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Monochromatic paths in random tournaments

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Abstract

We prove that, with high probability, any 2-edge-coloring of a random tournament on n vertices contains a monochromatic path of length $\Omega(n/\sqrt{\log n})$. This resolves a conjecture of Ben-Eliezer, Krivelevich, and Sudakov and implies a nearly tight upper bound on the oriented size Ramsey number of a directed path.

KEYWORDS
monochromatic directed path, monochromatic oriented path, Ramsey theory, size Ramsey number

1 | INTRODUCTION

Ramsey theory refers to a large body of mathematical results, which roughly say that any sufficiently large structure is guaranteed to have a large well-organized substructure. For example, the celebrated theorem of Ramsey [12] says that for any fixed graph H, every 2-edge-coloring of a sufficiently large complete graph contains a monochromatic copy of H. The *Ramsey number of H* is defined to be the smallest order of a complete graph satisfying this property.

In this paper, we study an analogous phenomenon for oriented graphs. An *oriented graph* is a directed graph which can be obtained from a simple undirected graph by orienting its edges. The undirected graph, obtained by ignoring edge orientations of an oriented graph, is called its *underlying graph*.

A *tournament* is an orientation of the complete graph. Given directed graphs G and H, we write $G \to H$ if any 2-edge-coloring of G contains a monochromatic copy of H. The *oriented Ramsey number* of H is defined to be the smallest n for which $T \to H$ for every tournament T on n vertices.

While in the undirected case the Ramsey number exists and is finite for every H, in the directed case the Ramsey number can be infinite. Indeed, given a directed graph H that contains a directed cycle and any tournament T, we color the edges of T as follows. Denote the vertices of T by $v_1, \ldots, v_n$ and color edges $\overrightarrow{v_i v_j}$ red if $i < j$ and blue otherwise. It is easy to see that this coloring has no monochromatic directed cycle, so, in particular, there is no monochromatic copy of H.

Therefore it only makes sense to study the Ramsey properties for acyclic graphs. We note that the oriented Ramsey number of an acyclic graph is always finite. This follows since every acyclic graph

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is a subgraph of a transitive tournament, and the oriented Ramsey number of transitive tournaments is finite by essentially the same argument as for the complete graphs in the undirected Ramsey case. One of the most basic classes of acyclic graphs are oriented paths and in particular, directed paths (which are oriented paths whose edges are all oriented in the same direction). In this paper, we study the problem of finding such monochromatic paths in tournaments.

Another major difference between the undirected and the oriented Ramsey numbers is the fact that there is only one complete graph on n vertices, while there are many tournaments on n vertices. In particular, the answer to how long a monochromatic path we can find in a tournament on n vertices T, depends on T as well as the coloring of the edges. We thus define $m(T)$ to be the largest m such that $T \to \overrightarrow{P_m}$, where $\overrightarrow{P_m}$ is the directed path on m vertices.

The celebrated Gallai-Hasse-Roy-Vitaver theorem [8, 10, 15, 16], states that any directed graph, whose underlying graph has chromatic number at least n, contains a directed path on n vertices. A simple consequence of this theorem is that $m(T) \geq \sqrt{n}$, for any tournament T on n vertices. Indeed, let T be a 2-colored tournament on n vertices, let T_R be the subgraph of T consisting of red edges and T_B the subgraph consisting of blue edges. Since $\chi(T) = n$ we have $\chi(T_R) \geq \sqrt{n}$ or $\chi(T_B) \geq \sqrt{n}$ (by $\chi(G)$, where G is an oriented graph, we mean the chromatic number of its underlying graph). In either case the aforementioned theorem implies there is a monochromatic path on at least $\sqrt{n}$ vertices.

To see that this is tight, consider the following 2-coloring of a *transitive tournament* T on n vertices, whose vertices are $1, \ldots, n$ and $\overrightarrow{xy}$ is an edge if and only if $x < y$; for convenience we assume that n is a perfect square. Partition the vertices of T into subsets A_i of size $\sqrt{n}$, such that all vertices in A_i are smaller than all vertices in A_j, for $i < j$. Color the edges within A_i blue and the other edges red. It is easy to see that a monochromatic path in this coloring has at most $\sqrt{n}$ vertices. In particular $m(T) \leq \sqrt{n}$, so $m(T) = \sqrt{n}$.

The above resolves the problem of minimizing the value of $m(T)$ among all n-vertex tournaments. It is natural to consider the opposite question: what is the *maximum* of $m(T)$ and which T attains this maximum?

This question was implicitly posed by Ben-Eliezer, Krivelevich, and Sudakov in [4], where they note that $m(T) \leq \frac{2n}{\sqrt{\log n}}$ for any n-vertex tournament. Indeed, it is well known and easy to see that any tournament of order n has a transitive subtournament of order $\log n$. Using this we can find a sequence of vertex-disjoint transitive subtournaments A_i of order $\frac{1}{2}\log n$ covering all but at most $\sqrt{n}$ vertices. We denote the set of remaining vertices by B. We now 2-color each of A_i, as described above, to ensure that the longest monochromatic path within A_i is of length $\sqrt{|A_i|}$. We then color all edges from A_i to A_j blue if $i < j$ and red if $i > j$. Finally, we color the edges going out of B red and edges going into B blue, while edges within B can be colored arbitrarily. In this coloring, the longest monochromatic path has length at most $\frac{2n}{\log n}\sqrt{\frac{\log n}{2}} + \sqrt{n} \leq \frac{2n}{\sqrt{\log n}}$.

Are there tournaments that achieve this bound? Intuitively, such tournaments should be "far away from being transitive". With this in mind, Ben-Eliezer, Krivelevich, and Sudakov [4] conjectured that random tournaments achieve this bound, up to a constant factor, with high probability.

The random tournament on n vertices, which we denote by T_n, is obtained by orienting each edge uniformly at random and independently of other edges. With respect to this probability space we say an event A holds *with high probability* if the probability that A occurs tends to 1 as $n \to \infty$.

To support their conjecture, Ben-Eliezer, Krivelevich, and Sudakov show that a random tournament satisfies $m(T_n) \geq \frac{cn}{\log n}$ with high probability, where $c > 0$ is a constant. Here we improve this bound, proving the following essentially tight result.

Theorem 1 *There is a constant $c > 0$ such that a random tournament $T = T_n$ satisfies $T \to \overrightarrow{P_m}$, with high probability, where $m = \frac{cn}{\sqrt{\log n}}$.*

Theorem 1 resolves the question of the maximal value of $m(T_n)$, up to a constant factor, with respect to a directed path. This gives rise to a natural next question: is it possible to generalize it to other graphs, in place of the directed path? In this direction, we prove a generalization of Theorem 1 for arbitrarily oriented paths, which is tight up to a constant factor. Given an arbitrarily oriented path P, we denote by $\ell(P)$ the length of the longest directed subpath of P.

Theorem 2 *There is a constant $c > 0$ such that, with high probability, if T is a random tournament on $c(\ell\sqrt{\log \ell} + n)$ vertices, then $T \to P$, for every oriented path P on n vertices with $\ell(P) \leq \ell$.*

Theorem 1 is related to the study of size Ramsey numbers, which was initiated by Erdős, Faudree, Rousseau, and Schelp [7] in 1972, and has received considerable attention since then. The *size Ramsey number* of a graph H is defined to be the minimum of $e(G)$ (the number of edges of G) over all graphs G for which $G \to H$. Answering a question of Erdős, Beck [2] proved in 1983 that the size Ramsey number of the undirected path on n vertices is linear in n.

Here we consider the following natural analogue for oriented paths. Given an oriented graph H, we define the *oriented size Ramsey number*, denoted by $r_e(H)$, to be

$$r_e(H) = \min\{e(G) : G \to H,\ G \text{ is an oriented graph}\}.$$

Ben-Eliezer, Krivelevich, and Sudakov [4] studied this number for the directed path, obtaining the following estimates, for some constants c_1 and c_2.

$$c_1 \frac{n^2 \log n}{(\log \log n)^3} \leq r_e\left(\overrightarrow{P_n}\right) \leq c_2 n^2 (\log n)^2.$$

We note that this illustrates the difference between the oriented and directed size Ramsey numbers (where in the directed case, G is allowed to be any directed graph). Indeed, the directed size Ramsey number of P_n is $\Theta(n^2)$, as follows from results by Raynaud [13] (see also [9] for a simple proof) and Reimer [14].

Note that Theorem 1 immediately implies the following upper bound on $r_e\left(\overrightarrow{P_n}\right)$, which is tight up to a factor of $O((\log \log n)^3)$.

Corollary 3 *There is a constant $c > 0$ such that*

$$r_e\left(\overrightarrow{P_n}\right) \leq cn^2 \log n.$$

1.1 | Organization of the paper

In the following section, we list several results that we shall need for the proof of Theorem 1. In Section 3, we prove an asymmetric version of Theorem 1 that applies to pseudorandom tournaments from which we easily deduce Theorem 1. We prove Theorem 2 in Section 4. We conclude the paper in Section 5 with some remarks and open problems.

Throughout the paper we do not try to optimize constants, all logarithms are in base 2 and we omit floor and ceiling signs whenever these are not crucial. By 2-coloring, we always mean a coloring of edges in two colors.

2 | PRELIMINARIES

In this section, we list several general results we need for the proof of Theorem 1. We start with a simple observation.

Observation 4 Let G be a directed graph in which every vertex has in-degree at least k. Then G contains a directed cycle of length at least $k+1$.

Proof Consider a longest directed path $v_1 \dots v_l$ in G. Note that v_1 cannot have any in-neighbors outside of the path, by the maximality assumption on the path. But, as v_1 has in-degree at least k, v_1 needs to have an in-neighbor v_i on the path with $i \geq k+1$. Now, $(v_1 \dots v_i)$ is a directed cycle of length at least $k+1$, as required. ∎

We give several simple definitions. Given two subsets of vertices of a directed graph G, let $e_G(A,B)$ denote the number of edges of G oriented from A to B; we often omit G and write $e(A,B)$ when it is clear which G it refers to. If G is a 2-colored graph, we denote by $e_R(A,B)$ the number of red edges from A to B, and by $e_B(A,B)$ the number of blue edges from A to B.

Definition 5 An oriented graph is said to be (ε,k)-*pseudorandom* if for every two disjoint sets A and B of size at least k, we have $e(A,B) \geq \varepsilon|A||B|$.

Our proof of Theorem 1 works for any (ε,σ)-pseudorandom graph, in place of a random tournament. However, we note that our definition of pseudorandomness does not coincide with the one used by Ben-Eliezer, Krivelevich, and Sudakov in [4]. In particular, they defined a graph to be k-pseudorandom if between any two sets A,B of size k there is an edge oriented from A to B.

The following Lemma shows that a random tournament is $(\varepsilon,\sigma\log n)$-pseudorandom with arbitrary $\varepsilon < \frac{1}{2}$ and $\sigma = \sigma(\varepsilon)$. This is the only property of random tournaments that we will use in the proof.

Lemma 6 *For any* $0 < \varepsilon < \frac{1}{2}$ *there is a constant* $\sigma = \sigma(\varepsilon)$ *such that if* $T = T_n$, *then with high probability* T *is* $(\varepsilon,\sigma\log n)$-*pseudorandom.*

Proof Let $\delta = \frac{1}{2} - \varepsilon$. Let A,B be a fixed pair of disjoint sets of vertices of size $k = \sigma\log n$, for a constant σ. Each of the k^2 possible edges is oriented from A to B with probability $1/2$, independently of all other edges, so if X denotes the number of such edges, it is a binomially distributed random variable ($X \sim \mathrm{Bin}\left(k^2, \frac{1}{2}\right)$).

As such, Chernoff bounds (see appendix A of [1]) imply the following.

$$\mathbb{P}\left(X < \left(\frac{1}{2} - \delta\right)k^2\right) = \mathbb{P}\left(X > \left(\frac{1}{2} + \delta\right)k^2\right) \leq e^{-2\delta^2 k^2}.$$

Now as there are at most $\binom{n}{k}^2$ choices for A and B, the probability that there is a pair of subsets A,B having $e(A,B) < \left(\frac{1}{2} - \delta\right)k^2$ is, by the union bound, at most:

$$\binom{n}{k}^2 e^{-2\delta^2 k^2} \leq e^{2k\log n - 2\delta^2 k^2} = e^{2\sigma\log^2 n(1-\delta^2\sigma)} = o(1),$$

given that $\sigma > \delta^{-2}$.

Finally, given two sets of size $a = |A| \geq k$ and $b = |B| \geq k$, by double counting the number of pairs of subsets of size k a given edge is in, we get that $e(A, B) \geq \frac{\binom{a}{k}\binom{b}{k}\left(\frac{1}{2}-\delta\right)k^2}{\binom{a-1}{k-1}\binom{b-1}{k-1}} \geq \left(\frac{1}{2} - \delta\right) ab$.

So, by setting $\sigma = 2\left(\frac{1}{2} - \varepsilon\right)^{-2}$, we see that T is $(\varepsilon, \sigma \log n)$-pseudorandom with high probability. ∎

The following lemma is due to Ben-Eliezer, Krivelevich, and Sudakov [3, 4] and is a useful application of the Depth-first search (DFS) algorithm.

Lemma 7 *Given an oriented graph G, there is a directed path P such that vertices of $G - P$ can be partitioned into two disjoint sets U and W such that $|U| = |W|$ and all the edges between U and W are oriented from W to U.*

Proof We start with $U = \emptyset$, $W = V(G)$ and $P = \emptyset$. We repeat the following procedure, throughout of which P is a path, $|W| \geq |U|$ and all edges between U and W are oriented from W to U. If P is empty we take any vertex from W to be the new path P and remove the vertex from W. Otherwise, we consider the endpoint v of P; if v has any out-neighbors in W we use one of them to extend P and remove it from W, and otherwise we remove v from P and add it to U. Note that at each step either $|W|$ decreases by one or $|U|$ increases by 1 so the value $|W| - |U|$ decreases by exactly 1 per step, in particular it reaches 0, at which point we stop. At this point, P, U, and W satisfy the requirements of the lemma. ∎

The following lemma will prove useful at several places in the proof of Theorem 1. It will mostly be used by exploiting pseudorandomness to imply the conditions of the lemma are satisfied.

Lemma 8 *Let $\varepsilon > 0$, and let A and B be disjoint sets of n vertices of a directed graph G. Suppose that $e(B, A) \geq \varepsilon n^2$, and $e(X, Y) > 0$ for every two subsets $X \subseteq A$ and $Y \subseteq B$ of size at least $\frac{\varepsilon}{8}n$. Then there is a directed cycle, alternating between A and B, whose length is at least $\frac{\varepsilon}{4}n$.*

Proof Consider the graph H, consisting only of edges between A and B. We show that H contains a cycle of length at least $\frac{\varepsilon}{4}n$. Note that it suffices to show that there is a path P in H, consisting of at least $\frac{3\varepsilon}{4}n$ vertices. Indeed, let Y be the set of the first $\frac{\varepsilon}{8}n$ vertices of P that are in B and let X be the set of the last $\frac{\varepsilon}{8}n$ vertices of P in A. As vertices of P alternate between A and B, Y is in the first third of the path while X is in the last third. By the assumptions, there is an edge from X to Y, which completes a cycle containing the middle third of P, so has at least the required length.

The vertices of H may be partitioned into a directed path P and two sets U and W of equal size such that there are no edges from U to W, by Lemma 7 applied to H. By the above, we may assume that P has at most $\frac{3\varepsilon}{8}n$ vertices in each of A and B. Write $U_A = U \cap A$ and similarly for U_B, W_A, W_B, P_A, P_B. Then $|U| = |W|$ and $|A| = |B|$ imply that $|P|$ is even, which in turn due to P alternating between A and B implies $|P_A| = |P_B|$. Combining these equalities, we obtain $|U_A| = |W_B|$ and $|U_B| = |W_A|$. Note that, as there are no edges from U_A to W_B, by the assumptions we have $|U_A| < \frac{\varepsilon}{8}n$. So the edges from B to A can be covered by $V(P) \cup U_A \cup W_B$, which is a set of size smaller than εn, so there are fewer than εn^2 such edges, a contradiction to the assumption that $e(B, A) \geq \varepsilon n^2$. ∎

The following theorem is a result of Raynaud [13] (see also [9] for a simple proof) about directed monochromatic paths in 2-colorings of the complete directed graph.

Theorem 9 (Raynaud [13]) *In every 2-coloring of the complete directed graph on n vertices, there is a directed monochromatic path of length $\frac{n}{2}$.*

We restate the Gallai-Hasse-Roy-Vitaver theorem mentioned in the "Introduction" section.

Theorem 10 *Let G be a directed graph, whose underlying graph has chromatic number at least n. Then G contains a directed path of length $n-1$.*

The following is an asymmetric variant of a result mentioned in the introduction; its proof is again a simple consequence of Theorem 10, so we omit the details.

Corollary 11 *In every 2-coloring of a tournament on at least $xy+1$ vertices, we can either find a red path of length x or a blue path of length y.*

3 | MAIN RESULT

Given directed graphs G, H_1 and H_2, we write $G \to (H_1, H_2)$ if in every 2-coloring of G there is a blue copy of H_1 or a red copy of H_2. Note that $G \to (H, H)$ is the same as $G \to H$.

The following theorem is a generalization of Theorem 1, that is applicable for pseudorandom graphs, and treats the asymmetric case. The statement for pseudorandom graphs is convenient for the proof of Theorem 2 which we give in the next section.

Theorem 12 *Given $0 < \varepsilon < \frac{1}{2}$ and $0 < \sigma$, let G be an $(\varepsilon, \sigma \log n)$-pseudorandom tournament on n vertices. There is a constant $c > 0$, such that $G \to \left(\overrightarrow{P_r}, \overrightarrow{P_s}\right)$ provided $r, s \leq cn$ and $rs \leq \frac{cn^2}{\log n}$.*

We note that, by setting $r = s = \frac{cn}{\sqrt{\log n}}$ and combining with Lemma 6, we obtain Theorem 1, while, by taking $r = s = \frac{cn}{\log n}$, we obtain the previously best result of Ben-Eliezer, Krivelevich, and Sudakov [4] (in fact, they proved the special case of Theorem 12 where $r = cn$ and $s = \frac{cn}{\log n}$).

Proof Let us fix a coloring of the edges of G. The proof differs depending on the monochromatic cycle structure of G. Let $a = 24\varepsilon^{-1}\sigma$ and $b = 12\varepsilon^{-1}a$; we say that

$$\text{a cycle } C \text{ is } \begin{cases} \textit{short} & \text{if } |C| < a \log n, \\ \textit{medium} & \text{if } a \log n \leq |C| \leq b \log n, \\ \textit{long} & \text{if } b \log n < |C|. \end{cases}$$

Our proof is divided into two parts. In the first part we consider the case where there are many vertex disjoint monochromatic medium cycles, whereas in the second part we consider the case where there are many vertices that are not contained in any medium monochromatic cycle.

Case 1: many disjoint medium monochromatic cycles

Suppose that there is a collection of vertex-disjoint medium monochromatic cycles that cover at least $n/2$ vertices. Then, without loss of generality, there are pairwise disjoint medium blue cycles $C_1 \ldots, C_t$, that cover at least $\frac{n}{4}$ vertices. Note that $t \geq \frac{n}{4b \log n} =$

$\frac{n}{48\varepsilon^{-1}a\log n}$, by the upper bound on the length of the cycles. We will show that in this case there is a monochromatic path of length linear in n.

We define an auxiliary 2-coloring H of the complete directed graph on vertex set $[t]$ as follows. The edge ij is blue if at least $\frac{a}{4}\log n$ vertices in C_i have a blue out-neighbor in C_j; otherwise, ij is red.

Let M be a maximum *red-red* matching in H, that is, M is a matching whose edges are colored red in both directions; we call such edges *red-red*.

Suppose first that M consists of at most $\frac{t}{4}$ edges. Then, by maximality of M, the set of vertices not in M spans no red-red edges. In particular, H contains a blue tournament T' of order $t/2$. As any tournament contains a Hamilton path there is a blue directed path of order $t/2$ in H. Let $B_1, \ldots, B_{t/2}$ be the blue cycles corresponding to the vertices in this path, preserving the order of the path. We use the following claim to find a long blue path.

Claim 13 Let $C_1, \ldots, C_k$ be a sequence of pairwise vertex-disjoint directed cycles in a directed graph G, such that for each $i < k$, at least r vertices of C_i have an out-neighbor in C_{i+1}. Then there is a path of length at least $(k-1)r$ in G.

Proof We start the path at an arbitrary vertex v_1 of C_1, we follow C_1 to the last vertex that sends an edge toward C_2, and then follow such an edge to a vertex $v_2 \in V(C_2)$. We repeat this for $i < k$: starting from v_i we follow C_i until the last vertex that sends an edge toward C_{i+1} and then follow that edge to obtain v_{i+1}. By the assumption, there are at least r vertices with an edge toward C_{i+1} so the part of the path from v_i to v_{i+1} is of length at least r. Hence, the path we obtain has the desired length. ∎

Using Claim 13 with the blue cycles B_i and blue edges between them, we find a monochromatic path of length at least $\left(\frac{t}{2}-1\right)\cdot\frac{a}{4}\log n \geq cn$, provided c is small enough.

Now suppose that M consists of at least $t/4$ edges. We use the following claim to find red cycles whose intersection with existing blue cycles C_i is large. Then we repeat the above argument for intersections of red and blue cycles, with the added benefit that now the setting is more symmetric.

Claim 14 If both $\overrightarrow{ij}$ and $\overrightarrow{ji}$ are red edges of H, then there is a red cycle in $V(C_i)\cup V(C_j)$ whose intersection with C_i has size at least $\frac{3a\varepsilon}{32}\log n$.

Proof Since $\overrightarrow{ij}$, $\overrightarrow{ji}$ are red, there are subsets $A \subseteq C_i$ and $B \subseteq C_j$, of size $\frac{3a}{4}\log n$, with no blue edges between A and B. By pseudorandomness, $e_R(B,A) \geq \varepsilon|A||B|$, and for any subsets $X \subseteq A, Y \subseteq B$ of sizes at least $\frac{\varepsilon|A|}{8}$ we have $e_R(X,Y) \geq \varepsilon|X||Y|$ (as $\frac{3a\varepsilon}{32} \geq \sigma$). By Lemma 8, there is a red cycle, alternating between A and B, of length at least $\frac{3a\varepsilon}{16}\log n$, so its intersection with C_i has the required size. ∎

For each edge in M we apply Claim 14 to obtain a collection of disjoint medium blue cycles $B_1, \ldots, B_k$ and disjoint red cycles $R_1, \ldots, R_k$, with $k \geq \frac{t}{4}$, such that $|I_i| \geq \frac{3a\varepsilon}{32}\log n \geq 2\sigma\log n$, where $I_i = B_i \cap R_i$.

We now define an auxiliary 2-coloring of the complete directed graph on vertex set $[k]$, similarly to the one given above: here $\overrightarrow{ij}$ is blue if at least $|I_i|/4$ vertices of I_i send a blue edge toward I_j, and red otherwise. Note that when $\overrightarrow{ij}$ is red, at least $\frac{|I_i|}{4}$ vertices of I_i send a red edge toward I_j (indeed, otherwise, we find a subset of I_i of size at least $|I_i|/2 \geq \sigma\log n$ which sends no edges to I_j, a contradiction to pseudorandomness).

By Theorem 9, there is a monochromatic path of length $\frac{k}{2}$ in the auxiliary graph. Now, by Claim 13, there is a monochromatic path of length at least $\frac{k}{2} \cdot \frac{\sigma}{2} \log n \geq cn$, provided c is small enough.

Case 2: there is a large set of vertices spanning no medium cycles

We now assume that there is a subset U of at least $n/2$ vertices that spans no medium monochromatic cycles.

We first show that, in fact, U does not span long monochromatic cycles either. Suppose to the contrary that $C = (v_1 v_2 \dots v_k)$ is a long monochromatic cycle in U of minimum length; without loss of generality, C is blue. Note that all chords of C of length at least $|C|/6$ are red, as otherwise we can obtain a blue cycle of length at least $|C|/6$ but less than $|C|$, a contradiction to the choice of C or the assumption that there are no medium blue cycles in U. Let $A = \{v_1, \dots, v_{k/3}\}$ and $B = \{v_{k/2+1}, \dots, v_{5k/6}\}$. As explained above, all the edges between A and B are red. By Lemma 8 (which can be applied due to pseudorandomness as $\frac{\varepsilon|A|}{8} \geq \frac{\varepsilon b}{24} \log n > \sigma \log n$), $A \cup B$ spans a red cycle C of length at least $\frac{\varepsilon|A|}{4} \geq \frac{\varepsilon b}{12} \log n = a \log n$, so C is either a medium cycle or a shorter monochromatic long cycle. Either way, we reach a contradiction, hence there are no monochromatic long cycles.

Let $m = |U|$. We note that the fact that there are only short blue cycles implies the existence of an ordering of the vertices with few back blue edges.

Claim 15 There is an order of the vertices $u_1, \dots, u_m$ such that for every i there are at most $a \log n$ indices $j > i$ such that the edge $\overrightarrow{u_j u_i}$ exists and is blue.

Proof If there is a subtournament of T in which minimum blue in-degree is of size at least $a \log n$ then, by Observation 4, we can find a blue cycle of length at least $a \log n$, a contradiction. Hence, there is a vertex u_1 in U whose in-degree is at most $a \log n$. Similarly, if $u_1, \dots, u_{i-1}$ are defined, we may take u_i to be a vertex with in-degree at most $a \log n$ in $T_i = T \setminus \{u_1, \dots, u_{i-1}\}$. The order $u_1, \dots, u_m$ satisfies the requirements of the claim. ∎

We now take $d = 120\varepsilon^{-2}\sigma$ and $k = 10d \log n$, and define sets $U_1, \dots, U_{\frac{n}{2k}}$ by $U_i \equiv \{u_{(i-1)k+1}, \dots, u_{ik}\}$. Note that for each i we have $|U_i| = k$.

Claim 16 Let $i < j$, and let W_i and W_j be subsets of U_i and U_j, respectively, of size $k/10$. Then there is a a red edge from W_j to W_i and a blue edge from W_i to W_j.

Proof Let W_i and W_j be as in the claim. We start with the red edges. By pseudorandomness, as $|W_i| = |W_j| = \frac{k}{10} = d \log n \geq \sigma \log n$, we have $e(W_j, W_i) \geq \varepsilon |W_j||W_i|$. Also, by the property of the order, given by Claim 15, at most $|W_i| a \log n$ of the edges from W_j to W_i are blue. It follows that $e_R(W_j, W_i) \geq \varepsilon |W_j||W_i| - |W_i| a \log n = |W_j||W_i| \left(\varepsilon - \frac{a \log n}{|W_j|}\right) \geq \left(\varepsilon - \frac{24\varepsilon^{-1}\sigma \log n}{120\varepsilon^{-2}\sigma \log n}\right) |W_j||W_i| = \frac{4\varepsilon}{5}|W_j||W_i| > 0$, as desired.

For the blue edges, let us assume, contrary to the statement of the claim, that all the edges from W_i to W_j are red. By the previous paragraph $e_R(W_j, W_i) \geq \frac{4\varepsilon}{5}|W_i||W_j|$, while for any subsets $X \subseteq W_i, Y \subseteq W_j$ of size at least $\frac{\varepsilon}{10}|W_i| \geq \sigma \log n$ we have $e_R(X, Y) \geq \varepsilon |X||Y| > 0$. Therefore, by Lemma 8 with parameter $\frac{4}{5}\varepsilon$, there is a red cycle of length at least $\frac{\varepsilon}{5}|W_i| = 24\varepsilon^{-1}\sigma \log n = a \log n$, which is a contradiction to the assumption that there are only short cycles. ∎

Recall that we are looking for a blue directed path of length r or a red directed path of length s. Let $x = \frac{4rk}{n}, y = \frac{4sk}{n}$. We say that a monochromatic path is *long* if it is blue and of length at least x or if it is red and of length at least y.

We note that in any tournament of order $\frac{k}{5} \geq \sigma \log n$ we can find a long path. Indeed, this follows from Corollary 11, as $xy+1 = \frac{(40d)^2 rs \log^2 n}{n^2} + 1 \leq (40d)^2 c \log n + 1 \leq \sigma \log n$, provided c is small enough.

Within each U_i we repeat the following: we find a long monochromatic path and remove its start and end vertices, then repeat with the remaining graph as long as we can find a long monochromatic path. Note that we remove only two vertices per round, and as long as we have at least $\frac{k}{5}$ vertices left, we can continue, so this process runs for at least $\frac{2k}{5}$ rounds. In particular, we find at least $\frac{2k}{5}$ corresponding start and end points of long paths within U_i.

We call U_i red if we found more red long paths, and blue otherwise. Without loss of generality, there is a collection of $\frac{n}{4k}$ red sets U_i, which we denote by $R_1, \ldots, R_{\frac{n}{4k}}$, preserving the order of the U_i's.

Denote the set of start points in R_i by S_i and the set of endpoints by E_i. Then, by construction, S_i and E_i are disjoint and have size at least $\frac{k}{5}$. Let X_i be the subset of vertices of S_i that are starting points of a red path of length at least iy contained in $R_1 \cup \ldots \cup R_i$.

Claim 17 For any $i \leq \frac{n}{4k}$, we have $|X_i| \geq \frac{k}{10}$.

Proof We prove the claim inductively. For the basis, $X_1 = S_1$, so $|X_1| \geq \frac{k}{5}$. We assume the claim is true for i, so $|X_i| \geq \frac{k}{10}$.

Consider the set Y_{i+1} of vertices of E_{i+1} with a red edge toward X_i. Given $v \in Y_{i+1}$, let $u \in S_{i+1}$ be the corresponding start point of a red long path in R_{i+1}, and let w be a red out-neighbor of v in X_i. By taking the red path of length y in R_{i+1} from u to v, appending to it the edge vw and a path of length iy starting at w, given by the inductive assumption, we find a path of length $(i+1)y$ starting at u, hence $u \in X_{i+1}$.

If $|Y_{i+1}| \leq \frac{k}{10}$, then X_i and $E_{i+1} \setminus Y_{i+1}$ are both of size at least $\frac{k}{10}$, but there are no red edges from the second set to the first, a contradiction to Claim 16. It follows that $|Y_{i+1}| \geq \frac{k}{10}$, so by taking the start points corresponding to vertices in Y_{i+1}, we find at least $\frac{k}{10}$ vertices in X_{i+1}, completing the proof. ∎

The statement of Claim 17, for $i = \frac{n}{4k}$, implies that there is a red monochromatic path of length $\frac{n}{4k} y = s$, thus completing the proof of Theorem 12 in this case.

To complete the proof, consider a maximal collection of disjoint monochromatic medium cycles. If it covers more than $\frac{n}{2}$ vertices then we are done by Case 1. Otherwise, let U be the set of remaining vertices, then $|U| \geq \frac{n}{2}$ and there are no medium cycles in U, so we are done by Case 2. ∎

We note that in the above proof, by tracking the required constants we find that the value $c = \left(\frac{\varepsilon^2}{4800\sigma}\right)^2$ suffices. Using Lemma 6 and optimizing the above expression over ε we obtain that $c = 2^{21}$ suffices in the statement of Theorem 1.

4 | ARBITRARILY ORIENTED PATHS

We denote by $P_{n_1,\ldots,n_k}$ the oriented path consisting of k maximal directed subpaths, with the i-th one of length n_i. Recall that $\ell(P)$ is the length of the longest directed subpath of an oriented path P. Our

aim in this section is to extend Theorem 12 to arbitrarily oriented paths. We prove the following result, note that Theorem 2 easily follows from this result, by Lemma 6.

Theorem 18 *Given $\varepsilon, \sigma > 0$, there is a constant c such that the following holds. Let T be an $(\varepsilon, \sigma \log |T|)$-pseudorandom tournament on $c(\ell\sqrt{\log \ell} + n)$ vertices. Then $T \to P$, for every oriented path P on n vertices with $\ell(P) \leq \ell$.*

Theorem 18 is tight, up to a constant factor. To see this, recall, from the tightness argument for Theorem 1, that any tournament of size at most $\frac{1}{2}\ell\sqrt{\log \ell}$ can be colored without having a monochromatic $\overrightarrow{P_\ell}$, so certainly no copy of P. In addition, as $|P| = n$, any tournament on at most $n - 1$ vertices does not contain P. Combining these two observations we conclude that any tournament of size $\frac{1}{4}(\ell\sqrt{\log \ell} + n)$ can be colored without having a monochromatic copy of P.

Theorem 18 follows from Theorem 12, with some additional ideas. Before turning to the proof, we mention a few preliminaries.

Let A and B be disjoint subsets of $V(G)$, where G is an oriented graph. Let $G(A, B)$ be the subgraph consisting only of edges of G oriented from A to B. We say that (A, B) is a *k-mindegree pair* if the underlying graph of $G(A, B)$ has minimum degree at least k. The following simple lemma shows how to find k-mindegree pairs in graphs with sufficiently many edges.

Lemma 19 *Let G be a directed graph on n vertices with at least dn edges. Then G contains a $d/4$-mindegree pair.*

Proof We note that there is a bipartition $\{X, Y\}$ of $V(G)$ with $e(X, Y) \geq dn/4$. Indeed, if $\{X, Y\}$ is a random bipartition (that is, vertices are put in X with probability $1/2$ independently of other vertices), then the expected number of edges from X to Y is $e(G)/4 \geq dn/4$. Hence the required partition exists.

Now consider the underlying graph of $G(X, Y)$. This graph has at least $dn/4$ edges. Now remove, one by one, vertices of degree less than $d/4$ until no such vertices remain. Note that fewer than $dn/4$ edges are removed in this process, which implies that not all vertices were removed, that is, the resulting graph has minimum degree at least $d/4$. Denote by X' and Y' the sets of vertices remaining in X and Y, respectively. Then (X', Y') is a $d/4$-mindegree pair. ∎

Given an oriented path $P = P_{n_1,\ldots,n_k}$, let P_i denote the i-th maximal directed subpath of P. The following lemma is the main machinery that we shall need in the proof of Theorem 18.

Lemma 20 *Let G be a directed graph. Suppose that $e(G) \geq 4(x+n)|G|$ and that every subset of at least x vertices contains a $\overrightarrow{P_\ell}$. Then any oriented path P on n vertices, with $l(P) \leq l$, is a subgraph of G.*

Proof By Lemma 19, there is an $(x + n)$-mindegree pair (A, B) in G. Let $P = P_{n_1,\ldots,n_k}$. We prove by induction on k, that given the assumptions of the lemma, we can embed P with last vertex v in A if P_k is directed toward v, and in B otherwise. For the basis, the case $k = 1$, the choices of A and B imply that $|A|, |B| \geq x + n$ so within both A and B we can find a copy of P_1.

Let us assume that the statement holds for paths consisting of $k - 1$ maximal directed subpaths. Then we can find $P' = P_{n_1,\ldots,n_{k-1}-1}$ in G. Let v be the last vertex of P'. We assume that v is an end vertex of P'_{k-1}, so $v \in A$, the other case can be treated in a similar fashion.

Let S be the set of out-neighbors of v in B that are not in P'. As v has at least $x+n$ out-neighbors in B, and $|P'| \leq n$, we have $|S| \geq x$. By the assumption we can embed $P_k = \overrightarrow{P_{n_k}}$ in S, as $n_k \leq \ell$; denote its end vertex by u. Now combining P', the edge vu and a copy of P_k in S starting with u, we obtain a copy of P with the last vertex in B, and P_k oriented away from it, as desired. ∎

We are now ready to prove Theorem 18.

Proof of Theorem 18 Let $x = \varepsilon 2^{-12}|T|$, we choose c large enough in order for $x \geq n$ and $2\sigma \log x \geq \sigma \log |T|$ to hold. We first note that every subset of at least x vertices of T contains a monochromatic $\overrightarrow{P_\ell}$, provided c is large enough. Indeed, every induced subgraph T' of T on x vertices is $(\varepsilon, 2\sigma \log x)$-pseudorandom. By Theorem 12, T' contains a monochromatic path of length at least $\frac{\sqrt{c_1}\, x}{\sqrt{\log x}} \geq \ell$ (here c_1 is the constant given by Theorem 12; provided that c is sufficiently large), as claimed.

Claim 21 Let $y = |T|/32$, then every induced subgraph H of T on at least y vertices, satisfies $H \to (P, \overrightarrow{P_\ell})$.

Proof Let H be as in the claim, and let us assume that H_R does not contain $\overrightarrow{P_\ell}$ as a subgraph. This, combined with the above argument, implies that every subset of x vertices of H contains a blue $\overrightarrow{P_\ell}$. Furthermore, by Lemma 7, there are disjoint sets U and W, such that $|U| = |W| \geq (|H| - \ell)/2 \geq |H|/4$ and all edges from U to W are blue. By pseudorandomness of T, it follows that $e_B(H) \geq e(U, W) \geq \varepsilon |U||W| \geq \frac{\varepsilon}{16} y|H| \geq 4(x+n)|H|$ (here we use $x = \varepsilon 2^{-12}|T|$ and $x \geq n$). Now, it follows from Lemma 20 that H contains a blue copy of P, as required. ∎

Without loss of generality, red is the majority color in T. It follows that $e_R(T) \geq |T|(|T|-1)/4 \geq 4(y+n)|T|$. By Claim 21, we may assume that every subset of y vertices of T contains a red $\overrightarrow{P_\ell}$, because otherwise there is a blue copy of P, and we are done. It now follows from Lemma 20 that T contains a red copy of P, completing the proof of Theorem 18. ∎

5 | CONCLUDING REMARKS AND OPEN PROBLEMS

Restating Theorem 1, we proved that, with high probability, in every 2-coloring of a random tournament on $\Omega(n\sqrt{\log n})$ vertices there is a monochromatic path of length n. A simple consequence of Theorem 10 generalizes the result to k colors, implying the following result.

Theorem 22 *With high probability in any k-edge coloring of a random tournament on $\Omega(n^{k-1}\sqrt{\log n})$ vertices, there is a monochromatic path of length n. Furthermore, there is a k-edge coloring of any tournament on $\frac{1}{2}n^{k-1}(\log n)^{1/k}$ vertices with no monochromatic path of length n.*

Proof sketch Let T be an $(\varepsilon, \sigma \log |T|)$-pseudorandom tournament on $\Omega(n^{k-1}\sqrt{\log n})$ vertices, and consider a k-coloring of T. Then by Theorem 10, in color k there is either a monochromatic path $\overrightarrow{P_n}$ or an independent set of size $\Omega(n^{k-2}\sqrt{\log n})$, on which we can use induction, using Theorem 12 as the basis.

For the second part, suppose that T is a tournament on $N = \frac{1}{2^k}n^{k-1}(\log n)^{1/k}$. Following the approach presented in the Introduction, we may partition the vertices of T into

transitive subtournaments on $\frac{1}{2}\log n$ vertices and a remainder of size at most $\sqrt{n}$. Within the transitive parts, we color the edges so that there is no monochromatic path of length at least $(\frac{1}{2}\log n)^{1/k}$ (this can be done by generalizing the two colors construction for transitive tournaments, also given in the Introduction). We color the edges between the m parts according to a k-coloring of the complete graph on m vertices that has no monochromatic directed path of length at least $2m^{1/(k-1)}$ or any monochromatic directed cycle (this can be done using a grid construction; we omit further details). The length of the longest monochromatic path in this coloring is at most $\left(\frac{\log n}{2}\right)^{1/k} \cdot 2\left(\frac{2N}{\log n}\right)^{1/(k-1)} + \sqrt{n} \leq n$, as required. ∎

The above results give a bound which is best possible up to a polylog factor. It would be very interesting to close this gap.

Theorem 22 improves the best known upper bound for k-color oriented size Ramsey number of directed paths. Together with the lower bound from [4] we have the following bounds.

$$\frac{c_1 n^{2k}(\log n)^{1/k}}{(\log\log n)^{(k+2)/k}} \leq r_e\left(\overrightarrow{P_n}, k+1\right) \leq c_2 n^{2k}\log n.$$

Note that for $k = 1$ the gap between the lower and upper bounds is a factor of $O(\log\log n)$, whereas when $k \geq 2$ there is a polylog gap.

Theorem 2 is a generalization of Theorem 1 to arbitrarily oriented paths instead of directed paths. In a forthcoming paper [6], we further generalize Theorem 1 to oriented trees: we show that given any oriented tree T on n vertices, with high probability in any 2-coloring of a random tournament T on $cn(\log n)^{5/2}$ vertices, we can find a monochromatic copy of T. To achieve this we use many ideas and concepts of this paper combined with ideas from [5], as well as some new ideas. This bound is tight up to a polylog factor ($n-1$ is a trivial lower bound). It would be interesting to obtain a tight upper bound.

Note added in proof. After this paper was submitted, two of the authors [11] improved on the result of Ben-Eliezer, Krivelevich, and Sudakov [4]. They obtained a lower bound on the oriented size Ramsey number of the directed path that matches, up to a constant factor, the upper bounds that follows from Theorem 1, thus establishing that $r_e(\overrightarrow{P_n}) = \Theta(n^2\log n)$. They also improve the lower bound for more colors, by showing that the following holds, where c_3 is a positive constant.

$$r_e\left(\overrightarrow{P_n}, k+1\right) \geq c_3 n^{2k}(\log n)^{2/(k+1)}.$$

Note that this still leaves a polylog gap between the lower and upper bounds of the k-color size Ramsey number of the directed path, where $k \geq 3$. It would be interesting to close this gap.

Note added in proof. After the review of this paper has taken place, authors, together with Sven Heberle [6], resolved the generalization of the problem to oriented trees, tight up to a constant factor. In particular, they show that in any *2*-colouring of a random tournament T on $cn(\log n)^{5/2}$ vertices, there is a monochromatic copy of T.

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REFERENCES

[1] N. Alon and J. H. Spencer, *The probabilistic method*, 4th ed., Wiley Series in Discrete Mathematics and Optimization, John Wiley & Sons, Inc., Hoboken, NJ, 2016.

[2] J. Beck, *On size Ramsey number of paths, trees, and circuits. I*, J. Graph Theory **7** (1983), no. 1, 115–129.

[3] I. Ben-Eliezer, M. Krivelevich, and B. Sudakov, *Long cycles in subgraphs of (pseudo)random directed graphs*, J. Graph Theory **70** (2012), no. 3, 284–296.

[4] I. Ben-Eliezer, M. Krivelevich, and B. Sudakov, *The size Ramsey number of a directed path*, J. Combin. Theory Ser. B **102** (2012), no. 3, 743–755.

[5] M. Bucić, S. Letzter, and B. Sudakov, *Directed Ramsey number for trees*, ArXiv e-prints, http://arxiv.org/abs/1708.04504 (to appear).

[6] M. Bucić, S. Heberle, S. Letzter, and B. Sudakov, Monochromatic trees in random tournaments, (to appear).

[7] P. Erdős et al. *The size Ramsey number*, Period. Math. Hungar. **9** (1978), no. 1–2, 145–161.

[8] T. Gallai, *On directed paths and circuits*, Theory of Graphs, Proc. Colloq., Tihany, 1966, Hungary, (1968), pp. 115–118.

[9] A. Gyárfás, *Vertex coverings by monochromatic paths and cycles*, J. Graph Theory **7** (1983), no. 1, 131–135.

[10] M. Hasse, *Zur algebraischen Begründung der Graphentheorie. I*, Math. Nachr. **28** (1965), 275–290.

[11] S. Letzter and B. Sudakov, *The oriented size Ramsey number of directed paths*, ArXiv e-prints, https://arxiv.org/abs/1712.02403 (to appear).

[12] F. P. Ramsey, *On a problem of formal logic*, Proc. London Math. Soc. **S2–30** (1929), no. 1, 264.

[13] H. Raynaud, *Sur le circuit hamiltonien bi-coloré dans les graphes orientés*, Period. Math. Hungar. **3** (1973), 289–297.

[14] D. Reimer, *The Ramsey size number of dipaths*, Discrete Math. **257** (2002), no. 1, 173–175.

[15] B. Roy, *Nombre chromatique et plus longs chemins d'un graphe*, Rev. Française Informat. Recherche Opérationnelle **1** (1967), no. 5, 129–132.

[16] L. M. Vitaver, *Determination of minimal coloring of vertices of a graph by means of Boolean powers of the incidence matrix*, Dokl. Akad. Nauk SSSR **147** (1962), 758–759.

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