Locally identifying coloring in bounded expansion classes of graphs
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Abstract
A proper vertex coloring of a graph is said to be locally identifying if (i) the vertex-coloring is proper (i.e. no adjacent vertices receive the same color), and (ii) for any adjacent vertices $u, v$, the set of colors assigned to the closed neighborhood of $u$ differs from the set of colors assigned to the closed neighborhood of $v$ whenever these neighborhoods are distinct. The locally identifying chromatic number of the graph $G$ (or lid-chromatic number, for short), denoted by $\chi_{lid}(G)$, is the smallest number of colors required in any locally identifying coloring of $G$.

1 Introduction

A vertex-coloring is said to be locally identifying if (i) the vertex-coloring is proper (i.e. no adjacent vertices receive the same color), and (ii) for any adjacent vertices $u, v$, the set of colors assigned to the closed neighborhood of $u$ differs from the set of colors assigned to the closed neighborhood of $v$ whenever these neighborhoods are distinct. The locally identifying chromatic number of the graph $G$ (or lid-chromatic number, for short), denoted by $\chi_{lid}(G)$, is the smallest number of colors required in any locally identifying coloring of $G$.

Locally identifying colorings of graphs have been recently introduced by Esperet et al. [6] and later studied by Foucaud et al. [7]. They are related to identifying codes [8, 9], distinguishing colorings [1, 3, 5] and locating-colorings [4].
example, upper bounds on lid-chromatic number have been obtained for bipartite graphs, $k$-trees, outerplanar graphs and bounded degree graphs. An open question asked by Esperet et al. [6] was to know whether $\chi_{lid}$ is bounded for the class of planar graphs. In this paper, we answer positively to this question proving more generally that $\chi_{lid}$ is bounded for any class of bounded expansion.

In Section 3, we first give a tight bound of $\chi_{lid}$ in term of the tree-depth. Then we use the fact that any class of bounded expansion admits a low tree-depth coloring (that is a $k$-coloring such that each triplet of colors induces a graph of tree-depth 3, for some constant $k$) to prove that it has bounded lid-chromatic number.

In Section 4, we focus on minor closed classes of graphs which have bounded expansion and give an alternative bound on the lid-chromatic number, which gives an explicit bound for planar graphs.

The next section is devoted to introduce notation and preliminary results.

## 2 Notation and preliminary results

Let $G = (V, E)$ be a graph. For any vertex $u$, we denote by $N_G(u)$ its neighborhood in $G$ and by $N_G[u]$ its closed neighborhood in $G$ ($u$ together with its adjacent vertices). The notion of neighborhood can be extended to sets as follows: for $X \subseteq V$, $N_G[X] = \{w \in V(G) \mid \exists v \in X, w \in N[v]\}$ and $N_G(X) = N_G[X] \setminus X$. When the considered graph is clearly identified, the subscript is dropped.

The degree of vertex $u$ is the size of its neighborhood. The distance between two vertices $u$ and $v$ is the number of edges in a shortest path between $u$ and $v$. For $X \subseteq V$, we denote by $G[X]$ the subgraph of $G$ induced by $X$.

We say that two vertices $u$ and $v$ are twins if $N[u] = N[v]$ (although they are often called true twins in the literature, we call them twins for convenience). In particular, $u$ and $v$ are adjacent vertices. Note that if $u$ and $v$ are adjacent but not twins, there exists a vertex $w$ which is adjacent to exactly one vertex among $\{u, v\}$, i.e. $w \in N[u] \Delta N[v]$ (where $\Delta$ is the symmetric difference between sets). We say that $w$ distinguishes $u$ and $v$, or simply $w$ distinguishes the edge $uv$. For a subset $X \subseteq V$, we say that a subset $Y \subseteq V$ distinguishes $X$ if for every pair $u, v$ of non-twin vertices of $X$, there exists a vertex $w \in Y$ that distinguishes the edge $uv$.

Let $c : V \to \mathbb{N}$ be a vertex-coloring of $G$. The coloring $c$ is proper if adjacent vertices have distinct colors. We denote by $\chi(G)$ the chromatic number of $G$, i.e. the minimum number of colors in a proper coloring of $G$. For any $X \subseteq V$, let $c(X)$ be the set of colors that appear on the vertices of $X$. A locally identifying coloring (lid-coloring for short) of $G$ is a proper vertex-coloring $c$ of $G$ such that for any two adjacent vertices $u$ and $v$ that are not twins (i.e. $N[u] \neq N[v]$), we have $c(N[u]) \neq c(N[v])$. A graph $G$ is $k$-lid-colorable if it admits a locally identifying coloring using at most $k$ colors and the minimum number of colors needed for any locally identifying coloring of $G$ is the locally identifying chromatic number (lid-chromatic number for short) denoted by $\chi_{lid}(G)$. For a vertex $u$, we say that $u$ sees color $a$ if $a \in c(N[u])$. For two adjacent vertices
u and v, a color that is in the set $c(N[u]) \Delta c(N[v])$ separates u and v, or simply separates the edge uv. The notion of chromatic number (resp. lid-chromatic number) can be extended to a class of graphs $\mathcal{C}$ as follows: $\chi(\mathcal{C}) = \sup\{\chi(G), G \in \mathcal{C}\}$ (resp. $\chi_{ld}(\mathcal{C}) = \sup\{\chi_{ld}(G), G \in \mathcal{C}\}$).

The following theorem is due to Bondy [2]:

**Theorem 1** (Bondy’s theorem [2]). Let $A = \{A_1, \ldots, A_n\}$ be a collection of n distinct subsets of a finite set $X$. There exists a subset $X'$ of $X$ of size at most $n - 1$ such that the sets $A_i \cap X'$ are all distinct.

**Corollary 2.** Let $C$ be a n-clique subgraph of $G$. There exists a vertex subset $S(C) \subseteq V(G)$ of size at most $n - 1$ that distinguishes all the pair of non-twin vertices of $C$.

**Proof.** Let $C$ be a n-clique subgraph of $G$ induced by the vertex set $V(C) = \{v_1, v_2, \ldots, v_n\}$. Let $A = \{N[v_i] | v_i \in V(C)\}$ be a collection of distinct subsets of the finite set $X = \bigcup_{1 \leq i \leq n} N[v_i]$. Note that some $v_i$’s might be twins in $G$ (i.e. $N[v_i] = N[v_j]$ for some $v_i, v_j \in V(C)$) and therefore $|A|$ could be smaller than $n$. By Bondy Theorem, there exists $S(C) \subseteq X$ of size at most $|A| - 1 \leq n - 1$ such that for any distinct elements $A_i, A_j$ of $A$, we have $A_i \cap S(C) \neq A_j \cap S(C)$.

Let us prove that $S(C)$ is a set of vertices that distinguish all the pairs of non-twin vertices of $C$. For a pair of non-twin vertices $v_i, v_j$ of $C$, we have $N[v_i] \not\subseteq N[v_j]$. By definition of $S(C)$, we have $N[v_i] \cap N[v_j] \not\subseteq N[v_j] \cap S(C)$, then there exists $w \in S(C)$ that belongs to $N[v_i] \Delta N[v_j]$. Therefore, $w$ distinguishes the edge $v_iv_j$. \hfill \Box

3 Bounded expansion classes of graphs

A rooted tree is a tree with a special vertex, called the root. The height of a vertex $x$ in a rooted tree is the number of vertices on a path from the root to $x$ (hence, the height of the root is 1). The height of a rooted tree $T$ is the maximum height of the vertices of $T$. If $x$ and $y$ are two vertices of $T$, $x$ is an ancestor of $y$ in $T$ if $x$ belongs to the path between $y$ and the root. The closure $\text{clos}(T)$ of a rooted tree $T$ is the graph with vertex set $V(T)$ and edge set $\{xy \mid x$ is an ancestor of $y$ in $T, x \neq y\}$. The tree-depth $\text{td}(G)$ of a connected graph $G$ is the minimum height of a rooted tree $T$ such that $G$ is a subgraph of $\text{clos}(T)$. If $G$ is not connected, the tree-depth of $G$ is the maximum tree-depth of its connected components.

Let $p$ be a fixed integer. A low tree-depth coloring of a graph $G$ (relatively to $p$) is a coloring of the vertices of $G$ such that the union of any $i \leq p$ color classes induces a graph of tree-depth at most $i$. Let $\chi_{td}^p(G)$ be the minimum number of colors required in such a coloring. Note that as tree-depth one graphs and tree-depth two graphs are respectively the stables and star forests, $\chi_{td}^1$ and $\chi_{td}^2$ respectively correspond to the usual chromatic number and the star chromatic number.
In the following of this section, we first give a tight bound on the lid-chromatic number in terms of tree-depth.

**Proposition 3.** For any graph $G$, $\chi_{lid}(G) \leq 2td(G) - 1$ and this is tight.

Using this bound, we then bound the lid-chromatic number in terms of $\chi^{td}_3$.

**Theorem 4.** For any graph $G$,

$$\chi_{lid}(G) \leq 6(\chi^{td}_3(G)).$$

Classes of graphs of bounded expansion have been introduced by Nešetřil and Ossona de Mendez [10]. These classes contain minor closed classes of graphs and any class of graphs defined by an excluded topological minor. Actually, these classes of graphs are closely related to low tree-depth colorings:

**Theorem 5 (Theorem 7.1 [10]).** A class of graphs $\mathcal{C}$ has bounded expansion if and only if $\chi^{td}_p(\mathcal{C})$ is bounded for any $p$.

We therefore deduce the following corollary from Theorems 4 and 5:

**Corollary 6.** For any class $\mathcal{C}$ of bounded expansion, $\chi_{lid}(\mathcal{C})$ is bounded.

It is in particular true for a class of bounded tree-width. A consequence is that $\chi_{lid}$ is bounded for chordal graphs by a function of the clique number (which is equals to the tree-width plus 1 for a chordal graph). It is conjectured by Esperet et al. [6] that $\chi_{lid}(G) \leq 2\omega(G)$ if $G$ is chordal.

We now prove Proposition 3.

**Proof of Proposition 3.** Let us first prove that the bound is tight. Consider the graph $H_n$ obtained from a complete graph, with vertex set $\{a_1, \ldots, a_n\}$, by adding a pendant vertex $b_i$ to every $a_i$ but one, say for $1 \leq i < n$. The tree-depth of this graph is at least $n$ as it contains a $n$-clique. Indeed, given a rooted tree $T$, two vertices at the same height are non-adjacent in $\text{clos}(T)$, we thus need at least $n$ levels. Actually the tree-depth of this graph is at most $n$ since the tree $T$ rooted at $a_1$, and such that $a_i$ has two sons $a_{i+1}$ and $b_i$, for $1 \leq i < n$, has height $n$ and is such that $\text{clos}(T)$ contains $H_n$ as a subgraph.

Let us show that in any lid-coloring of $H_n$ all the vertices must have distinct colors, and thus use $2n - 1 = 2td(H_n) - 1$ colors. Indeed, two vertices $a_i$ must have different colors as the coloring is proper. A vertex $b_i$ cannot use the same color as a vertex $a_i$, as otherwise the vertex $a_i$ would only see the $n$ colors used in the clique, just as $a_n$. Similarly if two vertices $b_i$ and $b_j$ would use the same color, the vertices $a_i$ and $a_j$ would see the same set of colors.

Let us now focus on the upper bound. We prove the result for a connected graph and by induction on the tree-depth of $G$, denoted by $k$. The result is clear for $k = 1$ (the graph is a single vertex).

Let $G$ be a graph of tree-depth $k > 1$ and let $T$ be a rooted tree of height $k$ such that $G$ is a subgraph of $\text{clos}(T)$. If $T$ is a path, the result is clear since there are only $k$ vertices. So assume that $T$ is not a path, and let $r$ be the root
of $T$. Let $s$ be the smallest height such that there are at least two vertices of height $s + 1$. We name $r_i$, for $i \in \{1, \ldots, s\}$, the unique vertex of height $i$. Let $R = \{r_1, \ldots, r_s\}$. Note that each of the vertices of $R$ is adjacent to all the vertices of $\text{clos}(T)$. Therefore, we can choose the way we label the $s$ vertices in $R$ (i.e. we can choose the height of each of them in $T$) without changing $\text{clos}(T)$.

Necessarily, $G \setminus R$ has at least two connected components. Let $G_1, \ldots, G_\ell$ be its connected components and thus $\ell \geq 2$. We choose $T$ such that $s$ is minimal. It implies that for each $i \in \{1, \ldots, s\}$, $r_i$ has neighbors in all the components $G_1, \ldots, G_\ell$. Indeed, if it is not the case, by permuting the elements of $R$ (this is possible by the above remark), we can assume without loss of generality that $r_s$ does not have a neighbor in $G_\ell$. Therefore, the set of edges $e(r_s, G_\ell) = \{r_s x : x \in V(G_\ell)\}$ of $\text{clos}(T)$ are not used by $G$. Then let $T'$ be the tree obtained from $T$ by moving the whole component $G_\ell$ one level up in such a way that the root of the subtree corresponding to $G_\ell$ is now the son of $r_{s-1}$ (instead of $r_s$ previously). Note that $\text{clos}(T')$ is isomorphic to $\text{clos}(T) \setminus e(r_s, G_\ell)$ and thus $G$ is a subgraph of $\text{clos}(T')$. This new tree $T'$ has two vertices at height $s$, contradicting the minimality of $s$.

Any connected component $G_j$ has tree-depth at most $k' = k - s < k$. By induction, for each $j \in \{1, \ldots, \ell\}$, there exists a lid-coloring $c_j$ of $G_j$ using colors in $\{1, \ldots, 2k' - 1\}$. For each $c_j$, there is a minimum value $s_j$ such that every vertex $r_i$ sees a color in $\{1, \ldots, s_j\}$ in $G_j$. We choose a $(2k' - 1)$-lid-coloring $c_j$ of $G_j$ such that $s_j$ is minimized. Note that for each color $a \leq s_j$, there exists $r_i \in R$ such that $r_i$ sees color $a$ in $G_j$ but no other color of $\{1, \ldots, s_j\}$. Otherwise, after permuting colors $a$ and $s_j$, every vertex $r_i \in R$ would see a color in $\{1, \ldots, s_j - 1\}$, contradicting the minimality of $s_j$. Assume without loss of generality that $s_1 \geq s_2 \geq \ldots \geq s_\ell$.

We replace in $c_j$ the colors $1, 2, \ldots, s_1$ by $1', 2', \ldots, s_1'$. Note that now each vertex $r_i$ sees a color in $\{1', \ldots, s_1'\}$ (in $G_1$) and a color in $\{1, \ldots, s_2\}$ (in $G_2$). Furthermore, the other vertices of $G$ (that is the vertices in $G_1, \ldots, G_\ell$) do not have this property since $s_1 \geq s_2$. Thus at this step every edge $xr_i$ with $x$ in some $G_j$ is separated.

Now we color each vertex $r_i$ with color $i^*$. Let $c : V(G) \rightarrow \{1^*, \ldots, s^*\} \cup \{1', \ldots, s_1'\} \cup \{1, \ldots, 2k' - 1\}$ be the current coloring of $G$.

Note that now every distinguishable edge $xy$ in some $G_j$ is separated. Indeed, either $xy$ was distinguished in $G_j$ and it has been separated by $c_j$, or $xy$ is distinguished by some $r_i$ and it is separated by the color $i^*$. Note also that $c$ is a proper coloring.

It remains to deal with the edges $r_ir_j$. For that purpose we will refine some color classes. In the following lemma we show that such refinements do not damage what we have done so far.

**Claim.** Consider a graph $G$ and a coloring $\varphi : V(G) \rightarrow \{1, \ldots, k\}$. Consider any refinement $\varphi'$ of $\varphi$, obtained from $\varphi$ by recoloring with color $k + 1$ some vertices colored $i$, for some $i$. Any edge $xy$ of $G$ properly colored (resp. separated) by $\varphi$ is properly colored (resp. separated) by $\varphi'$.

Indeed if $\varphi(x) \neq \varphi(y)$ then $\varphi'(x) \neq \varphi'(y)$, and if $i \in \varphi(N[x]) \Delta \varphi(N[y])$ then...
The class $C$ minor closed is $C$ proper minor closed class of graphs $K$ class of graphs is included in the class $K$ pair of adjacent vertices will be in some common graph $H$ with successive edge deletions, vertex deletions and edge contractions. A class $C$ minor closed is a graph that does not have $K$-minor free graph if for any graph $G$ of $C$, for any minor $H$ of $G$, we have $H \in C$. The class $C$ is minor closed if it is the not the class of all graphs. Let $H$ be a graph. A $H$-minor free graph is a graph that does not have $H$ as a minor. We denote by $\mathcal{X}_n$ the $K_n$-minor-free class of graphs. It is clear that any proper minor closed class of graphs is included in the class $\mathcal{X}_n$ for some $n$. It is folklore that any proper minor closed class of graphs $C$ has a bounded chromatic number $\chi(C)$.

Let $G$ and $H$ be two graphs. $H$ is a minor of $G$ if $H$ can be obtained from $G$ with successive edge deletions, vertex deletions and edge contractions. A class $C$ is minor closed if for any graph $G$ of $C$, for any minor $H$ of $G$, we have $H \in C$. The class $C$ is proper if it is the not the class of all graphs. Let $H$ be a graph. A $H$-minor free graph is a graph that does not have $H$ as a minor. We denote by $\mathcal{X}_n$ the $K_n$-minor-free class of graphs. It is clear that any proper minor closed class of graphs is included in the class $\mathcal{X}_n$ for some $n$. It is folklore that any proper minor closed class of graphs $C$ has a bounded chromatic number $\chi(C)$.

$i$ or $k + 1 \in \varphi '(N[x]) \Delta \varphi '(N[y])$.

Let us define a relation $R$ among vertices in $R$ by $r_1 \mathcal{R} r_2$ if and only if $c(N[r_1]) = c(N[r_2])$. Let $R_1, \ldots, R_n$ be the equivalence classes of the relation $R$ (note that each $R_i$ forms a clique since every $r_i$ has distinct colors). We have $\bar{s} \geq s_1$. Indeed, by definition of $s_1$ and the coloring $c_1$, for each color $a \in \{1', \ldots, s_1'\}$, there exists $r_i \in R$ that sees $a$ in $G_1$ but no other color of $\{1', \ldots, s_1'\}$. This vertex $r_i$ belongs to some equivalence class $R_j$ and thus all the vertices of $R_j$ sees color $a$ in $G_1$ but no other color of $\{1', \ldots, s_1'\}$.

By Corollary 2, there is a vertex set $S(R_i)$ of size at most $|R_i| - 1$ which distinguishes all pairs of non-twin vertices in $R_i$. We give to the vertices of $S(R_i)$ new distinct colors. By the previous claim, this last operation does not damage the coloring, and now all the distinguishable edges are separated.

Since for this last operation we need $s - \bar{s}$ new colors, since we used $2k - 1$ colors $\{1, \ldots, 2k - 1\}$, $s_1$ colors $\{1', \ldots, s_1'\}$ and $s$ colors $\{1^*, \ldots, s^*\}$, the total number of colors is $(s - \bar{s}) + (2k - 1) + s_1 + s = 2k - 1 + s_1 - \bar{s} \leq 2k - 1$. This concludes the proof of the theorem.

We are now ready to prove Theorem 4:

**Proof of Theorem 4.** Let $\alpha$ be a low tree-depth coloring of $G$ with parameter $p = 3$ and using $\chi^t_3(G)$ colors. Let $A = \{a_1, a_2, a_3\}$ be a triplet of three distinct colors and let $H_A$ be the subgraph of $G$ induced by the vertices colored by a color of $A$. Since $H_A$ has tree-depth at most 3, by Proposition 3, $H_A$ admits a $lid$-coloring $c_A$ with five colors (says colors 1 to 5). We extend $c_A$ to the whole graph by giving color 0 to the vertices in $V(G) \setminus V(H_A)$.

Let $A_1, A_2, \ldots, A_k$ be the $k = (\chi^t_3(G))$ distinct triplets of colors. We now construct a coloring $c$ of $G$ giving to each vertex $x$ of $G$ the $k$-uplet

$$(c_{A_1}(x), c_{A_2}(x), \ldots, c_{A_k}(x)).$$

The coloring $c$ is using $6^k$ colors. Clearly it is a proper coloring: each pair of adjacent vertices will be in some common graph $H_A$ and will receive distinct colors in this graph. Let $x$ and $y$ be two adjacent vertices with $N[x] \neq N[y]$. Let $w$ be a vertex adjacent to only one vertex among $x$ and $y$. Let $A = \{a(x), a(y), a(w)\}$. Vertices $x$ and $y$ are not twins in the graph $H_A$. Hence $c_A(N[x]) \neq c_A(N[y])$ and therefore, $c(N[x]) \neq c(N[y])$. \qed

4 Minor closed classes of graphs

Let $G$ and $H$ be two graphs. $H$ is a minor of $G$ if $H$ can be obtained from $G$ with successive edge deletions, vertex deletions and edge contractions. A class $C$ is minor closed if for any graph $G$ of $C$, for any minor $H$ of $G$, we have $H \in C$. The class $C$ is proper if it is the not the class of all graphs. Let $H$ be a graph. A $H$-minor free graph is a graph that does not have $H$ as a minor. We denote by $\mathcal{X}_n$ the $K_n$-minor-free class of graphs. It is clear that any proper minor closed class of graphs is included in the class $\mathcal{X}_n$ for some $n$. It is folklore that any proper minor closed class of graphs $C$ has a bounded chromatic number $\chi(C)$.
The class of graphs of bounded expansion includes all the proper minor closed classes of graphs. Thus, by Corollary 6, proper minor closed classes have bounded lid-chromatic number. In this section, we focus on these latter classes and give an alternative upper bound on the lid-chromatic number. This gives us an explicit upper bound for the lid-chromatic number of planar graphs.

Consider any proper minor closed class of graphs $\mathcal{G}$. Since $\mathcal{G}$ is proper, there exists $n$ such that $\mathcal{G}$ does not contain $K_n$, that is, $\mathcal{G} \subseteq \mathcal{K}_n$. Let $\mathcal{G}^N$ be the class of graphs defined by $H \in \mathcal{G}^N$ if and only if there exists $G \in \mathcal{G}$ and $v \in G$ such that $H = G[N(v)]$. Note that $\mathcal{G}^N$ is a minor-closed class of graphs. Indeed, given any $H \in \mathcal{G}^N$, let $G \in \mathcal{G}$ and $v \in V(G)$ such that $H = G[N(v)]$. Let $H'$ be any minor of $H$. Since $\mathcal{G}$ is minor-closed and $H$ is a subgraph of $G$, there exists a minor $G'$ of $G$ such that $H' = G'[N(v)]$. Therefore, $H'$ belongs to $\mathcal{G}^N$.

We prove the following result on minor-closed classes of graphs:

**Theorem 7.** Let $\mathcal{G}$ be a proper minor closed class of graphs and let $n \geq 3$ be such that $\mathcal{G} \subseteq \mathcal{K}_n$. Then

$$\chi_{\text{lid}}(\mathcal{G}) \leq 4 \cdot \chi_{\text{lid}}(\mathcal{G}^N) \cdot \chi(\mathcal{G})^{n-3}$$

The class of trees is exactly the class $\mathcal{K}_3$. Esperet et al. [6] proved the following result.

**Proposition 8 ([6]).** $\chi_{\text{lid}}(\mathcal{K}_3) \leq 4$.

It is clear that $\mathcal{K}_3^N$ is the class of stable graphs and therefore, $\chi_{\text{lid}}(\mathcal{K}_3^N) = 1$. Note that Theorem 7 implies Proposition 8.

Assume that $\chi_{\text{lid}}(\mathcal{K}_{n-1})$ is bounded for some $n \geq 4$. It is clear that $\mathcal{K}_n^N = \mathcal{K}_{n-1}$. Then, by Theorem 7, we have $\chi_{\text{lid}}(\mathcal{K}_n) \leq 4 \cdot \chi_{\text{lid}}(\mathcal{K}_{n-1}) \cdot \chi(\mathcal{K}_n)^{n-3}$. Since $\chi_{\text{lid}}(\mathcal{K}_{n-1})$ and $\chi(\mathcal{K}_n)$ are bounded, $\chi_{\text{lid}}(\mathcal{K}_n)$ is bounded.

Esperet et al. [6] also proved the following result.

**Proposition 9 ([6]).** If $G$ is an outerplanar graph, $\chi_{\text{lid}}(G) \leq 20$.

We can then deduce from Theorem 7 and Proposition 9 the following corollary:

**Corollary 10.** Let $\mathcal{P}$ be the class of planar graphs. Then $\chi_{\text{lid}}(\mathcal{P}) \leq 1280$.

**Proof.** Any graph $G \in \mathcal{P}$ is $\{K_{3,3}, K_5\}$-minor free and thus $\mathcal{P}$ is a proper minor closed class of graphs. Moreover, the neighborhood of any vertex of $G \in \mathcal{P}$ is an outerplanar graph. By Proposition 9, we have $\chi_{\text{lid}}(\mathcal{P}^N) \leq 20$. Furthermore, the Four-Color-Theorem gives $\chi(\mathcal{P}) = 4$. By Theorem 7, $\chi_{\text{lid}}(\mathcal{P}) \leq 4 \times 20 \times 4^2 = 1280$.

We finally give the proof of Theorem 7.

**Proof of Theorem 7.** Let $G \in \mathcal{G}$ and let $u$ be a vertex of minimum degree. For any $i$, define $V_{u,i}$ as the set of vertices of $G$ at distance exactly $i$ from $u$ and let $G_{u,i} = G[V_{u,i}]$. Let $s$ be the largest distance from a vertex of $V$ to $u$. In other words, there are $s + 1$ nonempty sets $V_{u,i}$ (note that $V_{u,0} = \{u\}$).
For any $i$, contracting in $G$ the subgraph $G[H_{u,i}]$ in a single vertex $x$ gives a graph $G'$ in $C$ such that $x$ is exactly adjacent to every vertex of $G_{u,i}$. Therefore, for any $i$, $G_{u,i} \in \mathcal{E}^N$. Hence, $\chi_{lid}(G_{u,i}) \leq \chi_{lid}(\mathcal{E}^N)$ for any $i$. Moreover, $\mathcal{E}^N \subseteq \mathcal{K}_{n-1}$. Indeed, suppose that there exists $H \in \mathcal{E}^N$ that admits $K_{n-1}$ as a minor. Therefore there exists $G \in \mathcal{E}$ such that $H = G[N(v)]$ for some $v \in G$. Taking $v$ together with its neighborhood would give $K_n$ as a minor, that contradicts the fact that $\mathcal{E} \subseteq \mathcal{K}_n$. Hence, any $G_{u,i} \in \mathcal{K}_{n-1}$.

We construct a lid-coloring of $G$ using $4 \cdot \chi_{lid}(\mathcal{E}^N) \cdot \chi(\mathcal{E})^{n-3}$ colors. This coloring is constructed with three different colorings of the vertices of $G$: $c_1$ which uses 4 colors, $c_2$ which uses $\chi_{lid}(\mathcal{E}^N)$ colors and $c_3$ which is itself composed of $n-3$ colorings with $\chi(\mathcal{E})$ colors. The final color $c(v)$ of a vertex $v$ will be the triplet $(c_1(v), c_2(v), c_3(v))$. Hence the coloring $c$ uses at most $4\chi_{lid}(\mathcal{E}^N)\chi(\mathcal{E})^{n-3}$ colors. The coloring $c_1$ is used to separate the pairs of vertices that lie in distinct sets $V_{u,i}$. The coloring $c_2$ separates the pairs of vertices that lie in the same set $V_{u,i}$ and are not twins in $G_{u,i}$. Finally, the coloring $c_3$ separates the pairs of vertices that lie in the same set $V_{u,i}$, that are twins in $G_{u,i}$ but that are not twins in $G$.

The coloring $c_1$ is simply defined by $c_1(v) \equiv i \mod 4$ if $v \in V_{u,i}$.

To define $c_2$, we define for each $i$, $0 \leq i \leq s$, a lid-coloring $c_2^i$ of $G_{u,i}$ using colors 1 to $\chi_{lid}(\mathcal{E}^N)$. Then $c_2$ is defined by $c_2(v) = c_2^i(v)$ if $v \in V_{u,i}$.

We now define the coloring $c_3$. Let $V_{u,i}^{id}$ be the set of vertices of $V_{u,i}$ that have a twin in $G_{u,i}$:

$$V_{u,i}^{id} = \{v \in V_{u,i} \mid \exists w \in V_{u,i}, N_{G_{u,i}}[v] = N_{G_{u,i}}[w]\}.$$ 

Let $G_{u,i}^{id} = G_{u,i}[V_{u,i}^{id}]$. Since the relation “be twin” is transitive (i.e. if $u$ and $v$ are twins, and $v$ and $w$ are twins, then $u$ and $w$ are twins), then $G_{u,i}^{id}$ is clearly a union of cliques. In addition, since $G_{u,i} \in \mathcal{K}_{n-1}$, the connected components of $G_{u,i}^{id}$ are cliques of size at most $n-2$.

Let $C$ be a clique of $G_{u,i}^{id}$. By Corollary 2, there exists a subset $S(C) \subseteq V(G)$ of at most $n-3$ vertices that distinguishes all the pairs of non-twin vertices of $C$. Note that by definition of $C$, $S(C) \cap V_{u,i} = \emptyset$, and thus $S(C) \subseteq V_{u,i-1} \cup V_{u,i+1}$.

Let $S = \{(v, C) \mid v \in S(C)\}$. $C$ and $S$ are a clique in a graph $G_{u,i}^{id}$. We partition $S$ in $s \times (n-3)$ sets $S^k_i$, $1 \leq i \leq s$, $1 \leq k \leq n-3$, such that:

- if $(v, C) \in S^k_i$ for some $k$, then $v \in V_{u,i}$;
- if $(v, C)$ and $(w, C')$ are two elements of $S^k_i$, then $C \neq C'$.

This partition can be done because each set $S(C)$ has size at most $n-3$.

For each $S^k_i = \{(x_{i1}, C_{i1}), (x_{i2}, C_{i2}), \ldots, (x_{ik}, C_{ik})\}$, we define a graph $H^k_i$ as follows. We start from the graph induced by $V_{u,i} \cup V(C_{i1}) \cup V(C_{i2}) \cup \ldots \cup V(C_{ik})$. Then, for each $(x_j, C_j)$ in $S^k_i$, we contract $C_j$ in a single vertex $y_j$ and finally, we contract the edge $x_jy_j$ on the vertex $x_j$. Note that $V_{u,i}$ is the vertex set of $H^k_i$. Note also that $H^k_i \in \mathcal{E}$ since it is obtained from a subgraph of $G$ by successive edge-contractions. Therefore, $\chi(H^k_i) \leq \chi(\mathcal{E})$. 

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We now define a proper coloring $c_{i,k}^j$ of $H^k_i$ with colors 1 to $\chi(G)$. Let $c_{i,k}^j$ be the coloring of vertices of $G$ defined by $c_{i,k}^j(v) = c^i_{j,k}(v)$ if $v \in V_{u,i}$. Finally, $c_{i,3}$ is defined by $c_{i,3}(v) = (c_1(v), \ldots, c_{i,3}^{n-3}(v))$, and the final color of $v$ is $c(v) = (c_1(v), c_2(v), c_3(v))$.

We now prove that $c$ is a lid-coloring of $G$. First, $c$ is a proper coloring.

Indeed, two adjacent vertices that are not in the same set $V_{u,i}$, lie in consecutives set $V_{u,i}$ and $V_{u,i+1}$ and thus have different colors in $c_1$, and two adjacent vertices in the same set $V_{u,i}$ have different colors in $c_2$ (which induces a proper coloring on $V_{u,i}$).

Let now $x$ and $y$ be two adjacent vertices with $N[x] \neq N[y]$. We will prove that $c(N[x]) \neq c(N[y])$. We distinguish three cases.

Case 1: $x \in V_{u,i}$ and $y \in V_{u,i+1}$.

If $x = u$, then $y$ has a neighbor $v$ in $V_{u,i+2} = V_{u,2}$. Indeed, $u$ is taken with minimum degree, so $y$ has at least as many neighbors as $u$ and does not have the same neighborhood than $u$, implying that $y$ has a neighbor in $V_{u,2}$. Then $c_1(v) = 2 \notin c_1(N[u])$ and so $c(N[x]) \neq c(N[y])$.

Otherwise, $x$ has neighbor $v$ in $V_{u,i-1}$ and $c_1(v) \equiv i - 1 \pmod{4} \in c_1(N[x])$. On the other hand, all the neighbors of $y$ belong to $V_{u,i} \cup V_{u,i+1} \cup V_{u,i+2}$ and therefore $c_1(N[y]) \subseteq \{i, i+1, i+2 \pmod{4}\}$. Thus, $c(N[x]) \neq c(N[y])$.

Case 2: $x$ and $y$ belong to $V_{u,i}$ and they are not twins in $V_{u,i}$ (i.e. $N_{V_{u,i}}[x] \neq N_{V_{u,i}}[y]$).

By definition of the coloring $c_{2}^3$, there exists a color $a$ that separates $x$ and $y$, i.e. $a \in c_{2}^3(N_{V_{u,i}}[x]) \triangle c_{2}^3(N_{V_{u,i}}[y])$. Then we necessarily have $c(N[x]) \neq c(N[y])$.

Case 3: $x$ and $y$ belong to $V_{u,i}$ and they are twins in $V_{u,i}$ (i.e. $N_{V_{u,i}}[x] = N_{V_{u,i}}[y]$).

In this case, vertices $x$ and $y$ are in the set $V_{u,i}^{adj}$. Let $C$ be the clique of $G_{u,i}$ containing $x$ and $y$. Let $v \in S(C)$ that distinguishes $x$ and $y$; thus, $v \in V_{u,j}$ for $j = i - 1$ or $j = i + 1$. Wlog, $v \in N[x]$ but $v \notin N[y]$. Let $S_k^j$ be the part of $S$ that contains $(v,C)$. Suppose that there exists a neighbor $w$ of $y$ such that $c(v) = c(w)$. Then $w$ lies in $V_{u,j}$ because of the coloring $c_1$. However, in the graph $H_{j}^k$, the vertex $v$ is adjacent to all the neighbors of $y$ in $V_{u,j}$, and in particular is adjacent to $w$; therefore, $c_{j,k}^i(v) \neq c_{j,k}^i(w)$, a contradiction. Therefore, the vertex $y$ does not have any neighbor that has the same color as $v$. Hence, $c(v) \notin c(N[y])$, and $c(N[x]) \neq c(N[y])$.

□
References


