Isomorphism for Tournaments of Small Twin Width

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— Abstract -

We prove that isomorphism of tournaments of twin width at most k can be decided in time $k^{O(\log k)}n^{O(1)}$. This implies that the isomorphism problem for classes of tournaments of bounded or moderately growing twin width is in polynomial time. By comparison, there are classes of undirected graphs of bounded twin width that are isomorphism complete, that is, the isomorphism problem for the classes is as hard as the general graph isomorphism problem. Twin width is a graph parameter that has been introduced only recently (Bonnet et al., FOCS 2020), but has received a lot of attention in structural graph theory since then. On directed graphs, it is functionally smaller than clique width. We prove that on tournaments (but not on general directed graphs) it is also functionally smaller than directed tree width (and thus, the same also holds for cut width and directed path width). Hence, our result implies that tournament isomorphism testing is also fixed-parameter tractable when parameterized by any of these parameters.

Our isomorphism algorithm heavily employs group-theoretic techniques. This seems to be necessary: as a second main result, we show that the combinatorial Weisfeiler-Leman algorithm does not decide isomorphism of tournaments of twin width at most 35 if its dimension is o(n). (Throughout this abstract, n is the order of the input graphs.)

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1 Introduction

The tournament isomorphism problem (TI) was recognized as a particularly interesting special case of the graph isomorphism problem (GI) early-on. Already in 1983, Babai and Luks [3] proved that TI is solvable in time $n^{O(\log n)}$; it took 33 more years for Babai [2] to prove that the general GI is in quasi-polynomial time. An important fact that makes TI more accessible than GI is that tournaments always have solvable automorphism groups. This is a consequence of the observation that the automorphism groups of tournaments have odd order and the famous Feit-Thompson Theorem [18] stating that all groups of odd order are solvable. However, even Babai's powerful new machinery did not help us to

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78:2 Isomorphism for Tournaments of Small Twin Width

improve the upper bound for TI, as one might have hoped. But TI is not only special from a group-theoretic perspective. Another remarkable result, due to Schweitzer [42], states that TI reduces to the problem of deciding whether a tournament has a nontrivial automorphism; the so-called *rigidity problem*. It is an open question whether the same holds for general graphs.

While there is an extensive literature on GI restricted to classes of graphs (see [25] for a recent survey), remarkably little is known for restrictions of TI. Ponomarenko [40] proved that TI is in polynomial time for tournaments whose automorphism group contains a regular cyclic subgroup, and recently Arvind, Ponomarenko, and Ryabov [1] proved that TI is in polynomial time for edge-colored tournaments where at least one edge color induces a (strongly) connected spanning subgraph of bounded degree (even fixed-parameter tractable when parameterized by the out-degree). While both of these results are very interesting from a technical perspective, they consider classes of tournaments that would hardly be called natural from a graph-theoretic point of view. Natural graph parameters that have played a central role in the structural theory of tournaments developed by Chudnovsky, Seymour and others [13, 14, 15, 16, 19] are cut width and path width. The more recent theory of structural sparsity [20, 21, 36, 37] highlights *clique width* and *twin width*. Here twin width is the key parameter. Not only is it functionally smaller than the other parameters, which means that if cut width, path width, or clique width is bounded, then twin width is bounded as well, it is also known [23] that a class of tournaments has bounded twin width if and only if it has a property known as monadic dependence (NIP). Dependence is a key property studied in classical model theory. A class of graphs is monadically dependent if and only if all set systems definable in this class by a first-order transduction have bounded VC dimension. This property seems to characterize precisely the graph classes that are regarded as structurally sparse. Since twin width of graphs and binary relational structures has been introduced in [11], it received a lot of attention in algorithmic structural graph theory [5, 6, 7, 8, 9, 10, 21, 22, 23, 29, 44]. (We defer the somewhat unwieldy definition of twin width to Section 2.3.) Our main result states that tournament isomorphism is fixed-parameter tractable when parameterized by twin width.

▶ **Theorem 1.1.** The isomorphism problem for tournaments of twin width at most k can be solved in time $k^{O(\log k)} \cdot n^{O(1)}$.

Interestingly, isomorphism testing for undirected graphs of bounded twin width is as hard as the general GI. This follows easily from the fact that an $\Omega(\log n)$ -subdivision of every graph with n vertices has bounded twin width [5]. Once more, this demonstrates the special role of the tournament isomorphism problem, though here the reason is not group-theoretic, but purely combinatorial.

Note that the dependence on the twin width k of the algorithm in Theorem 1.1 is subexponential, so our result implies that TI is in polynomial time even for tournaments of twin width $2^{O(\sqrt{\log n})}$. Since twin width is functionally smaller than clique width, our result implies that TI is also fixed-parameter tractable when parameterized by clique width. Additionally, we prove that the twin width of a tournament is functionally smaller than its *directed tree width*, a graph parameter originally introduced in [31]. Since the directed tree width of every directed graph is smaller than its cut width or directed path width, the same also holds for these two parameters. Hence, TI is fixed-parameter tractable also when parameterized by directed tree width, directed path width or cut width. To the best of our knowledge, this was not known for any of these parameters. The fact that twin width is functionally smaller than directed tree width, directed path width and cut width on tournaments is interesting in its own right, because this result does not extend to general directed graphs (for any of the three parameters).

Our proof of Theorem 1.1 heavily relies on group-theoretic techniques. In a nutshell, we show that bounded twin width allows us to cover a tournament by a sequence of directed graphs that have a property resembling bounded degree sufficiently closely to apply a group-theoretic machinery going back to Luks [33] and developed to great depth since then (see, e.g., [2, 3, 27, 35, 38]). Specifically, we generalize arguments that have been introduced by Arvind et al. [1] for TI on edge-colored tournaments where at least one edge color induces a spanning subgraph of bounded out-degree.

Yet one may wonder if this heavy machinery is even needed to prove our theorem, in particular in view of the fact that on many natural graph classes, including, for example, undirected graphs of bounded clique width [26], the purely combinatorial Weisfeiler-Leman algorithm is sufficient to decide isomorphism (see, e.g., [24, 32]). We prove that this is not the case for tournaments of bounded twin width.

▶ **Theorem 1.2.** For every $k \ge 2$ there are non-isomorphic tournaments T_k and T'_k of order $|V(T_k)| = |V(T'_k)| = O(k)$ and twin width at most 35 that are not distinguished by the k-dimensional Weisfeiler-Leman algorithm.

We remark that it was known before that the Weisfeiler-Leman algorithm fails to decide tournament isomorphism. Indeed, Dawar and Kopczynski (unpublished) proved that for every $k \geq 2$ there are non-isomorphic tournaments U_k and U'_k of order $|V(U_k)| = |V(U'_k)| = O(k)$ that are not distinguished by the k-dimensional Weisfeiler-Leman algorithm. Theorem 1.2 strengthens this result by constructing tournaments where additionally the twin width is bounded by a fixed constant.

The paper is organized as follows. After introducing the necessary preliminaries in Section 2, Theorem 1.1 is proved in Sections 3 and 4. First, we give our main combinatorial arguments in Section 3. After that, the mainly group-theoretic isomorphism algorithm of Theorem 1.1 is presented in Section 4. Theorem 1.2 is proved in Section 5. Finally, in Section 6 we compare twin width to other width measures for directed graphs. All omitted proofs can be found in the full version.

2 Preliminaries

2.1 Graphs

Graphs in this paper are usually directed. We often emphasize this by calling them "digraphs". However, when we make general statements about graphs, this refers to directed graphs and includes undirected graphs a special case (directed graphs with a symmetric edge relation). We denote the vertex set of a graph G by V(G) and the edge relation by E(G). The vertex set V(G) is always finite and non-empty. The edge relation is always anti-reflexive, that is, graphs are loop-free, and there are no parallel edges. For a digraph G and a vertex $v \in V(G)$, we denote the set of out-neighbors and in-neighbors of v by $N_+(v)$ and $N_-(v)$, respectively. Also, the *out-degree* and *in-degree* of v are denoted by $\deg_+(v) \coloneqq |N_+(v)|$ and $\deg_-(v) \coloneqq |N_-(v)|$, respectively. Furthermore, $E_+(v)$ and $E_-(v)$ denote the set of outgoing and incoming edges into v, respectively. For $X \subseteq V(G)$, we write G[X] to denote the subgraph of G induced on X. For two sets $X, Y \subseteq V(G)$ we write $E_G(X, Y) \coloneqq \{(v, w) \in E(G) \mid v \in X, w \in Y\}$ to denote the set of directed edges from X to Y.

Let G be an undirected graph. A directed graph \vec{G} is an *orientation* of G if, for every undirected edge $\{v, w\} \in E(G)$, exactly one of (v, w) and (w, v) is an edge of \vec{G} , and there are no other edges present in \vec{G} . A *tournament* is an orientation of a complete graph.

78:4 Isomorphism for Tournaments of Small Twin Width

A tournament T is regular if $\deg_+(v) = \deg_+(w)$ for all $v, w \in V(T)$. In this case, $\deg_+(v) = \deg_-(v) = \frac{|V(G)|-1}{2}$ for all $v \in V(T)$. This implies that every regular tournament has an odd number of vertices.

Let G_1, G_2 be two graphs. An *isomorphism* from G_1 to G_2 is a bijection $\varphi \colon V(G_1) \to V(G_2)$ such that $(v, w) \in E(G_1)$ if and only if $(\varphi(v), \varphi(w)) \in E(G_2)$ for all $v, w \in V(G_1)$. We write $\varphi \colon G_1) \cong G_2$ to denote that φ is an isomorphism from G_1 to G_2 . Also, Iso (G_1, G_2) denotes the set of all isomorphisms from G_1 to G_2 . The graphs G_1 and G_2 are *isomorphic* if $Iso(G_1, G_2) \neq \emptyset$. The *automorphism group* of G_1 is $Aut(G_1) \coloneqq Iso(G_1, G_1)$.

An arc coloring of a digraph G is a mapping $\lambda : (E(G) \cup \{(v, v) \mid v \in V(G)\}) \to C$ for some set C of "colors". An arc-colored graph is a triple $G = (V, E, \lambda)$, where (V, E) is a graph an λ an arc coloring of (V, E). Isomorphisms between arc-colored graphs are required to preserve the coloring.

2.2 Partitions and Colorings

Let S be a finite set. A partition of S is a set $\mathcal{P} \subseteq 2^S$ whose elements we refer to as parts, such that any two parts are mutually disjoint, and the union of all parts is S. A partition \mathcal{P} refines another partition \mathcal{Q} , denoted by $\mathcal{P} \preceq \mathcal{Q}$, if for all $P \in \mathcal{P}$ there is some $Q \in \mathcal{Q}$ such that $P \subseteq Q$. We say a partition \mathcal{P} is trivial if $|\mathcal{P}| = 1$, which means that the only part is S, and it is discrete if $|\mathcal{P}| = 1$ for all $P \in \mathcal{P}$.

Every mapping $\chi: S \to C$, for some set C, induces a partition \mathcal{P}_{χ} of S into the sets $\chi^{-1}(c)$ for all c in the range of χ . In this context, we think of χ as a "coloring" of S, the elements $c \in C$ as "colors", and the parts $\chi^{-1}(c)$ of the partition as "color classes". If $\chi': S \to C'$ is another coloring, then we say that χ refines χ' , denoted by $\chi \preceq \chi'$, if $\mathcal{P}_{\chi} \preceq \mathcal{P}_{\chi'}$. The colorings are equivalent (we write $\chi \equiv \chi'$) if $\chi \preceq \chi'$ and $\chi \preceq \chi'$, i.e., $\mathcal{P}_{\chi} = \mathcal{P}_{\chi'}$.

2.3 Twin Width

Twin width [11] is defined for binary relational structures, which in this paper are mostly directed graphs. We need one distinguished binary relation symbol E_{red} that plays a special role in the definition of twin width. Following [11], we refer to elements of E_{red} as red edges. For every structure A, we assume the relation $E_{red}(A)$ to be symmetric and anti-reflexive, that is, the edge relation of an undirected graph, and we refer to the maximum degree of this graph as the red degree of A. If $E_{red}(A)$ is not explicitly defined, we assume $E_{red}(A) = \emptyset$ (and the red degree of A is 0).

Let $A = (V(A), R_1(A), \ldots, R_k(A))$ be a binary relational structure, where V(A) is a non-empty finite vertex set and $R_i(A) \subseteq (V(A))^2$ are binary relations on V(A) (possibly, $R_i = E_{\mathsf{red}}$ for some $i \in [k]$). We call a pair (X, Y) of disjoint subsets of V(A) homogeneous if for all $x, x' \in X$, and all $y, y' \in Y$ it holds that

- (i) $(x, y) \in R_i(A) \Leftrightarrow (x', y') \in R_i(A)$ and $(y, x) \in R_i(A) \Leftrightarrow (y', x') \in R_i(A)$ for all $i \in [k]$, and
- (ii) $(x, y) \notin E_{\mathsf{red}}(A)$ and $(y, x) \notin E_{\mathsf{red}}(A)$.

For a partition \mathcal{P} of V(A), we define A/\mathcal{P} to be the structure with vertex set $V(A/\mathcal{P}) \coloneqq \mathcal{P}$ and relations

 $R_i(A/\mathcal{P}) \coloneqq \{(X,Y) \in \mathcal{P}^2 \mid (X,Y) \text{ is homogeneous and } X \times Y \subseteq R_i(A)\}$

for all $R_i \neq E_{\mathsf{red}}$, and

$$E_{\mathsf{red}}(A/\mathcal{P}) \coloneqq \{ (X,Y) \in \mathcal{P}^2 \mid (X,Y) \text{ is not homogeneous and } X \neq Y \}.$$

A contraction sequence for A is a sequence of partitions $\mathcal{P}_1, \ldots, \mathcal{P}_n$ of V(A) such that $\mathcal{P}_1 = \{\{v\} \mid v \in V(A)\}$ is the discrete partition, $\mathcal{P}_n = \{V(A)\}$ is the trivial partition, and for every $i \in [n-1]$ the partition \mathcal{P}_{i+1} is obtained from \mathcal{P}_i by merging two parts, i.e., there are distinct $P, P' \in \mathcal{P}_i$ such that $\mathcal{P}_{i+1} = \{P \cup P'\} \cup (\mathcal{P}_i \setminus \{P, P'\})$. The width of a contraction sequence $\mathcal{P}_1, \ldots, \mathcal{P}_n$ of A is the minimum k such that for every $i \in [n]$ the structure A/\mathcal{P}_i has red degree at most k. The twin width of A, denoted by tww(A), is the minimum $k \ge 0$ such that A has a contraction sequence of width k.

Note that red edges are introduced as we contract parts of the partitions. However, the structure A we start with may already have red edges, which then have direct impact on its twin width. In particular, the twin width of a graph G may be smaller than the twin width of the structure G^{red} obtained from G by coloring all edges red. This fact is used later.

We also remark that for our isomorphism algorithms, we never have to compute a contraction sequence of minimum width or the twin width.

We state two simple lemmas on basic properties of twin width.

▶ Lemma 2.1 ([11]). Let A be a binary relational structure and $X \subseteq V(A)$. Then tww(A[X]) ≤ tww(A).

▶ Lemma 2.2. Let A be a structure over the vocabulary τ . Then there is a linear order < on V(A) such that tww(A, <) = tww(A).

2.4 Weisfeiler-Leman

In this section, we describe the k-dimensional Weisfeiler-Leman algorithm (k-WL). The algorithm has been originally introduced in its 2-dimensional form by Weisfeiler and Leman [46] (see also [45]). The k-dimensional version, coloring k-tuples, was introduced later by Babai and Mathon (see [12]).

Fix $k \geq 2$, and let G be a graph. For $i \geq 0$, we describe the coloring $\chi_{(i)}^{k,G}$ of $(V(G))^k$ computed in the *i*-th iteration of *k*-WL. For i = 0, each tuple is colored with the isomorphism type of the underlying ordered induced subgraph. So if H is another graph and $\bar{v} =$ $(v_1, \ldots, v_k) \in (V(G))^k$, $\bar{w} = (w_1, \ldots, w_k) \in (V(H))^k$, then $\chi_{(0)}^{k,G}(\bar{v}) = \chi_{(0)}^{k,H}(\bar{w})$ if and only if, for all $i, j \in [k]$, it holds that $v_i = v_j \Leftrightarrow w_i = w_j$ and $(v_i, v_j) \in E(G) \Leftrightarrow (w_i, w_j) \in E(H)$. If G and H are arc-colored, then the colors are also taken into account.

Now let $i \geq 0$. For $\bar{v} = (v_1, \ldots, v_k)$ we define

$$\chi_{(i+1)}^{k,G}(\bar{v}) \coloneqq \left(\chi_{(i)}^{k,G}(\bar{v}), \mathcal{M}_i(\bar{v})\right)$$

where

$$\mathcal{M}_i(\bar{v}) \coloneqq \left\{ \left\{ \left(\chi_{(i)}^{k,G}(\bar{v}[w/1]), \dots, \chi_{(i)}^{k,G}(\bar{v}[w/k]) \right) \mid w \in V(G) \right\} \right\}$$

and $\bar{v}[w/i] := (v_1, \ldots, v_{i-1}, w, v_{i+1}, \ldots, v_k)$ is the tuple obtained from \bar{v} by replacing the *i*-th entry by w (and $\{\{\ldots\}\}$ denotes a multiset).

Clearly, $\chi_{(i+1)}^{k,G} \preceq \chi_{(i)}^{k,G}$ for all $i \ge 0$. So there is a unique minimal $i_{\infty} \ge 0$ such that $\chi_{(i_{\infty}+1)}^{k,G} \equiv \chi_{(i_{\infty})}^{k,G}$ and we write $\chi^{k,G} \coloneqq \chi_{(i_{\infty})}^{k,G}$ to denote the corresponding coloring. The k-dimensional Weisfeiler-Leman algorithm takes as input a (possibly colored) graph G

The k-dimensional Weisfeiler-Leman algorithm takes as input a (possibly colored) graph G and outputs (a coloring that is equivalent to) $\chi^{k,G}$. This can be done in time $O(k^2n^{k+1}\log n)$ [30].

Let H be a second graph. The k-dimensional Weisfeiler-Leman algorithm distinguishes G and H if there is a color $c \in C$ such that

$$\left|\left\{\bar{v}\in (V(G))^k \mid \chi^{k,G}(\bar{v})=c\right\}\right| \neq \left|\left\{\bar{w}\in (V(H))^k \mid \chi^{k,H}(\bar{w})=c\right\}\right|.$$

We write $G \simeq_k H$ to denote that k-WL does not distinguish between G and H.

78:6 Isomorphism for Tournaments of Small Twin Width

A graph G is k-WL-homogeneous if for all $v, w \in V(G)$ it holds that $\chi^{k,G}(v,\ldots,v) = \chi^{k,G}(w,\ldots,w)$.

2.5 Group Theory

For a general background on group theory we refer to [41], whereas background on permutation groups can be found in [17]. Also, basics facts on algorithms for permutation groups are given in [43].

Basics for Permutation Groups. A permutation group acting on a set Ω is a subgroup $\Gamma \leq \text{Sym}(\Omega)$ of the symmetric group. The size of the permutation domain Ω is called the *degree* of Γ . If $\Omega = [n] \coloneqq \{1, \ldots, n\}$, then we also write S_n instead of $\text{Sym}(\Omega)$. For $A \subseteq \Omega$ and $\gamma \in \Gamma$ let $\gamma(A) \coloneqq \{\gamma(\alpha) \mid \alpha \in A\}$. The set A is Γ -invariant if $\gamma(A) = A$ for all $\gamma \in \Gamma$.

Let $\theta: \Omega \to \Omega'$ be a bijection. We write $\Gamma \theta \coloneqq \{\gamma \theta \mid \gamma \in \Gamma\}$ for the set of bijections from Ω to Ω' obtained from concatenating a permutation from Γ and θ . Note that $(\gamma \theta)(\alpha) = \theta(\gamma(\alpha))$ for all $\alpha \in \Omega$.

A set $S \subseteq \Gamma$ is a generating set for Γ if for every $\gamma \in \Gamma$ there are $\delta_1, \ldots, \delta_k \in S$ such that $\gamma = \delta_1 \ldots \delta_k$. In order to perform computational tasks for permutation groups efficiently the groups are represented by generating sets of small size (i.e., polynomial in the size of the permutation domain). Indeed, most algorithms are based on so-called strong generating sets, which can be chosen of size quadratic in the size of the permutation domain of the group and can be computed in polynomial time given an arbitrary generating set (see, e.g., [43]).

Group-Theoretic Methods for Isomorphism Testing. In this work, we shall be interested in a particular subclass of permutation groups. Let Γ be a group and let $\gamma, \delta \in \Gamma$. The *commutator* of γ and δ is $[\gamma, \delta] := \gamma^{-1}\delta^{-1}\gamma\delta$. The *commutator subgroup* $[\Gamma, \Gamma]$ of Γ is the unique subgroup of Γ generated by all commutators $[\gamma, \delta]$ for $\gamma, \delta \in \Gamma$. Note that $[\Gamma, \Gamma]$ is a normal subgroup of Γ . The *derived series of* Γ is the sequence of subgroups $\Gamma^{(0)} \succeq \Gamma^{(1)} \trianglerighteq \Gamma^{(2)} \trianglerighteq \ldots$ where $\Gamma^{(0)} := \Gamma$ and $\Gamma^{(i+1)} := [\Gamma^{(i)}, \Gamma^{(i)}]$ for all $i \ge 0$. A group Γ is *solvable* if there is some $i \ge 0$ such that $\Gamma^{(i)}$ is the trivial group (i.e., it only contains the identity element). The next theorem follows from the Feit-Thompson Theorem stating that every group of odd order is solvable.

► Theorem 2.3. Let T be a tournament. Then Aut(T) is solvable.

Next, we state several basic group-theoretic algorithms for isomorphism testing.

▶ Theorem 2.4 ([3, Theorem 4.1]). There is an algorithm that, given two tournaments T_1 and T_2 , computes Iso (T_1, T_2) in time $n^{O(\log n)}$.

Note that $\operatorname{Iso}(T_1, T_2)$ may be of size exponential in the number of vertices of T_1 and T_2 . However, if T_1 and T_2 are isomorphic (i.e., $\operatorname{Iso}(T_1, T_2) \neq \emptyset$), we have $\operatorname{Iso}(T_1, T_2) = \operatorname{Aut}(T_1)\varphi$ where $\varphi \in \operatorname{Iso}(T_1, T_2)$ is an arbitrary isomorphism from T_1 to T_2 . Hence, the set $\operatorname{Iso}(T_1, T_2)$ can be represented by a generating set for $\operatorname{Aut}(T_1)$ of size polynomial in $|V(T_1)|$ and a single element $\varphi \in \operatorname{Iso}(T_1, T_2)$. Let us stress at this point that all isomorphism sets computed by the various algorithms discussed in this work are represented in this way.

Let G_1 and G_2 be two (colored) directed graphs. Also let $\Gamma \leq \text{Sym}(V(G_1))$ be a permutation group and let $\theta: V(G_1) \to V(G_2)$ be a bijection. We define

 $\operatorname{Iso}_{\Gamma\theta}(G_1, G_2) \coloneqq \operatorname{Iso}(G_1, G_2) \cap \Gamma\theta = \{\varphi \in \Gamma\theta \mid \varphi \colon G_1 \cong G_2\}$

78:7

and $\operatorname{Aut}_{\Gamma}(G_1) := \operatorname{Iso}_{\Gamma}(G_1, G_1)$. Note that $\operatorname{Aut}_{\Gamma}(G_1) \leq \Gamma$ and, if $\operatorname{Iso}_{\Gamma\theta}(G_1, G_2) \neq \emptyset$, then $\operatorname{Iso}_{\Gamma\theta}(G_1, G_2) = \operatorname{Aut}_{\Gamma}(G_1)\varphi$ where $\varphi \in \operatorname{Iso}(G_1, G_2)$ is an arbitrary isomorphism from G_1 to G_2 .

▶ **Theorem 2.5** ([3, Corollary 3.6]). Let $G_1 = (V_1, E_1, \lambda_1)$ and $G_1 = (V_2, E_2, \lambda_2)$ be two arc-colored directed graphs. Also let $\Gamma \leq \text{Sym}(V_1)$ be a solvable group and $\theta: V_1 \to V_2$ a bijection. Then $\text{Iso}_{\Gamma\theta}(G_1, G_2)$ can be computed in polynomial time.

3 Small Degree Partition Sequences

In the following, we design an isomorphism test for tournaments of twin width k which runs in time $k^{O(\log k)}n^{O(1)}$. On a high level, the algorithm essentially proceeds in three phases. First, we use well-established group-theoretic methods going back to [3, 33] to reduce to the case where both input tournaments are 2-WL-homogeneous (without increasing the twin width). In the second step, we identify a substructure of an input tournament T (that is 2-WL-homogeneous) that has some kind of bounded-degree property. More concretely, we apply the 2-dimensional Weisfeiler-Leman algorithm and compute a sequence of colors c_1, \ldots, c_ℓ in the image of the 2-WL coloring $\chi^{2,T}$ so that the subgraph induced by all edges with a color from c_1, \ldots, c_ℓ has a certain type of bounded-degree property. After that, we rely on the computed bounded-degree structure to determine isomorphisms based on the group-theoretic graph isomorphism machinery. Similar tools have also been used in [1] to solve isomorphism of k-spanning tournaments. However, as we shall see below, the bounded-degree property guaranteed by the second step is weaker than the notion of k-spanning tournaments, which requires us to further extend the methods from [1].

In this section, we implement the second phase and prove the key combinatorial lemma (Lemma 3.6) underlying our isomorphism algorithm. Our arguments rely on the notion of *mixed neighbors* for a pair of vertices. For a pair $v, w \in V(T)$ of vertices we let

$$M(v,w) \coloneqq \left(N_{-}(v) \cap N_{+}(w)\right) \cup \left(N_{+}(v) \cap N_{-}(w)\right).$$

$$\tag{1}$$

We call the elements of M(v, w) the *mixed neighbors* of (v, w), and we call md(v, w) := |M(v, w)| the *mixed degree* of (v, w). The following simple observation links the mixed degree to twin width.

▶ **Observation 3.1.** There is an edge $(v, w) \in E(T)$ such that $md(v, w) \leq tww(T)$.

Proof. Let $k \coloneqq \operatorname{tww}(T)$ and let $\mathcal{P}_1, \ldots, \mathcal{P}_n$ be a contraction sequence of T of width k. Let $\{v, w\}$ be the unique 2-element part in \mathcal{P}_2 . Then $\operatorname{md}(v, w) = \operatorname{md}(w, v) \leq k$, and either $(v, w) \in E(T)$ or $(w, v) \in E(T)$.

In the following, let G_T be the directed graph with vertex set $V(G_T) \coloneqq V(T)$ and edge set $E(G_T) \coloneqq \{(v, w) \in E(T) \mid \operatorname{md}(v, w) \leq \operatorname{tww}(T)\}$. The next lemma implies that G_T has maximum out-degree at most $2 \cdot \operatorname{tww}(T) + 1$.

▶ Lemma 3.2. Suppose $k \ge 1$. Let T be a tournament and let $v \in V(T)$. Also let

 $W \coloneqq \{ w \in N_+(v) \mid \mathrm{md}(v, w) \le k \}.$

Then $|W| \leq 2k+1$.

78:8 Isomorphism for Tournaments of Small Twin Width

Proof. Let $\ell := |W|$. The induced subtournament T[W] has a vertex w of in-degree at least $(\ell - 1)/2$. Since $\operatorname{md}(v, w) \leq k$ and $(v, w') \in E(T)$ for all $w' \in W$, we have

$$|\{w' \in W \mid (w', w) \in E(T)\}| \le k.$$

Thus $\frac{\ell-1}{2} \leq k$, which implies that $|W| = \ell \leq 2k+1$.

So G_T is a subgraph of T of maximum out-degree $d \coloneqq 2 \cdot \text{tww}(T) + 1$. We remark that similar arguments also show that G_T has maximum in-degree at most d (technically, this property is not required by our algorithm, but it is helpful for the following explanations). Now, first suppose that G_T is strongly connected. Then the edges of G_T define a (strongly) connected spanning subgraph of maximum degree 2d (in-degree plus out-degree). In this situation, we can directly use the algorithm from [1] to test isomorphism in time $d^{O(\log d)}n^{O(1)}$.

So suppose G_T is not strongly connected. If T is 2-WL-homogeneous, then G_T is also not weakly connected (i.e., the undirected version of G_T is not connected). In this case, the basic idea is to identify further edges to be added to decrease the number of connected components while keeping some kind of bounded-degree property.

In the following, let \mathcal{Q} be a partition of V(T) that is non-trivial, that is, has at least two parts. The reader is encouraged to think of \mathcal{Q} as the partition into the (weakly) connected components of G_T , but the following results hold for any non-trivial partition \mathcal{Q} . We call an edge $(v, v') \in E(T)$ cross-cluster with respect to \mathcal{Q} if it connects distinct $Q, Q' \in \mathcal{Q}$. For a cross-cluster edge (v, v') with $Q \ni v, Q' \ni v'$, we let

$$\mathcal{M}_{\mathcal{Q}}(v,v') \coloneqq \left\{ Q'' \in \mathcal{Q} \setminus \{Q,Q'\} \mid Q'' \cap M(v,v') \neq \emptyset \right\}$$

and $\operatorname{md}_{\mathcal{Q}}(v, v') \coloneqq |\mathcal{M}_{\mathcal{Q}}(v, v')|.$

The next two lemmas generalize Observation 3.1 and Lemma 3.2.

▶ Lemma 3.3. Let T be a tournament and suppose Q is a non-trivial partition of V(T). Then there is a cross-cluster edge $(v, w) \in E(T)$ such that $md_Q(v, w) \leq tww(T)$.

Proof. Let $k \coloneqq \operatorname{tww}(T)$ and let $\mathcal{P}_1, \ldots, \mathcal{P}_n$ be a contraction sequence of T of width k. Note that \mathcal{P}_1 refines \mathcal{Q} and \mathcal{P}_n does not refine \mathcal{Q} , because \mathcal{Q} is nontrivial. Let $i \ge 1$ be minimal such that \mathcal{P}_{i+1} does not refine \mathcal{Q} .

Let $P, P' \in \mathcal{P}_i$ denote the parts merged in the step from \mathcal{P}_i to \mathcal{P}_{i+1} . Since \mathcal{P}_i refines \mathcal{Q} , there are $Q, Q' \in \mathcal{Q}$ such that $P \subseteq Q$ and $P' \subseteq Q'$. Moreover, $Q \neq Q'$, because \mathcal{P}_{i+1} does not refine \mathcal{Q} . We pick arbitrary elements $v \in P$ and $w \in P'$ such that $(v, w) \in E(T)$ (if $(w, v) \in E(T)$, we swap the roles of P and P'). Then (v, w) is a cross-cluster edge with respect to \mathcal{Q} .

Let $P_1, \ldots, P_{k'}$ be a list of all $P'' \in \mathcal{P}_{i+1} \setminus \{P \cup P'\}$ such that the pair $(P \cup P', P'')$ is not homogeneous. Then $k' \leq k$ by the definition of twin width. Since $\mathcal{P}_i \setminus \{P, P'\} = \mathcal{P}_{i+1} \setminus \{P \cup P'\}$ and \mathcal{P}_i refines \mathcal{Q} , there are $Q_1, \ldots, Q_{k'} \in \mathcal{Q}$ such that $P_i \subseteq Q_i$ for all $i \in [k']$.

Now let $Q'' \in \mathcal{Q} \setminus \{Q, Q', Q_1, \ldots, Q_{k'}\}$. Suppose for contradiction that $Q'' \cap M(v, w) \neq \emptyset$, and pick an element $w' \in Q'' \cap M(v, w)$. Then there is a $P'' \in \mathcal{P}_i \setminus \{P, P', P_1, \ldots, P_{k'}\} = \mathcal{P}_{i+1} \setminus \{P \cup P', P_1, \ldots, P_{k'}\}$ such that $w' \in P''$. But then the pair $(P \cup P', P'')$ is not homogeneous, which is a contradiction. So $Q'' \cap M(v, w) = \emptyset$. This implies that $\mathcal{M}_{\mathcal{Q}}(v, w) \subseteq \{Q_1, \ldots, Q_{k'}\}$. In particular, $\mathrm{md}_{\mathcal{Q}}(v, w) \leq k' \leq k$.

▶ Lemma 3.4. Suppose $k \ge 1$. Let T be a tournament and let Q be a non-trivial partition of V(T). Also let $Q \in Q$ and $v \in Q$. Let

$$\mathcal{W} \coloneqq \{Q' \in \mathcal{Q} \setminus \{Q\} \mid \exists w \in Q' \colon (v, w) \in E(T) \land \mathrm{md}_{\mathcal{Q}}(v, w) \le k\}.$$

Then $|\mathcal{W}| \leq 2k+1$.



Figure 1 The figure shows part of a tournament T. The colors c_1 and c_2 are shown in blue and green, respectively. Also, the parts of the partition Q_1 are highlighted in gray. Note that only green edges, which are outgoing from the middle part, are shown.

The proof is very similar to the proof of Lemma 3.2.

Proof. Let $\ell := |\mathcal{W}|$ and suppose $\mathcal{W} = \{Q_1, \ldots, Q_\ell\}$. For every $i \in [\ell]$ pick an element $w_i \in Q_i$ such that $(v, w_i) \in E(T)$ and $\operatorname{md}_{\mathcal{Q}}(v, w_i) \leq k$. We define $W := \{w_1, \ldots, w_\ell\}$. Then there is some $w \in W$ such that

$$|\{w' \in W \mid (w', w) \in E(T)\}| \ge \frac{\ell - 1}{2},$$

because the induced subtournament T[W] has a vertex of in-degree at least $(\ell - 1)/2$. Since $\operatorname{md}_{\mathcal{Q}}(v, w) \leq k$ and $(v, w') \in E(T)$ for all $w' \in W$, it follows that

$$|\{w' \in W \mid (w', w) \in E(T)\}| \le k.$$

Thus $\frac{\ell-1}{2} \leq k$, which implies that $|\mathcal{W}| = \ell \leq 2k + 1$.

Now, suppose we color all edges (v, w) of T with $md(v, w) \leq tww(T)$ using the color $c_1 = \mathsf{blue}$ (see Figure 1). Let \mathcal{Q}_1 be the partition into the (weakly) connected components of the graph induced by the blue edges and suppose that \mathcal{Q}_1 is non-trivial. We can compute isomorphisms between the different parts of \mathcal{Q}_1 using the algorithm from [1]. Next, let us color all cross-cluster edges $(v, w) \in E(T)$ with $\mathrm{md}_{\mathcal{Q}}(v, w) \leq \mathrm{tww}(T)$ using the color $c_2 =$ green. Then every vertex has outgoing green edges to at most 2 tww(T) + 1 other parts of \mathcal{Q}_1 (see Lemma 3.4). However, since a vertex may have an unbounded number of green neighbors in a single part, the out-degree of the graph induced by the green edges may be unbounded. So it is not possible to use the algorithm from [1] as a black-box on the components induced by blue and green edges. Luckily, the methods used in [1] can be extended to work even in this more general setting (see Section 4). So if the graph induced by the blue and green edges is connected, then we are again done. Otherwise, we let Q_2 denote the partition into (weakly) connected components of the graph induced by the blue and green edges. Now, we can continue in the same fashion identifying colors c_3, c_4, \ldots and corresponding partitions $\mathcal{Q}_3, \mathcal{Q}_4, \ldots$ until the graph induced by all edges of colors c_1, \ldots, c_ℓ is eventually connected.

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78:10 Isomorphism for Tournaments of Small Twin Width

Below, we provide a lemma that computes the corresponding sequence of partitions and edge colors using 2-WL. To state the lemma in its cleanest form, we restrict our attention to tournaments that are 2-WL-homogeneous. Recall that a tournament T is 2-WL-homogeneous if for all $v, w \in V(T)$ is holds that $\chi^{2,T}(v, v) = \chi^{2,T}(w, w)$.

We also require another piece of notation. For a directed graph G and a set of colors $C \subseteq \{\chi^{2,G}(v,w) \mid (v,w) \in E(G)\}$ we write G[C] for the directed graph with vertex set V(G[C]) := V(G) and edge set

$$E(G[C]) \coloneqq \{(v, w) \in E(G) \mid \chi^{2, G} \in C\}.$$

To prove Lemma 3.6 we need the following lemma about the connected components of the graphs G[C].

▶ Lemma 3.5. Let G be a 2-WL-homogeneous graph, and let C a set of colors in the range of $\chi^{2,G}$. Then the weakly connected components of G[C] equal the strongly connected components of G[C].

▶ Lemma 3.6. Let T be a 2-WL-homogeneous tournament of twin width tww(T) ≤ k. Then there is a sequence of partitions $\{\{v\} \mid v \in V(T)\} = \mathcal{Q}_0, \ldots, \mathcal{Q}_\ell = \{V(T)\}$ of V(T) where \mathcal{Q}_{i-1} refines \mathcal{Q}_i for all i, and a sequence of colors c_1, \ldots, c_ℓ in the range of $\chi^{2,T}$ such that (1) \mathcal{Q}_i is the partition into the strongly connected components of $T[\{c_1, \ldots, c_i\}]$ for every

- $i \in [\ell]$, and
- (2) for every $i \in [\ell]$ and every $v \in V(T)$ it holds that

$$|\{Q \in \mathcal{Q}_{i-1} \mid \exists w \in Q \colon \chi^{2,T}(v,w) = c_i\}| \le 2k+1.$$

Moreover, there is a polynomial-time algorithm that, given a tournament T and an integer $k \geq 1$, computes the desired sequences $\mathcal{Q}_0, \ldots, \mathcal{Q}_\ell$ and c_1, \ldots, c_ℓ or concludes that tww(T) > k.

Proof. We set $Q_0 = \{\{v\} \mid v \in V(T)\}$ and inductively define a sequence of partitions and colors as follows. Let $i \geq 0$ and suppose we already defined partitions $Q_0 \prec \cdots \prec Q_i$ and colors c_1, \ldots, c_i . If $Q_i = \{V(T)\}$, we set $\ell \coloneqq i$ and complete both sequences. Otherwise, there is a cross-cluster edge (v_{i+1}, w_{i+1}) with respect to Q_i such that $\operatorname{md}_{Q_i}(v_{i+1}, w_{i+1}) \leq k$ by Lemma 3.3. We set $c_{i+1} \coloneqq \chi^{2,T}(v_{i+1}, w_{i+1})$ and define Q_{i+1} to be the set of weakly connected components of $T[c_1, \ldots, c_{i+1}]$. By Lemma 3.5, these are also the strongly connected components.

First observe that $Q_i \prec Q_{i+1}$ since (v_{i+1}, w_{i+1}) is a cross-cluster edge with respect to Q_i , and v_{i+1}, w_{i+1} are contained in the same part of Q_{i+1} by Lemma 3.5. Also, Property 1 is satisfied by definition. For Property 2 note that every edge $(v, w) \in E(T)$ such that $\chi^{2,G}(v,w) = c_{i+1}$ is a cross-cluster edge with respect to Q_i . So Property 2 follows directly from Lemma 3.4.

Finally, it is clear from the description above that $Q_0 \prec \cdots \prec Q_\ell$ and c_1, \ldots, c_ℓ can be computed in polynomial time, or we conclude that $\operatorname{tww}(T) > k$.

4 The Isomorphism Algorithm

Based on the structural insights summarized in Lemma 3.6, we now design an isomorphism test for tournaments of small twin width.

The strategy of our algorithm is the following. We are given two tournaments T_1 and T_2 , and we want to compute $Iso(T_1, T_2)$. First, we reduce to the case where both T_1 and T_2 are 2-WL-homogeneous.

Towards this end, we start by applying 2-WL and, for j = 1, 2, compute the coloring χ^{2,T_j} . If 2-WL distinguishes the two tournaments, we can immediately conclude that they are non-isomorphic and return $\text{Iso}(T_1, T_2) = \emptyset$.

So suppose that 2-WL does not distinguish the tournaments. Then T_1 is 2-WL-homogeneous if and only if T_2 is 2-WL-homogeneous.

If the T_j are not 2-WL-homogeneous, we rely on the following standard argument. Let c_1, \ldots, c_p be the vertex colors. For $i \in [p]$ and j = 1, 2, let $P_{j,i}$ be the set of all $v \in V(T_j)$ such that $\chi^{2,T_j}(v,v) = c_i$. We recursively compute the sets $\Lambda_i := \operatorname{Iso}(T_1[P_{1,i}], T_2[P_{2,i}])$ for all $i \in [p]$. Note that this is possible since tww($T_1[P_{1,i}]) \leq \operatorname{tww}(T_1)$ and tww($T_2[P_{2,i}]) \leq \operatorname{tww}(T_2)$ for all $i \in [p]$ by Lemma 2.1. If there is some $i \in [p]$ such that $\Lambda_i = \emptyset$, then T_1 and T_2 are non-isomorphic, and we return $\operatorname{Iso}(T_1, T_2) = \emptyset$. Otherwise, the set Λ_i is a coset of $\Gamma_i := \operatorname{Aut}(T_1[P_{1,i}])$ for all $i \in [p]$, i.e., $\Lambda_i = \Gamma_i \theta_i$ for some bijection $\theta_i : P_{1,i} \to P_{2,i}$. As the automorphism group of a tournament, Γ_i is solvable (see Theorem 2.3). Moreover, since the color classes $P_{1,i}$ are invariant under automorphisms of T_1 , the automorphism group $\Gamma := \operatorname{Aut}(T_1)$ is a subgroup of the direct product $\prod_i \Gamma_i$, which is also a solvable group. Also, $\operatorname{Iso}(T_1, T_2) \subseteq \Gamma\theta$ where $\theta : V(T_1) \to V(T_2)$ is the unique bijection defined via $\theta(v) := \theta_i(v)$ for all $v \in V(T_1)$, where $i \in [p]$ is the unique index such that $v \in P_{1,i}$. So $\operatorname{Iso}(T_1, T_2) = \operatorname{Iso}_{\Gamma\theta}(T_1, T_2)$ can be computed in polynomial time using Theorem 2.5.

So we may assume that T_1 and T_2 are 2-WL-homogeneous. In this case, we apply Lemma 3.6 and obtain colors c_1, \ldots, c_{ℓ} and, for j = 1, 2, a partition sequence $\{\{v\} \mid v \in V(T_j)\} = \mathcal{Q}_{j,0}, \ldots, \mathcal{Q}_{j,\ell} = \{V(T_j)\}$ where $\mathcal{Q}_{j,i-1}$ refines $\mathcal{Q}_{j,i}$ for all $i \in [\ell]$.

Now, we iteratively compute for $i = 0, \ldots, \ell$ the sets $\operatorname{Iso}(T_j[Q], T_{j'}[Q'])$ for all $j, j' \in \{1, 2\}$ and all $Q \in \mathcal{Q}_{j,i}$ and $Q' \in \mathcal{Q}_{j',i}$. For i = 0 this is trivial since all parts have size 1. So suppose i > 0 and consider some elements $j, j' \in \{1, 2\}$ and $Q \in \mathcal{Q}_{j,i}, Q' \in \mathcal{Q}_{j',i}$. For simplicity, let us assume that j = 1 and j' = 2. Our goal is to compute $\operatorname{Iso}(T_1[Q], T_2[Q'])$. To do so, we exploit that we already computed all isomorphisms between all pairs of subgraphs of $T_1[Q]$ and $T_2[Q']$ induced by sets $R \in \mathcal{Q}_{1,i-1} \cup \mathcal{Q}_{2,i-1}$ and for which $R \subseteq Q$ or $R \subseteq Q'$. The next lemma describes the key subroutine of the main algorithm which achieves this goal. Note that, on the last level ℓ , we compute the set $\operatorname{Iso}(T_1, T_2)$ since $\mathcal{Q}_{j,\ell} = \{V(T_j)\}$ for both $j \in \{1, 2\}$.

To state the lemma, we need additional terminology. Let $T = (V, E, \lambda)$ be an arc-colored tournament. A partition \mathcal{Q} of V is λ -definable if there is a set of colors $C \subseteq \{\lambda(v, w) \mid v = w \lor (v, w) \in E\}$ such that

$$v \sim Q w \iff \lambda(v, w) \in C$$

for all $v, w \in V$ such that v = w or $(v, w) \in E$. We also say that \mathcal{Q} is λ -defined by C. If \mathcal{Q} is λ -defined by C then we can partition the colors in the range of λ into the colors in C, which we call *intra-cluster* colors, and the remaining colors, which we call *cross-cluster* colors. Note that if a color c is intra-cluster, then for all $(v, w) \in E$ with $\lambda(v, w) = c$ it holds that $v, w \in Q$ for some $Q \in \mathcal{Q}$, and if c is cross-cluster, then for all $(v, w) \in E$ with $\lambda(v, w) = c$ it holds that (v, w) is a cross-cluster edge, that is, $v \in Q$ and $w \in Q'$ for distinct $Q, Q' \in \mathcal{Q}$.

▶ Lemma 4.1. There is an algorithm that, given

- (A) an integer $d \geq 1$;
- (B) two arc-colored tournaments $T_1 = (V_1, E_1, \lambda_1)$ and $T_2 = (V_2, E_2, \lambda_2)$;
- (C) a set of colors C and for j = 1, 2 a partition Q_j of V_j that is λ_j -defined by C;
- (D) a color c^* that is cross-cluster with respect to Q_j for j = 1, 2 and
 - for every $v \in V_j$ it holds that

$$\left|\left\{Q \in \mathcal{Q}_j \mid \exists w \in Q \colon (v, w) \in E_j \land \lambda_j(v, w) = c^*\right\}\right| \le d;$$

78:12 Isomorphism for Tournaments of Small Twin Width

= for

$$F_j \coloneqq \left\{ (Q,Q') \in \mathcal{Q}_j^2 \mid Q \neq Q', \exists w \in Q, w' \in Q' \colon (w,w') \in E_j \land \lambda_j(w,w') = c^* \right\}$$

the directed graph $G_j = (\mathcal{Q}_j, F_j)$ is strongly connected; (E) Iso $(T_j[Q], T_{j'}[Q'])$ for every $j, j' \in \{1, 2\}$ and every $Q \in \mathcal{Q}_j, Q' \in \mathcal{Q}_{j'}$,

computes $\operatorname{Iso}(T_1, T_2)$ in time $d^{O(\log d)} \cdot n^{O(1)}$.

The proof builds on the algorithmic ideas presented in [1]. Since it is quite lengthy and technical, we only present a rough idea of the proof; the details can be found in the full version.

Proof Idea. The algorithm fixes an arbitrary vertex $r_1 \in V_1$ and for every $r_2 \in V_2$ computes the set $\text{Iso}((T_1, r_1), (T_2, r_2))$ of all isomorphisms $\varphi \in \text{Iso}(T_1, T_2)$ such that $\varphi(r_1) = r_2$. Observe that $\text{Iso}(T_1, T_2)$ is the union over all these sets.

The central idea is to iteratively compute larger and larger sets $W_{1,i} \subseteq V_1$ and $W_{2,i} \subseteq V_2$ such that

(1.1) there is some $\mathcal{W}_{j,i} \subseteq \mathcal{Q}_j$ such that $W_{j,i} = \bigcup_{Q \in \mathcal{W}_{i,i}} Q$, and

(1.2) $\varphi(W_{1,i}) = W_{2,i}$ for every $\varphi \in \text{Iso}((T_1, r_1), (T_2, r_2))$

and compute the set $\operatorname{Iso}((T_1[W_{1,i}], r_1), (T_2[W_{2,i}], r_2))$. Initially, we set $W_{1,0} \coloneqq R_1$ and $W_{2,0} \coloneqq R_2$ where R_1 and R_2 are the unique parts of \mathcal{Q}_1 and \mathcal{Q}_2 containing r_1 and r_2 , respectively. Note that the set $\operatorname{Iso}((T_1[W_{1,0}], r_1), (T_2[W_{2,0}], r_2))$ can easily be computed from Item E.

Now suppose we already computed Iso($(T_1[W_{1,i}], r_1), (T_2[W_{2,i}], r_2)$) for some $W_{1,i} \subseteq V_1$ and $W_{2,i} \subseteq V_2$ satisfying (I.1) and (I.2). Consider a vertex $u \in W_{1,i}$ that has an outgoing edge of color c^* to a vertex outside of $W_{1,i}$. Note that, if $W_{1,i} \neq V_1$, such a vertex exists by the second part of Item D. We call such a vertex a *boundary vertex*. Let $U_{1,i}$ denote the set of boundary vertices. For a boundary vertex $u \in U_{1,i}$ let $\mathcal{L}_{1,i+1}^u$ denote the set of all parts $Q \in \mathcal{Q}_1$ that are outside of $W_{1,i}$ and contain a vertex $v \in Q$ such that $(u, v) \in E_1$ and $\lambda_1(u, v) = c^*$. Also, we define $L_{1,i+1}^u := \bigcup_{Q \in \mathcal{L}_{1,i+1}^u} Q$. A visualization is given in Figure 2. Note that $|\mathcal{L}_{1,i+1}^u| \leq d$ by the first part of Item D.

For every boundary vertex $u \in U_{1,i}$ we construct an isomorphism-invariant tournament $\widetilde{T}_{1,i+1}^u$ with vertex set $\mathcal{L}_{1,i+1}^u$. Roughly speaking, for two distinct $Q, Q' \in \mathcal{L}_{1,i+1}^u$, in order to decide whether to add (Q, Q') or (Q', Q) to the edge set of $\widetilde{T}_{1,i+1}^u$, we take a majority vote on the edges between Q and Q' in T_1 (if there is a tie, we need to invoke further rules; see the full version for details).

Since $|\mathcal{L}_{1,i+1}^u| \leq d$, the automorphism group of $\widetilde{T}_{1,i+1}^u$ can be computed in time $d^{O(\log d)}$ by Theorem 2.4. Also, for each $Q \in \mathcal{L}_{1,i+1}^u$, the automorphism group of T[Q] is given as part of the input (see Item E). By taking a wreath product, we obtain a solvable permutation group $\Gamma \leq \text{Sym}(L_{1,i+1}^u)$ such that $\text{Aut}(T_1[L_{1,i+1}^u]) \leq \Gamma$. Using Theorem 2.5, this allows us to compute $\text{Aut}(T_1[L_{1,i+1}^u])$ and, more generally, compute the isomorphism sets between the corresponding subgraphs for different boundary vertices $u, u' \in V_1 \cup V_2$.

Now, we extend $W_{1,i}$ by all sets $L_{1,i+1}^u$, $u \in U_{1,i}$, to obtain the next layer $W_{1,i+1}$ (actually, for technical reasons, the final proof proceeds in a slightly different manner); the set $W_{2,i+1}$ is defined analogously. To compute the desired isomorphism set, we proceed as follows. For simplicity, first suppose that all sets $L_{1,i+1}^u$, $u \in U_{1,i}$, are pairwise disjoint. Then, we can again take a wreath product to obtain a solvable permutation group $\Delta \leq$ $\operatorname{Sym}(W_{1,i+1} \setminus W_{1,i})$ such that $\operatorname{Aut}(T_1[W_{1,i+1}], r_1) \leq \operatorname{Aut}(T_1[W_{1,i}], r_1) \times \Delta$. Using Theorem 2.5, this allows us to compute $\operatorname{Aut}(T_1[W_{1,i+1}], r_1)$. Similarly, we can also compute the set $\operatorname{Iso}((T_1[W_{1,i+1}], r_1), (T_2[W_{2,i+1}], r_2))$.



Figure 2 The figure shows the sets $W_{1,i}$ (orange), $U_{1,i}$ (blue) and $L_{1,i+1}^u$ computed in the proof sketch of Lemme 4.1. The color c^* is shown in green and gray regions depict parts of the partition Q_1 .

To cover the case that not all sets $L_{1,i+1}^u$, $u \in U_{1,i}$, are pairwise disjoint, we use the following trick. For each vertex $v \in W_{1,i+1} \setminus W_{1,i}$ let $\mu(v)$ denote the number of boundary vertices $u \in U_{1,i}$ such that $v \in L_{1,i+1}^u$. We replace each $v \in W_{1,i+1} \setminus W_{1,i}$ with $\mu(v)$ copies of the vertex; each copy is associated with one of the corresponding boundary vertices. Now, we can proceed as in the previous case to compute the set of isomorphisms. Afterwards, we rely on group-theoretic algorithms from [35] to "merge" the different copies of the same vertex again to finally obtain the group $\operatorname{Iso}((T_1[W_{1,i+1}], r_1), (T_2[W_{2,i+1}], r_2)).$

Note that the second part of Item D guarantees that we can continue this process until eventually $W_{1,i} = V_1$ and $W_{2,i} = V_2$, at which point we have computed the desired set $\text{Iso}((T_1, r_1), (T_2, r_2))$.

Building on the subroutine from Lemma 4.1, we can now design an isomorphism test for tournaments of bounded twin width following the outline given above.

▶ **Theorem 4.2.** There is an algorithm that, given two tournaments T_1 and T_2 and an integer $k \ge 1$, either concludes that tww(T_1) > k or computes Iso(T_1, T_2) in time $k^{O(\log k)} \cdot n^{O(1)}$.

5 The WL-Dimension of Tournaments of Bounded Twin Width

In this section, we prove Theorem 1.2. To prove that the WL algorithm on its own is unable to determine isomorphisms between tournaments of bounded twin width, we adapt a construction of Cai, Fürer and Immerman [12]. Towards this end, we first describe a construction of directed graphs with large WL dimension, and then argue how to translate those graphs into tournaments while preserving their WL dimension.

In the following, let G be a connected, 3-regular (undirected) graph. Let G^{red} denote the structure obtained from G be replacing every edge with a red edge and let $t := \mathsf{tww}(G^{\mathsf{red}})$.

Let us remark at this point that the Cai-Fürer-Immerman construction [12] replaces each vertex in G with a certain gadget, and those gadgets are connected along the edges of G. In order to bound the twin width of the resulting graph, we start with a graph G for which the

78:14 Isomorphism for Tournaments of Small Twin Width

twin width of G^{red} is bounded.¹ This is because the connections between gadgets are not homogeneous, so when contracting all gadgets in a contraction sequence, we obtain precisely the graph G^{red} which allows to "complete" the contraction sequence using that G^{red} has bounded twin width.

Now, let us formally describe the construction of tournaments with large WL dimension. By Lemma 2.2 there is some linear order < on V(G) such that tww($G^{\text{red}}, <$) = t. Also, let \vec{G} be an arbitrary orientation of G.

Recall that for every $v \in V(G)$ we denote by $E_+(v)$ the set of outgoing edges and $E_-(v)$ the set of incoming edges in \vec{G} . Also, we write E(v) to denote the set of incident (undirected) edges in G. For $a \in \mathbb{Z}_3$ we define

$$M_a(v) \coloneqq \left\{ f \colon E(v) \to \mathbb{Z}_3 \ \Big| \ \sum_{(v,w) \in E_+(v)} f(\{v,w\}) - \sum_{(w,v) \in E_-(v)} f(\{v,w\}) = a \pmod{3} \right\}$$

We also define $F_a(v)$ to contain all pairs $(f,g) \in (M_a(v))^2$ such that, for the minimal element $w \in N_G(v)$ (with respect to <) such that $f(vw) \neq g(vw)$, it holds that

 $f(vw) + 1 = g(vw) \pmod{3}.$

Observe that, for every distinct $f, g \in M_a(v)$, either $(f, g) \in F_a(v)$ or $(g, f) \in F_a(v)$. Let $\alpha \colon V(G) \to \mathbb{Z}_3$ be a function. We define the graph $\mathsf{CFl}_3(\vec{G}, <, \alpha)$ with vertex set

$$V(\mathsf{CFI}_3(\vec{G}, <, \alpha)) := \bigcup_{v \in V(G)} \{v\} \times M_{\alpha(v)}(v)$$

and edge set

$$\begin{split} E(\mathsf{CFI}_3(\vec{G},<,\alpha)) &\coloneqq \quad \Big\{\{(v,f)(w,g)\} \ \Big| \ vw \in E(G) \land f(vw) = g(vw) \Big\} \\ & \cup \Big\{((v,f)(v,g)) \ \Big| \ (f,g) \in F_{\alpha(v)}(v) \Big\}. \end{split}$$

Observe that $\mathsf{CFI}_3(\vec{G}, <, \alpha)$ is a *mixed graph*, i.e., it contains both directed and undirected edges. Also, we color the vertices of $\mathsf{CFI}_3(\vec{G}, <, \alpha)$ using the coloring $\lambda \colon V(\mathsf{CFI}_3(\vec{G}, <, \alpha)) \to C$ defined via $\lambda(v, f) \coloneqq v$ for all $(v, f) \in V(\mathsf{CFI}_3(\vec{G}, \alpha))$, i.e., each set $M_{\alpha(v)}(v)$ forms a color class under λ .

Now fix an arbitrary vertex $u_0 \in V(G)$. For every $i \in \mathbb{Z}_3$ we define the mapping $\alpha_i \colon V(G) \to \mathbb{Z}_3$ via $\alpha_i(u_0) \coloneqq i$ and $\alpha_i(w) \coloneqq 0$ for all $w \in V(G) \setminus \{u_0\}$.

▶ Lemma 5.1. $CFI_3(\vec{G}, <, \alpha_0) \cong CFI_3(\vec{G}, <, \alpha_1).$

Now, we analyse the WL algorithm on the graphs $\mathsf{CFI}_3(\vec{G}, <, \alpha)$ for different functions $\alpha \colon V(G) \to \mathbb{Z}_3$. We write $\mathsf{tw}(G)$ to denote the tree width of G.

▶ Lemma 5.2. Let k be an integer such that $tw(G) \ge k + 1$. Also let $\alpha, \beta: V(G) \to \mathbb{Z}_3$ be two functions. Then $\mathsf{CFl}_3(\vec{G}, <, \alpha) \simeq_k \mathsf{CFl}_3(\vec{G}, <, \beta)$.

Together, Lemmas 5.1 and 5.2 provide pairs of non-isomorphic graphs that are not distinguished by k-WL assuming tw(G) > k. Next, we argue how to turn these graphs into tournaments.

¹ We remark that, since G has maximum degree 3, the twin width of G^{red} is actually bounded in the twin width of G. However, we feel it is more convenient to directly bound the twin width of G^{red} .

We define the tournament $T = T(\vec{G}, <, \alpha)$ with vertex set

$$V(T) \coloneqq V(\mathsf{CFI}_3(\vec{G}, <, \alpha)) = \bigcup_{v \in V(G)} \{v\} \times M_{\alpha(v)}(v)$$

and edge set

$$\begin{split} E(T) &\coloneqq \Big\{ ((v,f)(v,g)) \ \Big| \ (f,g) \in F_{\alpha(v)}(v) \Big\} \\ & \cup \Big\{ ((v,f)(w,g)) \ \Big| \ v < w \land \{(v,f)(w,g)\} \notin E(\mathsf{CFI}_3(\vec{G},<,\alpha)) \Big\} \\ & \cup \Big\{ ((w,g)(v,f)) \ \Big| \ v < w \land \{(v,f)(w,g)\} \in E(\mathsf{CFI}_3(\vec{G},<,\alpha)) \Big\}. \end{split}$$

It can be shown that the relevant properties are preserved by this translation.

▶ Lemma 5.3. Let $\alpha, \beta : V(G) \to \mathbb{Z}_3$ be two functions. Then $T(\vec{G}, <, \alpha) \cong T(\vec{G}, <, \beta)$ if and only if $\mathsf{CFI}_3(\vec{G}, <, \alpha) \cong \mathsf{CFI}_3(\vec{G}, <, \beta)$.

▶ Lemma 5.4. Let $k \ge 2$ be an integer such that $\operatorname{tw}(G) \ge k+1$. Also let $\alpha, \beta \colon V(G) \to \mathbb{Z}_3$ be two functions. Then $T(\vec{G}, <, \alpha) \simeq_k T(\vec{G}, <, \beta)$.

To prove Theorem 1.2, we also need to bound the twin width of the resulting graph. Recall that $t := \text{tww}(G^{\text{red}})$ where G^{red} denotes the version of G where every edge is red.

▶ Lemma 5.5. For every function α : $V(G) \to \mathbb{Z}_3$ it holds that tww $(T(\vec{G}, <, \alpha)) \le \max(35, t)$.

Proof. Throughout the proof, we define $M(v) \coloneqq M_{\alpha(v)}(v)$ for every $v \in V(G)$. Since G is 3-regular, we have that |M(v)| = 9 for every $v \in V(G)$. So $|V(T(\vec{G}, <, \alpha))| = 9 \cdot |V(G)|$. Also note that (M(v), M(w)) is homogeneous for all distinct $v, w \in V(G)$ such that $\{v, w\} \notin E(G)$.

We construct a partial contraction sequence as follows. Let $n \coloneqq |V(G)|$. We define $\mathcal{P}_1, \ldots, \mathcal{P}_{8n+1}$ arbitrarily such that $\mathcal{P}_{8n+1} = \{M(v) \mid v \in V(G)\}$. Since G is 3-regular and |M(v)| = 9 for every $v \in V(G)$, we conclude that $(T(\vec{G}, <, \alpha))/\mathcal{P}_i$ has red degree at most $4 \cdot 9 - 1 = 35$ for every $i \in [8n + 1]$. Now observe that

 $\operatorname{tww}((T(\vec{G}, <, \alpha))/\mathcal{P}_{8n+1}) \le \operatorname{tww}(G^{\mathsf{red}}, <) = t.$

It follows that $\operatorname{tww}(T(\vec{G}, <, \alpha)) \leq \max(35, t)$ as desired.

With Lemma 5.5 in hand, we apply the construction $T(\vec{G}, <, \alpha)$ to a 3-regular base graph G which has tree width linear in the number of vertices, but the twin width of G^{red} is bounded. The existence of such graphs has already been observed in [5]. More precisely, the following theorem follows from combining the arguments from [5, Lemma 5.1] and the results from [4, 34].

▶ **Theorem 5.6.** There is a family of 3-regular graphs $(G_n)_{n\geq 1}$ such that $|V(G_n)| = O(n)$, tww $(G_n^{\text{red}}) \leq 6$ (where G_n^{red} denotes the version of G_n where all edges are turned into red edges), and tw $(G_n) \geq n$ for every $n \geq 1$.

Now, we are ready to give a proof for Theorem 1.2.

▶ Theorem 5.7. For every $k \ge 2$ there are non-isomorphic tournaments T_k and T'_k such that (1) $|V(T_k)| = |V(T'_k)| = O(k)$,

- (2) tww $(T_k) \le 35$ and tww $(T'_k) \le 35$, and
- (3) $T_k \simeq_k T'_k$.

78:16 Isomorphism for Tournaments of Small Twin Width

Proof. Let $k \ge 2$. Let G_{k+1} be the 3-regular graph obtained from Theorem 5.6. Note that $\operatorname{tw}(G_{k+1}) \ge k+1$.

We also fix an arbitrary orientation \vec{G}_{k+1} of G_{k+1} and let G_{k+1}^{red} denote the version of G_{k+1} where every edge is replaced by a red edge. We have $t := \text{tww}(G_{k+1}^{\text{red}}) \leq 6$ by Theorem 5.6. By Lemma 2.2 there is some linear order < on $V(G_{k+1})$ such that $\text{tww}(G_{k+1}^{\text{red}}, <) \leq t \leq 6$.

Now fix an arbitrary $u_0 \in V(G_{k+1})$. For $p \in \mathbb{Z}_3$ we define the mapping $\alpha_p \colon V(G_{k+1}) \to \mathbb{Z}_3$ via $\alpha_p(u_0) = p$ and $\alpha_p(w) = 0$ for all $w \in V(G_{k+1}) \setminus \{u_0\}$. We define $T_k \coloneqq T(\vec{G}_{k+1}, <, \alpha_0)$ and $T'_k \coloneqq T(\vec{G}_{k+1}, <, \alpha_1)$. We have $|V(T_k)| = |V(T'_k)| = 9 \cdot |V(G_{k+1})| = O(k)$. Also, tww(T_k) ≤ 35 and tww(T'_k) ≤ 35 by Lemma 5.5. Finally, $T_k \ncong T'_k$ by Lemmas 5.1 and 5.3, and $T_k \simeq_k T'_k$ by Lemma 5.4.

6 Twin Width is Smaller Than Other Widths

In this section, we compare twin width with other natural width parameters of tournaments. If f, g are mappings from (directed) graphs to the natural numbers, we say that f is *functionally* smaller than g on a class \mathcal{C} of graphs if for every k there is a k' such that for all graphs $G \in \mathcal{C}$, if $g(G) \leq k$ then $f(G) \leq k'$. We write $f \preceq_{\mathcal{C}} g$ to denote that f is functionally smaller than g on \mathcal{C} . We omit the subscript $_{\mathcal{C}}$ if \mathcal{C} is the class of all digraphs.

Natural width measures for directed graphs are *cut width*, *directed path width*, *directed tree* width, and *clique width*. On the class of tournaments twin width turns out to be functionally smaller than all of these. For clique width, it has already been shown in [11] that twin width is functionally smaller than clique width on undirected graphs; the proof easily extends to arbitrary binary relational structures and hence to tournaments.

We start by giving definitions for the other width measures. Let G be a digraph. For a linear order \leq on V(G) and a vertex $v \in V(G)$, we let $S_{\leq}(v) := \{w \in V(G) \mid w \leq v\}$ be the set of all vertices smaller than or equal to v in \leq . Let $s_{\leq}(v) := |E_G(S_{\leq}(v), V(G) \setminus S_{\leq}(v))|$ be the number of edges from $S_{\leq}(v)$ to its complements. The width of \leq is $\max_{v \in V(G)} s_{\leq}(v)$, and the *cut width* ctw(G) is the minimum over the width of all linear orders of V(G).

A directed path decomposition of a digraph G is a mapping $\beta : [p] \to 2^{V(G)}$, for some $p \in \mathbb{N}$, such that for every vertex $v \in V(G)$ there are $\ell, r \in [p]$ such that $v \in \beta(t) \iff \ell \leq t \leq r$, and for all edges $(v, w) \in E(G)$ there are $\ell, r \in [p]$ with $\ell \leq r$ such that $v \in \beta(r)$ and $w \in \beta(\ell)$. The sets $\beta(t), t \in [p]$, are the bags of the decomposition. The width of the decomposition is $\max_{t \in [p]} |\beta(t)| - 1$, and the directed path width dpw(G) is the minimum width of a directed path decomposition of G.

A digraph R is a rooted directed tree if there is a vertex $r_0 \in V(R)$ such that for every $t \in V(R)$ there is a unique directed walk from r_0 to t. Note that every rooted directed tree can be obtained from an undirected tree by selecting a root r_0 and directing all edges away from the root. For $t \in V(R)$ we denote by R_t the unique induced subgraph of R rooted at t.

Let G be a digraph. A directed tree decomposition of G is a triple (R, β, γ) where R is a rooted directed tree, $\beta: V(R) \to 2^{V(G)}$ and $\gamma: E(R) \to 2^{V(G)}$ such that **(D.1)** $\{\beta(t) \mid t \in V(R)\}$ is a partition of V(G), and

(D.2) for every $(s,t) \in E(R)$ the set $\gamma(s,t)$ is a hitting set for all directed walks that start and end in $\beta(R_t) \coloneqq \bigcup_{t' \in V(R_t)} \beta(t')$ and contain a vertex outside of $\beta(R_t)$.

For $t \in V(R)$ we define $\Gamma(t) := \beta(t) \cup \bigcup_{(s,s') \in E(t)} \gamma(s,s')$ where E(t) denotes the set of edges incident to t. The width of (R, β, γ) is defined as

width
$$(R, \beta, \gamma) \coloneqq \max_{t \in V(R)} |\Gamma(t)| - 1$$

The directed tree width dtw(G) is the minimum width of a directed tree decomposition of G.

Let us first recall the following well-known inequalities.

▶ **Proposition 6.1.** For all digraphs G, it holds that $dtw(G) \le dpw(G) \le ctw(G)$.

The proposition implies that dtw \preceq dpw \preceq ctw. It can be shown that tww $\not\preceq$ ctw and hence tww $\not\preceq$ dpw and tww $\not\preceq$ dtw on the class of all digraphs. In contrast, it turns out that on the class of tournaments, twin width is functionally smaller than directed tree width. Actually, this even holds for the larger class of semi-complete graphs. A digraph G is *semi-complete* if for all distinct $v, w \in V(G)$ at least one of the pairs (v, w), (w, v) is an edge. Note that every tournament is semi-complete.

▶ Theorem 6.2 ([28, Proposition 5]). Let G be a semi-complete graph. Then

 $dpw(G) \le 4(dtw(G) + 2)^2 + 7(dtw(G) + 2) - 1.$

▶ Theorem 6.3. Let G be a semi-complete graph. Then $tww(G) \le dpw(G)$.

In combination, we get that $tww(G) \le 4(dtw(G) + 2)^2 + 7(dtw(G) + 2) - 1$ for every semi-complete graph G. In particular

$$\mathsf{tww} \precsim_{\mathcal{S}} \mathsf{dtw},\tag{2}$$

where S denotes the class of all semi-complete digraphs. This inequality is strict even on tournaments, that is, dtw $\not\gtrsim_{\mathcal{T}}$ tww where \mathcal{T} denotes the class of all tournaments.

7 Conclusion

We prove that the isomorphism problem for classes of tournaments of bounded (or slowly growing) twin width is in polynomial time. Many algorithmic problems that can be solved efficiently on (classes of) tournaments can also be solved efficiently on (corresponding classes of) semi-complete graphs, that is, directed graphs where for every pair (v, w) of vertices at least one of the pairs (v, w), (w, v) is an edge (see, e.g., [39]). Contrary to this, we remark that isomorphism of semi-complete graphs of bounded twin width is GI-complete: we can reduce isomorphism of oriented graphs to isomorphism of semi-complete graphs by replacing each non-edge by a bidirectional edge. This reduction preserves twin with.

Classes of tournaments of bounded twin width are precisely the classes that are considered to be structurally sparse. Formally, these are the classes that are monadically dependent, which means that all set systems definable over the tournaments in such a class have bounded VC dimension. The most natural set systems definable within a tournament are those consisting of the in-neighbors of the vertices and of the out-neighbors of the vertices. Bounded twin width implies that the VC dimension of these two set systems is bounded, but the converse does not hold. It is easy to see that the VC dimensions of the in-neighbors and out-neighbors systems as well as the set system consisting of the mixed neighbors of all edges are within a linear factor of one another. As a natural next step, we may ask if isomorphism of tournaments where the VC-dimension of these systems is bounded is in polynomial time.

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78:18 Isomorphism for Tournaments of Small Twin Width

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