

Conflict-free coloring of graphs

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Abstract

We study the conflict-free chromatic number χ_{CF} of graphs from extremal and probabilistic point of view. We resolve a question of Pach and Tardos about the maximum conflict-free chromatic number an n -vertex graph can have. Our construction is randomized. In relation to this we study the evolution of the conflict-free chromatic number of the Erdős-Rényi random graph $G(n, p)$ and give the asymptotics for $p = \omega(1/n)$. We also show that for $p \geq 1/2$ the conflict-free chromatic number differs from the domination number by at most 3.

MSC classes: 05C35, 05C15, 05C80, 05D40, 05C69.

1 Introduction and definitions

Let $G = (V, E)$ be a simple graph. For every $x \in V$ we denote by $N(x) = \{y \in V : xy \in E\}$ its *neighborhood* and by $N[x] = N(x) \cup \{x\}$ its *closed neighborhood*. A (not necessarily proper) vertex coloring χ of G is called *conflict-free*, if for each vertex $x \in V$, there exists a vertex y in $N[x]$ whose color is different from the color of each other vertex in $N[x]$. We then say that y has *unique color* in $N[x]$. The *conflict-free chromatic number* $\chi_{CF}(G)$ is the smallest r , such that there exists a conflict-free r -coloring of G . Conflict-free coloring can be interpreted as a relaxation of the usual *proper coloring* concept where each vertex x is required to have a unique color in its own closed neighborhood $N[x]$. Hence $\chi_{CF}(G) \leq \chi(G)$ for every graph G .

The study of conflict-free colorings was originated in the work of Even, Lotker, Ron, and Smorodinsky [4] and Smorodinsky [9] who were motivated by the problem of frequency assignment in cellular networks. (See the recent survey by Smorodinsky [10].) In most of these classical instances the graphs studied arise from a geometric setting. Recently Pach and Tardos [7] initiated

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the study of the problem for abstract graphs and hypergraphs. Here we continue the consideration of conflict-free colorings of abstract graphs.

Note that, unlike the proper coloring number, the conflict-free chromatic number is not monotone. In particular, in the two extremes $\chi_{CF}(K_n) = 2$ for the complete graph and $\chi_{CF}(\bar{K}_n) = 1$ for the empty graph, while the conflict-free chromatic number of general graphs can be arbitrarily high. We investigate this parameter from extremal and probabilistic points of view.

Pach and Tardos [7] raised the problem of determining the order of magnitude of $\chi_{CF}(n) := \max\{\chi_{CF}(G) : |V(G)| = n\}$, the largest conflict-free chromatic number an n -vertex graph can have. From above they showed $\chi_{CF}(n) = O(\ln^2 n)$ but from below they could only prove that the conflict-free coloring number of the random graph $G(n, \frac{1}{2})$ is asymptotically almost surely $\Omega(\ln n)$, hence $\chi_{CF}(n) = \Omega(\ln n)$. Here asymptotically almost surely means probabilities tending to 1 as n goes to infinity and it will be abbreviated below as a.a.s.

At first one could try to improve the lower bound $\chi_{CF}(n)$ by considering the random graph $G(n, p)$ with some $p = p(n) \neq 1/2$. In our first theorem we give tight estimates (holding a.a.s.) for the conflict-free chromatic number of these random graphs. Our bounds show that some probabilities $p(n) \rightarrow 0$ yield the highest conflict-free coloring numbers for the $G(n, p(n))$, but these are only a constant factor larger than those of $G(n, 1/2)$.

To state our theorem we introduce

$$\mu = \mu(p) = \max\{ip(1-p)^{i-1} : i \in \mathbb{N}^+\}$$

for $0 < p < 1$. Notice that the maximum is taken at $i = \lfloor 1/p \rfloor$ so we have

$$\mu(p) = \left\lfloor \frac{1}{p} \right\rfloor p(1-p)^{\lfloor 1/p \rfloor - 1},$$

and (as simple calculation shows) this is a strictly increasing function tending to e^{-1} as p goes to 0.

Theorem 1. *For every $\varepsilon > 0$ and every function $0 < p = p(n) < 1 - \varepsilon$ such that $np(n) \rightarrow \infty$, the following holds a.a.s.*

$$(1 - \varepsilon) \frac{\ln(np)}{-\ln(1 - \mu(p))} \leq \chi_{CF}(G(n, p)) \leq (1 + \varepsilon) \frac{\ln(np)}{-\ln(1 - \mu(p))}.$$

Note that the theorem implies $\chi_{CF}(G(n, p)) = O(\log n)$ a.a.s. for all p considered. It is not hard to show that the $O(\log n)$ upper bound is also valid a.a.s. in the full range of $p \in [0, 1]$. For the range $p = O(1/p)$ this follows from $\chi_{CF}(G) \leq \chi(G) \leq \Delta(G) + 1$, but in this range we are not able to determine the asymptotics.

For $1/2 \leq p < 1$ we can prove an even tighter result: the conflict-free coloring number differs by at most 3 from the domination number. A set S of vertices of a graph G constitutes a *dominating set* if each $v \in V$ is either in S or is adjacent to a vertex in S . The *domination number* $D(G)$ is the smallest size of a dominating set in G .

Theorem 2. *For every graph G ,*

$$\chi_{CF}(G) \leq D(G) + 1.$$

Furthermore, for $\frac{1}{2} \leq p(n)$ a.a.s.

$$D(G(n, p(n))) - 3 \leq \chi_{CF}(G(n, p(n))).$$

The domination number of the random graph with constant p was pinned down to be one of two integers a.a.s. by Wieland and Godbole [11]. Furthermore, it was observed by Glebov, Liebenau, and Szabó [5] that the same result holds also for a variable $p(n)$. The following is a corollary of these results for the range of our interest:

Theorem 3 (Corollary of [11, 5]). *For $1/2 \leq p < 1$ the domination number $D(G(n, p(n)))$ is either $\left\lfloor \frac{\ln n - 2 \ln \ln n + \ln \ln \frac{1}{1-p}}{-\ln(1-p)} \right\rfloor + 1$ or one more a.a.s.*

Hence the behavior of χ_{CF} is also very well understood in this range. In fact, we prove Theorem 2 by calculating the a.a.s. lower bound on $\chi_{CF}(G(n, p))$ and comparing it with the a.a.s. domination number. Notice that using Theorem 3 Theorem 2 implies Theorem 1 for the range $p \geq 1/2$, where we have $\mu(p) = p$. We mention that for the range $p < \frac{1}{2}$ the results of [11, 5] on the domination number and Theorem 1 imply that the conflict-free chromatic number and the domination number *differ* in the asymptotics.

In our final result we resolve the open problem of Pach and Tardos [7] regarding $\chi_{CF}(n)$ by constructing n -vertex graphs G with $\chi_{CF}(G) = \Omega(\ln^2 n)$.

Theorem 4.

$$\chi_{CF}(n) = \Theta(\ln^2 n).$$

The structure of the paper is the following: in Section 2 we prove Theorems 1 and 2, while Theorem 4 is proven in Section 3. For simplicity we routinely omit floor and ceiling signs as long as they do not influence the validity of our asymptotic statements.

Notation. Let G be a graph with vertex set $V = V(G)$ and let $A \subseteq V$. We say that $N_G^{(1)}(A) = \{v \in V \setminus A : |N(v) \cap A| = 1\}$ is the *one-neighborhood* of A and $\bar{N}_G(A) = V \setminus \bigcup_{x \in A} N[x]$ is the *non-neighborhood* of A . The subscript G is omitted if it is clear from the context.

We use $\binom{V}{m}$ to denote the set of all m -element subsets of V .

2 Evolution of the conflict-free chromatic number in random graphs

2.1 Upper bounds

A simple upper bound is obtained from the fact that any proper coloring is a conflict-free coloring, so

$$\chi_{CF}(G) \leq \chi(G).$$

However, this bound is a.a.s. not tight for the random graph $G(n, p)$ in the range of p we are interested in, i.e., for $p = \omega(1/n)$.

Another inequality involves domination. If a set of vertices S is a dominating set of G then one can construct a conflict-free coloring of G with $|S| + 1$ colors

by giving $|S|$ distinct colors to the vertices in S and one further color to vertices in $V(G) \setminus S$. Hence for every graph G

$$\chi_{CF}(G) \leq D(G) + 1.$$

This proves the upper bound in Theorem 2.

The rest of this section deals with the upper bound in Theorem 1.

Regarding conflict-free colorings the crucial property of a vertex x is whether it has exactly one neighbor in some color class S and hence the color of S is unique in $N[x]$. For a fixed set S and a fixed vertex $x \in V \setminus S$ the probability of this happening is $|S|p(1-p)^{|S|-1}$. This motivates our definition of $\mu(p)$ in Section 1 as the maximum of this probability for any color class size. We let $m = \lfloor 1/p \rfloor$ stand for the “most desirable” color class size maximizing the above probability and giving $\mu = mp(1-p)^{m-1}$.

Since the upper bound in Theorem 2 implies the upper bound in Theorem 1 for $p \geq \frac{1}{2}$, we assume $p < \frac{1}{2}$ from now on. To start we prove two technical lemmas for random graphs.

First we give an explicit bound on the probability that the domination number of a random graph is extremely low. We need the explicit bound in because we will use the union bound for more than a constant number of similar events and thus the a.a.s. bound of Theorem 3 is not enough.

Lemma 1. *For any $\ell \in \mathbb{N}^+$ and p with $\frac{100}{\ell} < p < \frac{1}{2}$ we have that*

$$\mathbb{P}[D(G(\ell, p)) < m] < 0.9^\ell,$$

where $m = \lfloor 1/p \rfloor$ as before.

Proof Throughout the proof we will use that $m - 1 < \frac{1}{p} < \frac{\ell}{100}$. Let $S \subset V$ be a set of size $m - 1$. The probability that a vertex $x \in V \setminus S$ has no neighbor in S is

$$\mathbb{P}[N(x) \cap S = \emptyset] = (1-p)^{|S|} \geq (1-p)^{1/p} > 1/4.$$

The events that $N(x) \cap S = \emptyset$ are independent for $x \in V \setminus S$, hence S is dominating with probability $< (3/4)^{\ell-m+1}$. The probability in the lemma is

$$\begin{aligned} \mathbb{P}\left[\exists S \in \binom{V}{m-1} : \bar{N}(S) = \emptyset\right] &< \binom{\ell}{m-1} (3/4)^{\ell-m+1} \\ &< 0.9^\ell. \end{aligned}$$

□

We know that the expected size of the one-neighborhood of a set of vertices of size m is $(|V| - m)\mu$. The following is a routine observation that the actual size deviates largely from this expectation with a very low probability.

Lemma 2. *For every $\delta > 0$ there exists a $K = K(\delta)$ such that for any $p = p(\ell) > \frac{K}{\ell}$ in $G(\ell, p)$ we have that*

$$\mathbb{P}\left[\exists S \in \binom{V}{m} : |N^{(1)}(S)| < (1-\delta)\mu(\ell - m)\right] < e^{-\frac{\delta^2}{4}\mu\ell},$$

where $m = \lfloor 1/p \rfloor$ and $\mu = \mu(p) = mp(1-p)^{m-1}$.

Proof For an arbitrary set $S \subset V$ of size m and vertex $x \in V \setminus S$, the probability that x has exactly one neighbor in S is μ . The random variable $|N^{(1)}(S)|$ is the sum of $\ell - m$ mutually independent characteristic variables and its expectation is $\mu(\ell - m)$. Hence by the Chernoff bound and the union bound we have

$$\begin{aligned} \mathbb{P} \left[\exists S \in \binom{V}{m} : |N^{(1)}(S)| < (1 - \delta)\mu(\ell - m) \right] &< \binom{\ell}{m} e^{-\frac{\delta^2}{2}\mu(\ell - m)} \\ &\leq \left((eK)^{\frac{1}{K}} e^{-\frac{\delta^2}{3}\mu} \right)^\ell, \end{aligned}$$

and the bound follows if K is sufficiently large. \square

Let us choose $\delta = \delta(\varepsilon) > 0$ such that it satisfies

$$\frac{1 + \varepsilon}{-\ln(1 - \mu(p))} > \frac{1}{-\ln(1 - (1 - \delta)\mu(p))} + \delta \quad (1)$$

and assume $K = K(\delta)$ from the Lemma 2 satisfies $K > 100$ so we can also use Lemma 1. Assuming $p = p(n)$ satisfies $np \rightarrow \infty$ (or even the weaker condition $p > \frac{K^*}{n}$ for $K^* = e^{K/\delta}$) we give a deterministic algorithm which a.a.s. constructs a conflict-free coloring of $G(n, p)$ using $(1 + \varepsilon) \frac{\ln(np)}{-\ln(1 - \mu)}$ colors. In this algorithm $d(G_i)$ denotes the *degeneracy* of the graph G_i , i.e., the largest minimum degree a non-empty subgraph of G_i has.

Algorithm CFC(G, p, δ)

Input: graph G , $V(G) = [n]$, $p \in [0, 1]$, $\delta > 0$.

Set $G_1 := G$, $n_1 := n$, $i := 1$, $m = \left\lfloor \frac{1}{p} \right\rfloor$, $\mu = mp(1 - p)^{m-1}$, $K = K(\delta) > 100$.

while $n_i > \ln \ln n$ and $p > \frac{K}{n_i}$ **do**

 select an independent set S_i by starting with $S_i = \emptyset$ and iteratively adding the smallest vertex in $\overline{N_{G_i}(S_i)}$ until either $\overline{N_{G_i}(S_i)} = \emptyset$ or $|S_i| = m$.

 Color vertices in S_i with color i , color vertices in $N_{G_i}^{(1)}(S_i)$ with color 0,

 define $G_{i+1} := G_i - (S_i \cup N_{G_i}^{(1)}(S_i))$, $n_{i+1} := |V(G_{i+1})|$, $i := i + 1$

Color G_i properly using $d(G_i) + 1$ new colors.

Notice that all executions of the main **while**-loop of the algorithm use a separate color and only color 0 is used in many executions. Note also that this color 0 is a “filler color” as it is never used as the unique color in the closed neighborhood of some vertex to ensure the conflict-free property of the coloring is obtained.

Let I be the last value of the index i in the algorithm. Clearly the algorithm colors all vertices with $I + d(G_I) + 1$ colors. To see that this coloring is conflict-free let $w \in V(G)$ be an arbitrary vertex and let i be the largest index with $w \in V(G_i)$. If $i < I$, then there is a unique vertex in $N[w]$ of color i (which may or may not be w itself). If $i = I$, then w has unique color in $N[w]$.

To finish the proof it is enough to bound the values of I and $d(G_I)$ a.a.s. We start with I . Note that for any $1 \leq i \leq I$ the sets S_1, \dots, S_{i-1} selected

by the algorithm, and hence the vertex set $V(G_i)$ as well, depend only on the edges incident to $S_1 \cup \dots \cup S_{i-1}$. Thus, given any way the main **while**-loop is executed for the first $i - 1$ times, the graph G_i is still a random graph $G(n_i, p)$. Now we estimate the probability that $|N_{G_i}^{(1)}(S_i)| < (1 - \delta)\mu(n_i - m)$. This can happen either with $|S_i| = m$ or with $|S_i| < m$. The probability of the former is bounded by Lemma 2, while the latter implies that S_i is dominating in G_i , the probability of which is bounded by Lemma 1. Using the explicit bounds in the lemmas and the fact that the sizes of the graphs considered are decreasing and lower bounded by a super-constant function of n we conclude that a.a.s. in no iteration do we have either of these anomalies:

$$\sum_{i=1}^{I-1} e^{-\delta^2 \mu n_i / 4} + 0.9^{n_i} \leq \sum_{\ell=\ln \ln n}^n e^{-\delta^2 \mu \ell / 4} + 0.9^\ell = o(1).$$

Thus a.a.s. we must have $n_{i+1} \leq (1 - (1 - \delta)\mu)n_i$ for each $i < I$. Using $n_1 = n$ and $n_{I-1} > K/p$ we have a.a.s.

$$I < \frac{\ln(np/K)}{-\ln(1 - (1 - \delta)\mu)} + 2.$$

It remains to show that a.a.s. $d(G_I) < \delta \ln(np)$ and using the defining inequality (1) for δ the upper bound in Theorem 1 follows. We use again the observation that independent of the executions of the **while**-loop G_I is a random graph $G(n_I, p)$ with n_I being small enough to trigger one of the halting conditions.

If we have $p \leq K/n_I$, then the expected degree of any vertex in $G(n_I, p)$ is less than K . Hence either a.a.s. $d(G_I) \leq K$ by the results of Pittel, Spencer, and Wormald [8] and Łuczak [6] and we are done as $K < \delta \ln(np)$, or n_I is bounded by a constant, in which case we can color G_I with $n_I \leq \delta \ln(np)$ colors. If, however, $p > K/n_I$ we must have $n_I \leq \ln \ln n$ to halt the **while**-loop, so we have $\ln(np) > \ln(Kn/n_I) = \Omega(\ln n)$. Thus we have $d(G_I) < n_I < \delta \ln(np)$ if n is large enough.

Note that the $\ln \ln n$ bound in the halting condition of the algorithm can be replaced by any function that tends to infinity and is $o(\ln n)$.

Furthermore, observe that if $d(G_I) < \delta \ln(np)$ (which happens a.a.s.), one can efficiently color G_I with $\delta \ln(np)$ colors properly. A linear time algorithm for coloring G_I with at most $d(G_I) + 1$ colors first iteratively removes a lowest degree vertex from the graph, then colors them greedily in the reverse order. Hence, the running time of the algorithm CFC is linear in the size of the input graph.

2.2 Lower bounds

Tardos and Pach [7] used the concept of *universality* to show the lower bound $\chi_{CF}(G(n, \frac{1}{2})) = \Omega(\ln n)$. A graph G is called *k-universal* if for all sets $B \subseteq A \subseteq V(G)$ with $|A| \leq k$ there exists a vertex $x \in V(G) \setminus A$ with $N(x) \cap A = B$. We introduce a similar concept, which is more closely related to the idea of conflict-free coloring. We call a graph G *(k, f)-spoiling*, if for any k disjoint subsets $A_1, \dots, A_k \subseteq V(G)$ with $|A_i| \leq f$ for every $i \in [k]$, there exists a vertex $x \in V(G) \setminus \bigcup_i A_i$ such that for each A_i we have $|N(x) \cap A_i| \neq 1$, and for each A_i

with $|A_i| = f$, $|N(x) \cap A_i| \geq 2$. The vertex x is called a *f-spoiler* for (A_1, \dots, A_k) and we say that (A_1, \dots, A_k) is *spoiled* by x . We call a graph *k-spoiling*, if it is (k, f) -spoiling for *some* f .

The following observation just serves to give an intuition for the concept.

Observation 1. *A $2k$ -universal graph G is $(k, 2)$ -spoiling and consequently k -spoiling.*

The next lemma is the essence of all lower bounds in Theorem 1.

Lemma 3. *If G is k -spoiling, then $\chi_{CF}(G) > k$.*

Proof Let G be (k, f) -spoiling for some f and consider an arbitrary k -coloring χ of $V(G)$. We need to show that it is not conflict-free. We define subsets $A_1, \dots, A_k \subseteq V(G)$. For each color i which is used less than f times by χ , we define A_i to be the whole color class $\chi^{-1}(\{i\})$. For each color i which is used on at least f vertices by χ , we set an arbitrary f -subset of vertices with color i to be A_i . Since G is (k, f) -spoiling we find a vertex x which is an f -spoiler for these sets. Clearly, $N[x]$ has no unique color, showing that χ is not conflict-free. \square

We first prove the tight lower bound of Theorem 2 via studying the spoilers of $G(n, p)$ for $p \geq \frac{1}{2}$. Comparing the bound of Theorem 3 of Wieland and Godbole [11] and Glebov, Liebenau, and Szabó [5] with the bound in the following lemma finishes the proof.

Lemma 4. *The graph $G(n, p)$ with $1/2 \leq p < 1$ is a.a.s. k -spoiling for $k = \left\lfloor \frac{\ln n - 2 \ln \ln n + \ln \ln \frac{1}{1-p} - \ln 3}{-\ln(1-p)} \right\rfloor$.*

Proof We show that $G(n, p)$ is a.a.s. $(k, 3)$ -spoiling. Take any set $A \subseteq V$ with $|A| \leq 3$ and $x \in V \setminus A$. For $A = \emptyset$ we cannot have $|N(x) \cap A| = 1$. For $|A| = 1$ we have

$$\mathbb{P}[|N(x) \cap A| \neq 1] = 1 - p,$$

for $|A| = 2$ we have

$$\mathbb{P}[|N(x) \cap A| \neq 1] = 1 - 2p(1 - p) \geq 1 - p,$$

and finally for $|A| = 3$ we have

$$\mathbb{P}[|N(x) \cap A| \geq 2] = 1 - 3p(1 - p)^2 - (1 - p)^3 \geq 1 - p.$$

Then for any family $\mathcal{A} = \{A_1, \dots, A_k\}$ of k sets of size at most $f = 3$, the probability that a fixed vertex $x \in V \setminus \bigcup_{i=1}^k A_i$ is a spoiler is

$$\mathbb{P}[x \text{ is a spoiler for } \mathcal{A}] \geq (1 - p)^k.$$

Thus

$$\mathbb{P} \left[\mathcal{A} \text{ is not spoiled by any } x \in V \setminus \bigcup_{i=1}^k A_i \right] \leq (1 - (1 - p)^k)^{n-3k}.$$

There are at most $(n+1)^{3k}$ ways \mathcal{A} can be selected, so by the union bound we have

$$\begin{aligned} \mathbb{P}[G(n,p) \text{ is not } (k,3)\text{-spoiling}] &\leq (n+1)^{3k} \exp(-(n-3k)(1-p)^k) \\ &\leq \exp\left(3 \frac{\ln n - 2 \ln \ln n + \ln \ln \frac{1}{1-p} - \ln 3}{-\ln(1-p)} \ln n - n \frac{3 \ln^2 n}{-n \ln(1-p)} + o(1)\right) = o(1), \end{aligned}$$

assuming $p \leq 1 - \frac{1}{n}$. Otherwise $k = 0$ and the statement of the lemma becomes trivial, since every graph is 0-spoiling. \square

The next lemma provides the lower bound in Theorem 1 when $p \leq \frac{1}{2}$.

Lemma 5. *For every $\varepsilon > 0$ there exists a constant $K = K(\varepsilon)$ such that for all p with $K/n \leq p \leq 1/2$, the graph $G(n,p)$ is a.a.s. k -spoiling for $k = \left\lfloor (1-\varepsilon) \frac{\ln(np)}{-\ln(1-\mu)} \right\rfloor$.*

Proof Similarly to the last section, we fix $m = \left\lfloor \frac{1}{p} \right\rfloor$. We show that $G(n,p)$ is a.a.s. $(k,6m)$ -spoiling. First we observe that for any fixed $S \subset V$ of size at most $6m$ and a fixed vertex $x \in V \setminus S$, the probability that x spoils S is at least $1 - \mu$. Note that $1 - \mu$ is exactly the probability if $|S| = m$ and by the definition of μ as a maximum it is at least this much for other sizes strictly below $6m$. A simple way to see the bound for $|S| = 6m$ is to partition S into six parts of size m each. The probability that x has exactly one neighbor in any one of them is μ , these events are independent, so the probability that this holds for at least two of them is exactly $1 - (1 - \mu)^6 - 6\mu(1 - \mu)^5$. Since we have $\mu > e^{-1}$ this is larger than $1 - \mu$.

Note that $k < 3 \ln(np)$ since $\mu > 1/e$. First we fix a family \mathcal{A} of k disjoint sets of size at most $6m$ each and estimate the probability that no vertex $x \in V \setminus \bigcup \mathcal{A}$ is a spoiler for it.

$$\begin{aligned} \mathbb{P}\left[\nexists x \in V \setminus \bigcup \mathcal{A} : x \text{ spoils } \mathcal{A}\right] &\leq (1 - (1 - \mu)^k)^{n - |\bigcup \mathcal{A}|} \\ &\leq \exp\left(-\frac{n}{2}(1 - \mu)^k\right) \\ &\leq \exp\left(-\frac{(np)^\varepsilon}{2p}\right), \end{aligned}$$

where in the second inequality we use the fact that $|\bigcup \mathcal{A}| \leq 6mk < n/2$ for K large enough.

The union bound for the probability that this happens for any family \mathcal{A} of k sets of size at most $6m$ each is enough now to finish the proof:

$$\begin{aligned} \mathbb{P}\left[\exists \mathcal{A} \forall x \in V \setminus \bigcup \mathcal{A} : x \text{ does not spoil } \mathcal{A}\right] &< \left(\sum_{i \leq 6m} \binom{n}{i}\right)^k \exp\left(-\frac{(np)^\varepsilon}{2p}\right) \\ &< (np)^{6mk} \exp\left(-\frac{(np)^\varepsilon}{2p}\right) \\ &< \exp\left(\frac{18 \ln^2(np)}{p} - \frac{(np)^\varepsilon}{2p}\right) \\ &= o(1). \end{aligned}$$

□

3 Graphs with large conflict-free chromatic number

In this section we show the existence of n -vertex graphs G with $\chi_{CF}(G) = \Omega(\ln^2 n)$. This gives the correct order of magnitude of $\chi_{CF}(n)$ and proves Theorem 4.

To show the statement, we construct an n -vertex graph G using random methods. The vertex set is partitioned into classes L_1, \dots, L_k of size $\frac{n}{k}$ each, with $k = \lfloor \ln n \rfloor$. The edges will be selected at random, independently of each other. To define the probabilities we let the *weight* of a vertex $x \in L_i$ be

$$w_x = 0.99^i.$$

The probability of an edge between vertices $x \in L_i$ and $y \in L_j$ is equal to

$$\mathbb{P}[xy \in E(G)] := w_x w_y = 0.99^{i+j}.$$

The *weight* of a set $S \subseteq V$ is defined to be the sum of the weights of its elements,

$$w(S) = \sum_{v \in S} w_v.$$

For a vertex coloring χ we say that *vertex v takes care of itself* if the color of v is unique in $N[v]$, i.e. every $u \in N(v)$ has a color different from $\chi(v)$. We say that a *color class S takes care of a vertex x* if $x \in N^{(1)}(S)$. The crucial probability, denoted by $p(x, S)$, that a vertex $x \in L_i$ is taken care of by a color class S not containing x is equal to

$$\begin{aligned} p(x, S) &= \mathbb{P}[|N(x) \cap S| = 1] = \sum_{s \in S} \mathbb{P}[N(x) \cap S = \{s\}] \\ &= \sum_{s \in S} w_s w_x \prod_{y \in S \setminus \{s\}} (1 - w_y w_x) \\ &< w_x \sum_{s \in S} w_s \exp\left(-\sum_{y \in S \setminus \{s\}} w_y w_x\right) \\ &= w_x \sum_{s \in S} w_s \exp(-w(S)w_x + w_s w_x) \\ &\leq w_x w(S) e^{-w_x w(S) + 0.99}. \end{aligned}$$

Note that since the function ze^{-z} has a unique maximum at $z = 1$, we always have $p(x, S) < e^{-0.01}$. If χ is a conflict-free coloring, then every vertex is taken care of either by itself or by a color class not containing this vertex.

We call a set *heavy* if its weight is larger than \sqrt{n} , otherwise we call it *light*. Note that since any vertex has weight at least $0.99^{\ln n} > n^{-0.02}$, we obtain for any light color class S

$$|S| < w(S)n^{0.02} < n^{0.52}.$$

In the following lemma we list three properties, which hold a.a.s. for our random G and, together, imply that no conflict-free coloring exists with $o(\ln^2 n)$ colors. As usual, $\alpha(G)$ denotes the *independence number* of G , i.e. the size of a largest independent set.

Lemma 6. *For G the following three properties hold a.a.s.*

- (i) $\alpha(G) \leq n^{0.6}$.
- (ii) For every heavy set $S \subseteq V$, we have $|N^{(1)}(S)| < n^{0.6}$.
- (iii) Let $r = \lfloor 10^{-5} \ln^2 n \rfloor$. For all pairwise disjoint light sets $S_1, \dots, S_r \subseteq V$, we have $|\bigcup_{i=1}^r N^{(1)}(S_i)| < n - n^{0.7}$.

Proof Since the probability for each pair of vertices to be an edge of G is at least $0.99^{2 \ln n}$, the largest independent set is at most as large as it is in $G(n, 0.99^{2 \ln n})$. It is well-known (see, for example Theorem 11.25 (ii) in Bollobás's book [3] for more details) that for $2.27/n \leq p \leq 1/2$, a.a.s. the largest independent set in $G(n, p)$ has size at most $2 \frac{\ln(np)}{p}$. Thus, the largest independent set in G a.a.s. has size at most $2 \frac{\ln(0.99^{2 \ln n} n)}{0.99^{2 \ln n}} < n^{0.6}$.

For the second statement fix a subset $S \subseteq V$ with weight at least $n^{0.5}$ and a set $A \subseteq V \setminus S$ with at least $n^{0.6}$ elements. We estimate the probability that all elements $x \in A$ are in the one-neighborhood of S .

$$\begin{aligned} \mathbb{P} \left[N^{(1)}(S) \supseteq A \right] &= \prod_{x \in A} p(x, S) \\ &\leq \prod_{x \in A} w_x w(S) e^{-w_x w(S) + 1} \\ &< (n^{0.48} \exp(-n^{0.48} + 1))^{n^{0.6}} \\ &= \exp(-n^{1.08}(1 + o(1))). \end{aligned}$$

(Here we used that $w_x w(S) > 0.99 \ln n n^{0.5} > n^{0.48}$ and that ze^{-z} is decreasing in the interval $[1, \infty)$.) Summing up over all the at most $2^n \cdot 2^n$ choices of S and A we obtain that the probability that (ii) fails tends to 0.

For the third part fix subsets S_1, \dots, S_r with $w(S_i) \leq \sqrt{n}$ and B with $|B| = n^{0.7}$. We estimate the probability that all $x \in V \setminus B$ are in the one-neighborhood of at least one of the S_i .

For this we first show that $\sum_{i=1}^r p(x, S_i) > 0.01 \ln n$ for at most half of the vertices $x \in V$. Indeed, otherwise

$$\begin{aligned} \frac{n}{2} \cdot 0.01 \ln n &\leq \sum_{x \in V} \sum_{i=1}^r p(x, S_i) \\ &= \sum_{i=1}^r \sum_{x \in V} p(x, S_i) \\ &\leq r (100e + 100 + 200) \frac{n}{\ln n}, \end{aligned}$$

contradicting the definition of r . For the last estimate we used that for a fixed color class S_i , $\sum_{x \in V} p(x, S_i) \leq \frac{n}{\ln n} \sum_{j=1}^{\infty} z_j e^{-z_j + 1}$, where z_j is a geometric

progression with quotient 0.99. The terms of the sum for $z_j \leq 1$ can be estimated by ez_j and hence this part is at most $\frac{e}{1-0.99} = 100e$. The sum of the terms for $z_j \geq 2$ can be estimated by $100 \int_1^\infty ze^{-z+1} dz = 200$. And finally the sum of the terms for $1 < z_j < 2$ can be estimated by 100, since there are at most 100 such z_j 's, and for each of them the value of the function is at most 1.

Let $V' \subseteq V$ be the set of those vertices $x \in V$ for which $\sum_{i=1}^r p(x, S_i) \leq 0.01 \ln n$. Then by the above $|V'| \geq n/2$.

$$\begin{aligned} \mathbb{P}[\forall x \in V \setminus B \exists i \text{ with } |N(x) \cap S_i| = 1] &= \prod_{x \in V \setminus B} \left(1 - \prod_{i=1}^r (1 - p(x, S_i)) \right) \\ &\leq \exp \left(- \sum_{x \in V \setminus B} \prod_{i=1}^r (1 - p(x, S_i)) \right) \\ &\leq \exp \left(- \sum_{x \in V \setminus B} e^{-5 \sum_{i=1}^r p(x, S_i)} \right) \\ &\leq \exp \left(- \left(\frac{n}{2} - n^{0.7} \right) e^{-0.05 \ln n} \right) \\ &\leq \exp \left(-n^{0.95} (1/2 - o(1)) \right) \end{aligned}$$

Here we used that in the range of our interest, i.e. for $0 < z = p(x, S_i) < e^{-0.01}$, we have $1 - z > e^{-5z}$.

The sets S_1, \dots, S_r and B with the given properties can be chosen at most

$$\binom{n}{n^{0.7}} \left((n+1)^{\sqrt{n}} \right)^r = e^{O(n^{0.7} \ln n)}$$

ways, where we first choose a set B of size $n^{0.7}$ from V , and then choose one by one the vertices forming the sets S_1, \dots, S_r . Hence with probability tending to 1 the third condition holds. \square

Finally, we show how the above properties imply the existence of graphs without a conflict-free coloring with $10^{-5} \ln^2 n$ colors.

Proof of Theorem 4. Let us take a graph G having properties (i) – (iii) of Lemma 6 with a sufficiently large vertex set. Take an arbitrary r -coloring c of G , where $r = \lfloor 10^{-5} \ln^2 n \rfloor$ as in the lemma. We prove that c is not a conflict-free coloring. We define the following sets:

- The set of all vertices that take care of themselves, that is

$$T = \{x \in V : \forall y \in N(x), c(x) \neq c(y)\}$$
- The set of all vertices that are taken care of by a heavy color class, that is

$$H = \{x \in V : \exists z \in N(x) : |c^{-1}(c(z))| > \sqrt{n} \wedge \forall y \in N[x] \setminus \{z\}, c(z) \neq c(y)\}$$
- The set of all vertices that are taken care of by a light color class, that is

$$L = \{x \in V : \exists z \in N(x) : |c^{-1}(c(z))| \leq \sqrt{n} \wedge \forall y \in N[x] \setminus \{y\}, c(z) \neq c(y)\}.$$

If c were a conflict-free coloring, then $V = T \cup H \cup L$.

Vertices taking care of themselves. A set of vertices that take care of themselves and have the same color must form an independent set in G . Hence by (i)

any color class can contain at most $n^{0.6}$ vertices that take care of themselves. So $|T| \leq rn^{0.6}$.

Vertices taken care of by heavy color classes. Fix a heavy color class S . By (ii) at most $n^{0.6}$ vertices are taken care of by S . Hence $|H| \leq rn^{0.6}$.

Vertices taken care of by light color classes. Let S_1, \dots, S_{r^*} be the light color classes of χ . By (iii) at most $n - n^{0.7}$ vertices are taken care of by the S_i 's. Hence $|L| \leq n - n^{0.7}$.

Thus, $|T \cup H \cup L| < n = |V|$, and c is not conflict-free. This concludes the proof that c is not a conflict-free coloring. \square

4 Remarks and open problems

Radio networks. Recently, Noga Alon pointed out to us that the lower bound from Theorem 4 is similar to the one obtained by Alon, Bar-Noy, Linial, and Peleg [1]. Here we discuss briefly the relation of the two results. The notation in [1] is different from the one we use here, as they look at a much more applied problem. Creating a small dictionary between their and our notations, they speak about *processors* when we have vertices, a *radio network* is what we call a graph, *transmitting at step i* corresponds to having color i , and the *transmission* itself is a color class. The problem they analyze is the following. At the beginning, one processor (the *sender*) has a message M , and the process stops when M is delivered to every processor of the network. The communication in the network works as follows: in step i , every processor from transmission T_i that already received M sends it to all adjacent processors. A processor *receives* a message in a given step if precisely one of its neighbors transmits in this step. If none of its neighbors transmits, it hears nothing. If more than one neighbor transmits, a collision occurs and the processor hears only noise. A sequence of transmissions is a *broadcast schedule* for the sender s in a network if after applying the transmissions, every processor in the network has a copy of the message. Alon, Bar-Noy, Linial, and Peleg [1] showed that the shortest length of a broadcast schedule is $\Omega(\ln^2 n)$ for some radio networks with n processors. The matching upper bound of $O(\ln^2 n)$ for any radio networks with n processors was established earlier Bar-Yehuda, Goldreich, and Itai [2].

On the one hand, Alon et al. [1] do not restrict a processor to be part of only one transmission, while in our setting, a vertex has exactly one color. On the other hand, in our setting we do not have any scheduling structure, and a vertex does not have to wait until it receives the message to “transmit”. Hence, none of the lower bounds implies the other immediately. However, observe that in the proof of Theorem 4 we do *not* use the fact that color classes are disjoint. Consequently our construction gives a common generalization of Theorem 2.1 of [1] and our Theorem 4, as follows.

Let us denote by $\chi'_{CF}(n)$ the smallest integer such that every graph G on n vertices satisfies the following. There exists a family $\mathcal{F} \subseteq 2^{V(G)}$ of subsets of $V(G)$ of size $|\mathcal{F}| \leq \chi'_{CF}(n)$ such that for every vertex $x \in V(G)$, there exists a set $F \in \mathcal{F}$ with $|N_G(x) \cap F| = 1$. Both our paper and [1] deal with problems with further requirements on the family \mathcal{F} . We insist that they form a partition of the vertex set, whereas Alon et al. require an ordering of the sets

in \mathcal{F} with certain properties to exist. Proving a lower bound for χ'_{CF} therefore implies the corresponding lower bounds in both papers. The construction in [1] has chromatic number 2, so it does not provide a meaningful lower bound for $\chi'_{CF} \leq \chi_{CF} \leq \chi(G)$. The proof of Theorem 4 does work in this more general scenario and shows a lower bound of order $\ln^2 n$. The corresponding upper bound follows either from [7] or [2].

Theorem 5. $\chi'_{CF}(n) = \Theta(\ln^2 n)$.

Open problems. At the two extreme values of p the trivial upper bounds given by the chromatic number and the domination number plus one are tight. For the very sparse range of $p = o(1/n)$ the random graph $G(n, p)$ is a.a.s. a tree, hence both $\chi(G(n, p))$ and $\chi_{CF}(G(n, p))$ are a.a.s. 2. On the other end for $p \geq \frac{1}{2}$ we showed that $|\chi_{CF} - D| \leq 3$. The particular questions which remain to be answered:

- In what range is $\chi_{CF}(G(n, p)) = D(G(n, p)) + 1$ a.a.s.?
- In what range $\chi(G(n, p)) = \chi_{CF}(G(n, p))$ a.a.s.? In particular we would be interested in where the threshold of 3-conflict-free colorability is and how much it is different, if at all, from the threshold of 3-colorability.
- Does $\chi_{CF}(G(n, p))$ behave in a unimodal way? For example one might consider the median function and ask whether it is unimodal.

It is an interesting general question to characterize those graphs where equality holds for $\chi_{CF}(G) = \chi(G)$ or $\chi_{CF}(G) = D(G) + 1$.

By the concentration results of [11, 5] we have the concentration of $\chi_{CF}(G(n, p))$ on two values a.a.s. whenever $\chi_{CF}(G(n, p)) = D(G(n, p)) + 1$. For what range of p does the two-values-concentration hold a.a.s.? We have a concentration on three values a.a.s. whenever $\ln 3 / \ln(1 - p) \approx 0$. In the worst case, when $p = 1/2$, we have concentration on 5 values a.a.s. For $p \geq \frac{\sqrt{5}-1}{2}$, we have concentration on four values a.a.s. (For this we need to consider the $(k, 2)$ -spoiling property and adapt the proof of Lemma 4.) It would be interesting to obtain a concentration on 2 values for a wider range of p .

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