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Chromatic number, clique subdivisions, and the conjectures of Hajós and Erdős-Fajtlowicz

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Abstract

For a graph G , let $\chi(G)$ denote its chromatic number and $\sigma(G)$ denote the order of the largest clique subdivision in G . Let $H(n)$ be the maximum of $\chi(G)/\sigma(G)$ over all n -vertex graphs G . A famous conjecture of Hajós from 1961 states that $\sigma(G) \geq \chi(G)$ for every graph G . That is, $H(n) \leq 1$ for all positive integers n . This conjecture was disproved by Catlin in 1979. Erdős and Fajtlowicz further showed by considering a random graph that $H(n) \geq cn^{1/2}/\log n$ for some absolute constant $c > 0$. In 1981 they conjectured that this bound is tight up to a constant factor in that there is some absolute constant C such that $\chi(G)/\sigma(G) \leq Cn^{1/2}/\log n$ for all n -vertex graphs G . In this paper we prove the Erdős-Fajtlowicz conjecture. The main ingredient in our proof, which might be of independent interest, is an estimate on the order of the largest clique subdivision which one can find in every graph on n vertices with independence number α .

1 Introduction

A *subdivision* of a graph H is any graph formed by replacing edges of H by internally vertex disjoint paths. This is an important notion in graph theory, e.g., the celebrated theorem of Kuratowski uses it to characterize planar graphs. For a graph G , we let $\sigma(G)$ denote the largest integer p such that G contains a subdivision of a complete graph of order p . Clique subdivisions in graphs have been extensively studied and there are many results which give sufficient conditions for a graph G to have large $\sigma(G)$. For example, Bollobás and Thomason [5], and Komlós and Szemerédi [13] independently proved that every graph of average degree at least d has $\sigma(G) \geq cd^{1/2}$ for some absolute constant c . Motivated by a conjecture of Erdős, in [2] the authors further showed that when $d = \Omega(n)$ in the above subdivision one can choose all paths to have length two. Similar result for subdivisions of general graphs with $O(n)$ edges (a clique of order $O(\sqrt{n})$ clearly satisfies this) was obtained in [10]. For a given graph G , let $\chi(G)$ denote its chromatic number. A famous conjecture made by Hajós in 1961 states that $\sigma(G) \geq \chi(G)$. Dirac [7] proved that this conjecture is true for all $\chi(G) \leq 4$, but in 1979, Catlin [6] disproved the conjecture for all $\chi(G) \geq 7$. Subsequently, several researchers further

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studied this problem. On the negative side, by considering random graphs, Erdős and Fajtlowicz [8] in 1981 showed that the conjecture actually fails for almost all graphs. On the positive side, recently Kühn and Osthus [16] proved that all graphs of girth at least 186 satisfy Hajós' conjecture. Thomassen [19] studied the relation of Hajós' conjecture to several other problems of graph theory such as Ramsey theory, maximum cut problem, etc., and discovered many interesting connections.

In this paper, we revisit Hajós' conjecture and study to what extent the chromatic number of a graph can exceed the order of its largest clique subdivision. Let $H(n)$ denote the maximum of $\chi(G)/\sigma(G)$ over all n -vertex graphs G . The example of graphs given by Erdős and Fajtlowicz which disprove Hajós' conjecture in fact has $\sigma(G) = \Theta(n^{1/2})$ and $\chi(G) = \Theta(n/\log n)$. Thus it implies that $H(n) = \Omega(n^{1/2}/\log n)$. In [8], Erdős and Fajtlowicz conjectured that this bound is tight up to a constant factor so that $H(n) = O(n^{1/2}/\log n)$. Our first theorem verifies this conjecture.

Theorem 1.1 *There exists an absolute constant C such that $H(n) \leq Cn^{1/2}/\log n$ for $n \geq 2$.*

The proof shows that we may take $C = 10^{120}$, although we do not try to optimize this constant. For the random graph $G = G(n, p)$ with $0 < p < 1$ fixed, Bollobás and Catlin [4] determined $\sigma(G)$ asymptotically almost surely and later Bollobás [3] determined $\chi(G)$ asymptotically almost surely. These results imply, by picking the optimal choice $p = 1 - e^{-2}$, the lower bound $H(n) \geq (\frac{1}{e\sqrt{2}} - o(1))n^{1/2}/\log n$.

For a graph G , let $\alpha(G)$ denote its independence number. Theorem 1.1 actually follows from the study of the relation between $\sigma(G)$ and $\alpha(G)$, which might be of independent interest. Let $f(n, \alpha)$ be the minimum of $\sigma(G)$ over all graphs G on n vertices with $\alpha(G) \leq \alpha$.

Theorem 1.2 *There exist absolute positive constants c_1 and c_2 such that the following holds.*

1. *If $\alpha < 2 \log n$, then $f(n, \alpha) \geq c_1 n^{\frac{\alpha}{2\alpha-1}}$, and*
2. *if $\alpha = a \log n$ for some $a \geq 2$, then $f(n, \alpha) \geq c_2 \sqrt{\frac{n}{a \log a}}$.*

Note that for $\alpha = 2 \log n$, both bounds from the first and second part gives $f(n, \alpha) \geq \Omega(\sqrt{n})$. Moreover, both parts of this theorem establish the correct order of magnitude of $f(n, \alpha)$ for some range of α . For $\alpha = 2$, it can be shown that in the triangle-free graph constructed by Alon [1], every set of size at least $37n^{2/3}$ contains at least n edges. This implies that the complement of this graph has independence number 2 and the largest clique subdivision of size $t < 37n^{2/3}$. Indeed, if there is a clique subdivision of order $t \geq 37n^{2/3}$, then between each of the at least n pairs of nonadjacent vertices among the t vertices of the subdivided clique, there is at least one additional vertex along the path between them in the subdivision. However, this would require at least $t + n$ vertices in the n -vertex graph, a contradiction. On the other hand, for $\alpha = \Theta(\log n)$, by considering $G(n, p)$ with constant $0 < p < 1$, one can see that the second part of Theorem 1.2 is tight up to the constant factor. Even for $\alpha = o(\log n)$, by considering the complement of $G(n, p)$ for suitable $p \ll 1$, one can easily verify that there exists an absolute constant c' such that $f(n, \alpha) \leq O(n^{\frac{1}{2} + \frac{c'}{\alpha}})$.

Theorem 1.2 can also be viewed as a Ramsey-type theorem which establishes an upper bound on the Ramsey number of a clique subdivision versus an independent set.

Notation. A graph $G = (V, E)$ is given by a pair of its vertex set $V = V(G)$ and edge set $E = E(G)$. The edge density of G is the ratio $|E|/\binom{|V|}{2}$. For a subset X of vertices, we use $G[X]$ to denote the induced subgraph of G on the set X . Throughout the paper \log denotes the natural logarithm. We systematically omit floor and ceiling signs whenever they are not crucial, for the sake of clarity of presentation. We also do not make any serious attempt to optimize absolute constants in our statements and proofs.

2 Deducing Theorem 1.1 from Theorem 1.2

Theorem 1.1 is a quick corollary of Theorem 1.2. To see this, let $C = \max\left(e^8, \frac{16}{c_1 e}, \frac{4}{c_2 \sqrt{e}}\right)$, where c_1, c_2 are the constants from Theorem 1.2. We will prove Theorem 1.1 by induction on n . Suppose we want to prove the claim for n , and are given a graph G on n vertices with $\chi(G) = k$. We may assume that $k \geq C$ (and thus $n \geq C$) as otherwise the claim is trivially true. If $\alpha := \alpha(G) < 4n/k$, then the bounds in Theorem 1.2 easily give us the desired bound. Indeed, consider the two cases. Let $a = \alpha/\log n$. If also $\alpha < 2\log n$, so that $a < 2$, we can use the first part of Theorem 1.2 to get

$$\frac{\chi(G)}{\sigma(G)} \leq \frac{k}{c_1 n^{\frac{\alpha}{2\alpha-1}}} \leq \frac{k}{c_1 n^{\frac{1}{2} + \frac{1}{4\alpha}}} < \frac{4n/\alpha}{c_1 n^{\frac{1}{2} + \frac{1}{4\alpha}}} = \frac{n^{1/2}}{\log n} \cdot \frac{4}{c_1 a e^{\frac{1}{4a}}} \leq \frac{n^{1/2}}{\log n} \cdot \frac{16}{c_1 e} \leq C \frac{n^{1/2}}{\log n},$$

where we used the fact that the minimum of $a e^{\frac{1}{4a}}$ in the domain $(0, 2]$ occurs at $a = 1/4$. If $\alpha(G) \geq 2\log n$, so that $a \geq 2$, then by using the second part of Theorem 1.2 we get

$$\frac{\chi(G)}{\sigma(G)} \leq \frac{\sqrt{a \log a} \cdot k}{c_2 \sqrt{n}} \leq \frac{\sqrt{a \log a} \cdot 4n/(a \log n)}{c_2 \sqrt{n}} = \frac{n^{1/2}}{\log n} \cdot \frac{4\sqrt{\log a}}{c_2 \sqrt{a}} \leq \frac{n^{1/2}}{\log n} \cdot \frac{4}{c_2 \sqrt{e}} \leq C \frac{n^{1/2}}{\log n},$$

where we used the fact that the maximum of $\frac{\log a}{a}$ occurs at $a = e$.

Otherwise, $\alpha(G) \geq 4n/k$. By deleting a maximum independent set, we get an induced subgraph G' on $n' \leq n - 4n/k$ vertices, with chromatic number at least $k - 1$, and a clique subdivision of size at least $\sigma(G') \geq \chi(G')/H(n') \geq (k - 1)/H(n')$. Note that if $n' < e^2$, then $k \leq 1 + n' < 9 < C$, and this case was already settled. So we may assume $n' \geq e^2$. Hence, by induction on n , we have

$$\frac{\chi(G)}{\sigma(G)} \leq \frac{k}{\sigma(G')} \leq \left(\frac{k}{k-1}\right) H(n') \leq \frac{k}{k-1} \cdot \frac{C n'^{1/2}}{\log n'}. \quad (1)$$

As the function $x^{1/2}/\log x$ is increasing for $x \geq e^2$, the right-hand side of (1) is maximized at $n' = (1 - 4/k)n$. Consequently, we have

$$\begin{aligned} \frac{\chi(G)}{\sigma(G)} &\leq \frac{k}{k-1} \cdot \frac{C n'^{1/2}}{\log n'} \leq \left(\frac{k}{k-1}\right) \left(1 - \frac{4}{k}\right)^{1/2} \left(1 + \frac{\log(1 - 4/k)}{\log n}\right)^{-1} \frac{C n^{1/2}}{\log n} \\ &\leq \left(1 - \frac{1}{k}\right) \left(1 + \frac{\log(1 - 4/k)}{\log n}\right)^{-1} \frac{C n^{1/2}}{\log n} \leq \left(1 - \frac{1}{k}\right) \left(1 - \frac{8}{k \log n}\right)^{-1} \frac{C n^{1/2}}{\log n} \\ &\leq C \frac{n^{1/2}}{\log n}, \end{aligned}$$

where in the second to last inequality we used

$$\log(1 - x) = -(x + \frac{x^2}{2} + \frac{x^3}{3} + \dots) > -(x + x^2 + x^3 + \dots) > -2x$$

for $0 < x < 1/2$, which holds with $x = 4/k$ from $k \geq C \geq e^8$, and in the last inequality we used $n \geq C \geq e^8$. We therefore have $H(n) \leq Cn^{1/2}/\log n$, which completes the proof. \square

3 Tools and the idea of the proof

The proof of Theorem 1.2 makes use of four main tools that we describe in this section. In the end of the section we outline the proof of Theorem 1.2 using these tools.

Our first tool is a theorem independently proved by Bollobás and Thomason [5], and Komlós and Szemerédi [13]. They determined up to a constant factor the minimum number of edges which guarantees a K_t -subdivision in a graph on n vertices, solving an old conjecture made by Erdős and Hajnal, and also by Mader.

Theorem 3.1 (Bollobás-Thomason, Komlos-Szemerédi) *Every graph G with n vertices and at least $256t^2n$ edges satisfies $\sigma(G) \geq t$.*

We remark that Theorem 3.1 implies $H(n) = O(n^{1/2})$. Indeed, a graph G with chromatic number k has a subgraph with minimum degree at least $k-1$ and hence by Theorem 3.1 satisfies $\sigma(G) = \Omega(k^{1/2})$. We thus get $\frac{\chi(G)}{\sigma(G)} = O(k^{1/2}) = O(n^{1/2})$. As this bound holds for all G on n vertices, we have $H(n) = O(n^{1/2})$. Our goal is to prove the better bound $H(n) = O(n^{1/2}/\log n)$.

The theorem above can be used as a black box to indirectly construct clique subdivisions in certain cases. However, in order to directly construct a large clique subdivision in a graph, we first find a large subset in which only a small number of edges is missing, and then for each such missing edge, find internally vertex-disjoint paths connecting the two endpoints. For technical reasons, we reverse the two steps. That is, we first find a large subset of vertices such that every pair of vertices can be connected by many internally vertex-disjoint paths (Lemma 3.1), and then find a further subset in which only a small proportion of edges is missing (Lemma 3.2). It would be nice if these two steps were sufficient in proving Theorem 1.1. Unfortunately, a naive application of these two steps together with Theorem 3.1 will only imply our main result for a certain range of parameters, more precisely, when the graph is dense enough depending on the independence number. Thus to handle the case when the graph is sparse, we develop another lemma (Lemma 3.3), which essentially says that in the sparse case, we can find a subgraph in which the parameters work (see the discussion before Lemma 3.3).

The next tool is based on a simple yet surprisingly powerful lemma whose proof uses a probabilistic argument known as dependent random choice. Early versions of this technique were developed in the papers [12, 14, 17]. Later, variants were discovered and applied to various problems in Ramsey theory and extremal graph theory (see the survey [11] for more details). The following lemma says that every graph of large enough density contains a large subset in which every pair of vertices are connected by many internally vertex-disjoint paths.

Lemma 3.1 *Assume that d and n are given so that $d^2n \geq 1600$. If $G = (V, E)$ has n vertices and edge density d , then there is a vertex subset $U \subset V$ with $|U| \geq dn/50$ vertices such that every pair of vertices in U have at least $10^{-9}d^5n$ internally vertex-disjoint paths of length 4 which uses only vertices from $V \setminus U$ as internal vertices.*

Proof: Let V_1 be a random subset of V of size $\lceil n/2 \rceil$ and let $V_2 = V \setminus V_1$. Then it is easy to check that $\mathbb{E}[e(V_1, V_2)] \geq \frac{d}{2} \binom{n}{2}$ and therefore we may pick such a partition $V = V_1 \cup V_2$ with $e(V_1, V_2) \geq \frac{d}{2} \binom{n}{2}$. Throughout the proof we restrict our graph to the bipartite graph induced by the edges between V_1 and V_2 .

Pick a vertex $v_0 \in V_2$ uniformly at random, and let $X \subset V_1$ be the neighborhood of v_0 . The probability of a fixed vertex $v \in V_1$ belonging to X is $\mathbb{P}(v \in X) = \deg(v)/|V_2|$ and thus by the Cauchy-Schwarz inequality and $n \geq 2$,

$$\mathbb{E}[|X|^2] \geq \mathbb{E}[|X|]^2 = \left(\sum_{v \in V_1} \frac{\deg(v)}{|V_2|} \right)^2 = \left(\frac{e(V_1, V_2)}{|V_2|} \right)^2 \geq \left(\frac{d(n-1)}{2} \right)^2 \geq \frac{d^2n^2}{16}.$$

Call a pair (v, w) of vertices in V_1 *bad* if v and w have at most $d^2n/800$ common neighbors, and call it *good* otherwise. Let b be the number of bad pairs in X . Note that for a bad pair (v, w) , the probability that both v and w belongs to X is at most $\mathbb{P}(v, w \in X) \leq d^2n/(800|V_2|)$. Consequently, the expectation of b is at most

$$\mathbb{E}[b] \leq \frac{d^2n}{800|V_2|} \binom{n}{2} \leq \frac{d^2n^2}{800}.$$

Thus we have

$$\mathbb{E}[|X|^2 - 40b] \geq \frac{d^2n^2}{80}.$$

Therefore we have a choice of v_0 for which $|X|^2 - 40b \geq d^2n^2/80 \geq 0$. Fix this choice of v_0 (and X). Note that this in particular implies $|X| \geq dn/10$ and $b \leq |X|^2/40$.

Call a vertex in X *bad* if it forms a bad pair with at least $|X|/4$ vertices in X . By the bound on b , we know that there are at most $|X|/5$ bad vertices in X . Let U be an arbitrary subcollection of non-bad vertices in X of size $|X|/5 \geq dn/50$. We claim that U is a set which has all the claimed properties.

Since the vertices of U form a bad pair with at most $|X|/4$ vertices in X , for every two distinct vertices v, w in U , the number of vertices in $X \setminus U$ with which both v, w form a good pair is at least

$$|X| - |U| - 2 \cdot \frac{|X|}{4} = \frac{3|X|}{10}.$$

Moreover, whenever we have a vertex x which forms a good pair with both v and w , by the definition of a good pair, we can find at least $(d^2n/800)(d^2n/800 - 1)$ paths of length 4 connecting v and w which uses only vertices from $V \setminus U$ as internal vertices. Therefore by collecting the facts, we see that given $d^2n \geq 1600$, the number of such paths of length 4 between v and w is at least

$$\left(\frac{3|X|}{10} \right) \cdot \left(\frac{d^2n}{800} \right) \left(\frac{d^2n}{800} - 1 \right) \geq \frac{3d^5n^3}{100 \cdot 800 \cdot 1600} \geq 10^{-8}d^5n^3.$$

Note that interior (without endpoints) of any given path of length 4 connecting v and w can intersect at most $3n^2$ other such paths. This implies that there are at least $10^{-8}d^5n^3/(3n^2) \geq 10^{-9}d^5n$ internally vertex-disjoint paths connecting v and w which uses only vertices from $V \setminus U$ as internal vertices. This completes the proof. \square

The following lemma asserts that every graph of small independence number contains a large subset in which only a small proportion of edges are missing.

Lemma 3.2 *Let $0 < \rho < 1$ and α be a positive integer. Then for every positive integer $s \leq \lceil \rho^{\alpha-1}n \rceil$, every graph G on n vertices with independence number at most α contains a subset of size s with at most ρs^2 nonadjacent pairs of vertices.*

Proof: If $s = 1$, then the claim is clearly true. Thus we assume that $s \geq 2$. Let t be an integer satisfying $t \geq s$. It suffices to find a subset of order t which has at most $\rho t^2/2$ nonadjacent pairs, since by an averaging argument over all subsets of this t -set of order s , we can find a subset of order s which has at most

$$\frac{\rho t^2}{2 \binom{t}{2}} \cdot \binom{s}{2} \leq \rho s^2$$

edges missing.

Let $V_0 = V(G)$. We will find a sequence $V_0 \supset V_1 \supset \dots$ of subsets such that the induced subgraph of G with vertex set V_i has independence number at most $\alpha - i$ and at least $\rho^i n$ vertices. Notice this is satisfied for $i = 0$. If V_i has a vertex which has at least $\rho|V_i|$ non-neighbors in V_i , then let $V_{i+1} \subset V_i$ be the subset of non-neighbors, so $|V_{i+1}| \geq \rho|V_i|$. Since the induced subgraph of G with vertex set V_{i+1} has independence number at most $\alpha - i - 1$, we can continue the induction. Otherwise, every vertex of V_i has less than $\rho|V_i|$ non-neighbors, so there are less than $\rho|V_i|^2/2$ nonadjacent pairs in V_i , in which case we are done. If this process continues through $\alpha - 1$ steps, we get a set $V_{\alpha-1}$ of order at least $\rho^{\alpha-1}n$, and independence number at most one, so this is a clique of order at least s , which completes the proof. \square

Suppose we are trying to prove Theorem 1.2 for $\alpha < 2 \log n$. First apply Lemma 3.1 to find a subset U of size $\Omega(dn)$ in which each pair is connected by $\Omega(d^5n)$ internally vertex-disjoint paths of length 4. Then apply Lemma 3.2 to U with a suitable choice of ρ , and hope to find a subset of size $\Omega(n^{\alpha/(2\alpha-1)})$, in which $O(d^5n)$ edges are missing. By Lemma 3.1 we can use internally vertex-disjoint paths of length 4 instead of missing edges to get a clique subdivision on these vertices. A crucial observation is that this only works if U is large enough (that is, if d is large enough).

Our next lemma can be used to overcome this difficulty. The idea of this lemma first appeared in a 1972 paper of Erdős-Szemerédi [9], and has also been useful in other problems (for example, [18]). It shows that if a sparse graph does not have large independence number, then it contains an induced subgraph with many vertices whose independence number is much smaller than in the original graph. We will later see that with the help of this lemma, the strategy above can be modified to find a subset of size $\Omega(n^{\alpha/(2\alpha-1)})$ with $O(d^5n)$ non-adjacent pairs (we use the same strategy for $\alpha \geq 2 \log n$).

Lemma 3.3 *Let $0 < d \leq 1$. Let G be a graph, I be a maximum independent set of G with $|I| = \alpha$, and V_1 be a vertex subset of $V \setminus I$ with $|V_1| = N$ such that each vertex in V_1 has at most $d|I|$ neighbors in I . Then there is a subset $U \subset V_1$ with $|U| \geq \left(\frac{\epsilon}{d}\right)^{-d\alpha} N$ such that the induced subgraph of G with vertex set U has independence number at most $d\alpha$.*

Proof: For every vertex $v \in V_1$ fix a subset of I of size $\lfloor d|I| \rfloor$ which contains all neighbors of v in I . Since the number of such subsets of I is at most $\binom{|I|}{\lfloor d|I| \rfloor} \leq \left(\frac{\epsilon}{d}\right)^{d\alpha}$, one of them contains neighborhoods of at least $|V_1| \left(\frac{\epsilon}{d}\right)^{-d\alpha}$ vertices of V_1 . Let $U \subset V_1$ be the set of these vertices. We have that $|U| \geq \left(\frac{\epsilon}{d}\right)^{-d\alpha} N$, and the number of vertices in I which have a neighbor in U is at most $d|I|$.

Note that all the vertices in I which do not have a neighbor in U can be added to an independent subset of U to make a larger independent set. Since I is an independent set of size α , there are at least $(1 - d)\alpha$ such vertices. Moreover, since G has independence number at most α , the induced subgraph of G on U has independence number at most $d\alpha$. \square

3.1 Outline of the proof

We next outline the proof of Theorem 1.2, which gives a lower bound on $\sigma(G)$ for a graph G with n vertices and independence number α . The proof strategy depends on whether or not the graph G is dense.

When G is dense the proof splits into two cases, depending on the size of α (see Lemma 4.1 in the next section). If $\alpha \leq 2 \log n$, then we apply Lemma 3.1 to obtain a large vertex subset U in which every pair of vertices in U are the endpoints of a large number of internally vertex-disjoint paths of length 4. We then apply Lemma 3.2 to obtain a subset $S \subset U$ of large order s such that $G[S]$ has few missing edges. The vertices of S form the vertices of a K_s -subdivision. Indeed, for every pair of adjacent vertices in S , we use the edges between them as paths, and for every pair of non-adjacent vertices, we use paths of length 4 between them. These paths can be chosen greedily using that each pair of vertices in S are the endpoints of many internally vertex-disjoint paths of length 4 and there are few missing edges within S . This completes the case $\alpha \leq 2 \log n$ of Lemma 4.1. If $\alpha > 2 \log n$, using the fact G is dense, we apply Theorem 3.1 to obtain the desired large clique subdivision.

For sparse G we prove a lower bound on $\sigma(G)$ in terms of the number n of vertices, the independence number $\alpha = \alpha(G)$, and the edge density d of G (see Lemma 4.2 in the next section). The proof is by induction on n , the base case $n = 1$ being trivial. The cases $d < n^{-1/4}$ or $\alpha \geq n/16$ can be trivially verified, so we may suppose $d > n^{-1/4}$ and $\alpha < n/16$. One easily finds an independent set I and a vertex subset V'' which is disjoint from I with $|V''| \geq n/8$ such that I is a maximum independent set in $G[V'' \cup I]$ such that every vertex in V'' has at most $8d|I|$ neighbors in I . If $G[V'']$ has edge density at most $d/10$, then, by the induction hypothesis, $G[V'']$, and hence G as well, contains a K_s -subdivision of the desired size. So we may suppose $G[V'']$ has edge density at least $d/10$. Apply Lemma 3.1 to find a large subset $V_1 \subset V''$ such that every pair of vertices in V_1 are the endpoints of a large number of internally vertex-disjoint paths of length 4. Applying Lemma 3.3, we find a large subset $U \subset V_1$ such that the independence number of $G[V_1]$ is small. Finally, we then apply Lemma 3.2 to obtain a subset $S \subset U$ of large order s such that $G[S]$ has few missing edges. Just as in the

dense case discussed above, the set S form the vertices of the desired K_s -subdivision.

4 Proof of Theorem 1.2

In this section we prove Theorem 1.2 using the tools and the strategy we developed in the previous section. We separately consider two cases depending on the relation between the edge density d and the independence number α of the graph. The following lemma establishes the case when the graph is dense.

Lemma 4.1 *Fix a constant $0 < c \leq 1$. The following holds for every graph G with $n \geq 10^{14}c^{-5}$ vertices, edge density d , and independence number α .*

(i) *If $\alpha \leq 2 \log n$ and $d \geq c$, then $\sigma(G) \geq 10^{-6}c^{5/2}n^{\alpha/(2\alpha-1)}$.*

(ii) *If $\alpha = a \log n$ for some $a \geq 2$ and $d \geq c/(a \log a)$, then $\sigma(G) \geq \sqrt{\frac{c}{600}} \sqrt{\frac{n}{a \log a}}$.*

Proof: (i) Given a graph G as in the statement of the lemma, since $d^2n \geq 1600$, we can apply Lemma 3.1 to get a vertex subset U of size $dn/50$ such that every pair of vertices in U have at least $10^{-9}d^5n$ internally vertex-disjoint paths of length 4 between them whose internal vertices lie in $V \setminus U$.

We may assume $\alpha \geq 2$, as otherwise $\alpha = 1$, G is a clique, and $\sigma(G) = n$. By applying Lemma 3.2 to U with $\rho = (10^{-7}d^3n^{-1})^{1/(2\alpha-1)}$ (note that $\rho < 1$), we find a vertex subset $S \subset U$ of size

$$s = \lceil \rho^{\alpha-1}|U| \rceil = \left\lceil (10^{-7}d^3)^{(\alpha-1)/(2\alpha-1)} \cdot \frac{d}{50} \cdot n^{\alpha/(2\alpha-1)} \right\rceil \geq 10^{-6}d^{5/2}n^{\alpha/(2\alpha-1)}$$

with at most

$$\rho s^2 \leq 2\rho^{2\alpha-1}|U|^2 = 2 \cdot 10^{-7}d^3n^{-1} \cdot (dn/50)^2 \leq 10^{-10}d^5n,$$

nonadjacent pairs, where we used the fact that $s^2 \leq 2\rho^{2\alpha-2}|U|^2$, which follows from the inequality $s \geq 10^{-6}d^{5/2}n^{\alpha/(2\alpha-1)} \geq 10^{-6}d^{5/2}n^{1/2} \geq 10$ (recall that $n \geq 10^{14}c^{-5}$).

We claim that the vertices of S form the vertices of a K_s -subdivision. For every pair of adjacent vertices in S , we use the edges between them as paths, and for every pair of non-adjacent vertices, we use paths of length 4 between them. Since the number of non-adjacent pairs of vertices is at most $10^{-10}d^5n$, and each such pair has at least $10^{-9}d^5n \geq 3 \cdot 10^{-10}d^5n$ internally vertex-disjoint paths of length 4 connecting them which uses only vertices from $V \setminus S$ as internal vertices, we can greedily pick one path for each non-adjacent pair to construct a K_s -subdivision. Indeed, note that the use of a certain path of length 4 can destroy at most 3 other such paths for each other non-adjacent pair since they have disjoint interiors.

(ii) Since $d \geq c/(a \log a)$, the total number of edges in the graph is

$$d \binom{n}{2} \geq \frac{c(n-1)}{2a \log a} n.$$

Therefore by Theorem 3.1, we can find a K_s -subdivision for s satisfying

$$s \geq \sqrt{\frac{c(n-1)}{512a \log a}} \geq \sqrt{\frac{c}{600}} \sqrt{\frac{n}{a \log a}}.$$

□

Let $f(n, \alpha, d)$ be the maximum t such that every graph G on n vertices with independence number at most α and edge density d contains a K_t -subdivision. First note that by Turán's theorem, we have a lower bound on d in terms of α .

Proposition 4.1 *Let G be a graph with n vertices, edge density d , and independence number α . If $\alpha \leq n/2$, then $d \geq 1/(2\alpha)$.*

Proof: By Turán's theorem and convexity of the function $g(x) = \binom{x}{2}$, we know $d \binom{n}{2} \geq \alpha \binom{n/\alpha}{2} = n(n/\alpha - 1)/2$, from which it follows that $d \geq \frac{(n/\alpha - 1)}{n-1} \geq \frac{1}{2\alpha}$. □

The next lemma establishes a good bound on $f(n, \alpha, d)$ when d is small (depending on α). This can be used to handle the remaining case of the proof of Theorem 1.2.

Lemma 4.2 *Let G be a graph with n vertices, edge density d , and independence number α . If $\alpha \leq n/2$, $d \leq 10^{-20}$, and $d\alpha \log(1/d) \leq (\log n)/100$, then we have $f(n, \alpha, d) \geq (1/50)d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}$.*

Proof: The proof is by induction on n . Note that by $\alpha \leq n/2$ and Proposition 4.1, we have $d \geq 1/(2\alpha)$. Thus we only need to consider the range $1/(2\alpha) \leq d \leq 1$.

We first verify some initial cases. Namely, we prove that if either $d < n^{-1/4}$ or $\alpha > n/16$ holds, then the bound $f(n, \alpha, d) \geq (1/50)d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}$ is true.

If $d < n^{-1/4}$, then by the fact $d \geq 1/(2\alpha)$ we have

$$(1/50)d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}} \leq n^{-1} n^{\frac{1}{2} + \frac{1}{20}} \leq 1.$$

Therefore the statement is true in this case by the trivial bound $f(n, \alpha, d) \geq 1$. From now on, we may assume that $d \geq n^{-1/4}$, from which it follows that $n \geq d^{-4} \geq 10^{80}$.

If $\alpha > n/16$ and $d \geq n^{-1/4}$, then by applying Theorem 3.1 we can find a clique subdivision of order at least

$$\sqrt{d \binom{n}{2} / 256n} = \sqrt{\frac{d(n-1)}{512}} \geq \sqrt{\frac{dn}{600}}.$$

We claim that this is larger than $(1/50)d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}$. Indeed, it suffices to show that $(1/50)d^4 n^{\frac{1}{40d\alpha}} \leq \sqrt{d/600}$, which is implied by

$$d^{7/2} n^{\frac{1}{40d\alpha}} \leq 2.$$

In the range $n^{-1/4} \leq d \leq 1$ with $\alpha > n/16$, the left-hand side is an increasing function and hence maximized at $d = 1$. When $d = 1$ we have $d^{7/2} n^{\frac{1}{40d\alpha}} \leq n^{\frac{2}{5n}} < 2$. This finishes the proof of the initial cases.

Now assume that some n is given and the lemma has been proved for all smaller values of n . By the observations above, we may also assume that $d \geq 1/(2\alpha)$, $\alpha \leq n/16$, and $d \geq n^{-1/4}$, which implies $n \geq 10^{80}$. Let G be a graph on n vertices with edge density d , and independence number at most α . Let $V' \subset V(G)$ be the set of vertices of degree at most $2dn$, so $|V'| \geq n/2$.

Let I be a maximum independent set in the induced subgraph of G with vertex set V' . Note that $|I| \leq \alpha$. Let $X \subset V'$ be the set of vertices with at least $8d|I|$ neighbors in I , and let $V'' = V' \setminus (X \cup I)$. Then by counting the number of edges incident to vertices of I in two different ways, we get

$$|X| \cdot 8d|I| \leq |I| \cdot 2dn,$$

from which we get the bound $|X| \leq n/4$. Therefore, we get $|V''| \geq |V'| - |X| - |I| \geq n/8$. Let $n' = |V''| \geq n/8$, and let d' be the edge density and α' be the independence number, respectively, of the graph $G[V'']$. Note that $\alpha' \leq \alpha$.

Case 1 : $d' \leq d/10$.

We want to apply the inductive hypothesis in this case. We first show that the new parameters n', d', α' satisfy all the imposed conditions. First we have $\alpha' \leq \alpha \leq n/16 \leq n'/2$, and second $d' \leq d \leq 10^{-20}$. Finally, since $t \log(1/t)$ is increasing for $t \leq e^{-1}$,

$$d' \alpha' \log(1/d') \leq \frac{d}{10} \alpha \log(10/d) \leq \frac{d\alpha \log(1/d)}{2} \leq \frac{\log n}{200} \leq \frac{\log(n')}{100}.$$

Thus we can use the induction bound $\sigma(G) \geq f(n', \alpha', d') \geq \frac{1}{50} (d')^4 (n')^{\frac{1}{2} + \frac{1}{40d'\alpha'}}$. Let $d' = qd$, so $q \leq 1/10$. As $\alpha' \leq \alpha$ note that

$$\begin{aligned} f(n', \alpha', d') &\geq \frac{1}{50} (d')^4 (n')^{\frac{1}{2} + \frac{1}{40d'\alpha'}} \geq \frac{1}{50} (d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}) (q^4 n^{\frac{1}{40d\alpha} (\frac{1}{q} - 1)}) / 8 \\ &= \frac{1}{400} (d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}) (e^{\frac{\log n}{40d\alpha} (\frac{1}{q} - 1) - 4 \log(\frac{1}{q})}). \end{aligned}$$

Since $40d\alpha \leq d\alpha \log(1/d) \leq \log n/100$, we have that $\frac{\log n}{40d\alpha} (\frac{1}{q} - 1) - 4 \log(\frac{1}{q}) \geq 100(\frac{1}{q} - 1) - 4 \log(\frac{1}{q})$ and the right-hand side of the above displayed inequality is minimized when q is maximized. By using $q \leq 1/10$ we see that

$$\sigma(G) \geq f(n', \alpha', d') \geq d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}.$$

Case 2 : $d' > d/10$.

Note that by the inequalities $d \geq n^{-1/4}$ and $n \geq 10^{80}$, we have

$$(d')^2 n' \geq d^2 n / 800 \geq n^{1/2} / 800 \geq 1600.$$

Therefore we can apply Lemma 3.1 to $G[V'']$ and find a subset $V_1 \subset V''$ with $|V_1| \geq d'n'/50 \geq dn/4000$ and the property that every pair of vertices in V_1 has at least $10^{-9}(d')^5 n' \geq 10^{-15} d^5 n$ internally vertex-disjoint paths of length 4 between them, which only use vertices in $V'' \setminus V_1$. Then by Lemma 3.3, we get a subset $U \subset V_1$ with (note that $d \leq 10^{-20}$ and $d\alpha \geq 1/2$)

$$|U| \geq \left(\frac{e}{8d}\right)^{-8d\alpha} |V_1| \geq \left(\frac{e}{8d}\right)^{-8d\alpha} \frac{dn}{4000} \geq e^{-15d\alpha \log(1/d)} n = d^{15d\alpha} n$$

such that the induced subgraph of G with vertex set U has independence number at most $\beta := \lceil 8d\alpha \rceil \geq 4$. Redefine U as an arbitrary subset of size $u = \lfloor e^{-15d\alpha \log(1/d)} n \rfloor$. Note that $u \geq e^{-15d\alpha \log(1/d)} n/2$ since $d\alpha \log(1/d) \leq (\log n)/100$.

Let $\rho = (d^{(6-30d\alpha)} n^{-1})^{1/(2\beta-1)}$. We have $\rho < 1$ from $d \leq 1$, $d\alpha \log(1/d) \leq (\log n)/100$, and $\beta \geq 4$, since

$$\rho^{2\beta-1} = d^{(6-30d\alpha)} n^{-1} \leq d^{-30d\alpha} n^{-1} = e^{30d\alpha \log(1/d)} n^{-1} \leq n^{3/10} \cdot n^{-1} < 1.$$

By applying Lemma 3.2 with this value of ρ to the graph $G[U]$, we get a subset S of size $s := \lceil \rho^{\beta-1} u \rceil$ with at most ρs^2 non-adjacent pairs. Note that if $s = 1$, then S contains no non-adjacent pairs, and if $s \geq 2$, then S contains at most $\rho s^2 \leq 4\rho^{2\beta-1} u^2$ non-adjacent pairs. In any case, S has at most $4\rho^{2\beta-1} u^2$ non-adjacent pairs. By definition, $\beta = \lceil 8d\alpha \rceil \geq 8d\alpha - 1$ and therefore $15d\alpha \leq 2\beta + 2$. Thus, the number of vertices in S is at least

$$s \geq \rho^{\beta-1} u \geq (d^{(6-30d\alpha)} n^{-1})^{(\beta-1)/(2\beta-1)} \cdot (d^{15d\alpha} n/2) = \frac{1}{2} d^{\frac{6\beta-6+15d\alpha}{2\beta-1}} n^{\frac{1}{2} + \frac{1}{2(2\beta-1)}} \geq \frac{1}{2} d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}$$

and the number of non-adjacent pairs in S is at most

$$\rho s^2 \leq 4\rho^{2\beta-1} u^2 \leq 4(d^{6-30d\alpha} n^{-1})(d^{30d\alpha} n^2) = 4d^6 n.$$

The vertices of S form the vertices of a K_s -subdivision, where we use the edges between them as paths, and for the pairs in S that are not adjacent, we use paths of length 4 between them. We can greedily pick these paths of length 4 as there are at most $4d^6 n$ edges missing, and each pair of vertices have $10^{-15} d^5 n \geq 3 \cdot 4d^6 n$ internally vertex-disjoint paths of length 4 between them, where we used the fact that $d \leq 10^{-20}$. This completes the proof. \square

Note that the lemma above is no longer true if we completely remove the restriction $\alpha \leq n/2$. For example, if $\alpha = n - 1$, then we can have $d = 1/\binom{n}{2}$, for which we have $d^4 n^{1/2+1/(40d\alpha)} \gg n$. The conclusion of the lemma is clearly impossible in this case since the total number of vertices is n .

The proof of Theorem 1.2 easily follows from the two lemmas above.

Proof of Theorem 1.2: Let G be a graph with n vertices, edge density d , and independence number α . Let $c = 10^{-20}$ and $c_1 = c_2 = c' = 10^{-114}$. If $n \leq 10^{14} c^{-5} = 10^{114}$, then we have $\sigma(G) \geq 1 \geq c'n$. Thus we assume that $n > 10^{14} c^{-5}$.

Case 1: $\alpha \leq 2 \log n$.

If $d \geq c$, then by the first part of Lemma 4.1 we have $\sigma(G) \geq (10^{-6} c^{5/2}) n^{\alpha/(2\alpha-1)} \geq c' n^{\alpha/(2\alpha-1)}$.

On the other hand if $d \leq c$, then we have $d\alpha \log(1/d) \leq (\log n)/1000$ and $\alpha \leq 2 \log n \leq n/2$. Lemma 4.2 therefore implies

$$\sigma(G) \geq \frac{1}{50} d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}.$$

From the inequality $d\alpha \log(1/d) \leq (\log n)/1000$, we have $d^4 n^{1/(80d\alpha)} = e^{-4 \log(1/d) + (\log n)/(80d\alpha)} \geq e^{-4 \log(1/d) + (25/2) \log(1/d)} > 1$, and thus the above is at least

$$\frac{n^{\frac{1}{2} + \frac{1}{80d\alpha}}}{50} \geq \frac{n^{\frac{1}{2} + \frac{1}{\alpha}}}{50} \geq \frac{n^{\frac{\alpha}{2\alpha-1}}}{50} \geq c' n^{\alpha/(2\alpha-1)}.$$

Case 2: $\alpha = a \log n$ for some $a > 2$.

If $d \geq \frac{c}{a \log a}$, then by the second part of Lemma 4.1 we have

$$\sigma(G) \geq \sqrt{\frac{c}{600}} \sqrt{\frac{n}{a \log a}} \geq c' \sqrt{\frac{n}{a \log a}}.$$

Thus we may assume that $d \leq \frac{c}{a \log a}$. If $\alpha > n/2$, then $a > n/(2 \log n)$ and thus $c' \sqrt{n/(a \log a)} < 1$. Therefore we trivially have $\sigma(G) \geq 1 > c' \sqrt{n/(a \log a)}$ in this case.

Otherwise, $\alpha \leq n/2$ and $d \leq \frac{c}{a \log a} \leq c$ since $a \geq 2$. We also have $d \alpha \log(1/d) \leq (\log n)/100$. Indeed, as $t \log(1/t)$ is increasing for $t \leq e^{-1}$, to verify this inequality one can substitute $d = \frac{c}{a \log a}$ and $\alpha = a \log n$. By Lemma 4.2,

$$\sigma(G) \geq \frac{1}{50} d^4 n^{\frac{1}{2} + \frac{1}{40d\alpha}}.$$

Note that as in Case 1 we have $d^4 n^{1/(80d\alpha)} = e^{-4 \log(1/d) + \log n/(80d\alpha)} > 1$, and thus the above is at least

$$\frac{n^{\frac{1}{2} + \frac{1}{80d\alpha}}}{50} \geq \frac{n^{\frac{1}{2}}}{50} \geq c' \sqrt{\frac{n}{a \log a}}.$$

□

5 Concluding Remarks

In this paper we established the conjecture of Erdős and Fajtlowicz that $\frac{\chi(G)}{\sigma(G)} \leq \frac{Cn^{1/2}}{\log n}$ for every graph G on n vertices. The main part of the proof is Theorem 1.2, which gives a lower bound on $f(n, \alpha)$, the minimum of $\sigma(G)$ over all graphs G on n vertices with $\alpha(G) \leq \alpha$. It would be interesting to determine the order of growth of $f(n, \alpha)$. As remarked in the introduction, determining $f(n, \alpha)$ is equivalent to the following Ramsey-type problem. Determine the minimum n for which every red-blue edge-coloring of K_n contains a red subdivision of K_s or a blue $K_{\alpha+1}$.

Theorem 1.2 and the remarks afterwards determines the order of growth of $f(n, \alpha)$ for $\alpha = 2$ and $\alpha = \Theta(\log n)$. We conjecture that the lower bound $f(n, \alpha) \geq c_1 n^{\frac{\alpha}{2\alpha-1}}$ is tight up to a constant factor also for all $\alpha < 2 \log n$. As in the case $\alpha = 2$, to prove such a result it would be sufficient to find a $K_{\alpha+1}$ -free graph G on n vertices in which every subset of order $Cn^{\frac{\alpha}{2\alpha-1}}$ contains at least n edges. Then the complement of G will have independence number at most α and no clique subdivision of order $Cn^{\frac{\alpha}{2\alpha-1}}$ (the proof is as in the case $\alpha = 2$, see the introduction). A potential source of such graphs G are (n, d, λ) -graphs, introduced by Alon. An (n, d, λ) -graph is a d -regular graph on n vertices for which λ is the second largest in absolute value eigenvalue of its adjacency matrix. An (n, d, λ) -graph G which is $K_{\alpha+1}$ -free with $d = \Omega\left(n^{1-\frac{1}{2\alpha-1}}\right)$ and $\lambda = O\left(\sqrt{d}\right)$ would satisfy the desired property by the expander mixing lemma (see, e.g., Theorem 2.11 in the survey [15]). It is worth mentioning that this would be up to a constant factor the densest (n, d, λ) -graph with $\lambda = O(\sqrt{d})$ which is $K_{\alpha+1}$ -free (see, e.g., Theorem 4.10 of [15]). The construction of Alon [1] in the case $\alpha = 2$ is the only known example of such graphs. We think it would be quite interesting to find examples for larger α , which would have other applications as well.

We make the following conjecture on the order of the largest clique subdivision which one can find in a graph with chromatic number k .

Conjecture 5.1 *There is a constant $c > 0$ such that every graph G with chromatic number $\chi(G) = k$ satisfies $\sigma(G) \geq c\sqrt{k \log k}$.*

The bound in Conjecture 5.1 would be best possible by considering a random graph of order $O(k \log k)$. Recall the result of Bollobás and Thomason [5] and Komlós and Szemerédi [13] which says that every graph G of average degree d satisfies $\sigma(G) = \Omega(\sqrt{d})$. This is enough to imply the bound $\sigma(G) = \Omega(\sqrt{k})$ for G with $\chi(G) = k$, but not the extra logarithmic factor. Much of the techniques developed in this paper to solve Theorem 1.1 are most useful in rather dense graphs. These techniques do not appear sufficient to solve Conjecture 5.1, as in this conjecture one needs to handle clique subdivisions in rather sparse graphs.

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