Polynomial bounds for chromatic number
II. Excluding a star-forest

Alex Scott[1]
Mathematical Institute, University of Oxford, Oxford OX2 6GG, UK

Paul Seymour[2]
Princeton University, Princeton, NJ 08544

Sophie Spirkl[3]
University of Waterloo, Waterloo, Ontario N2L3G1, Canada

July 5, 2021; revised January 11, 2022

[1]Research supported by EPSRC grant EP/V007327/1.
[2]Supported by AFOSR grant A9550-19-1-0187, and by NSF grant DMS-1800053.
[3]We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC), [funding reference number RGPIN-2020-03912]. Cette recherche a été financée par le Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG), [numéro de référence RGPIN-2020-03912].

Abstract

The Gyárfás-Sumner conjecture says that for every forest H, there is a function f_H such that if G is H-free then $\chi(G) \leq f_H(\omega(G))$ (where χ, ω are the chromatic number and the clique number of G). Louis Esperet conjectured that, whenever such a statement holds, f_H can be chosen to be a polynomial. The Gyárfás-Sumner conjecture is only known to be true for a modest set of forests H, and Esperet's conjecture is known to be true for almost no forests. For instance, it is not known when H is a five-vertex path. Here we prove Esperet's conjecture when each component of H is a star.

1 Introduction

The Gyárfás-Sumner conjecture [6, 20] asserts:

1.1 Conjecture: *For every forest H, there is a function f such that $\chi(G) \leq f(\omega(G))$ for every H-free graph G.*

(We use $\chi(G)$ and $\omega(G)$ to denote the chromatic number and the clique number of a graph G, and a graph is *H-free* if it has no induced subgraph isomorphic to H.) This remains open in general, though it has been proved for some very restricted families of trees (see, for example, [1, 7, 8, 9, 11, 13, 14]).

A class $\mathcal{C}$ of graphs is *χ-bounded* if there is a function f such that $\chi(G) \leq f(\omega(G))$ for every graph G that is an induced subgraph of a member of $\mathcal{C}$ (see [15] for a survey). Thus the Gyárfás-Sumner conjecture asserts that, for every forest H, the class of all H-free graphs is χ-bounded. Esperet [5] conjectured that every χ-bounded class is *polynomially χ-bounded*, that is, f can be chosen to be a polynomial. Neither conjecture has been settled in general. There is a survey by Schiermeyer and Randerath [19] on related material.

In particular, what happens to Esperet's conjecture when we exclude a forest? For which forests H can we show the following?

1.2 Esperet's conjecture: *There is a polynomial f_H such that $\chi(G) \leq f_H(\omega(G))$ for every H-free graph G.*

Not for very many forests H, far fewer than the forests that we know satisfy 1.1. For instance, 1.2 is not known when $H = P_5$, the five-vertex path. (This case is of great interest, because it would imply the Erdős-Hajnal conjecture [3, 4, 2] for P_5, and the latter is currently the smallest open case of the Erdős-Hajnal conjecture.)

We remark that, if in 1.2 we replace $\omega(G)$ by $\tau(G)$, defined to be the maximum t such that G contains $K_{t,t}$ as a subgraph, then all forests satisfy the modified 1.2. More exactly, the following is shown in [16]:

1.3 *For every forest H, there is a polynomial f_H such that $\chi(G) \leq f_H(\tau(G))$ for every H-free graph G.*

One difficulty with 1.2 is that we cannot assume that H is connected, or more exactly, knowing that each component of H satisfies 1.2 does not seem to imply that H itself satisfies 1.2. For instance, while $H = P_4$ satisfies 1.2, we do not know the same when H is the disjoint union of two copies of P_4.

As far as we are aware, the only forests that were already known to satisfy 1.2 are those of the following three results, and their induced subgraphs (a *star* is a tree in which one vertex is adjacent to all the others):

1.4 *The forest H satisfies 1.2 if either:*

- *H is the disjoint union of copies of K_2* (S. Wagon [21])*; or*
- *H is the disjoint union of H' and a copy of K_2, and H' satisfies 1.2* (I. Schiermeyer [18])*; or*
- *H is obtained from a star by subdividing one edge once* (X. Liu, J. Schroeder, Z. Wang and X. Yu [12])*.*

In the next paper of this series [17] we will show a strengthening of the third result of 1.4, that is, 1.2 is true when H is a "double star", a tree with two internal vertices, the most general tree that does not contain a five-vertex path. Our main theorem in this paper is a strengthening of the second result of 1.4:

1.5 *If H is the disjoint union of H' and a star, and H' satisfies 1.2, then H satisfies 1.2.*

A *star-forest* is a forest in which every component is a star. From 1.5 and the result of [17], we deduce

1.6 *If H' is a double star, and H is the disjoint union of H' and a star-forest, then H satisfies 1.2.*

As far as we know (although it seems unlikely), these might be all the forests that satisfy 1.2.

2 The proof

We will need the following well-known version of Ramsey's theorem:

2.1 *For $k \geq 1$ an integer, if a graph G has no stable subset of size k, then*

$$|V(G)| \leq \omega(G)^{k-1} + \omega(G)^{k-2} + \cdots + \omega(G).$$

Consequently $|V(G)| < \omega(G)^k$ if $\omega(G) > 1$.

Proof. The claim holds for $k \leq 2$, so we assume that $k \geq 3$ and the result holds for $k-1$. Let X be a clique of G of cardinality $\omega(G)$, and for each $x \in X$ let W_x be the set of vertices nonadjacent to x. From the inductive hypothesis, $|W_x| \leq \omega(G)^{k-2} + \cdots + \omega(G)$ for each x; but $V(G)$ is the union of the sets $W_x \cup \{x\}$ for $x \in X$, and the result follows by adding. This proves 2.1. ∎

If $X \subseteq V(G)$, we denote the subgraph induced on X by $G[X]$. When we are working with a graph G and its induced subgraphs, it is convenient to write $\chi(X)$ for $\chi(G[X])$. Now we prove 1.5, which we restate:

2.2 *If H' satisfies 1.2, and H is the disjoint union of H' and a star, then H satisfies 1.2.*

Proof. H is the disjoint union of H' and some star S; let S have $k+1$ vertices. Since H' satisfies 1.2, and $\chi(G) = \omega(G)$ for all graphs with $\omega(G) \leq 1$, there exists c' such that $\chi(G) \leq \omega(G)^{c'}$ for every H'-free graph G. Choose $c \geq k+2$ such that

$$x^c - (x-1)^c \geq 1 + x^{k+2} + x^{k(k+2)+c'}$$

for all $x \geq 2$ (it is easy to see that this is possible).

Let G be an H-free graph, and write $\omega(G) = \omega$; we will show that $\chi(G) \leq \omega^c$ by induction on ω. If $\omega = 1$ then $\chi(G) = 1$ as required, so we assume that $\omega \geq 2$. Let $n = \omega^{k+1}$. If every vertex of G has degree less than ω^c, then the result holds as we can colour greedily, so we assume that some vertex v has degree at least ω^c. Let N be the set of all neighbours of v in G. Let X_1 be the largest clique contained in N; let X_2 be the largest clique contained in $N \setminus X_1$; and in general, let X_i be the largest clique contained in $N \setminus (X_1 \cup \cdots \cup X_{i-1})$. Since $|N| \geq \omega^c \geq n\omega$ (because $c \geq k+2$), it follows that $X_1, \dots, X_n \neq \emptyset$. Let $X = X_1 \cup \dots \cup X_n$, and $X_0 = N \setminus X$, and $t = |X_n|$. Thus $1 \leq t \leq \omega - 1$ (because $\omega(G[N]) < \omega$).

(1) $\chi(N \cup \{v\}) \leq t^c + n\omega$.

From the choice of X_n, it follows that the largest clique of $G[X_0]$ has cardinality at most $t < \omega$. From the inductive hypothesis, $\chi(X_0) \leq t^c$, and since $X \cup \{v\}$ has cardinality at most $n\omega$, it follows that $\chi(N \cup \{v\}) \leq t^c + n\omega$. This proves (1).

For each stable set $Y \subseteq X$ with $|Y| = k$, let A_Y be the set of vertices in $V(G) \setminus (N \cup \{v\})$ that have no neighbour in Y. Let A be the union of all the sets A_Y, and $B = V(G) \setminus (A \cup N \cup \{v\})$.

(2) $\chi(A) \leq (n\omega)^k \omega^{c'}$.

For each choice of Y, $G[A_Y]$ is H'-free (because $Y \cup \{v\}$ induces a copy of S with no edges to A_Y), and so $\chi(A_Y) \leq \omega^{c'}$. Since there are at most $|X|^k \leq (n\omega)^k$ choices of Y, it follows that the union A of all the sets A_Y has chromatic number at most $(n\omega)^k \omega^{c'}$. This proves (2).

(3) *For each $b \in B$, b has fewer than ω^k non-neighbours in X.*

Let Z be the set of vertices in X nonadjacent to b. Since $b \notin A$, $G[Z]$ has no stable set of cardinality k; and since it also has no clique of cardinality ω, 2.1 implies that $|Z| \leq (\omega - 1)^k < \omega^k$. This proves (3).

(4) $\chi(B) \leq (\omega - t)^c$.

Suppose that $C \subseteq B$ is a clique with $|C| = \omega - t + 1$. For each $c \in C$, (3) implies that c has a nonneighbour in fewer than ω^k of the cliques $X_1, \dots, X_n$; and so fewer than $(\omega - t + 1)\omega^k$ of the cliques $X_1, \dots, X_n$ contain a vertex with a non-neighbour in C. Since $(\omega - t + 1)\omega^k \leq \omega^{k+1} = n$, there exists $i \in \{1, \dots, n\}$ such that every vertex in X_i is adjacent to every vertex of C, and so $C \cup X_i$ is a clique. Since $|X_i| \geq |X_n| = t$, it follows that $|C \cup X_i| > \omega$, a contradiction. Thus there is no such clique C, and so $\omega(G[B]) \leq \omega - t$; and from the inductive hypothesis (since $t > 0$) it follows that $\chi(B) \leq (\omega - t)^c$. This proves (4).

From (1), (2), (4) we deduce that

$$\chi(G) \leq \chi(N \cup \{v\}) + \chi(A) + \chi(B) \leq t^c + n\omega + (n\omega)^k \omega^{c'} + (\omega - t)^c.$$

Since $1 \leq t \leq \omega - 1$ and $c \geq 1$, it follows that $t^c + (\omega - t)^c \leq 1 + (\omega - 1)^c$, and so

$$\chi(G) \leq 1 + n\omega + (n\omega)^k \omega^{c'} + (\omega - 1)^c \leq \omega^c$$

from the choice of c and since $\omega \geq 2$. This proves 1.5. ∎

References

[1] M. Chudnovsky, A. Scott and P. Seymour, "Induced subgraphs of graphs with large chromatic number. XII. Distant stars", *J. Graph Theory* **92** (2019), 237–254, `arXiv:1711.08612`.

[2] M. Chudnovsky, A. Scott, P. Seymour and S. Spirkl, "Erdős-Hajnal for graphs with no five-hole", submitted for publication, `arXiv:2102.04994`.

[3] P. Erdős and A. Hajnal, "On spanned subgraphs of graphs", *Graphentheorie und Ihre Anwendungen* (Oberhof, 1977).

[4] P. Erdős and A. Hajnal, "Ramsey-type theorems", *Discrete Applied Math.* **25** (1989), 37–52.

[5] L. Esperet, *Graph Colorings, Flows and Perfect Matchings*, Habilitation thesis, Université Grenoble Alpes (2017), 24, https://tel.archives-ouvertes.fr/tel-01850463/document.

[6] A. Gyárfás, "On Ramsey covering-numbers", in *Infinite and Finite Sets, Vol. II* (Colloq., Keszthely, 1973), *Coll. Math. Soc. János Bolyai* **10**, 801–816.

[7] A. Gyárfás, "Problems from the world surrounding perfect graphs", *Proceedings of the International Conference on Combinatorial Analysis and its Applications*, (Pokrzywna, 1985), *Zastos. Mat.* **19** (1987), 413–441.

[8] A. Gyárfás, E. Szemerédi and Zs. Tuza, "Induced subtrees in graphs of large chromatic number", *Discrete Math.* **30** (1980), 235–344.

[9] H. A. Kierstead and S.G. Penrice, "Radius two trees specify χ-bounded classes", *J. Graph Theory* **18** (1994), 119–129.

[10] H. A. Kierstead and V. Rödl, "Applications of hypergraph coloring to coloring graphs not inducing certain trees", *Discrete Math.* **150** (1996), 187–193.

[11] H. A. Kierstead and Y. Zhu, "Radius three trees in graphs with large chromatic number", *SIAM J. Disc. Math.* **17** (2004), 571–581.

[12] X. Liu, J. Schroeder, Z. Wang and X. Yu, "Polynomial χ-binding functions for t-broom-free graphs", `arXiv:2106.08871`.

[13] A. Scott, "Induced trees in graphs of large chromatic number", *J. Graph Theory* **24** (1997), 297–311.

[14] A. Scott and P. Seymour, "Induced subgraphs of graphs with large chromatic number. XIII. New brooms", *European J. Combinatorics* **84** (2020), 103024, `arXiv:1807.03768`.

[15] A. Scott and P. Seymour, "A survey of χ-boundedness", *J. Graph Theory* **95** (2020), 473–504, `arXiv:1812.07500`.

[16] A. Scott, P. Seymour and S. Spirkl, "Polynomial bounds for chromatic number. I. Excluding a biclique and an induced tree", submitted for publication, `arXiv:2104.07927`.

[17] A. Scott, P. Seymour and S. Spirkl, "Polynomial bounds for chromatic number. III. Excluding a double star", in preparation.

[18] I. Schiermeyer, "On the chromatic number of (P_5, windmill)-free graphs", *Opuscula Math.* **37** (2017), 609–615.

[19] I. Schiermeyer and B. Randerath, "Polynomial χ-binding functions and forbidden induced subgraphs: a survey", *Graphs and Combinatorics* **35** (2019), 1–31.

[20] D. P. Sumner, "Subtrees of a graph and chromatic number", in *The Theory and Applications of Graphs*, (G. Chartrand, ed.), John Wiley & Sons, New York (1981), 557–576.

[21] S. Wagon, "A bound on the chromatic number of graphs without certain induced subgraphs", *J. Combinatorial Theory, Ser. B*, **29** (1980), 345–346.