Three complexity results on coloring P_k-free graphs ☆

Hajo Broersma[a,1], Fedor V. Fomin[b,2], Petr A. Golovach[b,2], Daniël Paulusma[a,3]

[a] *School of Engineering and Computing Sciences, Durham University, DH1 3LE Durham, United Kingdom*

[b] *Department of Informatics, University of Bergen, PB 7803, 5020 Bergen, Norway*

Abstract

We prove three complexity results on vertex coloring problems restricted to P_k-free graphs, i.e., graphs that do not contain a path on k vertices as an induced subgraph. First of all, we show that the pre-coloring extension version of 5-coloring remains NP-complete when restricted to P_6-free graphs. Recent results of Hoàng et al. imply that this problem is polynomially solvable on P_5-free graphs. Secondly, we show that the pre-coloring extension version of 3-coloring is polynomially solvable for P_6-free graphs. This implies a simpler algorithm for checking the 3-colorability of P_6-free graphs than the algorithm given by Randerath and Schiermeyer. Finally, we prove that 6-coloring is NP-complete for P_7-free graphs. This problem was known to be polynomially solvable for P_5-free graphs and NP-complete for P_8-free graphs, so there remains one open case.

Key words: graph coloring, P_k-free graph, computational complexity

---

☆An extended abstract of this paper appeared in the proceedings of IWOCA 2009.

Email addresses: `hajo.broersma@durham.ac.uk` (Hajo Broersma), `fedor.fomin@ii.uib.no` (Fedor V. Fomin), `petr.golovach@ii.uib.no` (Petr A. Golovach), `daniel.paulusma@durham.ac.uk` (Daniël Paulusma)

[1]Supported by EPSRC Grant EP/G043434/1. Current address: Faculty of EEMCS, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands; e-mail: h.j.broersma@utwente.nl.

[2]Supported by the Norwegian Research Council.

[3]Supported by EPSRC Grant EP/D053633/1.

1. Introduction

In this paper we consider computational complexity issues related to vertex coloring problems restricted to P_k-free graphs. Due to the fact that the usual ℓ-Coloring problem is NP-complete for any fixed $\ell \geq 3$, there has been considerable interest in studying its complexity when restricted to certain graph classes. Without doubt one of the most well-known results in this respect is that ℓ-Coloring is polynomially solvable for perfect graphs. More information on this classic result and related work on coloring problems restricted to graph classes can be found in, e.g., [13] and [15]. Instead of repeating what has been written in so many papers over the years, we also refer to these surveys for motivation and background. Here we continue the study of ℓ-Coloring and its variants for P_k-free graphs, a problem that has been studied in several earlier papers by different groups of researchers (see, e.g., [2, 3, 6, 10–12, 16]). We summarize all these results in the table in Section 5.

1.1. Terminology

We refer to [1] for standard graph theory terminology and to [5] for terminology on computational complexity.

Let $G = (V, E)$ be a graph and k a positive integer. We say that G is *P_k-free* if G does not have a path on k vertices as an induced subgraph.

A (vertex) coloring of a graph $G = (V, E)$ is a mapping $\phi : V \to \{1, 2, \ldots\}$ such that $\phi(u) \neq \phi(v)$ whenever $uv \in E$. Here $\phi(u)$ is usually referred to as the color of u in the coloring ϕ of G. An ℓ-coloring of G is a mapping $\phi : V \to \{1, 2, \ldots, \ell\}$ such that $\phi(u) \neq \phi(v)$ whenever $uv \in E$. The problem ℓ-Coloring asks if a given graph has an ℓ-coloring.

In list-coloring we assume that $V = \{v_1, v_2, \ldots, v_n\}$ and that for every vertex v_i of G there is a list L_i of admissible colors (a subset of the natural numbers). Given these lists, a list-coloring of G is a coloring $\phi : V \to \{1, 2, \ldots\}$ such that $\phi(v_i) \in L_i$ for all $i \in \{1, 2, \ldots, n\}$; we say that ϕ *respects* the lists L_i.

In pre-coloring extension we assume that a (possibly empty) subset $W \subseteq V$ of G is pre-colored with $\phi_W : W \to \{1, 2, \ldots\}$ and the question is whether we can extend ϕ_W to a coloring of G. If ϕ_W is restricted to $\{1, 2, \ldots, \ell\}$ and we want to extend it to an ℓ-coloring of G, we say we deal with the *pre-coloring extension version* of ℓ-Coloring. In fact, we consider a slight variation on the latter problem which can be considered as list coloring, but which has the flavor of pre-coloring: lists have varying sizes including some of size 1. We will slightly abuse terminology and call these problems pre-coloring extension problems too.

1.2. Results of this paper

We prove the following three complexity results on vertex coloring problems restricted to P_k-free graphs.

First of all, in Section 2 we show that the pre-coloring extension version of 5-Coloring remains NP-complete when restricted to P_6-free graphs. Recent results of Hoàng et al. [6] imply that this problem is polynomially solvable on P_5-free graphs. Their algorithm for ℓ-Coloring for any fixed ℓ is in fact a list-coloring algorithm where the lists are from the set $\{1, 2, \ldots, \ell\}$.

Secondly, in Section 3 we show that the pre-coloring extension version of 3-Coloring is polynomially solvable for P_6-free graphs. The 3-Coloring problem was known to be polynomially solvable for P_6-free graphs from a paper by Randerath and Schiermeyer [12]. Their approach is as follows. First they note that the input graph G may be assumed to be K_4-free, i.e., does not contain a complete graph on four vertices as a subgraph, as otherwise it is not 3-colorable. Their algorithm then determines if G contains a C_5. If so, it exploits the existence of this C_5 in G in a clever way. If not, the authors use the Strong Perfect Graph Theorem to deduce that G is perfect. This allows them to use the polynomial time algorithm of Tucker [14] for finding a χ-coloring of a K_4-free perfect graph. Here χ denotes the *chromatic number* of a graph, i.e., the smallest ℓ such that the graph is ℓ-colorable. We follow a different approach. First, our algorithm is independent of the Strong Perfect Graph Theorem, and second it uses a recent characterization of P_6-free graphs in terms of dominating subgraphs [7]. This way we can indeed show that the pre-coloring extension version of 3-Coloring is polynomially solvable for P_6-free graphs, whereas the approach of Randerath and Schiermeyer [12] does not immediately lead to this result. The reason for this lies in the second part of their algorithm that focuses on K_4-free perfect graphs. Already for a subclass of this class, namely the class of bipartite graphs, Kratochvíl [10] showed that the pre-coloring extension version of 3-Coloring is an NP-complete problem.

Finally, in Section 4 we show that 6-Coloring is NP-complete for P_7-free graphs. This problem was known to be polynomially solvable for P_5-free graphs [6] and NP-complete for P_8-free graphs [16], so there remains one open case.

2. Pre-coloring extension of 5-coloring for P_6-free graphs

In this section we show that the pre-coloring extension version of 5-Coloring remains NP-complete when restricted to P_6-free graphs. We use a reduction from Not-All-Equal 3-Satisfiability with positive literals only which we denote as NAE 3SATPL. This NP-complete problem [5] is also known as Hypergraph 2-Colorability and is defined as follows. Given a set $X = \{x_1, x_2, \ldots, x_n\}$ of logical variables, and a set $\mathcal{C} = \{C_1, C_2, \ldots, C_m\}$ of three-literal clauses over X in which all literals are positive, does there exist a truth assignment for X such that each clause contains at least one true literal and at least one false literal?

We consider an arbitrary instance I of NAE 3SATPL and define a graph G_I and a pre-coloring on some vertices of G_I, and next we show that G_I is P_6-free and that the pre-coloring on G_I can be extended to a 5-coloring of G_I if and only if I has a satisfying truth assignment in which each clause contains at least one true literal and at least one false literal.

Theorem 1. *The pre-coloring extension version of* 5-Coloring *is NP-complete for P_6-free graphs.*

Proof. Let I be an instance of NAE 3SATPL with variables $\{x_1, x_2, \ldots, x_n\}$ and clauses $\{C_1, C_2, \ldots, C_m\}$. We define a graph G_I corresponding to I and lists of admissible colors for its vertices based on the following construction. We note here that the lists we introduce below are only there for convenience to the reader; it will be clear later that all lists other than $\{1, 2, \ldots, 5\}$ are in fact forced by the pre-colored vertices.

1. We introduce one new vertex for each of the clauses, and use the same labels $C_1, C_2, \ldots, C_m$ for these m vertices; we assume that for each of these vertices there is a list $\{1, 2, 3\}$ of admissible colors. We say that these vertices are of C-type and use $\mathcal{C}$ to denote the set of C-type vertices.

2. We introduce one new vertex for each of the variables, and use the same labels $x_1, x_2, \ldots, x_n$ for these n vertices; we assume that for each of these vertices there is a list $\{4, 5\}$ of admissible colors. We say that these vertices are of x-type and use $\mathcal{X}$ to denote the set of x-type vertices.

3. We join all C-type vertices to all x-type vertices to form a complete bipartite graph with $|\mathcal{C}||\mathcal{X}|$ edges.

4. For each clause C_j we fix an arbitrary order of its variables x_i, x_k, and x_r, and we introduce three pairs of new vertices $\{a_{i,j}, b_{i,j}\}$, $\{a_{k,j}, b_{k,j}\}$, $\{a_{r,j}, b_{r,j}\}$; we assume the following lists of admissible colors for these three pairs, respectively: $\{\{1,4\},\{2,5\}\}$, $\{\{2,4\},\{3,5\}\}$, $\{\{3,4\},\{1,5\}\}$. We say that these vertices are of a-type and b-type, and use $\mathcal{A}$ and $\mathcal{B}$ to denote the set of a-type and b-type vertices, respectively. We add edges between x-type and a-type vertices whenever the first index of the a-type vertex is the same as of the x-type vertex, and similarly for the b-type vertices. We add edges between C-type and a-type vertices whenever the second index of the a-type vertex is the same as the index of the C-type vertex, and similarly for the b-type vertices. Hence each clause with three variables is represented by three 4-cycles that have one C-type vertex in common.

5. For each a-type vertex we introduce a copy of a $K_{2,3}$, as follows: for $a_{i,j}$ we add five vertices $\{p_{i,j,1}, \ldots, p_{i,j,5}\}$, and we add all edges between $\{p_{i,j,1}, p_{i,j,2}, p_{i,j,3}\}$ and $\{p_{i,j,4}, p_{i,j,5}\}$. We say that these vertices are of p-type and use $\mathcal{P}$ to denote the set of p-type vertices. We add edges between each a-vertex and the p-vertices of its corresponding $K_{2,3}$ depending on its list of admissible colors. In particular, we join the a-vertex to the three p-vertices of its $K_{2,3}$ that have a third index which is not in its list of admissible colors. So, if $a_{i,j}$ has list $\{1,4\}$, we join it to $p_{i,j,2}, p_{i,j,3}, p_{i,j,5}$. We use $\mathcal{P}_1$ to denote the set of all p-type vertices with third index in $\{1,2,3\}$ and $\overline{\mathcal{P}_1}$ to denote all other p-type vertices.

6. For each b-type vertex we introduce a new copy of a $K_{2,3}$ on five vertices of q-type, in the same way as we introduced the p-type vertices for the a-type vertices. Edges are added in a similar way, depending on the indices and the lists. We use $\mathcal{Q}$ to denote the set of q-type vertices, $\mathcal{Q}_1$ to denote the set of all q-type vertices with third index in $\{1,2,3\}$ and $\overline{\mathcal{Q}_1}$ to denote all other q-type vertices.

7. We join all the p-type and q-type vertices with third indices $1,2,3$ to all the p-type and q-type vertices with third indices $4,5$ to form a complete bipartite graph with $|\mathcal{P}_1 \cup \mathcal{Q}_1||\overline{\mathcal{P}_1} \cup \overline{\mathcal{Q}_1}|$ edges.

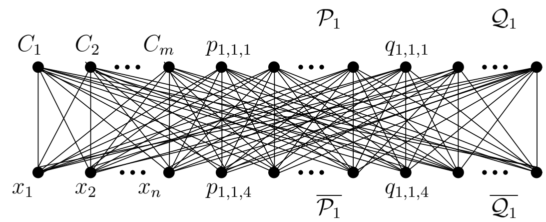

Figure 1: the (complete bipartite) subgraph of G_I induced by vertices of type C, p, q, x.

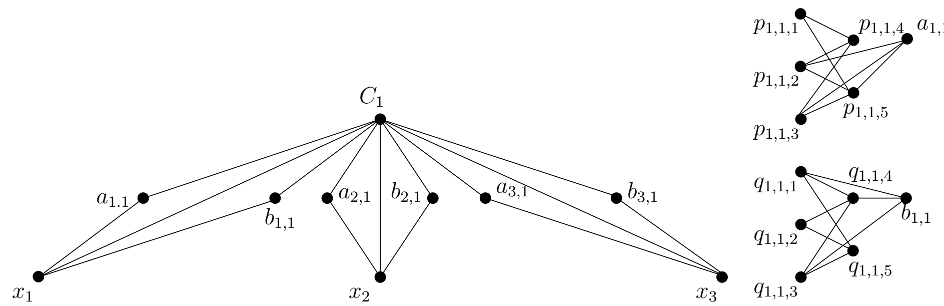

Figure 2: (i) the subgraph of G_I for clause C_1 with ordered variables x_1, x_2, x_3. (ii) how $a_{1,1}$ and $b_{1,1}$ are connected to $\mathcal{P}$ and $\mathcal{Q}$, respectively.

8. We join all x-type vertices to all p-type and q-type vertices with third indices $1, 2, 3$.

9. We join all C-type vertices to all p-type and q-type vertices with third indices $4, 5$.

10. We pre-color all the p-type and q-type vertices according to their third index, so $p_{i,j,\ell}$ will be pre-colored with color $\ell \in \{1, 2, \ldots, 5\}$. Note that we can now in fact replace all lists introduced earlier by $\{1, 2, \ldots, 5\}$, since the shorter lists will be forced by the given pre-coloring.

See Figures 1 and 2 for sketches of the ingredients in the construction of the graph G_I; in Figure 2 we illustrate an example in which C_1 is a clause with ordered variables x_1, x_2, x_3.

We now prove that G_I is P_6-free. In order to obtain a contradiction, suppose that the graph G_I contains an induced subgraph H that is isomorphic to P_6. We first consider the complete bipartite subgraph with bipartition classes $V_1 = \mathcal{C} \cup \mathcal{P}_1 \cup \mathcal{Q}_1$ and $V_2 = \mathcal{X} \cup \overline{\mathcal{P}_1} \cup \overline{\mathcal{Q}_1}$.

Suppose that H contains at least four vertices from $V_1 \cup V_2$. Since P_6 contains no independent set of cardinality four, H then contains at least one vertex from each of V_1 and V_2. This either yields a vertex with degree at least three in H or a cycle on four vertices in H, a contradiction. Hence $|V(H) \cap (V_1 \cup V_2)| \leq 3$. Since $\mathcal{A} \cup \mathcal{B}$ is an independent set, we also have $|V(H) \cap (\mathcal{A} \cup \mathcal{B})| \leq 3$. Since $|V(H)| = 6$, this implies that both inequalities are in fact equalities.

Let $V(H) = \{v_1, v_2, \ldots, v_6\}$ and $E(H) = \{v_1v_2, v_2v_3, v_3v_4, v_4v_5, v_5v_6\}$. By symmetry, we may assume that either $\{v_1, v_3, v_5\} \subset V(H) \cap (\mathcal{A} \cup \mathcal{B})$ or $\{v_1, v_3, v_6\} \subset V(H) \cap (\mathcal{A} \cup \mathcal{B})$. Noting that every vertex of $\mathcal{P} \cup \mathcal{Q}$ has at most one neighbor in $\mathcal{A} \cup \mathcal{B}$, in both cases $v_2 \in \mathcal{C} \cup \mathcal{X}$. We next observe that every vertex of $\mathcal{A} \cup \mathcal{B}$ has precisely one neighbor in $\mathcal{C}$ and precisely one neighbor in $\mathcal{X}$. This implies that we can neither have $\{v_2, v_4\} \subset \mathcal{X}$ nor $\{v_2, v_4\} \subset \mathcal{C}$. Since $v_2v_4 \notin E(G_I)$, we cannot have $v_4 \in \mathcal{C} \cup \mathcal{X}$. This rules out the first case, and in the remaining case we may assume $\{v_1, v_3, v_6\} \subset V(H) \cap (\mathcal{A} \cup \mathcal{B})$, with $v_2 \in \mathcal{C} \cup \mathcal{X}$ and $v_4 \in \mathcal{P} \cup \mathcal{Q}$. Since v_5 is a neighbor of v_4 while v_2 is not a neighbor of v_4, we find that $v_5 \notin \mathcal{C} \cup \mathcal{X}$. Hence $v_5 \in \mathcal{P} \cup \mathcal{Q}$. Because v_4v_5 is an edge and v_4, v_5 both belong to $\mathcal{P} \cup \mathcal{Q}$, one of them belongs to V_1 and the other one to V_2. However, then either v_2v_4 or v_2v_5 is an edge of G_I, because $v_2 \in \mathcal{C} \cup \mathcal{X}$ is either adjacent to all vertices in V_1 or else to all vertices in V_2. This is not possible, and we conclude that G_I is P_6-free.

We claim that I has a truth assignment in which each clause contains at least one true and at least one false literal if and only if the pre-coloring of G_I can be extended to a 5-coloring of G_I.

First suppose that I has a satisfying truth assignment in which each clause contains at least one true and at least one false literal. We use color 4 to color the x-type vertices representing the true literals and color 5 for the false literals. Now consider the lists assigned to the a-type and b-type vertices that come in pairs chosen from $\{\{1,4\},\{2,5\}\}$, $\{\{2,4\},\{3,5\}\}$, $\{\{3,4\},\{1,5\}\}$. If the adjacent x-type vertex has color 4, color 1, 2 or 3 is forced on one of the adjacent a-type or b-type vertices, respectively, while on the other one we can use color 5; similarly, if the adjacent x-type vertex has color 5, color 2, 3 or 1 is forced on one of the adjacent a-type or b-type vertices, respectively, while on the other one we can use color 4. Since precisely two of the three x-type vertices of one clause gadget have the same color, this leaves at least one of the colors 1, 2 and 3 admissible for the C-type vertex representing the clause. By coloring the vertices associated with each clause and variable as described above, a 5-coloring of the pre-colored graph G_I is obtained.

Now suppose that we have a 5-coloring of the graph G_I that respects the pre-coloring. Then each of the x-type vertices has color 4 or 5, and each of the C-type vertices has color 1, 2 or 3. We define a truth assignment that sets a variable to TRUE if the corresponding x-type vertex has color 4, and to FALSE otherwise. Suppose that one of the clauses contains only true literals. Then the three x-type vertices in the corresponding clause gadget of G_I all have color 4. Now consider the lists assigned to the a-type and b-type vertices of this gadget that come in pairs chosen from $\{\{1,4\},\{2,5\}\}$, $\{\{2,4\},\{3,5\}\}$, $\{\{3,4\},\{1,5\}\}$. Since the adjacent x-type vertices all have color 4, colors 1, 2 and 3 are forced on three of the a-type and b-type vertices adjacent to the C-type vertex of this gadget, a contradiction, since the C-type vertex has color 1, 2 or 3. This proves that every clause contains at least one false literal. Analogously, every clause contains at least one true literal. This completes the proof of Theorem 1. □

3. Pre-coloring extension of 3-coloring for P_6-free graphs

In this section we show that the pre-coloring extension version of 3-Coloring is polynomially solvable for P_6-free graphs. A key ingredient in our approach is the following characterization of P_6-free graphs [7]. Here a subgraph H of a graph G is said to be a dominating subgraph of G if every vertex of $V(G) \setminus V(H)$ has a neighbor in H.

Lemma 2 ([7]). *A graph G is P_6-free if and only if each connected induced subgraph of G on more than one vertex contains a dominating induced cycle on six vertices or a dominating (not necessarily induced) complete bipartite subgraph. Moreover, these dominating subgraphs can be obtained in polynomial time.*

Another key ingredient in our approach is the following lemma. Its proof follows from the fact that the decision problem in this case can be modeled and solved as a 2SAT-problem. This approach has been introduced by Edwards [4] and is folklore now, see also [6] and [12].

Lemma 3 ([4]). *Let G be a graph in which every vertex has a list of admissible colors of size at most 2. Then checking if G has a list-coloring is solvable in polynomial time.*

An important subroutine in our algorithm works as follows. Let G be a graph in which every vertex has a list of admissible colors. Let $U \subseteq V(G)$ contain all vertices that have a list consisting of exactly one color. For every vertex $u \in U$ we remove the unique color in its list from the lists of its neighbors. Next we remove u from G. We repeat this process in the remaining graph as long as there exists a vertex with a list of size 1. This process is called *updating* the graph. We note the following.

Lemma 4. *A graph G with lists of admissible colors on its vertices can be updated in polynomial time. If this results in a vertex with an empty list, then G does not have a list-coloring respecting the original lists.*

We are now ready to state the main result of this section. We prove a slightly stronger statement, namely that we can decide in polynomial time whether a P_6-free graph, in which each vertex has a list of admissible colors from the set $\{1, 2, 3\}$, has a coloring respecting these lists; note that a pre-coloring corresponds to lists of size 1 on the pre-colored vertices.

Theorem 5. *The pre-coloring extension version of* 3-Coloring *can be solved in polynomial time for P_6-free graphs.*

Proof. Suppose that our instance graph $G = (V, E)$ is connected (otherwise we treat the components of G separately) and that we have lists of admissible colors from the set $\{1, 2, 3\}$ on each vertex of G. We show how to check in polynomial time whether G allows a 3-coloring respecting these lists.

We first check if G has a dominating C_6. We can do this in $O(|V|^6)$ time by brute force. If so, we can solve our problem as follows. We assume a coloring on the C_6 (respecting the lists) and apply Lemma 4. Since all original lists are subsets of $\{1, 2, 3\}$ and the vertices not in the C_6 are dominated by the C_6, their new lists have size at most 2. This means that we can apply Lemma 3. Because the number of possible 3-colorings of the C_6 is at most 3^6, we can check all of them if necessary.

Now suppose that G does not have a dominating C_6. Then, by Lemma 2, we can construct in polynomial time a dominating complete (not necessarily induced) bipartite graph H of G with bipartition classes A and B. As we cannot assume that H has a bounded size, we must use the special structure of P_6-free graphs in a more advanced way. Below we show how.

Claim 1. In any eligible 3-coloring of G at least one of the sets A, B is monochromatic.

We prove Claim 1 as follows. Suppose that both A and B contain two vertices with different colors. Then either 4 colors must be used on $A \cup B$ or two vertices with the same color are adjacent. Both cases are not possible.

Due to Claim 1 we can proceed as follows. We first assume that A is monochromatic. If this does not result in a 3-coloring of G we repeat the procedure assuming that B is monochromatic.

So, from now on, we assume that all vertices of A are colored with color 1 (possibly after renaming the colors). We apply Lemma 4. Let G' denote the resulting graph after restoring one vertex $a \in A$ and its incident edges back into the graph; we need such a vertex later, in order to make use of the P_6-freeness. So, in G', the list of every vertex except a has size 2 or 3. Let R denote the subset of all vertices of G' with lists of size 3. If $R = \emptyset$, then we are done by Lemma 3.

Suppose that $R \neq \emptyset$. Note that the vertices in R are not adjacent to any vertex of A in the original graph G. Then they must be adjacent to at least one vertex of B, because H is a dominating subgraph of G. Since H is complete bipartite, all vertices of $B \cap V(G')$ are in $N_{G'}(a)$, and we redefine $B := N_{G'}(a)$ for convenience. We observe that every vertex of B has list $\{2, 3\}$, and consequently, R must be a subset of $Q = V(G') \setminus (\{a\} \cup B)$. We observe that B dominates R but not necessarily all vertices of Q. We analyze pairs of adjacent vertices of Q and distinguish a number of cases.

Case 1. *Q contains an edge pq such that p is adjacent to a vertex $b \in B \setminus N_{G'}(q)$ and q is adjacent to a vertex $c \in B \setminus N_{G'}(p)$.*

First note that the set $S = \{a, b, c, p, q\}$ induces a C_5 with possibly an additional edge bc in G'. Let R' be the subset of R consisting of vertices not dominated by S. If $R' = \emptyset$, we check all $O(3^5)$ eligible 3-colorings of S and apply Lemma 3 for every such coloring. Suppose the contrary, i.e., $R'_1 \neq \emptyset$. Let R'_1 consist of all vertices x of R' so that b or c has a neighbor in $B \cap N_{G'}(x)$. Let R'_2 consist of all vertices x of $R' \setminus R'_1$ so that both p and q have a neighbor in $B \cap N_{G'}(x)$. Let $R'_3 = R' \setminus (R'_1 \cup R'_2)$.

Claim 2. Any eligible 3-coloring of S will reduce the list size of every vertex in $R'_1 \cup R'_2$ by at least one color.

We prove Claim 2 as follows. A 3-coloring on S would color b, c, and at least one of p, q with color 2 or 3. Consequently, it will fix the color of every vertex $y \in B$ that is adjacent to b, c or to both p and q, because vertices in B have list $\{2, 3\}$. This has as further consequence that the list of every neighbor of such y will be reduced by at least one color. By definition, $R'_1 \cup R'_2$ only contains such neighbors. This proves Claim 2.

Suppose that $R'_3 = \emptyset$. Then, by Claim 2, we can apply Lemma 3 every time we guess a 3-coloring of S. Suppose that $R'_3 \neq \emptyset$. Because R is dominated by B, every vertex $x \in R'_3$ has a neighbor in B. By definition, there is no edge between $B \cap N_{G'}(x)$ and $\{b, c\}$, and only one of $\{p, q\}$ may have a neighbor in $B \cap N_{G'}(x)$. However, every $y \in B \cap N_{G'}(x)$ must be adjacent to one of p, q; otherwise $xyabpq$ is an induced P_6. This means that we can partition R'_3 into two sets T_1, T_2, where T_1 consists of all vertices of R'_3, whose neighbors in B are adjacent to p and not to q, and T_2 consists of all vertices of R'_3, whose neighbors in B are adjacent to q and not to p. Because $R'_3 \neq \emptyset$, at least one of T_1, T_2 is nonempty, and we analyze two subcases.

Case 1a. $T_1 \neq \emptyset$ and $T_2 \neq \emptyset$.

Let D_i be the set of vertices in B that have a neighbor in T_i for $i = 1, 2$.

Claim 3. Every vertex in D_1 is adjacent to every vertex in D_2.

We prove Claim 3 as follows. Let $b' \in D_1$ and $c' \in D_2$. Suppose that $b'c' \notin E(G')$. By definition, b' has a neighbor $p' \in T_1$, and c' has a neighbor $q' \in T_2$. Then $p'q' \in E(G')$; otherwise $p'b'pqc'q'$ is an induced P_6. However, then $qcab'p'q'$ is an induced P_6. This is not possible and completes the proof of Claim 3.

We now proceed as follows. Every eligible 3-coloring of S colors at least one of p, q with color 2 or 3. As a direct consequence, one of D_1, D_2 becomes monochromatic, because all the vertices in $D_1 \cup D_2 \subseteq B$ have list $\{2, 3\}$. Due to Claim 3, also the other set in $\{D_1, D_2\}$ becomes monochromatic. This means that the list size of every vertex in $R'_3 = T_1 \cup T_2$ is reduced by at least one color. By Claim 2, the same holds for every vertex in $R'_1 \cup R'_2$. Thus we may apply Lemma 3 every time we guess a 3-coloring of S.

Case 1b. $T_1 = \emptyset$ or $T_2 = \emptyset$.

We assume without loss of generality that $T_1 = \emptyset$. If q receives color 2 or 3 in the guessed 3-coloring of S then, as before, the subset of B that consists of vertices adjacent to q becomes monochromatic, and consequently, the list size of every vertex in $R'_3 = T_2$ reduces by at least one color. Recall that the same holds for every vertex in $R'_1 \cup R'_2$ due to Claim 2. This means that we may apply Lemma 3 every time we guess a 3-coloring of S.

Suppose that using color 2 or 3 on q does not result in a 3-coloring of G' in the end. Then we assign color 1 to q and update G' without removing a. We check if we are in Case 1. If so, we repeat the (polynomial time) procedure described in Case 1. If not, then we check whether we are in Case 2 or Case 3 described below; note that these two cases together cover all remaining possibilities.

Case 2. Case 1 does not apply, and Q contains an edge pq such that p is adjacent to a vertex $b \in B \cap N(q)$ and q is adjacent to a vertex $c \in B \setminus N(p)$.

The set $S = \{a, b, c, p, q\}$ now induces a C_5 with an edge bq and possibly an additional edge bc in G'. We define R' as in Case 1. If $R' = \emptyset$, then we are done just as in Case 1. Otherwise we define R'_1, R'_2, R'_3 as in Case 1. Then, in case $R'_3 = \emptyset$, we are done just as in Case 1. Suppose that $R'_3 \neq \emptyset$. We define T_1, T_2 as in Case 1. Suppose that $T_1 \neq \emptyset$. Then there exists a vertex $p' \in T_1$ with a neighbor $b' \in B$ such that b' is adjacent to p and not to q. Then we contradict our assumptions since we are in Case 1 with b' instead of b. Hence $T_1 = \emptyset$, and we can proceed as in Case 1b.

Case 3. Every two adjacent vertices $p, q \in Q$ have the same neighbors in B.

This means that all vertices in each component of Q have the same neighbors in B. We may assign color 1 to every vertex in Q that has color 1 in its list but that does not have a neighbor with color 1 in its list. Afterwards, we update G' (hence a is removed as well). Let $\mathcal{F}$ be the set of components of the resulting graph and consider each component $F \in \mathcal{F}$ separately.

Suppose that F only contains vertices whose lists have size at most 2. Then we can apply Lemma 3. Suppose that F contains at least one vertex x with a list of size 3. Because x is dominated by B, there must exist vertices in B that are adjacent to x and that still have list $\{2, 3\}$, so $B \cap V(F) \neq \emptyset$. Let $y \in B \cap V(F)$.

Claim 4. Assigning color 2 or 3 to y reduces the list of every vertex in $B \cap V(F)$ with at least one color.

We prove Claim 4 as follows. Let $\mathcal{C}$ be the set of components in the subgraph of F induced by $B \cap V(F)$. Let C be the component in $\mathcal{C}$ that contains y. Then C is a bipartite graph, every vertex of which has list $\{2, 3\}$. Hence, fixing a color of y fixes the color of all vertices in C. Let $C' \in \mathcal{C} \setminus \{C\}$ be a component that is connected to C in F by a path P that has all its internal vertices in Q.

First suppose that P has at least two internal vertices x, x'. By the assumption of Case 3, x and x' share the same neighbors in B. Hence, a neighbor in C of the internal vertices of P must receive the same color as a neighbor in C'. Now suppose that P has exactly one internal vertex x. If x has list $\{2, 3\}$, coloring C fixes the color of x and consequently the color of C'. If 1 is a color in the list of x, then by construction x has a neighbor x^* with 1 in its list. By the assumption of Case 3, x and x^* share the same neighbors in C'. Hence, we may add x^* as an internal vertex of P and return to the previous case, in which P has two internal vertices. We repeat these arguments for components in $\mathcal{C}$ connected to C or C' by a path that has all its internal vertices in Q, and so on. This proves Claim 4.

We now proceed as follows. We first consider the case in which y gets color 2. Then, by Claim 4, all colors on B are fixed and we may apply Lemma 3. If this does not lead to a 3-coloring of F, then we give y color 3 and apply Lemma 3 as well.

After checking every $F \in \mathcal{F}$ separately, we have either found (in polynomial time) an eligible 3-coloring of every component of $\mathcal{F}$, or a component in $\mathcal{F}$ that does not allow an eligible 3-coloring. In the first case we have found an eligible 3-coloring of G. In the second case we conclude that there does not exist an eligible 3-coloring of G with monochromatic A (and we need to verify if such a coloring exists with monochromatic B). This competes the proof of Theorem 5. □

4. 6-Coloring for P_7-free graphs

In this section we prove that 6-Coloring is NP-complete for P_7-free graphs. We use a reduction from 3-Satisfiability (3SAT). We consider an arbitrary instance I of 3SAT and define a graph G_I, and next we show that G_I is P_7-free and that G_I is 6-colorable if and only if I has a satisfying truth assignment.

Theorem 6. *The* 6-Coloring *problem is NP-complete for P_7-free graphs.*

Proof. Let I be an arbitrary instance of 3SAT with variables $\{x_1, x_2, \ldots, x_n\}$ and clauses $\{C_1, C_2, \ldots, C_m\}$. We define a graph G_I corresponding to I based on the following construction.

1. We introduce a gadget on 8 new vertices for each of the clauses, as follows. For each clause C_j we introduce a gadget with vertex set:

$\{a_{j,1}, a_{j,2}, a_{j,3}, b_{j,1}, b_{j,2}, b_{j,3}, c_{j,1}, c_{j,2}\}$ and edge set:
$\{a_{j,1}a_{j,2}, a_{j,1}a_{j,3}, a_{j,2}a_{j,3}, a_{j,1}b_{j,1}, a_{j,2}b_{j,2}, a_{j,3}b_{j,3}, b_{j,1}c_{j,1}, b_{j,1}c_{j,2}, b_{j,2}c_{j,1}, b_{j,2}c_{j,2}, b_{j,3}c_{j,1}, b_{j,3}c_{j,2}, c_{j,1}c_{j,2}\}$.
We say that these vertices are of a-type, b-type and c-type. These vertices induce disjoint components in G_I which we will call clause-components.

2. We introduce a gadget on 3 new vertices for each of the variables, as follows. For each variable x_i we introduce a complete graph with vertex set $\{x_i, \overline{x}_i, y_i\}$. We say that these vertices are of x-type (both the x_i and the $\overline{x}_i$ vertices) and of y-type. These vertices induce disjoint triangles in G_I which we will call variable-components.

3. For every clause C_j we fix an arbitrary order of its variables $x_{i_1}, x_{i_2}, x_{i_3}$. For $h = 1, 2, 3$ we add the edges $b_{j,h}x_{i_h}$ or $b_{j,h}\overline{x}_{i_h}$ depending on whether x_{i_h} or $\overline{x}_{i_h}$ is a literal in C, respectively. We also add the edge $b_{j,h}y_{i_h}$ for $h = 1, 2, 3$.

4. We introduce three additional vertices d_1, d_2 and z, and join d_1 and d_2 by an edge. We join all x_i to d_1 by edges, and all $\overline{x}_i$ to d_2.

5. We join z to all vertices of y-type, a-type, and c-type, and to d_1 and d_2.

6. We join all the x-type vertices and y-type vertices to all the a-type and c-type vertices.

7. Finally, we join d_1 and d_2 to all the a-type, b-type and c-type vertices.

See Figures 3-5 for an example of a graph G_I. In this example, C_1 is a clause with literals $x_1, \overline{x}_2$, and x_3.

We now prove that G_I is P_7-free. In order to obtain a contradiction, suppose that the graph G_I contains an induced subgraph H that is isomorphic to P_7. We observe that two distinct variable-components do not share a b-type vertex as a common neighbor.

First suppose that H contains both d_1 and d_2. Then, since $d_1d_2 \in E(H)$ and H has no cycles and no vertices with degree more than 2, H does neither

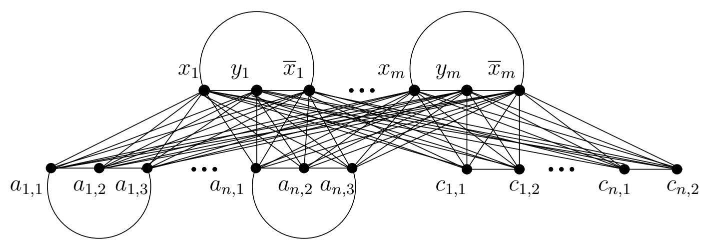

Figure 3: the subgraph of G_I induced by vertices of type a, c, x, y.

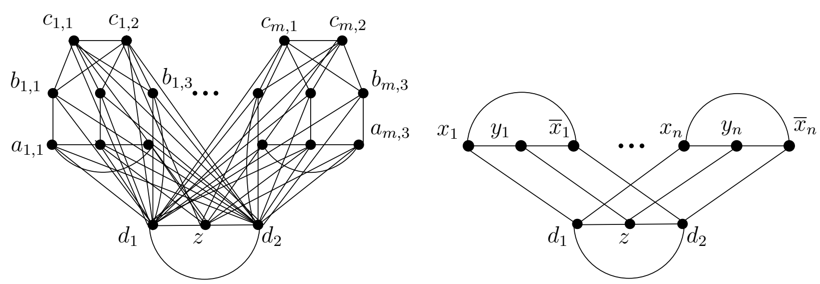

Figure 4: (i) the subgraph of G_I induced by d_1, d_2, z and vertices of type a, b, c. (ii) the subgraph of G_I induced by d_1, d_2, z and vertices of type x, y.

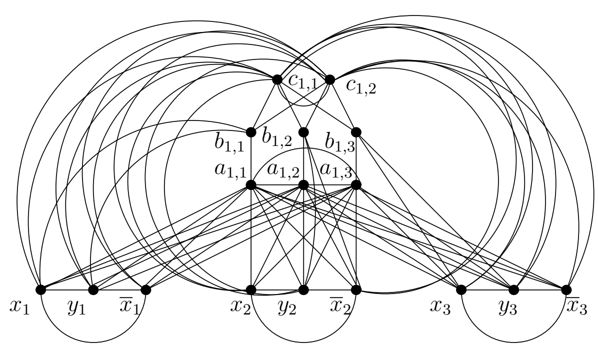

Figure 5: the subgraph of G_I for clause C_1 with ordered literals $x_1, \overline{x}_2, x_3$.

contain z nor any vertices of a-type, b-type or c-type, and at most two x-type vertices (with one positive and one negative literal in the case it contains two). The longest path we can obtain is a P_6, a contradiction. We conclude that H contains at most one of the vertices d_1 and d_2.

Next suppose that H contains both d_1 and z. Then, since $d_1z \in E(H)$ and H has no cycles and no vertices with degree more than 2, H does neither contain d_2 nor any vertices of a-type or c-type, and at most one b-type and at most one y-type vertex. Since $|V(H)| = 7$, this implies that H contains at least three vertices of x-type. Since d_1 is adjacent to all x_i and to z, H contains at most one x_i. So H contains at least two vertices $\overline{x}_j$ and $\overline{x}_k$. In H, $\overline{x}_j$ can only have neighbors in $\{x_j, y_j, b\}$ where b is the only possible b-type vertex in H. Recall that b can be adjacent to at most one of the variable-components. Since H contains at most one y-type vertex, at most one b-type vertex, and at most one x_i, this means that there cannot be three distinct vertices $\overline{x}_j$, $\overline{x}_k$ and $\overline{x}_r$ in H. So we conclude that H contains precisely one y-type vertex, one b-type vertex, one x_i and two distinct $\overline{x}_j$ and $\overline{x}_k$ (where possibly $i = j$ or $i = k$). But now d_1 has degree 3 in H, a contradiction. We conclude that H contains at most one of the vertices d_1 and z. By symmetry, H contains at most one of the vertices d_2 and z, and hence at most one of d_1, d_2 and z.

Next we are going to show that H contains at most two b-type vertices. To the contrary, first suppose that H contains at least four b-type vertices. Because the b-type vertices form an independent set, H contains exactly four of them, and the other three vertices of H also form an independent set. This implies that the other three are either of a-type and c-type or of x-type and y-type. The latter cannot occur, because two variable-components do not share a b-type vertex as a common neighbor. Hence, all vertices of H are of a-type, b-type and c-type. This implies that H is a subgraph of one clause-component, a contradiction. Next suppose that H contains precisely three b-type vertices. If $z \notin V(H)$, then, since all the x-type and y-type vertices are joined to all the a-type and c-type vertices, the other four vertices are either of a-type and c-type or of x-type and y-type. Again the former cannot occur since H is not a subgraph of one clause-component and the latter cannot occur, because two variable-components do not share a b-type vertex as a common neighbor. So we conclude that $z \in V(H)$. Then z and the three b-type vertices form an independent set in H, and the other three vertices also form an independent set in H. Just as in the case when H contains four b-type vertices, the only possibility is that these three other vertices are of

a-type and c-type. But since z is adjacent to all a-type and c-type vertices, we obtain a contradiction. We conclude that H contains at most two b-type vertices.

Together with the earlier conclusion that H contains at most one of d_1, d_2 and z, this implies that H contains at least four vertices from the set of all a-type, c-type, x-type and y-type vertices. Due to the adjacencies between these vertices and the fact that H has neither cycles nor vertices with degree more than 2, we find that all four are either of a-type and c-type or of x-type and y-type. In the former case z, d_1 and d_2 are no vertices of H. But then all vertices of H are of a-type, b-type and c-type, so H is contained in one clause-component, a contradiction. In the latter case we know that H contains vertices from at least two variable-components. Since these components have no b-type vertex as a common neighbor, they are connected through one of d_1, d_2 and z. Hence H contains vertices of precisely two of these components, implying that H contains precisely two b-type vertices. It is not difficult to check that the b-type vertices have degree 1 in H. This in turn implies that d_1 and d_2 are no vertices of H. Hence $z \in V(H)$ and z has two y-type neighbors in H. The other two vertices of H are of x-type and each of these x_i or $\overline{x}_i$ is adjacent to a b-type vertex and to y_i in H. But then this y_i and this b-type vertex are adjacent, our final contradiction. We conclude that G_I is P_7-free.

We claim that I has a satisfying truth assignment if and only if G_I is 6-colorable.

First suppose that I has a satisfying truth assignment. We use color 4 or 5 to color the x-type vertices representing the true literals and color 6 for the false literals. In particular, if x_i is true, we use color 5 to color the corresponding vertex; if $\overline{x}_i$ is true, we use color 4 to color the corresponding vertex. We use color 4 or color 5 to color the y-type vertices, depending on the colors we used for the x-type vertices. This yields a proper 3-coloring of all the variable-components with colors 4, 5 and 6. We extend this 3-coloring by using color 6 for z and colors 4 and 5 for d_1 and d_2, respectively. For the true literals of C_j, we can use color 6 for the corresponding b-type vertex, and color 1 for the other b-type vertices of the corresponding clause-component. Since each clause contains at least one true literal, we note that we do not use color 1 for all three b-type vertices of the clause-components. We can now use colors 2 and 3 for the c-type vertices and colors 1, 2 and 3 for the a-type vertices to extend the coloring to a 6-coloring of G_I.

Now suppose that we have a 6-coloring of G_I with colors $\{1, 2, \ldots, 6\}$. We assume that vertex z has color 6, that d_2 has color 5, and that d_1 has color 4. This implies that all a-type and c-type vertices have colors from $\{1, 2, 3\}$, and all three colors are used on the a-type vertices, and two of the three on the c-type vertices. This implies that all x-type vertices have colors from $\{4, 5, 6\}$ and all y-type vertices from $\{4, 5\}$. Without loss of generality, suppose that in one of the clause-components, the c-type vertices have colors 2 and 3. Then the b-type vertices in this clause-component can only have colors from $\{1, 6\}$. If all of them have color 1, we obtain a contradiction with the coloring of the three a-type vertices in this component. So at least one of the b-type vertices has color 6. The same holds if we had assumed another choice for the two colors used on the c-type vertices. This implies that the corresponding x-type vertex has color 4 or 5. We define a truth assignment that sets a literal to FALSE if the corresponding x-type vertex has color 6, and to TRUE otherwise. In this way we obtain a satisfying truth assignment for I. This completes the proof of Theorem 6. □

5. Conclusions and open problems

We proved that the pre-coloring extension version of 5-Coloring remains NP-complete for P_6-free graphs. Hoàng et al. [6] showed that the pre-coloring extension version of ℓ-Coloring is polynomially solvable on P_5-free graphs for any fixed ℓ. In contrast, determining the chromatic number is NP-hard on P_5-free graphs [9]. We showed that the pre-coloring extension version of 3-Coloring is polynomially solvable for P_6-free graphs. Finally, we proved that 6-Coloring is NP-complete for P_7-free graphs. Recently, Broersma et al. [2] showed that 4-Coloring is NP-complete for P_8-free graphs and that the pre-coloring extension version of 4-Coloring is NP-complete for P_7-free graphs. All these results together lead to the following table that shows the current status of ℓ-Coloring and its extension version for P_k-free graphs. This table also shows which cases are still open. We finish this paper with two other open problems on 3-Coloring that have intrigued many researchers: the complexity of 3-Coloring is open for graphs with diameter 2, and for graphs with diameter 3.

References

[1] J.A. Bondy and U.S.R. Murty, Graph Theory, Springer Graduate Texts in Mathematics 244, Springer, Berlin, 2008.

P_k-free	$\ell \rightarrow$ 3	3*	4	4*	5	5*	≥ 6	$\geq 6^*$
$k \leq 5$	P	P	P	P	P	P	P	P
$k = 6$	P	P	?	?	?	NP-c	?	NP-c
$k = 7$	?	?	?	NP-c	?	NP-c	NP-c	NP-c
$k = 8$	?	?	NP-c	NP-c	NP-c	NP-c	NP-c	NP-c
$k \geq 9$	?	?	NP-c	NP-c	NP-c	NP-c	NP-c	NP-c

Table 1: The complexity of ℓ-Coloring and its pre-coloring extension version (marked by *) on P_k-free graphs for fixed combinations of k and ℓ.

[2] H.J. Broersma, P.A. Golovach, D. Paulusma and J. Song, Updating the complexity status of coloring graphs without a fixed induced linear forest, Theoretical Computer Science, in press.

[3] D. Bruce, C.T. Hoàng, and J. Sawada, A certifying algorithm for 3-colorability of P_5-free graphs, in: Y. Dong, D.-Z. Du and O. H. Ibarra (Eds.), Proceedings of the 20th International Symposium on Algorithms and Computation (ISAAC 2009), Lecture Notes in Computer Science 5878, Springer, Berlin, 2009, pp. 594–604.

[4] K. Edwards, The complexity of coloring problems on dense graphs. Theoretical Computer Science 43 (1986) 337–343.

[5] M.R. Garey and D.S. Johnson, Computers and Intractability: A Guide to the Theory of NP-Completeness, Freeman, San Francisco, 1979.

[6] C.T. Hoàng, M. Kamiński, V. Lozin, J. Sawada, and X. Shu, Deciding k-colorability of P_5-free graphs in polynomial time, Algorithmica 57 (2010) 74–81.

[7] P. van 't Hof and D. Paulusma, A new characterization of P_6-free graphs, Discrete Applied Mathematics 158 (2010) 731–740.

[8] M. Hujter and Zs. Tuza, Precoloring extension II: graph classes related to bipartite graphs, Acta Mathematica Universitatis Comenianae 62 (1993) 1–11.

[9] D. Král, J. Kratochvíl, Zs. Tuza, and G.J. Woeginger, Complexity of coloring graphs without forbidden induced subgraphs, in: A. Brandstädt

and V. B. Le (Eds.), Proceedings of the 27th International Workshop on Graph-Theoretic Concepts in Computer Science (WG 2001), Lecture Notes in Computer Science 2204, Springer, Berlin, 2001, pp. 254–262.

[10] J. Kratochvíl, Precoloring extension with fixed color bound, Acta Mathematica Universitatis Comenianae 62 (1993) 139–153.

[11] V.B. Le, B. Randerath and I. Schiermeyer, On the complexity of 4-coloring graphs without long induced paths, Theoretical Computer Science 389 (2007) 330–335.

[12] B. Randerath and I. Schiermeyer, 3-Colorability $\in$ P for P_6-free graphs, Discrete Applied Mathematics 136 (2004) 299–313.

[13] B. Randerath and I. Schiermeyer, Vertex colouring and forbidden subgraphs - a survey, Graphs and Combinatorics 20 (2004) 1–40.

[14] A. Tucker, A reduction procedure for coloring perfect K_4-free graphs, Journal of Combinatorial Theory, Series B 43 (1987) 151–172.

[15] Zs. Tuza, Graph colorings with local restrictions - a survey, Discussiones Mathematicae Graph Theory 17 (1997) 161–228.

[16] G.J. Woeginger and J. Sgall, The complexity of coloring graphs without long induced paths, Acta Cybernetica 15 (2001)107–117.