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b-coloring of tight graphs

Frédéric Havet — Cláudia Linhares Sales — Leonardo Sampaio

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Domaine 2

A large blue rectangle occupies the lower half of the page. Overlaid on it is the text 'Rapport de recherche' in a white, serif font. The 'R' is significantly larger and more stylized than the other letters. A horizontal white brushstroke underline is positioned below the text.

Rapport
de recherche

b-coloring of tight graphs *

Frédéric Havet [†], Cláudia Linhares Sales [‡], Leonardo Sampaio [§]

Thème : Algorithmique, programmation, logiciels et architectures
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Abstract: A coloring c of a graph $G = (V, E)$ is a *b-coloring* if in every color class there is a vertex colored i whose neighborhood intersects every other color classes. The *b-chromatic number* of G , denoted $\chi_b(G)$, is the greatest integer k such that G admits a *b-coloring* with k colors. A graph G is *tight* if it has exactly $m(G)$ vertices of degree $m(G) - 1$, where $m(G)$ is the largest integer m such that G has at least m vertices of degree at least $m - 1$. Determining the *b-chromatic number* of a tight graph G is NP-hard even for a connected bipartite graph [15]. In this paper we show that it is also NP-hard for a tight chordal graph. We also show that the *b-chromatic number* of a split graph can be computed is polynomial. Then we define the *b-closure* and the partial *b-closure* of a tight graph, and use these concepts to give a characterization of tight graphs whose *b-chromatic number* is equal to $m(G)$. This characterization is used to develop polynomial time algorithms for deciding whether $\chi_b(G) = m(G)$, for tight graphs that are complement of bipartite graphs, P_4 -sparse and block graphs. We generalize the concept of pivoted tree introduced by Irving and Manlove [12] and show its relation with the *b-chromatic number* of tight graphs.

Key-words: graph coloring, *b-coloring*, precoloring extension, tight graphs

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***b*-coloration des graphes étriqués**

Résumé : Une k -coloration c d'un graphe G est une b -coloration si dans toute classe de couleur, il y a un sommet dont le voisinage intersecte toutes les autres classes de couleurs. The *nombre b -chromatique* d'un graphe est le plus grand entier k tel que G admette une b -coloration avec k couleurs. Un graphe est *étriqué* s'il a exactement $m(G)$ sommet de degré $m(G) - 1$, avec $m(G)$ le plus grand entier m tel que G ait au moins m sommets de degré au moins $m - 1$. Calculer le nombre b -chromatique d'un graphe étriqué est NP-dur même pour les graphes connexes bipartis [15]. Dans ce rapport, nous montrons que c'est également NP-difficile pour les graphes étriqués cordaux. Nous montrons également que le nombre b -chromatique d'un graphe split peut être calculé en temps polynomial. Ensuite nous définissons la b -clôture et la b -clôture partielle d'un graphe étriqué. Nous utilisons ces deux concepts pour concevoir des algorithmes en temps polynomial pour décider si $\chi_b(G) = m(G)$ pour les graphes étriqués qui sont bipartis, P_4 -sparse ou des block-graphes. Nous généralisons également le concept d'arbre pivoté de Irving and Manlove [12] et montrons sa relation avec le nombre b -chromatique des graphes étriqués.

Mots-clés : coloration de graphe, b -coloration, extension de précoloration, graphes étriqués

1 Introduction

A k -coloring of a graph $G = (V, E)$ is a function $c : V \rightarrow \{1, 2, \dots, k\}$, such that $c(u) \neq c(v)$ for all $uv \in E(G)$. The color class c_i is the subset of vertices of G that are assigned to color i . The chromatic number of G , denoted $\chi(G)$, is the least integer k such that G admits a k -coloring. Given a k -coloring c , a vertex v is a b -vertex of color i , if $c(v) = i$ and v has at least one neighbor in every color class c_j , $j \neq i$. A coloring of G is a b -coloring if every color class has a b -vertex. The b -chromatic number of a graph G , denoted $\chi_b(G)$, is the largest integer k such that G admits a b -coloring with k colors. These concepts were first defined in [12]. In that paper, Irving and Manlove proved that the problem of determining the b -chromatic number of a graph is NP-Hard. In fact, it was shown in [15] that deciding whether a graph admits a b -coloring with a given number of colors is an NP-complete problem, even for connected bipartite graphs. The following upper bound for the b -chromatic number of a graph, presented in [12], has been proved to be very useful. If G admits a b -coloring with m colors, then G must have at least m vertices with degree at least $m - 1$ (since each color class has one b -vertex). The m -degree of a graph G , denoted by $m(G)$, is the largest integer m such that G has m vertices of degree at least $m - 1$. It is easy to see that $\chi_b(G) \leq m(G)$ for every graph G . A vertex of G with degree at least $m(G)$ is called a *dense* vertex. The preceding upper bound leads us to the definition of a class of graphs which are tight with respect to the number and degree of their dense vertices:

Definition 1 (tight graph). A graph G is *tight* if it has exactly $m(G)$ dense vertices, each of which has degree $m(G) - 1$.

In this paper, we mainly investigate the following decision problem:

TIGHT b -CHROMATIC PROBLEM

Instance: A tight graph G .

Question: Does $\chi_b(G)$ equals $m(G)$?

A direct consequence of the NP-completeness result shown in [15] is the following:

Theorem 2. *The TIGHT b -CHROMATIC PROBLEM is NP-complete for connected bipartite graphs.*

For any positive k , P_k denotes a path with k vertices. A graph G is P_4 -sparse if every set of five vertices of G induces at most one P_4 . Bonomo et al. [1] proved that the b -chromatic number of P_4 -sparse graphs can be determined in polynomial time. They asked if this result could be extended to *distance-hereditary graphs*, that are graphs in which every induced path is a shortest path. We answer in the negative to this question by showing the following stronger result (Theorem 3). *The TIGHT b -CHROMATIC PROBLEM is NP-complete for chordal distance-hereditary graphs.* We recall that a graph is *chordal* if it does not contain any induced cycle of size greater than 3.

The proof of our NP-completeness result is a reduction from 3-EDGE-COLORABILITY. We reduce an instance of this problem to a graph which is slightly more than a *split graph*, i.e. a graph whose vertex set may be partitioned into a clique and an independent set. Hence a natural question is to ask about the complexity of finding the b -chromatic number of a given split graph. We show in Theorem 5 that it can be solved in polynomial time.

In Section 3, we introduce the b -closure G^* of a graph G . We show that for a tight graph G , $\chi_b(G) = m(G)$ if and only if $\chi(G^*) = m(G)$. Hence if one can determine the chromatic number of the closure in polynomial time, one can also solve the TIGHT b -CHROMATIC PROBLEM in polynomial time. We show that it is the case for (tight) complement of bipartite graphs. Indeed, we prove that the closures of such graphs are also complements of bipartite graphs and the chromatic number of the complement of a bipartite graph can be determined in polynomial time. This was unknown since the characterization of complements of bipartite graphs with $\chi_b(G) = k$ given by [13] does not lead to a polynomial algorithm for determining their b -chromatic number.

Moreover, we introduce the definition of pivoted tight graph and use this definition to give a sufficient condition for a tight graph to satisfy $\chi_b(G) < m(G)$.

The method of computing the *b*-closure of a graph and then the chromatic number of it does not yield polynomial-time algorithms to solve the TIGHT *b*-CHROMATIC PROBLEM for all classes of tight graphs. However, for some of them, we show in Section 4, that the TIGHT *b*-CHROMATIC PROBLEM may be solved in polynomial time using a slight modification of the closure, the *partial closure*. It is the case for block graphs and P_4 -sparse graphs. It is already known that deciding if $\chi_b(G) = m(G)$ is polynomial time solvable for P_4 -sparse graphs [1]. However, our linear-time algorithm for tight P_4 -sparse graphs is faster than the $O(|V|^3)$ algorithm of [1]. It is also interesting to see how our general method can be used to solve these problems.

2 Chordal graphs

Theorem 3. *The TIGHT *b*-CHROMATIC PROBLEM is NP-complete for chordal distance-hereditary graphs.*

Proof. The problem belongs to NP since a *b*-coloring with $m(G)$ colors is a certificate. To show that it is also NP-complete, we present a reduction from 3-EDGE-COLORABILITY of 3-regular graphs, which is known to be NP-complete [10]. Let G be a 3-regular graph with n vertices. Set $V(G) = \{v_1, v_2, \dots, v_n\}$ and $E(G) = \{e_1, \dots, e_m\}$. Let I be the vertex-edge incidence graph of G , that is the bipartite graph with vertex set $V(I) = V(G) \cup E(G)$ in which an edge of G is adjacent to its two end-vertices. We construct from I a new graph H as follows. First, we add an edge between every pair of vertices in $V(G)$ and then, we add three disjoint copies of $K_{1,n+2}$. One can easily see that $d_H(v) = n - 1 + 3 = n + 2$, for $v \in V(G)$, and that $d_H(u) = 2$, for $u \in E(G)$. Moreover, each copy of $K_{1,n+2}$ has exactly one vertex with degree equal to $n + 2$. Consequently, $m(H) = n + 3$ and H is tight. In H , $V(G)$ is a clique and $E(G)$ is an independent set, so $H[A \cup B]$ is a split graph, and so it is chordal. As the disjoint copies of $K_{1,n+2}$ are themselves chordal graphs, we get that the entire graph H is chordal. One can easily check that H is also distance-hereditary. We now prove that G admits a 3-edge-coloring if and only if $\chi_b(H) = m(H) = n + 3$.

Let c be a 3-edge-coloring of $E(G)$ that uses colors $\{1, 2, 3\}$. We shall construct a *b*-coloring c' of H with $n + 2$ colors. Let $c'(u) = c(u)$, for $u \in E(G)$, and $c'(v_i) = i + 3$, for $1 \leq i \leq n$. Note that in this partial coloring, the vertices in $V(G)$ are *b*-vertices of their respective colors. To obtain the remaining *b*-vertices, one just have to appropriately color the copies of $K_{1,n+2}$, which can be easily done. Then, c' is a *b*-coloring of H with $m(H) = n + 3$ colors.

Now, let c' be a *b*-coloring of H that uses $n + 3$ colors. Since $V(G)$ is a clique, we may assume that $c'(v_i) = i + 3$, for $1 \leq i \leq n$. Since there are only $n + 3$ vertices of degree $n + 2$ in H , each vertex in $V(G)$ is an *b*-vertex. But then, since every vertex in $V(G)$ has degree exactly $n + 2$ in H , all its neighbors must have distinct colors. As a consequence, since no vertex in $V(G)$ is colored with one of the colors in $\{1, 2, 3\}$, for every vertex in $V(G)$, its 3 neighbours in $E(G)$ are colored with distinct colors in $\{1, 2, 3\}$. This implies that G admits a 3-edge-coloring of G , and completes the proof. \square

Remark 4. A graph $G = (V, E)$ is P_4 -laden [5] (resp. *extended P_4 -laden*) if for every set $S \subseteq V$ of six vertices, the subgraph induced by S contains at most one induced P_4 or is a split graph (resp. a *pseudo-split graph*, i.e. a $\{C_4, K_2\}$ -free graph). By definition, every P_4 -laden graph is extended P_4 -laden. One can check that the graph in the reduction of Theorem 3 is P_4 -laden, so the TIGHT *b*-CHROMATIC PROBLEM is NP-complete for P_4 -laden graphs.

The class of the extended P_4 -laden graphs contains many graph classes with few induced P_4 's. In particular, it contains the class of P_4 -tidy graphs [4] which in turn contains the ones of P_4 -lite [7], P_4 -extendible [6] and P_4 -reducible graphs [8]. A graph is P_4 -tidy if for every set A inducing a P_4 there is at most one vertex x such that the subgraph induced by $A \cup \{x\}$ has at most one induced P_4 . Bonomo, Koch, and Velasquez [2] proved that the *b*-chromatic number of a P_4 -tidy graph can be determined in polynomial time, thus extending the result in [1].

The three copies of $K_{1,n+2}$ play an important role in the reduction of the proof of Theorem 3, since one can show the following

Theorem 5. *If G is a split graph then $\chi_b(G) = m(G)$. Hence, the b -chromatic number of a split graph can be determined in polynomial time.*

Proof. Let G be a split graph and (K, S) a partition of $V(G)$ with K a clique and S an independent set such that $|K|$ is maximum. Every vertex in K has degree at least $|K| - 1$ and every vertex s in S has degree at most $|K| - 1$ otherwise $(K \cup \{s\}, S \setminus \{s\})$ would contradict the maximality of $|K|$. Hence $m(G) = |K|$.

Coloring the vertices in K with $|K|$ distinct colors and then extend it greedily to the vertices of S (This is possible since every vertex in S has degree smaller than $|K|$.) gives a b -colouring of G with $m(G) = |K|$ colours. \square

3 b -closure

Definition 6 (*b*-closure). Let G be a tight graph. The *b*-closure of G , denoted by G^* , is the graph with vertex set $V(G^*) = V(G)$ and edge set $E(G^*) = E(G) \cup \{uv \mid u \text{ and } v \text{ are non-adjacent dense vertices}\} \cup \{uv \mid u \text{ and } v \text{ are vertices with a common dense neighbour}\}$.

The next theorem proves the relation, for a tight graph G , between the parameters $\chi_b(G)$ and $\chi(G^*)$:

Lemma 7. *Let G be a tight graph. Then $\chi_b(G) = m(G)$ if and only if $\chi(G^*) = m(G)$.*

Proof. Set $m = m(G)$. Suppose that $\chi_b(G) = m$, and let c be a b -coloring of G with m colors. It is easy to see that the m dense vertices form a clique in G^* and so $\chi(G^*) \geq m$. Let us show that c is a proper coloring for G^* . Let $uv \notin E$ be such that $uv \in E(G^*)$. If both u and v are dense, as there are exactly m dense vertices in G , they must have distinct colors in c . Now, suppose that u or v is not a dense vertex. By the definition of G^* , u and v have a common dense neighbor, say d , in G . Since all dense vertices of G have degree $m - 1$ and c is a b -coloring, u and v must have been assigned distinct colors in c . Hence, $\chi(G^*) = m$.

Conversely, let c' be a proper coloring of G^* with m colors. In this case, since $E(G) \subseteq E(G^*)$, c' is also a proper coloring of G . It only remains to show that every color of c' has a b -vertex. As the dense vertices of G form a clique in G^* , they have distinct colors in c' . Moreover, for a dense vertex d of G , we have that $N_{G^*}(d)$ is a clique. As a consequence, d is a b -vertex. Therefore, $\chi_b(G) = m$. \square

Since $\omega(G^*) > m$ implies that $\chi(G^*) > m$, it follows:

Corollary 8. *Let G be a tight graph. If $\chi_b(G) = m(G)$, then $\omega(G^*) = \chi(G^*) = m(G)$.*

3.1 Complement of bipartite graphs

By Lemma 7, it is interesting to consider the b -closure of a tight graph G if the chromatic number of its closure can be determined in polynomial time. Indeed if so, one can decide in polynomial time if $\chi_b(G) = m(G)$. We now show that it is the case if G is the complement of bipartite graph.

Lemma 9. *The b -closure of the complement of a bipartite graph is a complement of a bipartite graph.*

Proof. Let G be a tight complement of a bipartite graph. Let $V(G) = X \cup Y$ where X and Y are two disjoint cliques in G . As $V(G^*) = V(G)$, and since $E(G) \subseteq E(G^*)$, the sets X and Y are cliques in G^* . So they also form a partition of $V(G^*)$ into two cliques. \square

Computing the chromatic number of the complement G of a bipartite graph \overline{G} is equivalent to compute the maximum size of a matching in this bipartite graph. Hence it can be done in $O(\sqrt{|V(G)|} \cdot |E(\overline{G})|)$ by the algorithm of Hopcroft and Karp [11] and in $O(|V(G)|^{2.376})$ using an approach based on the fast matrix multiplication algorithm [17].

Corollary 10. *Let G be a tight complement of bipartite graph. It can be decided in $O(\max\{\sqrt{|V(G)|} \cdot |E(\overline{G})|, |V(G)|^{2.376}\})$ if $\chi_b(G) = m(G)$.*

3.2 Pivoted graphs

In the study of the *b*-chromatic number of trees, Irving and Manlove [12] introduced the notion of a *pivoted tree*, and showed that a tree T satisfies $\chi_b(T) < m(T)$ if and only if it is pivoted. We generalize this notion and show how our generalization is related to the *b*-chromatic number of tight graphs.

Definition 11 (Pivoted Graph). Let G be a tight graph. We say that G is *pivoted* if there is a set N of non-dense vertices, with $|N| = k$, and a set of dense vertices D , with $|D| = m(G) - k + 1$, satisfying:

1. For every pair $u, v \in N$, u is adjacent to v , or there is a dense vertex w that is adjacent to both u and v .
2. For every pair $u \in N, d \in D$, either u is adjacent to d or u and d are both adjacent to a dense vertex w (not necessarily in D).

Theorem 12. *Let G be a tight graph. Then G is a pivoted graph if and only if $\omega(G^*) > m(G)$.*

Proof. First, assume that G is a pivoted graph. Then Definitions 6 and 11 immediately imply that $N \cup D$ is a clique of size $m + 1$ in G^* .

Reciprocally, assume that $\omega(G^*) > m$. Let $S \subseteq V(G^*)$ be a clique of size $m + 1$ in G^* . Let $N = \{v \in S \mid v \text{ is not dense in } G\}$ and $D = \{v \in S \mid v \text{ is dense in } G\}$. Let $u, v \in S$. If $u, v \in D$, there is nothing to show, since Definition 11 imposes no restrictions between dense vertices in G . If $u \in N, v \in D \cup N$, we have that either $uv \in E(G)$, or $ud, vd \in E(G)$, for a dense vertex $d \in V(G)$. So, it is easy to see that the sets N and D satisfy the requirements of Definition 11. \square

Lemma 7 and Theorem 12 have the following corollary.

Corollary 13. *Let G be a tight graph. If G is a pivoted graph, then $\chi_b(G) < m(G)$.*

Proof. As G is pivoted, Theorem 12 implies that $\omega(G^*) > m(G)$, and therefore $\chi(G^*) > m(G)$. Then, by Lemma 7, $\chi_b(G) < m(G)$. \square

There are graphs satisfying $\chi(G^*) > m(G)$ but not $\omega(G^*) > m(G)$. Figure 1 shows a chordal non-pivoted graph G with exactly $m(G) = 7$ dense vertices, each of degree 6, such that $\chi_b(G) < m(G)$.

In contrast to what happens with pivoted graphs, where a clique of size greater than m is formed in their *b*-closures, the graph of Figure 1 has clique number 7, but its *b*-closure produces an odd hole (by the five non-dense vertices in the bigger component) which causes $\chi(G^*) > 7$.

4 Partial *b*-closure

Definition 14 (partial *b*-closure). Let G be a tight graph. The *partial b-closure* of G , denoted G_p^* , is the graph with vertex set $V(G^*) = V(G)$ and edge set $E(G^*) = E(G) \cup \{uv \mid u \text{ and } v \text{ are vertices with a common dense neighbour}\}$.

Lemma 15. *Let G_p^* be the partial *b*-closure of a graph G , and let D be the set of $m(G)$ dense vertices of G . Then $\chi_b(G) = m(G)$ if and only if G_p^* admits a $m(G)$ -coloring where all the vertices in D have distinct colors.*

Proof. The proof is similar to the one of Lemma 7. In this case, since we do not add edges between all the pairs of dense vertices in G_p^* , we need the requirement that the $m(G)$ -colouring of G_p^* is such that all dense vertices have distinct colours. \square

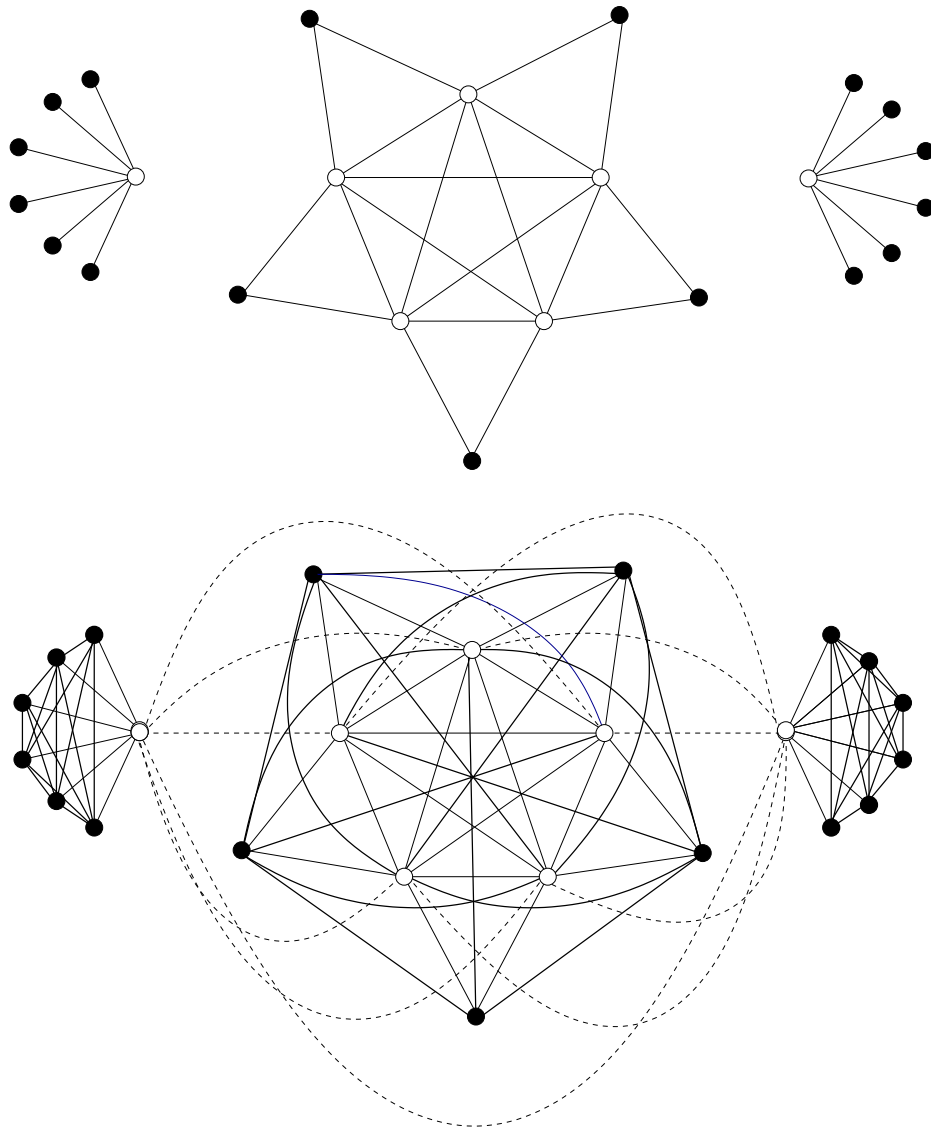


Figure 1: A non-pivoted chordal graph, satisfying $\chi_b(G) < m(G)$, and its b -closure G^* , satisfying $\chi(G^*) > \omega(G^*) = m(G)$ (the new edges between the dense vertices are dashed).

By Lemma 15, one can decide in polynomial time if $\chi_b(G) = m$ wherever it can be decided in polynomial time if the constrained coloring of its partial closure G_p^* exists. In particular, it is the case if the precoloring extension problem can be decided in polynomial time for G . We show that this is the case for block graphs and P_4 -sparse graphs.

4.1 Block graphs

The results presented in this subsection were obtained in cooperation with Ana Silva. A graph $G = (V, E)$ is a *block graph* if every of its blocks (maximal 2-connected subgraphs) is a complete graph. For an example, see Figure 2.

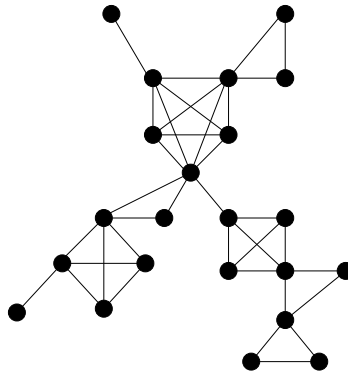


Figure 2: A block graph.

Lemma 16. *The partial b -closure of a block graph is chordal.*

Proof. By contradiction, assume that the partial b -closure G_p^* of a block graph G is not chordal. Then it has an induced cycle $C = (v_1, v_2, \dots, v_k)$ of length $k \geq 4$. For every edge $v_i v_{i+1}$ of C (indices must be taken modulo k) either $v_i v_{i+1} \in E(G)$ or there is a dense vertex $w_i \in V(G)$ such that $v_i w_i, w_i v_{i+1} \in E(G)$. In the latter case, the vertex w_i is adjacent to no v_j for $j \notin \{i, i + 1\}$ in G , otherwise both $v_j v_i$ and $v_j v_{i+1}$ would be edges of G_p^* and C would not be induced. Furthermore, this implies that all the existing w_i 's are distinct. Let C' be the cycle obtained from C by replacing each edge $v_i v_{i+1}$ by $v_i w_i v_{i+1}$ whenever $v_i v_{i+1} \notin E(G)$. Observe that C' is a cycle of G .

But, since G is a block graph, the vertices of any cycle (in particular, C') form a clique in G and thus also in G_p^* . Hence the vertices of C form a clique in G_p^* , a contradiction. \square

Marx [16] showed that the precoloring extension problem when all the C colours are used at most once is solvable in time $O(C \cdot |V(G)|^3)$ for a chordal graph G . Hence,

Corollary 17. *the TIGHT b -CHROMATIC PROBLEM can be decided in time $O(m(G)|V(G)|^3)$ for tight block graphs.*

Remark 18. A tree is a block graph, so using the partial closure method the TIGHT b -CHROMATIC PROBLEM for tight trees can be solved in time $O(m(G)|V(G)|^3)$. However, Irving and Manlove [12] gave a linear time algorithm to compute the b -chromatic number of any tree. Hence the TIGHT b -CHROMATIC PROBLEM can be solved in linear time for trees.

4.2 P_4 -sparse graphs

Lemma 19. *The partial b -closure of a P_4 -sparse graph is P_4 -sparse.*

Proof. Let G be a P_4 -sparse graph. Suppose, by way of contradiction, that G_p^* is not P_4 -sparse. Then there is at least one induced P_4 in G_p^* that is not in G . Let $P = (v_1, v_2, v_3, v_4)$ be such a P_4 in G_p^* . We will show that there are 5 vertices that induces two P_4 's in G , thus getting a contradiction. By symmetry, it is enough to consider the following five cases.

Case 1 : $v_1v_2 \in E(G)$, $v_2v_3 \in E(G)$ and $v_3v_4 \notin E(G)$.

Then, v_3 and v_4 are both adjacent to a dense vertex $w \in V(G)$ (by the definition of the partial b -closure). Note that $v_1w \notin E(G)$ (resp. $v_2w \notin E(G)$) otherwise $v_1v_4 \in E(G_p^*)$ (resp. $v_2v_4 \in E(G_p^*)$) and P would not be an induced P_4 in G_p^* . Hence, $\{v_1, v_2, v_3, w, v_4\}$ induces a P_5 which contains two induced P_4 .

Case 2 : $v_1v_2 \in E(G)$, $v_2v_3 \notin E(G)$ and $v_3v_4 \in E(G)$.

In this case, v_2 and v_3 are both adjacent to a dense vertex $w \in V(G)$ (again, by the definition of the b -closure). Note that $v_1w, v_4w \notin E(G)$, for otherwise, this would imply that $v_1v_3 \in E(G_p^*)$ ($v_2v_4 \in E(G_p^*)$), by the definition of the partial b -closure. But then, $\{v_1, v_2, w, v_3, v_4\}$ is an induced P_5 in G .

Case 3 : $v_1v_2 \notin E(G)$, $v_2v_3 \in E(G)$ and $v_3v_4 \notin E(G)$.

As $v_1v_2 \notin E(G)$, the vertices v_1 and v_2 are both adjacent to a dense vertex $w_1 \in V(G)$. Moreover, $w_1v_3 \notin E(G)$ (resp. $w_1v_4 \notin E(G)$), since for otherwise $v_1v_3 \in E(G_p^*)$ (resp. $v_1v_4 \in E(G_p^*)$) and P would not be an induced P_4 in G_p^* . By a similar argument, v_3 and v_4 are both adjacent to a dense vertex $w_2 \in V(G)$, which is not adjacent to v_1 and w_2 . Note that w_1 and w_2 are distinct since $w_1v_4 \notin E(G)$. If $w_1w_2 \notin E(G)$, then $\{v_1, w_1, v_2, v_3, w_2\}$ is an induced P_5 in G . If $w_1w_2 \in E(G)$, then $\{v_1, w_1, v_2, w_2, v_4\}$ induces two P_4 's in G .

Case 4 : $v_1v_2 \notin E(G)$, $v_2v_3 \notin E(G)$ and $v_3v_4 \in E(G)$.

Using arguments similar to the ones in the previous cases, we obtain that there are distinct dense vertices $w_1, w_2 \in V(G)$ satisfying $v_1w_1, v_2w_1, v_2w_2, v_3w_2 \in E(G)$, and $v_1w_2, v_4w_2, v_3w_1, v_4w_1 \notin E(G)$. If $w_1w_2 \in E(G)$ then $\{v_1, w_1, w_2, v_3, v_4\}$ induces a P_5 in G . If $w_1w_2 \notin E(G)$, then the set $\{v_1, w_1, v_2, w_2, v_3\}$ induces a P_5 in G .

Case 5 : $v_1v_2 \notin E(G)$, $v_2v_3 \notin E(G)$ and $v_3v_4 \notin E(G)$.

Again, by similar arguments to the ones used in the previous cases, there are distinct dense vertices $w_1, w_2, w_3 \in V(G)$ such that $v_1w_1, v_2w_1, v_2w_2, v_3w_2, v_3w_3, v_4w_3 \in E(G)$, and $v_3w_1, v_4w_1, v_1w_2, v_4w_2, v_1w_3, v_2w_3 \notin E(G)$. If $w_1w_3 \in E(G)$, the set $\{v_1, w_1, w_3, v_3, v_4\}$ induces two P_4 's in G . Henceforth we may assume that $w_1w_3 \notin E(G)$. If $w_1w_2, w_2w_3 \in E(G)$, then the set $\{v_1, w_1, w_2, w_3, v_4\}$ induces a P_5 in G . Hence by symmetry, we may assume that $w_2w_3 \in E(G)$. If $w_1w_2 \in E(G)$, then the set $\{v_1, w_1, v_2, w_2, v_3\}$ induces two P_4 's in G . If $w_1w_2 \notin E(G)$ the set $\{v_1, w_1, v_2, w_2, w_3\}$ induces two P_4 's in G .

□

Babel et al. [14] showed that the precoloring extension problem is linear-time solvable for $(q, q - 4)$ -graphs, which are graphs where no set of at most q vertices induces more than $q - 4$ different P_4 's. Hence,

Corollary 20. *The TIGHT b -CHROMATIC PROBLEM can be decided in linear time for tight P_4 -sparse graphs.*

Consequently, for tight P_4 -sparse graphs, this algorithm is faster than the $O(|V|^3)$ algorithm given in [1], that solves the more general case where the input graph is not necessarily tight.

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