonright\{a, b, c\}}$ is a peak or a flag, then $U_{\upharpoonright\{a, b, c\}}$ is a complete or an empty graph.*

Lemma 4.3 *Let G and G' be two digraphs on the same set V such that G and G' are (≤ 3) -hypomorphic up to complementation. Let $U := G \dot{+} G'$ and $a, b, c \in V$.*

- 1) *If $E(U_{\upharpoonright\{a, b, c\}})$ or $E(\bar{U}_{\upharpoonright\{a, b, c\}})$ is the set $\{\{a, b\}, \{b, c\}\}$, then $\{a, b\}$ is an oriented pair in G if and only if $\{b, c\}$ is an oriented pair in G .*
- 2) *If $E(U_{\upharpoonright\{a, b, c\}})$ or $E(\bar{U}_{\upharpoonright\{a, b, c\}})$ is the set $\{\{a, b\}\}$ and $\{a, b\}$ is an oriented pair in G , then $\{a, b\}$ is an interval of $G_{\upharpoonright\{a, b, c\}}$ and $G'_{\upharpoonright\{a, b, c\}}$.*
- 3) *If $E(U_{\upharpoonright\{a, b, c\}})$ or $E(\bar{U}_{\upharpoonright\{a, b, c\}})$ is the set $\{\{a, b\}\}$ and $\{a, b\}$ is a neutral pair in G , then $\{a, b\}$ is not an interval of $G_{\upharpoonright\{a, b, c\}}$, and $\{b, c\}$ is an oriented pair in G if and only if $\{a, c\}$ is an oriented pair in G . Moreover if $c \rightarrow_G a$ (resp. $c \xrightarrow{G} a$) then $b \rightarrow_G c$ (resp. $c \dots_G b$).*

Proof. 1) By contradiction. Without loss of generality (W.l.o.g.), we assume that $a \rightarrow_G b$ and $b \xrightarrow{G} c$, then $a \xleftarrow{G'} b$ and $b \dots_{G'} c$. If $\{a, c\}$ is an oriented pair in G not reversed in G' , then $G'_{\upharpoonright\{a, b, c\}} \not\cong G_{\upharpoonright\{a, b, c\}}$ and $G'_{\upharpoonright\{a, b, c\}} \not\cong \bar{G}_{\upharpoonright\{a, b, c\}}$ because exactly one of $G_{\upharpoonright\{a, b, c\}}$ and $G'_{\upharpoonright\{a, b, c\}}$ is a peak, which contradicts the 3-hypomorphy up to complementation. If $\{a, c\}$ is a neutral pair in G not reversed in G' , then $G'_{\upharpoonright\{a, b, c\}} \not\cong G_{\upharpoonright\{a, b, c\}}$ and $G'_{\upharpoonright\{a, b, c\}} \not\cong \bar{G}_{\upharpoonright\{a, b, c\}}$ because exactly one of $G_{\upharpoonright\{a, b, c\}}$ and $G'_{\upharpoonright\{a, b, c\}}$ is a flag, which contradicts the 3-hypomorphy up to complementation.

2) W.l.o.g, we assume that $E(U_{\upharpoonright\{a, b, c\}}) = \{\{a, b\}\}$ Then $E(\bar{U}_{\upharpoonright\{a, b, c\}}) = \{\{a, c\}, \{b, c\}\}$ and $\bar{U} = G \dot{+} G'$. We can assume that $a \rightarrow_G b$, then $a \xrightarrow{G'} b$.

- Case 1. $\{b, c\}$ is an oriented pair in G .

W.l.o.g we assume $b \rightarrow_G c$, thus $b \leftarrow_{\overline{G'}} c$. Since $a \rightarrow_G b$, $b \rightarrow_G c$ and $\{a, c\} \rightarrow_{\overline{G'}} b$, from the 3-hypomorphic up to complementation we have $a \rightarrow_G c$ and the conclusion follows.

• Case 2. $\{b, c\}$ is not an oriented pair in G .

W.l.o.g we can assume $b \text{---}_G c$, thus $b \cdots_{\overline{G'}} c$. From 1) of this lemma, $\{a, c\}$ is a neutral pair in G . Since G and $\overline{G'}$ are 3-hypomorphic up to complementation, $a \text{---}_G c$ and the conclusion follows.

3) We have $E(U_{\uparrow\{a,b,c\}})$ or $E(\overline{U}_{\uparrow\{a,b,c\}}) = \{\{a, b\}\}$ and $\{a, b\}$ is a neutral pair in \overline{G} .

W.l.o.g, we can assume that $E(U_{\uparrow\{a,b,c\}}) = \{\{a, b\}\}$ and $a \text{---}_G b$, so $a \cdots_{\overline{G'}} b$.

• Case 1. $\{a, c\}$ is an oriented pair in G not reversed in G' .

W.l.o.g, we assume that $a \rightarrow_G c$, so $a \rightarrow_{G'} c$. We have $U_{\uparrow\{a,b,c\}}$ is neither a complete graph nor an empty graph, so from Remark 4.2, each of $G_{\uparrow\{a,b,c\}}$ and $G'_{\uparrow\{a,b,c\}}$ is neither a peak nor a flag, so $b \leftarrow_G c$ and $b \leftarrow_{G'} c$.

• Case 2. $\{a, c\}$ is a neutral pair in G not reversed in G' .

W.l.o.g, we assume that $a \text{---}_G c$, so $a \text{---}_{G'} c$. As $a \text{---}_G \{b, c\}$ and $a \text{---}_{G'} c$ and $a \cdots_{G'} b$, then the 3-hypomorphy up to complementation applied to $G_{\uparrow\{a,b,c\}}$ gives $b \cdots_G c$, so $b \cdots_{G'} c$.

In the two cases we have $\{a, b\}$ is not an interval of $G_{\uparrow\{a,b,c\}}$. \square

Lemma 4.4 *Let G and G' be two digraphs on the same vertex set V such that G and G' are (≤ 3) -hypomorphic up to complementation, and $U := G \dot{+} G'$. Let $n \geq 3$ be an integer, $X := \{v_0, v_1, \dots, v_{n-1}\} \subset V$ and $x \in V \setminus X$.*

We assume that $U_{\uparrow X \cup \{x\}} = x \text{---} v_0 \text{---} v_1 \text{---} \dots \text{---} v_{n-1}$.

1) *If $G_{\uparrow X} = v_0 \rightarrow \dots \rightarrow v_{n-1}$, then $G_{\uparrow X \cup \{x\}} = x \rightarrow v_0 \rightarrow v_1 \rightarrow \dots \rightarrow v_{n-1}$ and $G'_{\uparrow X \cup \{x\}} = G^*_{\uparrow X \cup \{x\}}$.*

2) *If $G_{\uparrow X} = \overrightarrow{P}_n^f$, then $G_{\uparrow X \cup \{x\}}$ is isomorphic to $\overrightarrow{P}_{n+1}^f$ by an isomorphism f such that $f(v_i) = i + 1$ for each $i \in \{0, \dots, n - 1\}$ and $f(x) = 0$, and $G'_{\uparrow X \cup \{x\}} = G^*_{\uparrow X \cup \{x\}}$.*

Proof. 1) We have $E(U_{\uparrow\{x,v_0,v_1\}}) = \{\{x, v_0\}, \{v_0, v_1\}\}$ and $v_0 \rightarrow_G v_1$, then 1) of Lemma 4.3 gives $\{x, v_0\}$ is an oriented pair in G , reversed in G' , let $j \in \{2, 3 \dots n - 1\}$, we have $E(U_{\uparrow\{x,v_0,v_j\}}) = \{\{x, v_0\}\}$, then 2) of Lemma 4.3 applied to $\{x, v_0, v_j\}$ gives that $\{x, v_0\}$ is an interval of $G_{\uparrow\{x,v_0,v_j\}}$. As $v_0 \cdots_G v_j$, thus $x \cdots_G v_j$ and $x \cdots_{G'} v_j$. We have $U_{\uparrow\{x,v_1,v_2\}} = x \cdots v_1 \text{---} v_2$, $x \cdots_G v_2$ and $v_1 \rightarrow_G v_2$, then 2) of Lemma 4.3 gives $x \cdots_G v_1$ and $x \cdots_{G'} v_1$. As $v_0 \text{---}_G v_1$ and $x \cdots_G v_1$ then, from Remark 4.2, $G_{\uparrow\{x,v_0,v_1\}}$ is not a peak, thus $x \rightarrow_G v_0$ and $x \leftarrow_{G'} v_0$. Then, $G_{\uparrow X \cup \{x\}} = x \rightarrow v_0 \rightarrow v_1 \rightarrow \dots \rightarrow v_{n-1}$ and $G'_{\uparrow X \cup \{x\}} = G^*_{\uparrow X \cup \{x\}}$.

2) The proof is similar to that of first assertion. \square

Lemma 4.5 *Let G and G' be two digraphs on the same vertex set V such that G and G' are (≤ 4) -hypomorphic up to complementation, and $U := G \dot{+} G'$. Let $X := \{v_0, v_1, v_2, v_3\} \subset V$. If $U_{\uparrow X} = v_0 \text{---} v_1 \text{---} v_2 \text{---} v_3$, we have :*

1) *If $\{v_0, v_1\}$ is a neutral pair in G , then*

$$\{G_{\uparrow X}, G'_{\uparrow X}\} = \{H, \overline{H^*}\} \text{ or } \{G_{\uparrow X}, G'_{\uparrow X}\} = \{H^*, \overline{H}\},$$

where $H := v_1 \rightarrow v_3 \rightarrow v_0 \rightarrow v_2$.

2) If $(v_0 \rightarrow_G v_1 \text{ and } v_1 \rightarrow_G v_2)$ or $(v_0 \leftarrow_G v_1 \text{ and } v_1 \leftarrow_G v_2)$, then

$$\{G_{|X}, G'_{|X}\} = \left\{ \overrightarrow{P}_4, \left(\overrightarrow{P}_4 \right)^* \right\} \text{ or } \{G_{|X}, G'_{|X}\} = \left\{ \overrightarrow{P}_4^f, \left(\overrightarrow{P}_4^f \right)^* \right\}.$$

3) If $(v_0 \rightarrow_G v_1, v_1 \leftarrow_G v_2)$ or $(v_0 \leftarrow_G v_1 \text{ and } v_1 \rightarrow_G v_2)$, then

$$\{G_{|X}, G'_{|X}\} = \{v_0 < v_2 < v_1 < v_3, v_1 < v_0 < v_3 < v_2\}$$

$$\text{or } \{G_{|X}, G'_{|X}\} = \{v_2 < v_3 < v_0 < v_1, v_3 < v_1 < v_2 < v_0\}.$$

Proof. 1) As $\{v_0, v_1\}$ is a neutral pair in G , w.l.o.g, we assume that $v_0 \text{---}_G v_1$. Then $v_0 \dots_{G'} v_1$. We have $E(U_{|\{v_0, v_1, v_2\}}) = \{\{v_0, v_1\}, \{v_1, v_2\}\}$ and $v_0 \text{---}_G v_1$, so 1) of Lemma 4.3 applied to $\{v_0, v_1, v_2\}$ gives $\{v_1, v_2\}$ is a neutral pair in G reversed in G' . We have $E(U_{|\{v_1, v_2, v_3\}}) = \{\{v_1, v_2\}, \{v_2, v_3\}\}$, so 1) of Lemma 4.3 applied to $\{v_1, v_2, v_3\}$ gives $\{v_2, v_3\}$ is a neutral pair in G reversed in G' . According to the nature of the pair $\{v_1, v_2\}$, we have the following cases:

• Case 1. $v_1 \text{---}_G v_2$.

Then $v_1 \dots_{G'} v_2$. We have $v_0 \dots_U v_2$, then the 3-hypomorphy up to complementation applied to $\{v_0, v_1, v_2\}$ gives $\{v_0, v_2\}$ is an oriented pair in G not reversed in G' . We assume that $v_0 \rightarrow_G v_2$ and $v_0 \rightarrow_{G'} v_2$ (resp. $v_0 \leftarrow_G v_2$ and $v_0 \leftarrow_{G'} v_2$). As $U_{|\{v_0, v_2, v_3\}} = v_0 \dots v_2 \text{---} v_3$, then 3) of Lemma 4.3 gives $v_0 \leftarrow_G v_3$ and $v_0 \leftarrow_{G'} v_3$ (resp. $v_0 \rightarrow_G v_3$ and $v_0 \rightarrow_{G'} v_3$). As $U_{|\{v_0, v_1, v_3\}} = v_3 \dots v_0 \text{---} v_1$, then 3) of Lemma 4.3 gives $v_1 \rightarrow_G v_3$ and $v_1 \rightarrow_{G'} v_3$ (resp. $v_1 \leftarrow_G v_3$ and $v_1 \leftarrow_{G'} v_3$). Since $v_1 \text{---}_U v_2$ and $v_1 \dots_U v_3$, from Remark 4.2, $G_{|\{v_1, v_2, v_3\}}$ is not a flag, so $v_2 \text{---}_G v_3$ and $v_2 \dots_{G'} v_3$. Then $G'_{|\{v_0, v_1, v_2, v_3\}} = H$ and $G_{|\{v_0, v_1, v_2, v_3\}} = \overline{H}^*$ (resp. $G_{|\{v_0, v_1, v_2, v_3\}} = \overline{H}$ and $G'_{|\{v_0, v_1, v_2, v_3\}} = H^*$).

• Case 2. $v_1 \dots_G v_2$.

Then $v_1 \text{---}_{G'} v_2$. As $v_0 \dots_U v_2$ and $v_1 \text{---}_U v_2$ then, from Remark 4.2, $G_{|\{v_0, v_1, v_2\}}$ is not a flag, so $\{v_0, v_2\}$ is a neutral pair in G not reversed in G' . W.l.o.g. we can assume that $v_0 \text{---}_G v_2$, so $v_0 \text{---}_{G'} v_2$. Since $E(U_{|\{v_0, v_2, v_3\}}) = \{\{v_2, v_3\}\}$ and $\{v_2, v_3\}$ is a neutral pair in G , then 3) of Lemma 4.3 gives $v_0 \dots_G v_3$ and $v_0 \dots_{G'} v_3$. We have $v_0 \dots_{G'} \{v_1, v_3\}$, $v_0 \dots_G v_3$ and $v_0 \text{---}_G v_1$, so the 3-hypomorphy up to complementation applied to $\{v_0, v_1, v_3\}$ gives $v_1 \text{---}_{G'} v_3$, so $v_1 \text{---}_G v_3$. We have $v_1 \text{---}_{G'} \{v_2, v_3\}$, $v_1 \dots_G v_2$ and $v_1 \text{---}_G v_3$, then the 3-hypomorphy up to complementation applied to $\{v_1, v_2, v_3\}$ gives $v_2 \dots_{G'} v_3$, so $v_2 \text{---}_G v_3$. Then $G_{|\{v_0, v_1, v_2, v_3\}}$ and $G'_{|\{v_0, v_1, v_2, v_3\}}$ have respectively the types (4,2) and (3,3), so $G'_{|\{v_0, v_1, v_2, v_3\}} \not\cong G_{|\{v_0, v_1, v_2, v_3\}}$ and $G'_{|\{v_0, v_1, v_2, v_3\}} \not\cong \overline{G}_{|\{v_0, v_1, v_2, v_3\}}$, that contradict the 4-hypomorphy up to complementation.

2) • Case 1. $v_0 \rightarrow_G v_1$ and $v_1 \rightarrow_G v_2$.

Then $v_1 \rightarrow_{G'} v_0$ and $v_2 \rightarrow_{G'} v_1$. We have $v_0 \dots_U v_2$, if $\{v_0, v_2\}$ is an oriented pair in G , then one of the subdigraphs $G_{|\{v_0, v_1, v_2\}}$ and $G'_{|\{v_0, v_1, v_2\}}$ is a 3-cycle and the other is a total order of order 3, that contradict the 3-hypomorphy up to complementation, so $\{v_0, v_2\}$ is a neutral pair in G not reversed in G' , thus $G_{|\{v_0, v_1, v_2\}} = \overrightarrow{P}_3$ or \overrightarrow{P}_3^f , and $G'_{|\{v_0, v_1, v_2\}} = G_{|\{v_0, v_1, v_2\}}^*$. As $U_{|\{v_0, v_1, v_2, v_3\}}$ is a P_4 then, from Lemma 4.4, $G_{|\{v_0, v_1, v_2, v_3\}} = \overrightarrow{P}_4$ or \overrightarrow{P}_4^f , and $G'_{|\{v_0, v_1, v_2, v_3\}} = G_{|\{v_0, v_1, v_2, v_3\}}^*$.

• Case 2. $v_0 \leftarrow_G v_1$ and $v_1 \leftarrow_G v_2$.

Then $v_0 \rightarrow_{G'} v_1$ and $v_1 \rightarrow_{G'} v_2$. From Case 1, by exchanging the roles of G and G' , we have $G'_{\upharpoonright\{v_0, v_1, v_2, v_3\}} = \overrightarrow{P}_4$ or \overleftarrow{P}_4 , and $G_{\upharpoonright\{v_0, v_1, v_2, v_3\}} = (G')^*_{\upharpoonright\{v_0, v_1, v_2, v_3\}}$.

3) • Case 1. $v_0 \rightarrow_G v_1$ and $v_1 \leftarrow_G v_2$.

Then $v_0 \leftarrow_{G'} v_1$ and $v_1 \rightarrow_{G'} v_2$. As $v_1 \text{---}_U v_2$ and $v_0 \dots_U v_2$ then, from Remark 4.2, $G_{\upharpoonright\{v_0, v_1, v_2\}}$ is not a peak, so $\{v_0, v_2\}$ is an oriented pair in G not reversed in G' . We assume that $v_0 \rightarrow_G v_2$ and $v_0 \rightarrow_{G'} v_2$ (resp. $v_0 \leftarrow_G v_2$ and $v_0 \leftarrow_{G'} v_2$). We have $E(U_{\upharpoonright\{v_1, v_2, v_3\}}) = \{\{v_1, v_2\}, \{v_2, v_3\}\}$ and $v_1 \leftarrow_G v_2$, then 1) of Lemma 4.3 gives $\{v_2, v_3\}$ is an oriented pair in G reversed in G' , we have $E(U_{\upharpoonright\{v_0, v_2, v_3\}}) = \{\{v_2, v_3\}\}$, then 2) of Lemma 4.3 applied to $\{v_0, v_2, v_3\}$ gives $\{v_2, v_3\}$ is an interval of $G_{\upharpoonright\{v_0, v_2, v_3\}}$, so $v_0 \rightarrow_G v_3$ and $v_0 \rightarrow_{G'} v_3$ (resp. $v_0 \leftarrow_G v_3$ and $v_0 \leftarrow_{G'} v_3$). We have $E(U_{\upharpoonright\{v_0, v_1, v_3\}}) = \{\{v_0, v_1\}\}$ and $v_0 \rightarrow_G v_1$, then 2) of Lemma 4.3 applied to $\{v_0, v_1, v_3\}$ gives $\{v_0, v_1\}$ is an interval of $G_{\upharpoonright\{v_0, v_1, v_3\}}$, so $v_1 \rightarrow_G v_3$ and $v_1 \rightarrow_{G'} v_3$ (resp. $v_1 \leftarrow_G v_3$ and $v_1 \leftarrow_{G'} v_3$). We have $v_1 \leftarrow_G v_2$, $v_1 \rightarrow_G v_3$ and $v_1 \rightarrow_{G'} \{v_2, v_3\}$ (resp. $v_1 \rightarrow_{G'} v_2$, $v_1 \leftarrow_{G'} v_3$ and $v_1 \leftarrow_G \{v_2, v_3\}$), then the 3-hypomorphy up to complementation applied to $\{v_1, v_2, v_3\}$ gives $v_2 \rightarrow_G v_3$, so $v_2 \leftarrow_{G'} v_3$ (resp. $v_2 \leftarrow_{G'} v_3$, so $v_2 \rightarrow_G v_3$), thus $G_{\upharpoonright X} = v_0 < v_2 < v_1 < v_3$ and $G'_{\upharpoonright X} = v_1 < v_0 < v_3 < v_2$ (resp. $G_{\upharpoonright X} = v_2 < v_3 < v_0 < v_1$ and $G'_{\upharpoonright X} = v_3 < v_1 < v_2 < v_0$).

• Case 2. $v_0 \leftarrow_G v_1$ and $v_1 \rightarrow_G v_2$.

Then $v_0 \rightarrow_{G'} v_1$ and $v_1 \leftarrow_{G'} v_2$. From Case 1, by exchanging the roles of G and G' , we have $G'_{\upharpoonright X} = v_0 < v_2 < v_1 < v_3$ and $G_{\upharpoonright X} = v_1 < v_0 < v_3 < v_2$ or $G'_{\upharpoonright X} = v_2 < v_3 < v_0 < v_1$ and $G_{\upharpoonright X} = v_3 < v_1 < v_2 < v_0$. \square

Proposition 4.6 *Let G and G' be two digraphs on the same vertex set V , (≤ 5)-hypomorphic up to complementation. Let $U := G \dot{+} G'$. If U and \overline{U} are connected and G is not a tournament, then there exists $X \subset V$, such that $G_{\upharpoonright X} \simeq \overrightarrow{P}_4$ or \overleftarrow{P}_4 , and $G'_{\upharpoonright X} = G_{\upharpoonright X}^*$ or $G'_{\upharpoonright X} = \overline{G^*}_{\upharpoonright X}$.*

Proof. From Theorem 4.1, there exists $X := \{u_0, u_1, u_2, u_3\} \subset V$ such that $u_0 \text{---} u_1 \text{---} u_2 \text{---} u_3$ is an induced P_4 of U . The hypotheses of Lemma 4.5 are satisfied. If we have 1) or 2) of Lemma 4.5, then we conclude.

Now we consider that only the situation 3) of Lemma 4.5 holds. (\star)

That is if $X := \{u_0, u_1, u_2, u_3\} \subset V$ such that $u_0 \text{---} u_1 \text{---} u_2 \text{---} u_3$ is an induced P_4 of U , then $\{G_{\upharpoonright X}, G'_{\upharpoonright X}\} = \{u_0 < u_2 < u_1 < u_3, u_1 < u_0 < u_3 < u_2\}$ or $\{u_2 < u_3 < u_0 < u_1, u_3 < u_1 < u_2 < u_0\}$. From this, if $u_i \rightarrow_G u_{i+1}$ then $u_{i+1} \leftarrow_G u_{i+2}$ for each $i \in \{0, 1\}$.

We will show that the situation (\star) is impossible, which completes our proof.

As G is not a tournament, there exist $a, b \in V(G)$ such that $\{a, b\}$ is a neutral pair in G . From Corollary 3.4, $U = S(U_0, U_1, \dots, U_{m-1})$, where S is an indecomposable graph with at least 4 vertices and the U_i 's are graphs, for each $i \in \{0, 1, \dots, m-1\}$.

Claim 4.7 $\{a, b\} \not\subseteq V(U_i)$, for each $i \in \{0, 1, \dots, m-1\}$.

Proof. We assume by contradiction, that there exists $i \in \{0, 1, \dots, m-1\}$ such that $a, b \in V(U_i)$. Then from Theorem 3.1, there exist $v_0, v_1, v_2, v_3 \in V(U)$ such that one of the following cases holds.

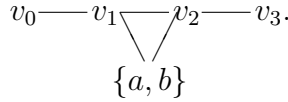
- Case 1. In U , we have $v_0 \text{---} v_1 \text{---} v_2 \text{---} \{a, b\}$.

Let $x \in \{a, b\}$. We have $U_{\uparrow\{v_0, v_1, v_2, x\}} = v_0 \text{---} v_1 \text{---} v_2 \text{---} x$, so from (\star) , $G_{\uparrow\{v_0, v_1, v_2, x\}}$ and $G'_{\uparrow\{v_0, v_1, v_2, x\}}$ are two total orders of order 4, w.l.o.g., we can assume that $G_{\uparrow\{v_0, v_1, v_2, x\}} = v_0 < v_2 < v_1 < x$ and $G'_{\uparrow\{v_0, v_1, v_2, x\}} = v_1 < v_0 < x < v_2$. Then $G_{\uparrow\{v_0, v_1, v_2, a, b\}} = v_0 < v_2 < v_1 < \{a, b\}$ and $G'_{\uparrow\{v_0, v_1, v_2, a, b\}} = v_1 < v_0 < \{a, b\} < v_2$. Clearly, since $G_{\uparrow\{v_2, a, b\}}$ is a peak and $v_2 \text{---}_U \{a, b\}$, from Remark 4.2, $a \text{---}_U b$. Since $G_{\uparrow\{v_1, a, b\}}$ is a peak and $v_1 \dots_U \{a, b\}$, from Remark 4.2, $a \dots_U b$. A contradiction.

- Case 2. In U , we have $v_0 \text{---} \{a, b\} \text{---} v_2 \text{---} v_3$.

The proof is similar to that of Case 1.

- Case 3. In U , we have



As $U_{\uparrow\{v_0, v_1, v_2, v_3\}} = v_0 \text{---} v_1 \text{---} v_2 \text{---} v_3$, from (\star) , $G_{\uparrow\{v_0, v_1, v_2, v_3\}}$ and $G'_{\uparrow\{v_0, v_1, v_2, v_3\}}$ are two total orders of order 4. W.l.o.g., we assume that $G_{\uparrow\{v_0, v_1, v_2, v_3\}} = v_0 < v_2 < v_1 < v_3$ and $G'_{\uparrow\{v_0, v_1, v_2, v_3\}} = v_1 < v_0 < v_3 < v_2$. Let $x \in \{a, b\}$. We have $E(U_{\uparrow\{x, v_2, v_3\}}) = \{\{x, v_2\}, \{v_2, v_3\}\}$ (resp. $E(U_{\uparrow\{x, v_0, v_1\}}) = \{\{v_0, v_1\}, \{x, v_1\}\}$) and $\{v_2, v_3\}$ (resp. $\{v_0, v_1\}$) is an oriented pair in G , then 1) of Lemma 4.3 applied to $\{x, v_2, v_3\}$ (resp. $\{x, v_0, v_1\}$) gives $\{x, v_2\}$ (resp. $\{x, v_1\}$) is an oriented pair in G reversed in G' . Since $E(U_{\uparrow\{x, v_1, v_3\}}) = \{\{x, v_1\}\}$, 2) of Lemma 4.3 applied to $\{x, v_1, v_3\}$ gives $\{x, v_1\}$ is an interval of $G_{\uparrow\{x, v_1, v_3\}}$, we have $v_1 \rightarrow_G v_3$, so $x \rightarrow_G v_3$ and $x \rightarrow_{G'} v_3$. We have $\{x, v_2\} \rightarrow_G v_3$, $x \rightarrow_{G'} v_3$, $v_3 \rightarrow_{G'} v_2$, then the 3-hypomorphy up to complementation applied to $\{x, v_2, v_3\}$ gives $x \rightarrow_{G'} v_2$, so $x \leftarrow_G v_2$. We have $G_{\uparrow\{v_2, a, b\}}$ is a peak and $v_2 \text{---}_U \{a, b\}$, then $a \text{---}_U b$. We have $G_{\uparrow\{v_3, a, b\}}$ is a peak and $v_3 \dots_U \{a, b\}$, then $a \dots_U b$. A contradiction. \square

From Claim 4.7, there are $i, j \in \{0, 1, \dots, m-1\}$, $i \neq j$, such that $a \in V(U_i)$ and $b \in V(U_j)$. For each $X := \{v_0, v_1, v_2, v_3\} \subset V$, if $v_0 \text{---} v_1 \text{---} v_2 \text{---} v_3$ is an induced P_4 of U , then from (\star) , $G_{\uparrow\{v_0, v_1, v_2, v_3\}}$ and $G'_{\uparrow\{v_0, v_1, v_2, v_3\}}$ are total orders, so $\{a, b\}$ is not a subset of X and $m \geq 5$. From Theorem 3.2, there is a subset $Y := \{v_0, v_1, \dots, v_{m-1}\}$ of $V(S)$ satisfying: $a, b \in Y$ and there is an isomorphism f from $U_{\uparrow Y}$ or $\bar{U}_{\uparrow Y}$ onto P_m or Q_m , such that $f(\{a, b\}) = \{v_0, v_{m-1}\}$.

- Case 1. $U_{\uparrow\{v_0, v_1, \dots, v_{m-1}\}} \simeq P_m$.

W.l.o.g, we can assume that $a = v_0$, $b = v_{m-1}$ and $U_{\uparrow\{v_0, v_1, \dots, v_{m-1}\}} = P_m$. We have for each $i \in \{0, 1, \dots, m-4\}$, $U_{\uparrow\{v_i, v_{i+1}, v_{i+2}, v_{i+3}\}} \simeq P_4$ then, from (\star) , $G_{\uparrow\{v_i, v_{i+1}, v_{i+2}, v_{i+3}\}}$ and $G'_{\uparrow\{v_i, v_{i+1}, v_{i+2}, v_{i+3}\}}$ are total orders, thus $\{v_j, v_{j+1}\}$ is an oriented pair in G reversed in G' for each $j \in \{0, 1, \dots, m-2\}$. For $i \in \{0, 1, \dots, m-4\}$, we have $U_{\uparrow\{v_{m-1}, v_i, v_{i+1}\}} = v_{m-1} \dots v_i \text{---} v_{i+1}$ and $\{v_i, v_{i+1}\}$ is an oriented pair in G , so 2) of Lemma 4.3 applied to $\{v_{m-1}, v_i, v_{i+1}\}$ gives $\{v_i, v_{i+1}\}$ is an interval of $G_{\uparrow\{v_{m-1}, v_i, v_{i+1}\}}$, then $\{v_0, v_1, \dots, v_{m-3}\}$ is an interval of $G_{\uparrow\{v_{m-1}, v_0, v_1, \dots, v_{m-3}\}}$. As $G_{\uparrow\{v_{m-4}, v_{m-3}, v_{m-2}, v_{m-1}\}}$ is a total order, $\{v_{m-3}, v_{m-1}\}$ is an oriented pair in G , then $\{v_0, v_{m-1}\} = \{a, b\}$ is oriented in G . A contradiction.

- Case 2. $U_{\uparrow\{v_0, v_1, \dots, v_{m-1}\}} \simeq Q_m$.

W.l.o.g, we can assume that $a = v_0$, $b = v_{m-1}$ and $U_{\uparrow\{v_0, v_1, \dots, v_{m-1}\}} = Q_m$.

Case 2.1. $m = 5$.

Then $U_{\uparrow\{v_0, v_1, v_2, v_3, v_4\}} = Q_5 =$

$$v_2 \text{---} v_1 \begin{array}{c} \diagdown \\ \diagup \end{array} v_3 \text{---} v_4 \\ v_0$$

, $a = v_0$ and $b = v_4$.

so $x \dots_G v_0$ and $x \dots_{G'} v_0$.

In G we have $v_0 \rightarrow v_1 \rightarrow \{x, v_2\} \rightarrow v_3$ and in G' we have $v_0 \leftarrow v_1 \leftarrow \{x, v_2\} \leftarrow v_3$, so $G'_{\uparrow X \cup \{x\}} \not\cong G_{\uparrow X \cup \{x\}}$. By types, $G'_{\uparrow X \cup \{x\}} \not\cong \overline{G}_{\uparrow X \cup \{x\}}$. We get a contradiction with the 5-hypomorphy up to complementation.

Case 1.3. $x \text{---}_U \{v_0, v_3\}$.

As $E(\overline{U}_{\uparrow \{x, v_0, v_2\}}) = \{\{v_0, v_2\}, \{v_2, x\}\}$ and $v_0 \dots_G v_2, 1)$ of Lemma 4.3 gives $\{x, v_2\}$ is a neutral pair in G . Since $E(\overline{U}_{\uparrow \{x, v_2, v_3\}}) = \{\{x, v_2\}\}$ (resp. $E(\overline{U}_{\uparrow \{x, v_1, v_2\}}) = \{\{x, v_2\}\}$ and $v_1 \rightarrow_G v_2$), 3) of Lemma 4.3 applied to $\{x, v_3, v_2\}$ (resp. $\{x, v_1, v_2\}$) gives $x \leftarrow_G v_3$ and $x \rightarrow_{G'} v_3$ (resp. $x \rightarrow_G v_1$ and $x \leftarrow_{G'} v_1$). We have $E(\overline{U}_{\uparrow \{x, v_0, v_3\}}) = \{\{v_0, v_3\}\}$, thus 3) of Lemma 4.3 applied to $\{x, v_0, v_3\}$ gives $x \rightarrow_G v_0$ and $x \leftarrow_{G'} v_0$. As $E(U_{\uparrow \{x, v_0, v_2\}}) = \{\{x, v_0\}\}$, 2) of Lemma 4.3 applied to $\{x, v_0, v_2\}$ gives $\{x, v_0\}$ is an interval of $G_{\uparrow \{x, v_0, v_2\}}$, then $x \dots_G v_2$ and $x \dots_{G'} v_2$. The induced digraphs $G_{\uparrow \{v_0, v_1, v_2, x\}}$ and $G'_{\uparrow \{v_0, v_1, v_2, x\}}$ are not isomorphic up to complementation, which gives a contradiction with the hypothesis G and G' are (≤ 5)-hypomorphic up to complementation.

• Case 2. $x \text{---}_U \{v_1, v_2\}$.

Case 2.1. $x \dots_U \{v_0, v_3\}$.

We have $E(\overline{U}_{\uparrow \{x, v_1, v_3\}}) = \{\{x, v_3\}, \{v_1, v_3\}\}$ and $v_1 \dots_G v_3$ (resp. $E(\overline{U}_{\uparrow \{x, v_0, v_2\}}) = \{\{x, v_0\}, \{v_0, v_2\}\}$ and $v_0 \dots_G v_2$), then 1) of Lemma 4.3 gives $\{x, v_3\}$ (resp. $\{x, v_0\}$) is a neutral pair in G . We have $E(\overline{U}_{\uparrow \{x, v_2, v_3\}}) = \{\{x, v_3\}\}$ and $v_2 \rightarrow_G v_3$ (resp. $E(\overline{U}_{\uparrow \{x, v_0, v_1\}}) = \{\{x, v_0\}, \{x, v_1\}\}$ and $v_0 \rightarrow_G v_1$), then 3) of Lemma 4.3 applied to $\{x, v_2, v_3\}$ (resp. $\{v_0, v_1, x\}$) gives $v_2 \leftarrow_G x$ and $v_2 \rightarrow_{G'} x$ (resp. $v_1 \rightarrow_G x$ and $v_1 \leftarrow_{G'} x$). We have $E(U_{\uparrow \{x, v_1, v_3\}}) = \{\{x, v_1\}\}$ (resp. $E(U_{\uparrow \{x, v_0, v_2\}}) = \{\{x, v_2\}\}$), then 2) of Lemma 4.3 applied to $\{x, v_1, v_3\}$ (resp. $\{v_0, v_2, x\}$) gives $\{x, v_1\}$ (resp. $\{x, v_2\}$) is an interval of $G_{\uparrow \{x, v_1, v_3\}}$ (resp. $G_{\uparrow \{v_0, v_2, x\}}$) then $x \dots_G v_3$ and $x \dots_{G'} v_3$ (resp. $x \dots_G v_0$ and $x \dots_{G'} v_0$). By types, $G'_{\uparrow \{v_0, v_1, v_2, x\}} \not\cong \overline{G}_{\uparrow \{v_0, v_1, v_2, x\}}$. If σ is an isomorphism from $G_{\uparrow \{v_0, v_1, v_2, x\}}$ onto $G'_{\uparrow \{v_0, v_1, v_2, x\}}$, then $\sigma(v_1) = v_1$ because v_1 is the only vertex in $\{v_0, v_1, v_2, x\}$, whose not adjacent to any neutral pair in $G_{\uparrow \{v_0, v_1, v_2, x\}}$; now since $d_{G_{\uparrow \{v_0, v_1, v_2, x\}}}^+(v_1) = 2$ and $d_{G'_{\uparrow \{v_0, v_1, v_2, x\}}}^+(v_1) = 1$, we deduce that $G'_{\uparrow \{v_0, v_1, v_2, x\}} \not\cong G_{\uparrow \{v_0, v_1, v_2, x\}}$. A contradiction.

Case 2.2. $x \text{---}_U v_3$ and $x \dots_U v_0$ or $x \text{---}_U v_0$ and $x \dots_U v_3$.

W.l.o.g., we can assume that $x \text{---}_U v_3$ and $x \dots_U v_0$.

We do the same proof as Case 1.2. In G we have $v_0 \rightarrow v_1 \rightarrow \{x, v_2\} \rightarrow v_3$ and in G' we have $v_0 \leftarrow v_1 \leftarrow \{x, v_2\} \leftarrow v_3$, so $G'_{\uparrow X \cup \{x\}}$ and $G_{\uparrow X \cup \{x\}}$ are not 5-hypomorphic up to complementation, a contradiction.

Case 2.3. $x \text{---}_U \{v_0, v_3\}$.

According to the nature of $\{x, v_2\}$ in G , we can distinguish the following subcases.

Case 2.3.1. $x \rightarrow_G v_2$ or $x \leftarrow_G v_2$.

W.l.o.g. we can suppose $x \rightarrow_G v_2$. As $x \text{---}_U v_2$ then $x \leftarrow_{G'} v_2$. We have $E(\overline{U}_{\uparrow \{x, v_0, v_2\}}) = \{\{v_0, v_2\}\}$, $v_0 \dots_G v_2$ and $x \rightarrow_G v_2$. So, 3) of Lemma 4.3 applied to $\{x, v_0, v_2\}$ gives $x \leftarrow_G v_0$ and $x \rightarrow_{G'} v_0$. We have $E(\overline{U}_{\uparrow \{x, v_0, v_3\}}) = \{\{v_0, v_3\}\}$ and $v_0 \dots_G v_3$, then 3) of Lemma 4.3 applied to $\{x, v_0, v_3\}$ gives $x \rightarrow_G v_3$ and $x \leftarrow_{G'} v_3$. We have $E(\overline{U}_{\uparrow \{x, v_1, v_3\}}) = \{\{v_1, v_3\}\}$ and $v_1 \dots_G v_3$. So 3) of Lemma 4.3 applied to $\{x, v_1, v_3\}$ gives $x \leftarrow_G v_1$ and $x \rightarrow_{G'} v_1$. We have that x is the only vertex in $\{v_0, v_2, v_3, x\}$, which is not adjacent to any neutral pair in $G_{\uparrow \{v_0, v_2, v_3, x\}}$. As $d_{G_{\uparrow \{v_0, v_2, v_3, x\}}}^+(x) \neq d_{G'_{\uparrow \{v_0, v_2, v_3, x\}}}^+(x)$, then $G'_{\uparrow \{v_0, v_2, v_3, x\}} \not\cong G_{\uparrow \{v_0, v_2, v_3, x\}}$.

$G_{|\{v_0, v_2, v_3, x\}}$. Moreover $G'_{|\{v_0, v_2, v_3, x\}} \not\cong \overline{G}_{|\{v_0, v_2, v_3, x\}}$ because their types are distinct. We get a contradiction with the 4-hypomorphy up to complementation.

Case 2.3.2. $x \dots_G v_2$.

Then $x \dots_{G'} v_2$. As $v_2 \dots_G \{x, v_0\}$, $v_0 \dots_{G'} v_2$ and $x \dots_{G'} v_2$, thus $x \dots_G v_0$, so $x \dots_{G'} v_0$. As $v_0 \dots_{G'} \{x, v_3\}$, $v_0 \dots_G v_3$ and $x \dots_G v_0$, then $x \dots_{G'} v_3$, so $x \dots_G v_3$. As $v_3 \dots_G \{x, v_1\}$, $v_1 \dots_{G'} v_3$ and $x \dots_{G'} v_3$, then $x \dots_G v_1$, so $x \dots_{G'} v_1$. Since $G_{|\{v_0, v_2, v_3, x\}}$ and $G'_{|\{v_0, v_2, v_3, x\}}$ have respectively the types (1, 4) and (2, 3), $G'_{|\{v_0, v_2, v_3, x\}}$ and $G_{|\{v_0, v_2, v_3, x\}}$ are not isomorphic up to complementation, a contradiction.

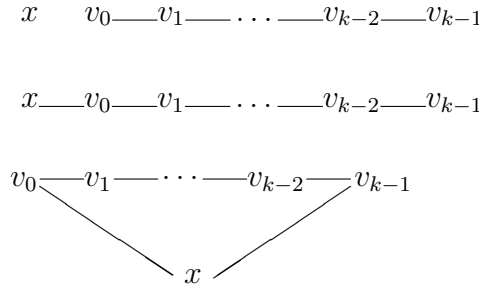
Case 2.3.3. $x \dots_G v_2$.

We do the same proof as Case 2.3.2. □

From Lemma 5.1, we obtain the following result.

Corollary 5.2 *Let G and G' be two digraphs on the same vertex set V such that G and G' are (≤ 5) -hypomorphic up to complementation. Let $U := G \dot{+} G'$, $X := \{v_0, v_1, \dots, v_{k-1}\} \subset V$ and $x \in V \setminus X$. If $G_{|X} = \overrightarrow{P}_k$ or \overrightarrow{P}_k^f , and $G'_{|X} = G^*_{|X}$ then,*

- 1) $x \dots_U \{v_1, \dots, v_{k-2}\}$.
- 2) *Up to isomorphism, $U_{|X \cup \{x\}}$ is one of the following graphs:*

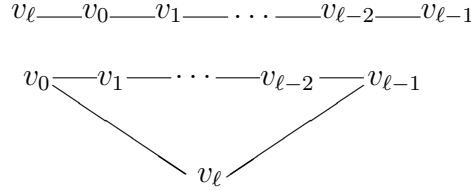


Proposition 5.3 *Let G and G' be two digraphs on the same set V of $n \geq 4$ vertices, such that G and G' are (≤ 5) -hypomorphic up to complementation and $U := G \dot{+} G'$ is connected. Let $X \subset V$.*

- 1) *If $G_{|X} \simeq \overrightarrow{P}_4$ and $G'_{|X} = G^*_{|X}$, then $G \simeq \overrightarrow{P}_n$ or $G \simeq \overrightarrow{C}_n$, and $G' = G^*$.*
- 2) *If $G_{|X} \simeq \overrightarrow{P}_4$ and $G'_{|X} = \overline{G}^*_{|X}$, then $G \simeq \overrightarrow{P}_n$ or $G \simeq \overrightarrow{C}_n$, and $G' = \overline{G}^*$.*
- 3) *If $G_{|X} \simeq \overrightarrow{P}_4^f$ and $G'_{|X} = G^*_{|X}$, then $G \simeq \overrightarrow{P}_n^f$ or $G \simeq \overrightarrow{C}_n^f$, and $G' = G^*$.*
- 4) *If $G_{|X} \simeq \overrightarrow{P}_4^f$ and $G'_{|X} = \overline{G}^*_{|X}$, then $G \simeq \overrightarrow{P}_n^f$ or $G \simeq \overrightarrow{C}_n^f$, and $G' = \overline{G}^*$.*

Proof. It suffices to prove 1) because 2), 3) and 4) are consequences of 1). As $G_{|X} \simeq \overrightarrow{P}_4$, let \overrightarrow{P}_ℓ be a largest induced oriented path in G reversed in G' . Clearly, $\ell \geq 4$. W.l.o.g. we can assume $\overrightarrow{P}_\ell = v_0 \longrightarrow v_1 \longrightarrow \dots \longrightarrow v_{\ell-1}$ and $G'_{|V(\overrightarrow{P}_\ell)} = v_0 \longleftarrow v_1 \longleftarrow \dots \longleftarrow v_{\ell-1}$.

So $U_{|V(\vec{P}_\ell)} = v_0 \text{---} v_1 \text{---} \dots \text{---} v_{\ell-2} \text{---} v_{\ell-1}$. If $V(\vec{P}_\ell) = V$, then $G = \vec{P}_\ell$ and $G' = G^*$. In the rest of this proof, we assume that $V \setminus V(\vec{P}_\ell) \neq \emptyset$. As U is connected, there exists $v_\ell \in V \setminus V(\vec{P}_\ell)$, such that $U_{|V(\vec{P}_\ell) \cup \{v_\ell\}}$ is connected. From 2) of Corollary 5.2, up to isomorphism, $U_{|V(\vec{P}_\ell) \cup \{v_\ell\}}$ is one of the following graphs:



If $U_{|V(\vec{P}_\ell) \cup \{v_\ell\}}$ is the graph $v_\ell \text{---} v_0 \text{---} v_1 \text{---} \dots \text{---} v_{\ell-2} \text{---} v_{\ell-1}$ then, from Lemma 4.4, we have $G_{|V(\vec{P}_\ell) \cup \{v_\ell\}} = v_\ell \rightarrow v_0 \rightarrow v_1 \rightarrow \dots \rightarrow v_{\ell-1}$ and $G'_{|V(\vec{P}_\ell) \cup \{v_\ell\}} = G^*_{|V(\vec{P}_\ell) \cup \{v_\ell\}}$, that contradict the fact that \vec{P}_ℓ is the largest induced oriented path in G reversed in G' . Then $U_{|V(\vec{P}_\ell) \cup \{v_\ell\}}$ is the second graph.

If there is x in $V \setminus (V(\vec{P}_\ell) \cup \{v_\ell\})$, we have $v_{i-1} \text{---} v_i \text{---} v_{i+1} \text{---} v_{i+2}$ for each $i \in \{1, \dots, \ell-2\}$, then from 1) of Lemma 5.1, $x \dots_U v_i$ for each $i \in \{1, \dots, \ell-1\}$, also we have $v_{\ell-1} \text{---} v_\ell \text{---} v_0 \text{---} v_1$, so from 1) of Lemma 5.1, $x \dots_U \{v_0, v_\ell\}$. Thus $x \dots_U (V(\vec{P}_\ell) \cup \{v_\ell\})$. As U is connected, $V = V(\vec{P}_\ell) \cup \{v_\ell\}$.

We have $G_{|\{v_0, v_1, \dots, v_{\ell-2}\}} = v_0 \rightarrow v_1 \rightarrow \dots \rightarrow v_{\ell-2}$ and $U_{|\{v_\ell, v_0, v_1, \dots, v_{\ell-2}\}} = v_\ell \text{---} v_0 \text{---} v_1 \text{---} \dots \text{---} v_{\ell-3} \text{---} v_{\ell-2}$, then from Lemma 4.4, $G_{|\{v_\ell, v_0, v_1, \dots, v_{\ell-2}\}} = v_\ell \rightarrow v_0 \rightarrow v_1 \rightarrow \dots \rightarrow v_{\ell-2}$ and $G'_{|\{v_\ell, v_0, v_1, \dots, v_{\ell-2}\}} = G^*_{|\{v_\ell, v_0, v_1, \dots, v_{\ell-2}\}}$.

We have $\bar{U}_{|\{v_{\ell-2}, v_{\ell-1}, v_\ell\}} = v_{\ell-2} \text{---} v_\ell \dots v_{\ell-1}$, $v_{\ell-2} \rightarrow_G v_{\ell-1}$ and $v_{\ell-2} \dots_G v_\ell$, then 3) Lemma 4.3 applied to $\{v_{\ell-2}, v_{\ell-1}, v_\ell\}$ gives $v_{\ell-1} \rightarrow_G v_\ell$ and $v_{\ell-1} \leftarrow_{G'} v_\ell$. Then $G = \overrightarrow{C_{\ell+1}}$ and $G' = G^*$.

Proof of Theorem 1.3. If G is a tournament then from Proposition 1.1, G and G' are total orders. If G is not a tournament, then using Proposition 4.6, there exists a subset X of $V(G)$ such that, $G_{|X} \simeq \overrightarrow{P}_4$ or \overrightarrow{P}_4^f , and $G'_{|X} = G^*_{|X}$ or $\overline{G^*}_{|X}$; then we conclude using Proposition 5.3.

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