An update on reconfiguring 10-colorings of planar graphs

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Abstract
The reconfiguration graph $R_k(G)$ for the $k$-colorings of a graph $G$ has as vertex set the set of all possible proper $k$-colorings of $G$ and two colorings are adjacent if they differ in the color of exactly one vertex. A result of Bousquet and Perarnau (2016) regarding graphs of bounded degeneracy implies that if $G$ is a planar graph with $n$ vertices, then $R_{12}(G)$ has diameter at most $6n$. We improve on the number of colors, showing that $R_{10}(G)$ has diameter at most $8n$ for every planar graph $G$ with $n$ vertices.

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1 Introduction and result

Let $G$ be a graph, and let $k$ be a non-negative integer. A (proper) $k$-coloring of $G$ is a function $\varphi : V(G) \to \{1, \ldots, k\}$ such that $\varphi(u) \neq \varphi(v)$ whenever $uv \in E(G)$. The reconfiguration graph $R_k(G)$ of the $k$-colorings of $G$ has as vertex set the set of all $k$-colorings of $G$, with two colorings adjacent if they differ in the color of exactly one vertex. That is, two $k$-colorings $\varphi_1$ and $\varphi_2$ are joined by a path in $R_k(G)$ if and only if we can transform $\varphi_1$ into $\varphi_2$ by recoloring vertices one by one, always keeping the coloring proper,
and the number of recolorings needed is equal to the distance between $\varphi_1$ and $\varphi_2$ in $R_k(G)$. Hence, it is natural to ask how the diameter of $R_k(G)$ depends on $k$ and the number of vertices of $G$, subject to various conditions ensuring the $k$-colorability of $G$.

The study of the reconfiguration graph for colorings was begun by the statistical physics community in the context of Glauber dynamics for random colorings; see for example [14, 18]. It has also recently attracted the attention because of its connections to the existence of FPTAS for the number of colorings, but also for its own structural and computational merit. For example, typical questions include deciding whether two colorings belong to the same component of the reconfiguration graph, or that of determining the diameter of its components. For more details, we refer the reader to the surveys by van den Heuvel [17] and by Nishimura [15].

A graph is $k$-degenerate if every subgraph of the graph contains a vertex of degree at most $k$. Clearly, every $k$-degenerate graph $G$ is $(k+1)$-colorable, but $R_{k+1}(G)$ may be disconnected (e.g. in the case $G = K_{k+1}$, but there are many more instances [2]). On the other hand, $R_{k+2}(G)$ is always connected [8]. Cereceda [7] conjectured the following.

**Conjecture 1.** If $G$ is a $k$-degenerate graph on $n$ vertices, then $R_{k+2}(G)$ has diameter $O(n^2)$.

This bound would be best possible [3]. Although the conjecture has resisted several efforts, there have been some partial results surrounding it [1, 6, 5, 9, 10, 11, 13]. The most important breakthrough is a theorem of Bousquet and Heinrich [5] where it was shown, among other results, that $R_{k+2}(G)$ has diameter $O(n^{k+1})$. In particular, the conjecture is still open even for $k = 2$.

Bousquet and Perarnau [6] gave the following bound in the situation when the number of colors is substantially larger than $k + 2$.

**Theorem 2** (Bousquet and Perarnau [6, Theorem 1]). If $G$ is a $k$-degenerate graph on $n$ vertices and $c \geq 2k + 2$, then $R_c(G)$ has diameter at most $(k + 1)n$.

It was also shown by Bartier and Bousquet [4] that $R_{k+4}(G)$ has diameter $O(n)$ for every $k$-degenerate chordal graph $G$ of bounded maximum degree. Another result in this direction was obtained by the second author [12] by showing that, for every graph $G$ of maximum average degree at most $k + \epsilon$ ($0 \leq \epsilon < 1$), the reconfiguration graph $R_{k+2}(G)$ has diameter $O(n \log n)^{k+1})$. In particular, for any fixed $k$, this diameter is $O(n^2)$, confirming Conjecture 1 for this class of graphs.

Planar graphs are 5-degenerate and have maximum average degree less than 6, and thus the aforementioned results imply that if $G$ is a planar graph with $n$ vertices, then $R_8(G)$ has diameter $O(n \log n)$ and $R_{12}(G)$ has diameter at most $6n$. This motivates the following question.

**Problem 3.** What is the minimum integer $\kappa$ such that for every planar graph $G$ with $n$ vertices, $R_\kappa(G)$ has diameter $O(n)$?

The object of this paper is to show $\kappa \leq 10$, improving on the bound 12 following from Theorem 2.
Theorem 4. Let $G$ be a planar graph on $n$ vertices. Then $R_{10}(G)$ has diameter at most $8n$.

Consider the coloring of the icosahedron graph $D$ where the opposite vertices get the same color. This gives a 6-coloring of $D$ where the closed neighborhood of each vertex contains all 6 colors, and hence this 6-coloring forms an isolated vertex in $R_6(D)$. Consequently, $R_6(G)$ does not even need to be connected for planar graphs, implying $\kappa \geq 7$. However, not much is known about $R_7(G)$ for planar graphs $G$. The 5-degenerate graphs for which $R_7(G)$ has quadratic diameter constructed in [3] (paths with four apex vertices) are non-planar. A natural candidate for a planar graph $G$ with $R_7(G)$ of quadratic diameter is as follows: Consider an embedding of $K_7$ on the torus. Cut this drawing along a non-contractible triangle (that is, a triangle not bounding a disk) and glue together many copies of the resulting cylinder (Figure 1 shows the graph obtained from gluing three copies). We obtain a planar graph with a 7-coloring such that the closed neighborhood of all but six vertices contains all 7 colors, so to recolor this graph, one has to "propagate" from the ends of the cylinder. However, this graph $G$ is 3-degenerate and chordal, and thus $R_7(G)$ in fact has linear diameter by the aforementioned result of Bartier and Bousquet [4]. Hence, we cannot exclude the possibility that the answer to Problem 3 is $\kappa = 7$.

2 Outline of the proof

In this section, we lay out our strategy for proving Theorem 4. Let us start off by noting that Theorem 4 will follow as an immediate consequence to the following theorem.
Theorem 5. Let $G$ be a planar graph. Let $\alpha$ be a 10-coloring of $G$. Then there exists a sequence of recolorings from $\alpha$ to some 9-coloring of $G$ that recolors every vertex either at most once, to a color distinct from 10, or exactly twice, first to the color 10 and then to a color distinct from 10.

Theorem 4 follows by a standard argument.

Proof of Theorem 4. Let $\alpha$ and $\beta$ be 10-colorings of $G$. To prove the theorem, it suffices to show that we can recolor $\alpha$ to $\beta$ by at most $8n$ recolorings.

By Theorem 5, we can recolor $\alpha$ to some 9-coloring $\alpha_1$ of $G$ by at most $2n$ recolorings and $\beta$ to some 9-coloring $\beta_1$ by at most $2n$ recolorings. By [16], there exists a partition of $V(G)$ into an independent set $I$ and a 3-degenerate graph $D$. From $\alpha_1$ and $\beta_1$ recolor the vertices in $I$ to color 10 (the color that is not used in $\alpha_1$ and $\beta_1$). Let $\alpha_2$ and $\beta_2$ denote the restrictions of $\alpha_1$ and $\beta_1$ to $D$. Applying Theorem 2, the distance between $\alpha_2$ and $\beta_2$ in $R_9(D)$ is at most $4|V(D)|$, and thus we can recolor $\alpha_2$ to $\beta_2$ by at most $4|V(D)|$ recolorings without using the color 10. This completes the proof.

The rest of this paper will be devoted to the proof of Theorem 5. In order to prove the theorem, we must first make a few definitions. A scene is a pair $(G, \alpha)$, where $G$ is a plane graph and $\alpha$ is a 10-coloring of $G$. We say that a sequence of recolorings from $\alpha$ to some coloring $\gamma$ of $G$ is valid if $\gamma$ uses only colors 1, ..., 9 and every vertex $v$ of $G$ is recolored either at most once (to the color $\gamma(v)$) or exactly twice, first to the color 10 and then to the color $\gamma(v)$. We say that the scene $(G, \alpha)$ is recolorable if $G$ admits a valid sequence of recolorings starting from $\alpha$.

The scene $(G, \alpha)$ is said to be a minimal counterexample if $(G, \alpha)$ is not recolorable and all scenes $(G', \beta)$ such that

- $|V(G')| < |V(G)|$, or
- $|V(G')| = |V(G)|$ and $|E(G')| > |E(G)|$, or
- $G' = G$ and $|\beta^{-1}(10)| > |\alpha^{-1}(10)|$

are recolorable.

Our aim will be to exclude the existence of a minimal counterexample, which will prove Theorem 5. We begin with an easy proposition.

Lemma 6. If $(G, \alpha)$ is a minimal counterexample, then $G$ is a triangulation and the color 10 appears in the closed neighborhood of every vertex of $G$ under $\alpha$.

Proof. Suppose that $G$ is not a triangulation; then for some face $f$ of $G$, there exist distinct non-adjacent vertices $u$ and $v$ incident with $f$. If $\alpha(u) \neq \alpha(v)$, we insert the edge $uv$. If $\alpha(u) = \alpha(v)$ we identify $u$ and $v$ into a new vertex $u'$. The resulting graph $G'$ is plane and, by minimality, $(G', \alpha)$ is recolorable (we consider $\alpha$ to be a coloring of $G'$ by defining $\alpha(u') = \alpha(u) = \alpha(v)$). As any valid sequence of recolorings in $G'$ easily translates into a valid sequence of recolorings in $G$, this shows that $G$ must be a triangulation.
Suppose that the color 10 does not appear on some vertex $v$ of $G$ or any of its neighbors. Recolor $v$ to the color 10 and let $\alpha'$ denote the resulting coloring. By minimality, $(G, \alpha')$ is recolorable. It follows, by definition, that $(G, \alpha)$ is recolorable.

We now analyze the structure of a minimal counterexample $(G, \alpha)$ by showing that $G$ cannot contain a number of induced subgraphs whose vertices are of prescribed degrees (here and in Section~3). Afterwards, we will show that no such minimal counterexample exists using the discharging method (see Section~4).

Let $H$ be an induced subgraph of $G$. By the minimality of $(G, \alpha)$, there exists a valid sequence of recolorings in $G - V(H)$ from the restriction of $\alpha$ to $G - V(H)$ to some coloring $\gamma$ of $G - V(H)$. Let us define a list assignment $L^H$ for $H$ by setting

$$L^H(v) = \{1, \ldots, 9\} \setminus \left( \bigcup_{u \in N_G(v) \setminus V(H)} \{\alpha(u), \gamma(u)\} \right)$$

for each $v \in V(H)$. We say that $L^H$ is an assignment of available colors to $H$ in $(G, \alpha)$; let us remark that there may be several different assignments of available colors, corresponding to different colorings of $G - V(H)$.

We have the following proposition. A sequence of recolorings of $H$ is said to be a once-only recoloring if every vertex of $H$ is recolored at most once. The induced subgraph $H$ of $G$ is said to be reducible in $(G, \alpha)$ if for every assignment of available colors $L^H$ to $H$, there exists a once-only recoloring of $H$ from the restriction of $\alpha$ to some $L^H$-coloring of $H$.

**Lemma 7.** In a minimal counterexample $(G, \alpha)$, no induced subgraph of $G$ is reducible.

**Proof.** Let $H$ be an induced subgraph of $G$. By minimality, $G - V(H)$ has a valid sequence of recolorings $\sigma$ to some coloring $\gamma$. Let $L^H$ be the corresponding assignment of available colors to $H$. Suppose for a contradiction $H$ is reducible. Then there exists a once-only recoloring $\sigma'$ of $H$ from the restriction of $\alpha$ to some $L^H$-coloring $\gamma_H$ of $H$. But $\sigma'$ followed by $\sigma$ is a valid sequence of recolorings in $G$. Indeed, recoloring of a vertex $v \in V(H)$ according to $\sigma'$ does not conflict with the colors of its neighbors in $G - V(H)$, since if $u \in V(G) \setminus V(H)$ and $uv \in E(G)$, then $\alpha(u) \notin L^H(v)$. Afterwards, recolorings of $u \in V(G) \setminus V(H)$ do not conflict with the color of its neighbors $v \in V(H)$, since $u$ can only be recolored to 10 or $\gamma(u)$ and neither of these colors belongs to $L^H(v)$. This is a contradiction. \hfill \square

It is often convenient to focus just on the sizes of the lists. For a function $s : X \to \mathbb{N}$ with $V(H) \subseteq X$, we say that a list assignment $L$ for $H$ is an $s$-list assignment if $|L(v)| \geq s(v)$ for every $v \in V(H)$. Let

$$s_G^H(v) = 9 - 2(\deg_G v - \deg_H v)$$

and

$$s_{G,\alpha}^H(v) = 9 - 2(\deg_G v - \deg_H v) + |(N_G(v) \cap \alpha^{-1}(10)) \setminus V(H)|$$

for $v \in V(H)$. 

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THE ELECTRONIC JOURNAL OF COMBINATORICS 27(4) (2020), #P4.51
Remark 8. Notice, by definition, that any assignment of available colors to $H$ in $(G, \alpha)$ is an $s^H_{G,\alpha}$-list assignment, and thus also an $s^H_G$-list assignment.

A motif $M$ consists of a graph $H_M$, a 10-coloring $\alpha_M$ of $H_M$, and an assignment $L_M$ of subsets of $\{1, \ldots, 9\}$ to vertices of $H_M$. For an induced subgraph $F$ of $H_M$, a motif $M'$ is an $F$-restriction of $M$ if $H_M' = F$, $\alpha_M'$ is the restriction of $\alpha_M$ to $F$, and $L_M'(v) \subseteq L_M(v)$ for $v \in V(F)$. The motif $M$ is oo-recolorable (to $\gamma$) if there exists a once-only recoloring of $H_M$ from $\alpha_M$ to an $L_M$-coloring $\gamma$ of $H_M$. For a scene $(G, \alpha)$ and an induced subgraph $H$ of $G$, we say a motif $M$ is induced by $H$ if $H_M = H$ and $\alpha_M$ is the restriction of $\alpha$ to $H$, and $L_H$ is an $s^H_{G,\alpha}$-list assignment. We use the following easy consequence of Lemma 7 and Remark 8 to constrain minimal counterexamples.

Lemma 9. Let $(G, \alpha)$ be a minimal counterexample. If $H$ is an induced subgraph of $G$, then there exist a motif $M$ induced by $H$ in $(G, \alpha)$ that is not oo-recolorable.

Proof. Let $\alpha_H$ be the restriction of $\alpha$ to $H$. By Lemma 7, $H$ is not reducible, and thus for some assignment $L^H$ of available colors to $H$ in $(G, \alpha)$, there does not exist any once-only recoloring from $\alpha_H$ to an $L^H$-coloring of $H$. Let $M$ be the motif with $H_M = H$, $\alpha_M = \alpha_H$, and $L_M = L^H$. Then $M$ is not oo-recolorable, and since $L^H$ is an $s^H_{G,\alpha}$-list assignment by Remark 8, the motif $M$ is induced by $H$. 

In the next section, we show a number of motifs that are oo-recolorable, and thus they cannot be induced in a minimal counterexample. Before we do that, let us point out the aspects of our argument that we consider to be novel: Our original plan was to restrict ourselves to once-only recolorings; this enables us to apply the method of reducible configurations which has not been previously used in the area, since we only need to forbid two colors (the initial and the final color) per neighbor outside of the configuration. A bit of a breakthrough for us then was the seemingly counterintuitive notion of valid sequences of recolorings, where we introduce new vertices of color 10 in order to eventually eliminate the color 10. This enables us to assume that color 10 appears in the closed neighborhood of every vertex, which is extremely useful in proving the reducibility of configurations.

3 Structure of minimal counterexample

In this section, we show in a series of lemmas that if $(G, \alpha)$ is a minimal counterexample, then $G$ has minimum degree at least five and does not contain any of the graphs in Figure 2 as induced subgraphs with the prescribed degrees of vertices. Let us start with a trivial observation.

Observation 10. Suppose $M$ is a motif. If $|V(H_M)| = 1$ and $|L_M(v)| \geq 1$ for the unique vertex $v \in V(H_M)$, then $M$ is oo-recolorable.

Corollary 11. If $(G, \alpha)$ is a minimal counterexample, then $G$ has minimum degree at least five.
Corollary 15. Let $M$ be a motif. If $|L_M(v)| > \deg_M v$ for every $v \in V(M)$, then $M$ is oo-recolorable.
Lemma 18. Let \( M \) be a motif, let \( v \) be a vertex of \( M \), and consider any color \( c \in L_M(v) \). If \( M \) is oo-recolorable unless \( \alpha_M(v) = 10 \), we have \( M \ominus (v \rightarrow c) = M - (v \rightarrow c) \).

Lemma 16. Let \( M \) be a motif, let \( v \) be a vertex of \( M \), and consider any color \( c \in L_M(v) \). If \( M \ominus (v \rightarrow c) \) is oo-recolorable, then \( M \) is oo-recolorable.

Proof. By assumptions, \( M \ominus (v \rightarrow c) \) is oo-recolorable via a sequence \( \sigma \) of recolorings. This sequence of recolorings can also be performed in \( M \), since no neighbor of \( v \) can be assigned the color \( \alpha_M(v) \). Finally, we can recolor \( v \) to \( c \), since no neighbor may end up with the color \( c \). This shows \( M \) is oo-recolorable. \( \square \)

We will generally repeatedly use the preceding claims to simplify the motif obtained by Lemma 9, often to one contradicting Corollary 15. For brevity, let us introduce a notation for this kind of arguments. Suppose \( m > |V(M)| \) is a positive integer and \( V(M) = \{ v_i : i \in I \} \) for some \( I \subseteq \{1, \ldots, m\} \). A vector \( (s_1, \ldots, s_m) \) describes \( M \) if \( s_i \) is an integer smaller or equal to \( |L(v_i)| \) for \( i \in I \) and \( s_i = 0 \) for \( i \in \{1, \ldots, m\} \setminus I \). Furthermore, a segment of this vector can be enclosed in square brackets; this indicates that there exists an index \( i \) in this segment such that \( \alpha_M(v_i) = 10 \). By \( M \sim (s_1, \ldots, s_i, \ldots, s_m) \xrightarrow{L} (s'_1, \ldots, s'_m) \sim M' \), we mean the following: The motif \( M \) is described by the vector \( (s_1, \ldots, s_m) \), and applying Lemma \( n \) with \( v = v_i \), we obtain a motif \( M' \) described by \( (s'_1, \ldots, s'_m) \), such that if \( M \) is not oo-colorable, then \( M' \) also is not oo-colorable. In case Lemma 14 or Lemma 16 with more than one color choice is applied, we also specify the color \( c \) over the arrow. In case the resulting motif \( M' \) is not further discussed (e.g., a contradiction with Corollary 15 is obtained), the \( \sim M' \) part is omitted. We can also chain several such statements in the natural way. In all the arguments, we without loss of generality assume that \( |L(v_i)| = s_i \), implicitly removing extra colors from the lists if needed.

Recall that by Lemma 6, the color 10 appears in the closed neighborhood of every vertex of a minimal counterexample. The proofs of Lemmas 17–23 below mainly rely on Observation 10 and Corollary 15 (which, in turn, relies on Lemma 14).

Lemma 17. Let \((G, \alpha)\) be a minimal counterexample and let \( v_1 \) and \( v_2 \) be adjacent vertices of \( G \). If \( \deg v_1 = \deg v_2 = 5 \), then either \( \alpha(v_1) = 10 \) or \( \alpha(v_2) = 10 \).

Proof. By Lemma 9, there exist a motif \( M \) induced by \( H = G[\{v_1, v_2\}] \) in \((G, \alpha)\) that is not oo-recolorable. If neither \( u \) nor \( v \) has color 10, then since the color 10 appears in the closed neighborhood of every vertex, we have \( s^H_{G,\alpha}(u) \geq 2 \) and \( s^H_{G,\alpha}(v) \geq 2 \). However, this contradicts Corollary 15. \( \square \)

We also need the following three easy observations.

Lemma 18. Let \( M \) be a motif such that \( H_M \) is an edge with vertices \( v_1 \) and \( v_2 \). If \( M \) is described by \((2, 1)\), then \( M \) is oo-recolorable unless \( \alpha_M^{-1}(10) \cap V(M) = \emptyset \), \( L_M(v_1) = \{\alpha_M(v_1), \alpha_M(v_2)\} \) and \( L_M(v_2) = \{\alpha_M(v_1)\} \).
Corollary 15. Suppose that $M$ is not oo-recolorable. If there exists a color $c_2 \in L_M(v_2) \setminus \{\alpha_M(v_1)\}$, then $M \sim (2,1) \overset{L_{14,c_2}}{\rightarrow} (1,\bullet)$, contradicting Observation 10. It follows that $L_M(v_2) = \{\alpha_M(v_1)\}$. Hence, if there exists a color $c_1 \in L_M(v_1) \setminus \{\alpha_M(v_1), \alpha_M(v_2)\}$, then $M \sim (2,1) \overset{L_{14,c_1}}{\rightarrow} (\bullet,1)$, contradicting Observation 10. Therefore, we have $L_M(v_1) = \{\alpha_M(v_1), \alpha_M(v_2)\}$, and in particular $\alpha_M^{-1}(10) \cap V(M) = \emptyset$.

\begin{lemma}
Let $M$ be a motif such that $H_M$ is a path $v_1v_2v_3$. If $M$ is described by $(2,2,2)$ and $\alpha^{-1}(10) \cap V(H_M) \neq \emptyset$, then $M$ is oo-recolorable.
\end{lemma}

\begin{proof}
Suppose for a contradiction $M$ is not oo-recolorable and that $\alpha^{-1}(10) \cap V(H_M) \neq \emptyset$. If $\alpha(v_1) = 10$, then $M \sim (2,2,2) \overset{L_{13}}{\rightarrow} (\bullet,2,2)$, contradicting Corollary 15. It follows by symmetry that $\alpha(v_2) = 10$; but then $M \sim (2,2,2) \overset{L_{12}}{\rightarrow} (\bullet,2,\bullet)$, contradicting Observation 10.
\end{proof}

\begin{lemma}
Let $M$ be a motif such that $H_M$ is a path $v_1v_2v_3$. If $M$ is described by $(1,4,1)$, then $M$ is oo-recolorable.
\end{lemma}

\begin{proof}
Suppose $M$ is not oo-recolorable. If there exists a color $c_1 \in L_M(v_1) \setminus \{\alpha_M(v_2)\}$, then $M \sim (1,4,1) \overset{L_{14,c_1}}{\rightarrow} (\bullet,3,1) \overset{L_{12}}{\rightarrow} (\bullet,\bullet,1)$, contradicting Observation 10. So we can assume by symmetry that $L_M(v_1) = L_M(v_3) = \{\alpha_M(v_2)\}$. But then for $c_2 \in L_M(v_2) \setminus \{\alpha_M(v_1), \alpha_M(v_2), \alpha_M(v_3)\}$, we have $M \sim (1,4,1) \overset{L_{14,c_2}}{\rightarrow} (1,\bullet,1)$, contradicting Corollary 15.
\end{proof}

We now make two observations about triangles in a minimal counterexample.

\begin{lemma}
Let $(G,\alpha)$ be a minimal counterexample. If $G$ contains a triangle $T$ with vertices $v_1$, $v_2$, and $v_3$ such that $v_1$ has degree five and $v_2$ and $v_3$ have degree at most six, then $\alpha^{-1}(10) \cap V(T) \neq \emptyset$.
\end{lemma}

\begin{proof}
By Lemma 9, there exists a motif $M$ induced by $T$ in $(G,\alpha)$ that is not oo-recolorable. Suppose for a contradiction that no vertex of $T$ has color 10. Since the color 10 appears in the closed neighborhood of every vertex, we have $s_{G,\alpha}(v_1) \geq 4$ and $s_{G,\alpha}(v_2), s_{G,\alpha}(v_3) \geq 2$. If there existed a color $c \in L_M(v_2) \setminus \{\alpha(v_1), \alpha(v_3)\}$, we would have $M \sim (4,2,2) \overset{L_{14,c}}{\rightarrow} (3,\bullet,1) \overset{L_{12}}{\rightarrow} (\bullet,\bullet,1)$, contradicting Observation 10. Therefore, $L_M(v_2) = \{\alpha(v_1), \alpha(v_3)\}$, and by symmetry, $L_M(v_3) = \{\alpha(v_1), \alpha(v_2)\}$. Then, letting $c'$ be a color in $L_M(v_1) \setminus \{\alpha(v_1), \alpha(v_2), \alpha(v_3)\}$, we have $M \sim (4,2,2) \overset{L_{14,c'}}{\rightarrow} (\bullet,2,2)$, contradicting Corollary 15.
\end{proof}

\begin{lemma}
Let $M$ be a motif such that $H_M$ is a triangle with vertices $v_1$, $v_2$, and $v_3$. If $M$ is described by $(4,3,1)$, then $M$ is oo-recolorable, and if $M$ is described by $(3,3,1)$ or $(3,3,2)$, then $M$ is oo-recolorable unless $\alpha_M^{-1}(10) = \emptyset$ and $L_M(v_1) = L_M(v_2) = \{\alpha_M(v_1), \alpha_M(v_2), \alpha_M(v_3)\}$ and $L_M(v_3) \subseteq \{\alpha_M(v_1), \alpha_M(v_2)\}$.
\end{lemma}

9
Proof. Suppose first that $M$ is described by $(3, 3, 1)$ or $(3, 3, 2)$, and that $M$ is not oo-recolorable. If there exists $c_3 \in L_M(v_3) \setminus \{\alpha_M(v_1), \alpha_M(v_2)\}$, then $M \sim (3, 3, 1) \xrightarrow{L_{14,c_3}} (2, 2, \bullet)$, contradicting Corollary 15. Hence, we have $L_M(v_3) \subseteq \{\alpha_M(v_1), \alpha_M(v_2)\}$, and by symmetry we can assume $\alpha_M(v_1) \in L_M(v_3)$. If there exists a color $c_1 \in L_M(v_1) \setminus \{\alpha_M(v_1), \alpha_M(v_2), \alpha_M(v_3)\}$, then we can first recolor $v_1$ by $c_1$, then $v_3$ by $\alpha_M(v_1)$ and finally $v_2$ by a color in $L_M(v_2) \setminus \{\alpha_M(v_1), c_1\}$, showing that $M$ is oo-recolorable, a contradiction. Therefore $L_M(v_1) = \{\alpha_M(v_1), \alpha_M(v_2), \alpha_M(v_3)\}$, and in particular $\alpha_M^{-1}(10) = \emptyset$. If $L_M(v_2) \neq L_M(v_1)$, then there would exist $c_2 \in L_M(v_2) \setminus \{\alpha_M(v_1), \alpha_M(v_2), \alpha_M(v_3)\}$, and $M \sim (3, 3, 1) \xrightarrow{L_{14,c_2}} (3, \bullet, 1) \xrightarrow{L_{12}} (\bullet, \bullet, 1)$, contradicting Observation 10. This gives the characterization of non-oo-recolorable motifs described by $(3, 3, 1)$ or $(3, 3, 2)$.

Suppose now $M$ is described by $(4, 3, 1)$; then we can delete a color from $L_M(v_1)$ to obtain a motif $M'$ described by $(3, 3, 1)$, but with $L_M(v_1) \neq L_M(v_2)$. The motif $M'$ is oo-recolorable by the previous paragraph, and thus $M$ is oo-recolorable as well.

We also require the following observation on diamonds in a minimal counterexample.

Lemma 23. Let $(G, \alpha)$ be a minimal counterexample. Let $v_1, \ldots, v_4$ be distinct vertices of $G$ such that the subgraph $F$ of $G$ induced by $\{v_1, v_2, v_3, v_4\}$ contains all possible edges except for $v_2v_4$. If $\deg v_1 \leq 7$, $\deg v_2 \leq 5$ and $\deg v_3, \deg v_4 \leq 6$, then $\alpha^{-1}(10) \cap V(F) \neq \emptyset$.

Proof. By Lemma 9, there exists a motif $M$ induced by $F$ in $(G, \alpha)$ that is not oo-recolorable. Suppose for a contradiction no vertex of $F$ has color 10. Since the color 10 appears in the closed neighborhood of every vertex, $M$ is described by $(2, 4, 4, 2)$. If there exists a color $c_4 \in L_M(v_4) \setminus \{\alpha(v_1), \alpha(v_2)\}$, then $M \sim (2, 4, 4, 2) \xrightarrow{L_{14,c_4}} (1, 4, 3, \bullet)$, contradicting Lemma 22. Therefore $L_M(v_4) = \{\alpha(v_1), \alpha(v_2)\}$. If there exists a color $c_1 \in L_M(v_1) \setminus \{\alpha(v_2), \alpha(v_3), \alpha(v_4)\}$, then $M \sim (2, 4, 4, 2) \xrightarrow{L_{14,c_1}} (\bullet, 3, 3, 1) \xrightarrow{L_{12}} (\bullet, \bullet, 3, 1) \xrightarrow{L_{12}} (\bullet, \bullet, \bullet, 1)$, contradicting Observation 10. Hence, $L_M(v_1) \subseteq \{\alpha(v_2), \alpha(v_3), \alpha(v_4)\}$. If there exists a color $c_3 \in L_M(v_3) \setminus \{\alpha(v_1), \ldots, \alpha(v_4)\}$, then $M \sim (2, 4, 4, 2) \xrightarrow{L_{14,c_3}} (2, 3, \bullet, 2) \xrightarrow{L_{12}} (2, \bullet, \bullet, 2)$, contradicting Corollary 15. Therefore, $L_M(v_3) = \{\alpha(v_1), \ldots, \alpha(v_4)\}$, and in particular $\alpha(v_2) \neq \alpha(v_4)$. Choose a color $c_2 \in L_M(v_2) \setminus \{\alpha(v_1), \alpha(v_2), \alpha(v_3)\}$.

- If $\alpha(v_2) \in L_M(v_1)$, we first recolor $v_2$ to $c_2$, then $v_1$ to $\alpha(v_2)$, and finally $v_4$ to $\alpha(v_1)$.
- Otherwise, $L_M(v_1) = \{\alpha(v_3), \alpha(v_4)\}$. We first recolor $v_2$ to $c_2$, then $v_3$ to $\alpha(v_2)$, then $v_1$ to $\alpha(v_3)$, and finally $v_4$ to $\alpha(v_1)$.

We are now ready to demonstrate that the graphs in Figure 2 are reducible.

Lemma 24. If $(G, \alpha)$ is a minimal counterexample, then $G$ contains none of the induced subgraphs with prescribed vertex degrees depicted in Figure 2.

Proof. Suppose for a contradiction $C$ is one of the graphs depicted in Figure 2 and contained in $G$ as an induced subgraph with the prescribed degrees of vertices. By Lemma 9, there exist a motif $M$ induced by $C$ in $(G, \alpha)$ that is not oo-recolorable. We prove that each of the cases are reducible separately, starting with $C_1$ and working our way towards $C_{16}$. We fix the labeling of vertices as indicated in Figure 2.
(C1) By Lemma 17, either \(\alpha(v_1) = \alpha(v_3) = 10\), or \(\alpha(v_2) = 10\). In the former case, 
\[M \sim ([1],[3],[1]) \overset{L_{12}}{\longrightarrow} (1,\bullet,1),\] 
contradicting Corollary 15. In the latter case, 
\[M \sim (1,[3],1) \overset{L_{13}}{\longrightarrow} (1,\bullet,1),\] 
again contradicting Corollary 15.

(C2) By Lemma 17 and symmetry, we can assume \(\alpha(v_3) = 10\). But then 
\[M \sim (1,3,[3]) \overset{L_{13}}{\longrightarrow} (1,3,\bullet) \overset{L_{12}}{\longrightarrow} (1,\bullet,\bullet),\] 
contradicting Observation 10.

(C3) If \(\alpha(v_2) = \alpha(v_4) = 10\), then 
\[M \sim (3,[3],3,[3]) \overset{L_{13}}{\longrightarrow} (3,\bullet,3,\bullet),\] 
contradicting Corollary 15. Hence, by Lemma 21 and symmetry, we can assume \(\alpha(v_3) = 10\). Now, there exists a color \(c \in L_M(v_1) \setminus \{\alpha(v_2),\alpha(v_4)\}\). However, then 
\[M \sim (3,3,[3],3) \overset{L_{14,c}}{\longrightarrow} (\bullet,2,[2],2),\] 
contradicting Lemma 19.

(C4) If \(\alpha(v_1) = 10\), then 
\[M \sim ([5],1,3,5,1) \overset{L_{13}}{\longrightarrow} (\bullet,1,3,5,1) \overset{L_{12}}{\longrightarrow} (\bullet,1,3,\bullet,1) \overset{L_{12}}{\longrightarrow} (\bullet,1,\bullet,\bullet,1),\] 
contradicting Corollary 15. If \(\alpha(v_3) = \alpha(v_5) = 10\), then 
\[M \sim (5,1,[3],[5],[1]) \overset{L_{12}}{\longrightarrow} ([5],1,[3],\bullet,[1]) \overset{L_{12}}{\longrightarrow} (\bullet,1,[3],\bullet,1) \overset{L_{13}}{\longrightarrow} (\bullet,1,\bullet,\bullet,1),\]
contradicting Corollary 15. Hence, Lemma 21 implies \( \alpha(v_4) = 10 \), and thus 
\[ M \sim (5, 1, 3, [5], 1) \xrightarrow{L_{13}} (5, 1, 3, \bullet, 1) \sim M'. \]
Let \( \{c_5\} = L_M(v_5) \). We have 
\[ M' \sim (5, 1, 3, \bullet, 1) \xrightarrow{L_{16}} (3, 1, 3, \bullet, \bullet), \]
and thus Lemma 22 implies that \( L_M(v_1) \) is the disjoint union of \( L_M(v_1) = \{\alpha(v_1), \alpha(v_2), \alpha(v_3)\} \) and \( \{\alpha(v_5), c_5\} \). In particular, \( c_5 \neq \alpha(v_1) \), and thus 
\[ M' \sim (5, 1, 3, \bullet, 1) \xrightarrow{L_{14}, c_5} (4, 1, 3, \bullet, \bullet), \]
contradicting Lemma 22.

(C5) If \( \alpha(v_1) = 10 \), then 
\[ M \sim ([5], 1, 3, 3, 1) \xrightarrow{L_{13}} ([1], 1, 3, 3, 1) \xrightarrow{L_{12}} ([1], 1, 3, 3, 1), \]
contradicting Corollary 15. If \( \alpha(v_3) = \alpha(v_4) = 10 \), then 
\[ M \sim ([5], 1, 3, 3, 1) \xrightarrow{L_{13}} ([1], 1, 3, 3, 1) \xrightarrow{L_{12}} ([1], 1, 3, 3, 1), \]
again contradicting Corollary 15. If \( \alpha(v_3) = \alpha(v_5) = 10 \), then 
\[ M \sim (5, 1, [3], 3, 1) \xrightarrow{L_{13}} (5, 1, [3], 3, 1) \xrightarrow{L_{16}} (3, [3], 3, 1), \]
contradicting Lemma 22. Hence, by Lemma 21 and symmetry, we can assume \( \alpha(v_2) = \alpha(v_3) = 10 \). But then, for any \( c_3 \in L_M(v_3) \setminus \{\alpha(v_1), \alpha(v_4)\} \), 
\[ M \sim (5, [3], 3, 3, 3) \xrightarrow{L_{13}} (5, [3], 3, 3, 3) \xrightarrow{L_{14}, c_3} (4, [1], 3, 3, 3), \]
contradicting Corollary 15.

(C6) If \( \alpha(v_1) = 10 \), then 
\[ M \sim ([5], 3, 3, 3, 3) \xrightarrow{L_{13}} ([3], 3, 3, 3, 3), \]
contradicting Corollary 15. Note that at most one of the adjacent vertices \( v_3 \) and \( v_4 \) can have color 10. Hence, by Lemma 21 and symmetry, we can assume \( \alpha(v_2) = 10 \). But then, for any \( c_3 \in L_M(v_3) \setminus \{\alpha(v_1), \alpha(v_4)\} \), 
\[ M \sim (5, [3], 3, 3, 3) \xrightarrow{L_{13}} (5, [3], 3, 3, 3) \xrightarrow{L_{14}, c_3} (4, [1], 3, 3, 3), \]
contradicting Lemma 22.

(C7) If \( \alpha(v_2) = 10 \), then 
\[ M \sim (3, [3], 5, 3, 3) \xrightarrow{L_{13}} (3, [3], 5, 3, 3) \xrightarrow{L_{12}} (3, [3], 5, 3, 3), \]
contradicting Corollary 15. Hence, by Lemma 17 we have \( \alpha(v_3) = 10 \). It follows that 
\[ M \sim (3, 3, [5], 3, 3) \xrightarrow{L_{13}} (3, 3, [5], 3, 3) \xrightarrow{L_{12}} (3, 3, [3], 3, 3), \]
which again contradicts Corollary 15.

(C8) If \( \alpha(v_1) = 10 \), then 
\[ M \sim ([7], 3, 3, 3, 3, 3) \xrightarrow{L_{13}} ([3], 3, 3, 3, 3, 3), \]
which contradicts Corollary 15. If \( \alpha(v_2) = \alpha(v_6) = 10 \), then 
\[ M \sim (7, [3], 3, 3, 3, [3]) \xrightarrow{L_{13}} (7, [3], 3, 3, 3, [3]) \xrightarrow{L_{12}} ([3], 3, 3, 3, [3]), \]
again contradicting Corollary 15. If \( \alpha(v_3) = \alpha(v_5) = 10 \), choose \( c_1 \in L_M(v_1) \setminus \{\alpha(v_2), \alpha(v_4), \alpha(v_6)\} \); we have 
\[ M \sim ([7], 3, [3], 3, 3, 3) \xrightarrow{L_{14}, c_1} ([3], 2, [2], 2, [2], [2]), \]
contradicting Lemma 19.

Hence, by Lemma 21 and symmetry, we can assume \( \alpha(v_2) = \alpha(v_5) = 10 \). For \( c_3 \in L_M(v_3) \setminus \{\alpha(v_1), \alpha(v_4)\} \), we have 
\[ M \sim ([7], [3], 3, 3, [3], 3) \xrightarrow{L_{13}} ([7], [3], 3, 3, [3], 3) \xrightarrow{L_{14}, c_3} ([3], [3], 2, [2], [2]), \]
contradicting Corollary 15.
If $\alpha(v) = 10$, then we have $M \sim ([7], 3, 3, 3, 3, 5, 3, 1) \xrightarrow{L_{13}} ([4], 3, 3, 3, 5, 3, 1) \xrightarrow{L_{12}} ([1], 3, 3, 3, \cdot, 3, 1)$, which contradicts Corollary 15. Therefore by Lemma 23 we can assume that at least one of $v_2$, $v_3$, $v_4$ has color 10 and at least one of $v_5$, $v_6$, $v_7$ has color 10. Choose a color $c_6 \in L_M(v_6) \setminus \{\alpha(v), \alpha(v_7)\}$, let $L_M(v_7) = \{c_7\}$, and choose a color $c_1 \in L_M(v_1) \setminus (\{c_6, c_7\} \cup \bigcup_{i=2}^{5}(\alpha(v_i)))$. Then $M \sim ([7], [3, 3, 3], [5, 3, 1]) \xrightarrow{L_{14}, c_1} ([1], 2, 2, 2, [4, 2, 1]) \sim M'$, where $L_{M'}(v_6) \neq \{\alpha(v), \alpha(v_7)\}$.

If $\alpha(v_5) = 10$, then we can continue with

$$M' \sim ([1], 2, 2, 2, [4, 2, 1]) \xrightarrow{L_{14}} ([6], 2, 2, 2, [4, 2, 1]) \xrightarrow{L_{13}} ([1], 2, 2, 2, [4, 2, 1]) \sim M'.$$

If $\alpha(v_4) = 10$, then

$$M'' \sim ([2, 2, 2, [4, 1, \cdot]) \xrightarrow{L_{12}} ([2, 2, 2, [4, 1, \cdot]) \xrightarrow{L_{19}} ([\cdot, \cdot, \cdot, \cdot, 1, \cdot]),$$

which contradicts Observation 10. If $\alpha(v_3) = 10$, then $M'' \sim ([2, 2, 2, [4, 1, \cdot]) \xrightarrow{L_{12}} ([2, 2, 2, [4, 1, \cdot]) \xrightarrow{L_{13}} ([2, 2, 2, [4, 1, \cdot]) \sim M''$. If $\alpha(v_2) = 10$, then $M'' \sim ([2, 2, 2, [4, 1, \cdot]) \xrightarrow{L_{12}} ([2, 2, 2, [4, 1, \cdot]) \xrightarrow{L_{14}} ([\cdot, \cdot, \cdot, 1, 4, 1])$, which again contradicts Lemma 20.

(C10) By Lemma 17 and symmetry, we can assume $v_5$ has color 10. By Lemma 23, it follows that $v_2$ or $v_3$ has color 10. We have $M \sim ([7], [1, 3], 5, [5], 3, 1) \xrightarrow{L_{13}} ([7], [1, 3], 5, [5], 3, 1) \sim M'$. Let $L_{M'}(v_i) = \{c_i\}$ for $i \in \{2, 7\}$ and choose $c_6 \in L_{M'}(v_6) \setminus \{\alpha(v_6), \alpha(v_7)\}$. Then there exists a color $c_1 \in L_{M'}(v_1) \setminus \{c_2, c_6, c_7, \alpha(v_2), \alpha(v_3), \alpha(v_6), \alpha(v_7)\}$, and

$$M' \sim ([7], [1, 3], \cdot, \cdot, 3, 1) \xrightarrow{L_{14}, c_1} ([1, 2], \cdot, \cdot, 2, 1) \sim M'',$$

where $L_{M''}(v_6) \neq \{\alpha(v_6), \alpha(v_7)\}$. This contradicts Lemma 18.

(C11) If $\alpha(v_1) = 10$, then $M \sim ([7], 3, 3, 3, 3, 3, 3, 3) \xrightarrow{L_{13}} ([\cdot, \cdot, \cdot, \cdot, \cdot, \cdot, \cdot, \cdot])$, contradicting Corollary 15. Lemma 23 thus implies $\alpha^{-1}(10) \cap \{v_2, v_3, v_4\} \neq \emptyset$ and $\alpha^{-1}(10) \cap \{v_5, v_6, v_7\} \neq \emptyset$. Now,

- for each $i \in \{2, 7\}$, if $\alpha(v_i) = 10$, apply Lemma 13 to $v_i$, and

THE ELECTRONIC JOURNAL OF COMBINATORICS 27(4) (2020), #P4.51
• for all $i \in \{2, \ldots, 7\}$, if $\alpha(v_i) \neq 10$ and $\deg_M^i(v_i) \leq 2$, then choose a color $c_i \in L_M(v_i) \setminus \alpha(N_M(v_i))$ and apply Lemma 14.

Let $M'$ denote the resulting motif. Note that one of the two cases always applies for $i = 2$ and $i = 7$, and thus $v_2, v_7 \not\in V(M')$.

Suppose that for some $i \in \{3, 4\}$, we have $v_i \in V(M')$ and $\alpha(v_i) \neq 10$. By the construction of $M'$, we have $\deg_M^i(v_i) = 3$, and thus $\alpha(v_{i-1}) \neq 10 \neq \alpha(v_{i+1})$.

Since $\alpha^{-1}(10) \cap \{v_2, v_3, v_4\} \neq \emptyset$, it follows that $i = 4$ and $\alpha(v_2) = 10$. Hence, the number of vertices $v_i \in V(M')$ such that $i \in \{3, 4\}$ and $\alpha(v_i) \neq 10$ is at most $|\alpha^{-1}(10) \cap \{v_2\}|$. Symmetrically, the number of vertices $v_i \in V(M')$ such that $i \in \{5, 6\}$ and $\alpha(v_i) \neq 10$ is at most $|\alpha^{-1}(10) \cap \{v_2\}|$.

Therefore, $\deg_M^i(v_i) \leq |\alpha^{-1}(10) \cap \{v_2\}|$. On the other hand, we have $|L_M(v_1)| = 7 = |V(M)|$. Note that during the construction of $M'$, the colors are removed from the list of $v_1$ only in the second case; hence,

$$|L_M(v_1)| \geq |L_M(v_1)| - (|V(M)| - |V(M')|) + |\alpha^{-1}(10) \cap \{v_2, v_7\}| = |V(M')| + |\alpha^{-1}(10) \cap \{v_2, v_7\}| - \deg_M^i(v_1) + \deg_M^i(v_1).$$

Therefore, $M'$ is oo-recolorable by Lemma 12 applied to $v_1$ and by Corollary 15. This is a contradiction.

(C12) If $\alpha(v_1) = 10$, let $c_1 \in L_M(v_1)$. We have

$$M \sim (\overbrace{[5], 3, 3, 5, 3, 3}^{\text{L16, c1}} \xrightarrow{\bullet, 2, 2, 4, 2, 2} \xrightarrow{\text{L14}} (\bullet, \bullet, 1, 4, 1, \bullet),$$

contradicting Lemma 20. If $\alpha(v_4) = 10$, we have

$$M \sim (5, 3, 3, [5], 3, 3) \xrightarrow{\text{L13}} (\overbrace{5, 3, 3, \bullet, 3, 3}^{\text{L14}} \xrightarrow{\bullet, 2, 2, \bullet, 2, 2},$$

which contradicts Corollary 15. If $\alpha(v_3) = 10$, then $M \sim (\overbrace{5, 3, [3], 5, 3, 3}^{\text{L14}} \xrightarrow{\bullet, 2, [2], 4, 2, 2} \xrightarrow{\text{L12}} (\bullet, 2, [2], \bullet, 2, 2),$ contradicting Corollary 15. The case $\alpha(v_5) = 10$ is symmetric. Therefore, Lemma 23 implies $\alpha(v_2) = \alpha(v_6) = 10$, and thus

$$M \sim (\overbrace{5, [3], 3, 5, 3, 3}^{\text{L13}} \xrightarrow{\bullet, 3, 5, 3, \bullet})$$

contradicting Corollary 15.

(C13) By Lemma 17, either $\alpha(v_2) = 10$ or $\alpha(v_3) = 10$, and thus either

$$M \sim (\overbrace{5, [3], 5, 3, 3, 1}^{\text{L13}} \xrightarrow{\bullet, 5, 3, 3, 1} \xrightarrow{\text{L12}} (\bullet, 5, \bullet, 3, 3, 1) \sim M',$$

or

$$M \sim (5, 3, [5], 3, 3, 1) \xrightarrow{\text{L13}} (\overbrace{5, 3, 3, 3, 1}^{\text{L12}} \xrightarrow{\bullet, 3, 3, 1}) \sim M'.$$

Let $\{c_6\} = L_M(v_6)$; we have $M' \sim (\overbrace{5, \bullet, 3, 3, 1}^{\text{L16, c6}} \xrightarrow{3, \bullet, 3, 1, \bullet})$ and by Lemma 22, we have $L_M(v_1) = L_M(v_4) = \{\alpha(v_1), \alpha(v_4), \alpha(v_5)\}$. Consequently, $L_M(v_1) = \{\alpha(v_1), \alpha(v_4), \alpha(v_5), c_6\}$, and in particular $c_6 \not\in \{\alpha(v_1), \alpha(v_5)\}$. Therefore $M' \sim (\overbrace{4, \bullet, 3, 2, \bullet})$, contradicting Lemma 22.
(C14) By Lemma 17, either $\alpha(v_2) = 10$ or $\alpha(v_3) = 10$, and thus either
\[
M \sim (5, [3], 5, 3, 1, 1) \xrightarrow{L_{13}} (5, \bullet, 5, 3, 1, 1) \xrightarrow{L_{12}} (5, \bullet, \bullet, 3, 1, 1) \sim M',
\]
or
\[
M \sim (5, 3, [\bar{3}], 3, 1, 1) \xrightarrow{L_{13}} (5, \bar{3}, \bullet, 3, 1, 1) \xrightarrow{L_{12}} (5, \bullet, \bullet, 3, 1, 1) \sim M'.
\]
Let $\{c_6\} = L_{M'}(v_6)$; we have $M' \sim (5, \bullet, \bullet, 3, 1, 1) \xrightarrow{L_{16,c_6}} (3, \bullet, \bullet, 3, 1, \bullet) \sim M^*$, and by Lemma 22, we have $L_{M'}(v_1) = L_{M'}(v_4) = \{\alpha(v_1), \alpha(v_4), \alpha(v_5)\}$. Consequently, $L_{M'}(v_1) = \{\alpha(v_1), \alpha(v_4), \alpha(v_5), \alpha(v_6), c_6\}$, and in particular $c_6 \neq \alpha(v_1)$. Therefore $M' \sim (5, \bullet, \bullet, 3, 1, 1) \xrightarrow{L_{14,c_6}} (4, \bullet, \bullet, 3, 1, \bullet)$, contradicting Lemma 22.

(C15) In this case $M$ is described by $(9, 3, 3, 3, 3, 3, 3, 3)$. Repeatedly apply Lemma 14 to the vertices $v_2, \ldots, v_8$ as long as there exists $i \in \{2, \ldots, 8\}$ such that the list of $v_i$ contains a color not appearing on its neighbors; let $M'$ denote the resulting motif. Note that $|L_{M'}(v_i)| > |V(M')|$ and that $|L_{M'}(v_i)| = \deg_M v_i$ and $L_{M'}(v_i) \subseteq \alpha(V(M'))$ for $i \in \{2, \ldots, 8\}$ such that $v_i \in V(M')$. Hence, there exists a color $c_1 \in |L_{M}(v_1)| \setminus \alpha(V(M'))$, and this color does not appear in the lists of vertices of $\{v_2, \ldots, v_8\} \cap V(M')$. Applying Lemma 14, $M' - (v_1 \rightarrow c_1)$ contradicts Corollary 15.

(C16) By Lemma 17 and symmetry, we can assume that $\alpha(v_5) = 10$. If $\alpha^{-1}(10) \cap \{v_2, v_3\} \neq \emptyset$, then $M \sim (3, [3], 1, 3, [\bar{3}]) \xrightarrow{L_{13}} (3, [3], 1, 3, \bullet) \xrightarrow{L_{12}} (3, [3, 1, \bullet, \bullet])$, which contradicts Lemma 22. Therefore, the color 10 does not appear in the closed neighborhood of $v_2$ in $C_{16}$. Since the color 10 appears in the closed neighborhood of every vertex in $G$, we have $s_{G,\alpha}^C(v_2) \geq 4$, and thus $M \sim (3, 4, 1, 3, [\bar{3}]) \xrightarrow{L_{13}} (3, 4, 1, 3, \bullet, \bullet)$, which contradicts Lemma 22. \hfill \square

4 Discharging phase

Consider a plane triangulation $G$, a vertex $v \in V(G)$ of degree $k \geq 3$, and its neighbors $v_1, \ldots, v_k$ in the clockwise order around $G$. We say that the subgraph of $G$ consisting of the cycle $v_1 \ldots v_k$, the vertex $v$, and the edges $v_i v_j$ for $i = 1, \ldots, k$ is a wheel, $v$ is its center and $v_1, \ldots, v_k$ its rim. Note that a wheel is not necessarily an induced subgraph of $G$. Let $T$ be the triangle bounding the outer face of $G$. Let $C$ be a graph and $d : V(C) \rightarrow \mathbb{N}$ a function assigning a prescribed degree to each vertex of $C$. We say that $C$ with the prescribed degrees $d$ appears in $G$ if there exists a wheel $W$ in $G$ and an injective function $f : V(C) \rightarrow V(W)$ such that

- for distinct $x, y \in V(C)$, $xy$ is an edge of $C$ if and only if $f(x)f(y)$ is an edge of $W$,
- for all $x \in V(C)$, $\deg_G f(x) \leq d(x)$, and
- $f(V(C)) \cap V(T) = \emptyset$. 

\[\text{THE ELECTRONIC JOURNAL OF COMBINATORICS 27(4) (2020), \#P4.51}\]

15
Hence, $C$ is an induced subgraph of $W$, but the subgraph $C$ of $G$ is not necessarily induced (since $W$ may not be an induced subgraph of $G$). Let us remark that the last technical condition from the definition of appearance will be later used to deal with this issue.

Lemma 25. Suppose $G$ is a plane triangulation such that every vertex not incident with the outer face of $G$ has degree at least five. If $|V(G)| \geq 4$, then one of the graphs with prescribed degrees depicted in Figure 2 appears in $G$.

Proof. Suppose for a contradiction none of these graphs appears in $G$. We assign the initial charge $ch_0(v) = 10 \cdot \deg v - 60$ to each vertex $v$ of $G$. Since $G$ is a triangulation, we have $|E(G)| = 3|V(G)| - 6$ by Euler’s formula, and thus

$$\sum_{v \in V(G)} ch_0(v) = 20|E(G)| - 60|V(G)| = -120. \quad (1)$$

A vertex is big if it either has degree at least 7 or it is incident with the outer face of $G$, medium if it has degree six and is not incident with the outer face of $G$, and small if it has degree five and is not incident with the outer face of $G$.

Our general aim will be to show that, provided $G$ does not contain any of the graphs depicted in Figure 2, we can redistribute the charge of vertices so that the total of their final charges violates (1), and this contradiction will clearly complete the proof.

Let us now describe the redistribution rules. Let us remark that for a rule sending some amount of charge from a vertex $v$ to another vertex $u$, we also specify faces incident with $v$ through which the charge leaves $v$, and an edge $e$ incident with $u$ along which the charge arrives to $u$. Additionally, we specify a face incident with $e$ through which the charge passes. This is for accounting purposes—e.g., in order to bound the amount of charge leaving a vertex, we will bound the amount of charge which leaves the vertex through each incident face.

(R1) A big vertex $v$ sends 2 units of charge to each adjacent small vertex $u$ along the edge $vu$; of this charge, one unit leaves $v$ and passes through one of the faces incident with the edge $uv$, while the other unit leaving $v$ passes through the other face incident with $uv$.

(R2) Suppose $vux$ is a face of $G$, $v$ is big, $u$ is small and $x$ is medium or small. Then $v$ sends 1 unit of charge to $u$; the charge leaves $v$ and passes through the face $vux$ to arrive to $u$ along the edge $xu$.

(R3) Suppose $v_1, \ldots, v_m$ for some $m \in \{3, \ldots, 6\}$ are consecutive neighbors of a medium vertex $x$ in the clockwise or the counterclockwise order, $v_1$ is small, $v_2, \ldots, v_{m-1}$ are medium and $v_m$ is big. Then $v_m$ sends 1 unit of charge to $v_1$; the charge leaves $v_m$ through the face $xv_{m-1}v_m$ and passes through the face $xv_1v_2$ to arrive to $v_1$ along the edge $v_2v_1$.

Note that (R2) applies in addition to the two units of charge sent by $v$ to $u$ by (R1), but the charge arrives to $u$ along a different edge. In case $x$ is small, the charge is also being
sent from $v$ to $x$ by (R2) with the roles of $u$ and $x$ exchanged. Furthermore, note that (R3) may possibly send charge from $v_m$ to $v_1$ twice around the same vertex $x$, once in the clockwise direction, once in the counterclockwise one (when $x$ is the center of a wheel whose rim contains $v_1$ and $v_m$ and every other vertex of the rim is medium); similarly, note that (R3) may also possibly send charge to $v_1$ twice through the face $xv_1v_2$ (when $xv_1v_2$ is adjacent to another face $v_mxv_2$ and $v_1v_m \notin E(G)$ – thus, $v_m$ would send a unit of charge clockwise around $x$ and another unit of charge anticlockwise around $v_2$, where $v_2$ here plays the role of $x$).

We now analyze the final charge $ch(v)$ of each vertex $v$ of $G$ after the redistribution of the charge. Clearly, for a medium vertex $v$, we have $ch(v) = ch_0(v) = 0$.

Consider now a small vertex $z$. We claim that for each edge $e = wz$ incident with $z$ and each face $f = wzx$ incident with $e$, a unit of charge passes through $f$ to arrive to $z$ along $e$, and thus $ch(z) = ch_0(z) + 10 \times 1 = 0$. Indeed, if $w$ is big, then this is the case by (R1). If $w$ is not big and $x$ is big, then a unit of charge passing through $f$ arrives to $z$ along $e$ from $x$ by (R2). If neither $w$ nor $x$ is big, then since $C_2$ does not appear in $G$, both of them are medium. Since $C_4$ does not appear in $G$, $x$ has a neighbor $y$ distinct from $z$ that is not medium. Let $v_1 = z$, $v_2 = w$, $v_3$, ..., $v_m$ be the neighbors of $x$ in order, where $v_3$, ..., $v_{m-1}$ are medium and $v_m$ is not medium. Since $C_3$, $C_6$, $C_8$ and $C_2$ do not appear in $G$, the vertex $v_m$ is not small, and thus $v_m$ is big. Consequently, a unit of charge passing through $f$ arrives to $z$ along $e$ from $v_m$ by (R3).

Suppose now $v$ is a vertex of degree $d \geq 7$ not incident with the outer face of $G$. For a face $f = vxy$, let $t_v(f)$ denote the total amount of charge that leaves $v$ through $f$; in the following, we omit the subscript $v$ as long as the vertex $v$ is fixed. If both $x$ and $y$ are small, then $t(f) = 4$ since two units leave through $f$ by (R1), one arriving along the edge $vx$ and the other along $vy$, and two by (R2), arriving along the edge $xy$ in both directions. If $x$ is small and $y$ is medium or vice versa, then $t(f) = 2$ since one unit leaves through $f$ by (R1) and one by (R2). If both $x$ and $y$ are medium, then $t(f) \leq 2$, since at most two units leave through $f$ by (R3). If $x$ is small and $y$ is big or vice versa, then $t(f) = 1$, since only one unit leaves through $f$ by (R1). Otherwise, $t(f) = 0$.

Furthermore, consider the faces $f_1$ and $f_2$ following $f$ in the clockwise order around $v$. Since $C_1$ does not appear in $G$, if $t(f) = 4$, then $t(f_1) \leq 2$ and $t(f_2) \leq 2$. Consequently, there are at most $\lfloor d/3 \rfloor$ faces $f$ incident with $v$ such that $t(f) = 4$. If $d \geq 8$, this implies

$$ch(v) \geq ch_0(v) - 2d - 2\lfloor d/3 \rfloor = 8d - 2\lfloor d/3 \rfloor - 60 \geq 0.$$ 

Hence, we can assume $d = 7$, and thus $ch_0(v) = 10$. Let $v_1$, ..., $v_7$ be the neighbors of $v$ in the clockwise order, and for $i = 1, \ldots, 7$, let $f_i$ be the face $vv_i$ (where $v_8 = v_1$). Let $s = \sum_{i=1}^7 t(f_i)$ be the total amount of charge sent by $v$. We argue that $s \leq 10$, and thus $ch(v) = ch_0(v) - s \geq 0$. To do so, we discuss several cases.

- $v$ is adjacent to two consecutive small vertices in the cycle consisting of neighbors of $v$. Thus $v$ is incident with a face $f$ such that $t(f) = 4$. By symmetry, we can assume $t(f_1) = 4$, and thus $v_1$ and $v_2$ are small. Since $C_1$ does not appear in $G$, $v_3$ and $v_7$ are not small.
If \(v_5\) is small, then since \(C_{16}\) does not appear in \(G\), both \(v_4\) and \(v_6\) are big and hence \(t(f_4) = t(f_5) = 1, t(f_3) = t(f_6) = 0\), and \(t(f_2), t(f_7) \leq 2\), implying \(s \leq 10\). Hence, we can assume \(v_5\) is not small.

Suppose \(v_6\) and \(v_7\) are both medium. Since \(C_{13}\) does not appear in \(G\), \(v_5\) is big, and thus \(t(f_4) + t(f_5) + t(f_3) = 1 + 1 + 1 = 3\). Otherwise, since \(v_3\) and \(v_4\) are not both medium, we have \(t(f_3) = 0\) and \(t(f_2) + t(f_4) \leq 3\). Hence \(t(f_2) + t(f_3) + t(f_4) \leq 3\), and symmetrically \(t(f_7) + t(f_6) + t(f_5) \leq 3\). It follows that \(s \leq 1 + 3 + 3 = 10\).

- **small vertices are not consecutive in the cycle consisting of neighbors of \(v\).** Consequently, \(t(f) \leq 2\) for each face incident with \(v\) and \(v\) is adjacent to at most three small vertices.

Before we proceed, let us make a useful observation:

\((\star)\) For any \(b \in \{1, \ldots, 5\}\), if none of \(v_b, v_{b+1}\) and \(v_{b+2}\) is small, then \(t(f_b) + t(f_{b+1}) \leq 3\).

This is clearly the case unless \(v_b, v_{b+1}\), and \(v_{b+2}\) are all medium and \(t(f_b) = t(f_{b+1}) = 2\). Then, let \(v_b, v, v_{b+2}, z_3, z_2, z_1\) be the neighbors of \(v_{b+1}\) in order. Since \(t(f_b) = t(f_{b+1}) = 2\), charge leaves \(v\) through \(f_b\) and \(f_{b+1}\) twice by (R3), and thus either both \(z_1\) and \(z_3\) are small, or none of \(z_1, z_2, z_3\) is big and at least one of them is small. But then either \(C_5\) or \(C_4\) appears in \(G\), which is a contradiction.

Let us now continue with the case analysis.

- **\(v\) is adjacent to three small vertices.** By symmetry we can assume \(v_1, v_3\), and \(v_5\) are small. Since \(C_{12}\) does not appear in \(G\), we can by symmetry assume \(v_2\) is big, and hence \(t(f_1) = t(f_2) = 1\). If \(v_4\) is big, then \(t(f_3) = t(f_4) = 1\) implying \(s \leq 4 \times 1 + 3 \times 2 = 10\). Thus, since \(C_1\) does not appear in \(G\), we can assume \(v_4\) is medium. Since \(C_5\) does not appear in \(G\), \(v_6\) and \(v_7\) cannot both be medium, and thus \(t(f_6) = 0\). Consequently, \(s \leq 1 + 1 + 2 + 2 + 2 + 0 + 2 = 10\).

- **\(v\) is adjacent to two small vertices, at distance two in the cycle on neighbors of \(v\).** By symmetry we can assume \(v_1\) and \(v_3\) are small. If \(v_5\) is big, then \(t(f_3) = t(f_5) = 0\) and \(s \leq 5 \times 2 = 10\). Hence, we can assume \(v_5\) is medium, and by symmetry \(v_6\) is medium. Since \(C_{11}\) does not appear in \(G\), \(v_4\) and \(v_7\) are not both medium; by symmetry, we can assume \(v_7\) is big, and thus \(t(f_4) = 0\) and \(t(f_7) = 1\). Furthermore, \(t(f_4) + t(f_5) \leq 3\) by \((\star)\), and thus \(s \leq 2 + 2 + 2 + 3 + 0 + 1 = 10\).

- **\(v\) is adjacent to two small vertices, at distance three in the cycle on neighbors of \(v\).** By symmetry we can assume \(v_1\) and \(v_4\) are small. If \(v_6\) is big or both \(v_5\)
and \( v_7 \) are big, then \( t(f_5) = t(f_6) = 0 \) and \( s < 5 \times 2 = 10 \); hence, we can by symmetry assume \( v_5 \) and \( v_6 \) are medium. Since \( C_5 \) does not appear in \( G \), \( v_2 \) and \( v_3 \) are not both medium, and thus \( t(f_1) + t(f_2) + t(f_3) < 2 + 0 + 1 = 3 \). Furthermore, \( t(f_5) + t(f_6) < 3 \) by (\( \ast \)), implying \( s < 3 + 2 + 3 + 2 = 10 \).

- \( v \) is adjacent to at most one small vertex. By symmetry we can assume no neighbor of \( v \) other than possibly \( v_1 \) is small. If \( v_1 \) is big for some \( i \in \{1, 3, 4, 5, 6\} \), then \( t(f_{i-1}) = t(f_i) = 0 \) (where \( f_0 = f_7 \) and \( s < 5 \times 2 = 10 \)). Hence, we can assume \( v_1 \) is medium for \( i \in \{3, 4, 5, 6\} \) and \( v_1 \) is medium or small. Since \( C_{15} \) does not appear in \( G \), \( v_2 \) and \( v_7 \) are not both medium; by symmetry, we can assume \( v_2 \) is big, and thus \( t(f_1) + t(f_2) < 1 \). By (\( \ast \)), \( t(f_3) + t(f_4) < 3 \) and \( t(f_5) + t(f_6) < 3 \), and thus \( s < 1 + 2 + 3 + 2 < 10 \).

We conclude that every vertex not incident with the outer face of \( G \) has non-negative final charge.

Finally, let us consider a vertex \( v \) incident with the outer face of \( G \). Since \( |V(G)| \geq 4 \) and \( G \) is a triangulation, we have \( \deg(v) \geq 3 \). Furthermore, the outer face \( f \) of \( G \) is incident only with big vertices by definition, and thus \( t(f) = 0 \). Since \( t(f') \leq 4 \) for every face \( f' \neq f \) incident with \( v \), we have \( \chi(v) \geq \chi_0(v) - (\deg v - 1) \times 4 = 6 \deg v - 56 \geq -38 \). Therefore, (1) together with the fact that no charge is created or lost in the redistribution process gives

\[
-120 = \sum_{v \in V(G)} \chi_0(v) - \sum_{v \in V(G)} \chi(v) \geq 3 \times (-38) = -114,
\]

which is a contradiction. \( \square \)

**Corollary 26.** If \( G \) is a plane triangulation of minimum degree at least five, then one of the graphs depicted in Figure 2 is an induced subgraph of \( G \) with prescribed vertex degrees.

**Proof.** If \( G \) contains a separating triangle, then let \( T \) be a separating triangle in \( G \) such that the open disk in the plane bounded by \( T \) is minimal; otherwise, let \( T \) be the triangle bounding the outer face of \( G \). Let \( G' \) be the induced subgraph of \( G \) drawn in the closed disk bounded by \( T \). By Lemma 25, one of the graphs \( C \) with prescribed degrees depicted in Figure 2 appears in \( G \), via a map \( f : V(C) \to V(W) \) for a wheel \( W \) in \( G' \). By the choice of \( G' \), observe that \( G' \) does not contain any separating triangle, and thus \( W \) is an induced subgraph of \( G' \), and thus also of \( G \). Since \( C \) is an induced subgraph of \( W \), it follows that \( C \) is an induced subgraph of \( G \). Furthermore, \( V(C) \cap V(T) = \emptyset \) by the last condition from the definition of appearance, and thus the vertices of \( f(V(C)) \) have the same degree in \( G' \) and in \( G \). \( \square \)

The proof of the main result is now straightforward.

**Proof of Theorem 5.** Suppose for a contradiction that there exists a non-recolorable scene \( (G, \alpha) \). Choose such a scene with the smallest number of vertices, among those with the largest number of edges, and among those with the largest number of vertices of color 10.

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Then \((G, \alpha)\) is a minimal counterexample, and thus \(G\) is a triangulation by Lemma 6, has minimum degree at least five by Corollary 11, and does not contain any of the induced subgraphs with prescribed vertex degrees depicted in Figure 2. However, this contradicts Corollary 26.

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